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Multifactorial balance assessment, falls prevention and rehabilitation

Edited by
Nattawan Utoomprurkporn, Marousa Pavlou and Dimitrios Kikidis

Coordinated by
Christos Nikitas

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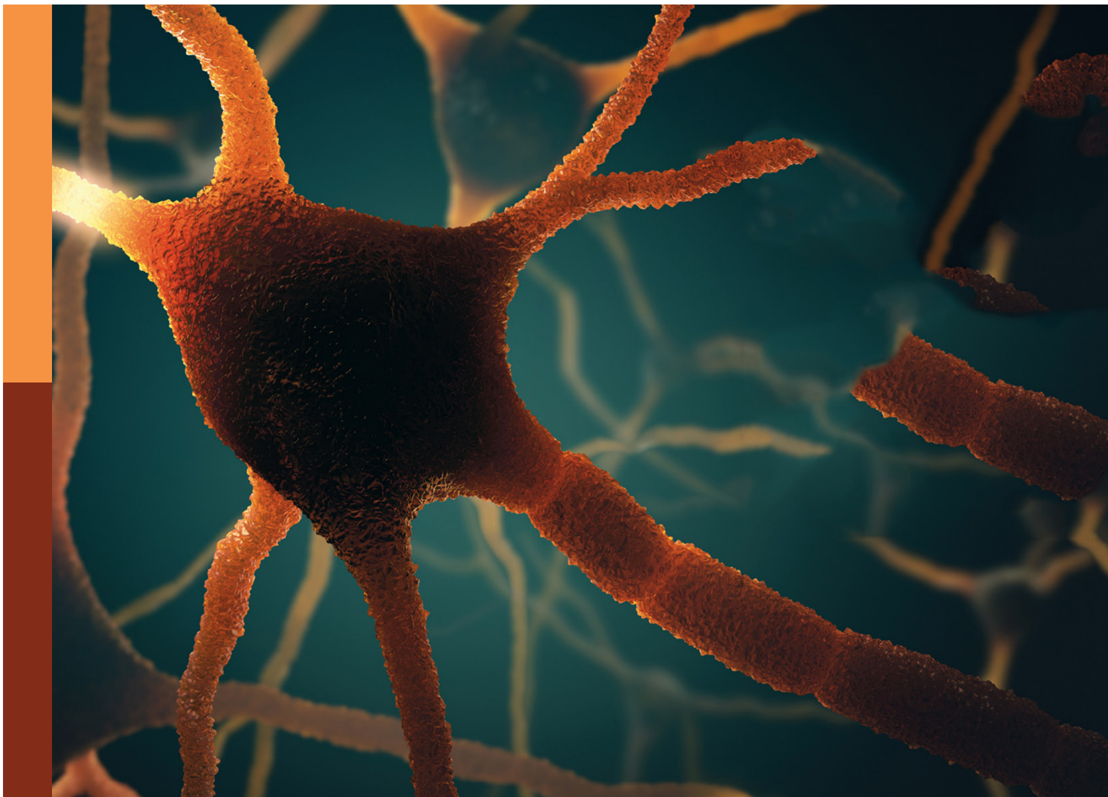

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Multifactorial balance assessment, falls prevention and rehabilitation

Topic editors
Nattawan Utoomprurkporn — Chulalongkorn University, Thailand
Marousa Pavlou — King's College London, United Kingdom
Dimitrios Kikidis — National and Kapodistrian University of Athens, Greece

Topic coordinator
Christos Nikitas — National and Kapodistrian University of Athens, Greece

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Robert Petersen,
Central Michigan University, United States

*CORRESPONDENCE
Nattawan Utoomprurkporn
✉ nattawan.u@chula.ac.th

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Editorial: Multifactorial balance assessment, falls prevention and rehabilitation

Dimitrios Kikidis[1], Brooke Nairn[2], Christos Nikitas[1], Marousa Pavlou[2,3], Nattawan Utoomprurkporn[4]* and Doris-Eva Bamiou[2,3]

[1]1st Department of Otorhinolaryngology, Head and Neck Surgery, National and Kapodistrian University of Athens, Hippocrateion General Hospital, Athens, Greece, [2]The Ear Institute, Faculty of Brain Sciences, University College London, London, United Kingdom, [3]Department of Neuro-Otology, Royal National Ear Nose Throat Hospital, University College, London Hospitals, London, United Kingdom, [4]Chulalongkorn University Faculty of Medicine, Bangkok, Thailand

KEYWORDS

balance rehabilitation, falls prevention, balance assessment, balance impairment, falls risk

Editorial on the Research Topic
Multifactorial balance assessment, falls prevention and rehabilitation

Falls remain a major public health challenge, particularly among adults aged 65 and older, with one-third of individuals in this population experiencing at least one fall annually and nearly 10 % suffering recurrent events (WHO Global Report, 2007; Sui et al.). Multifactorial in origin, involving the vestibular, visual, central nervous and proprioceptive systems, falls are correlated with several comorbidities, requiring multidisciplinary assessment. This Research Topic underscores the multifactorial nature of balance impairment by combining age-related sensorimotor decline, concurrent diagnoses and the possible effect of cognitive impairment.

Epidemiological data indicate that fall rates increase with advancing age and multimorbidity, while injury-related morbidity, hospital admissions, and mortality continue to rise globally (Sui et al.; Choo et al.). The burden is both clinical and economic: substantial direct costs (e.g., hospitalizations, rehabilitation) accompany indirect sequelae (e.g., effects on quality of life, loss of independence, fear of falling, social isolation, and caregiver strain), highlighting the need for preventive strategies and interventions.

Despite evidence-based recommendations supporting balance-based fall interventions, critical gaps persist. Chief among these is the underdevelopment of comprehensive assessment tools capable of capturing cognitive, sensory, and motor domains simultaneously, which limits the individualization of therapy. There is also limited integration of dual-task and neurocognitive training into standard rehabilitation protocols, which creates a barrier to addressing real-world fall risk (Nairn et al., 2025a). Moreover, adherence remains problematic with many older adults disengaging early, with up to a 50 % dropout rate of standard falls and balance programs, suggesting a mismatch between intervention design and patient-centered factors (Pavlou et al., 2013; Simek et al., 2012). Finally, the full value of indirect benefits including reduced caregiver burden and enhanced self-confidence, remains largely uncaptured in current evaluations, impeding policy buy-in.

Current trends in clinical practice reflect a gradual shift from single-domain interventions to multifactorial programs tailored to individual needs (Elrod and Wong). Established exercise protocols such as the Otago protocol (Wang and Kim) are being supplemented with dual-task and cognitive components to address fall risk more holistically and personally (Nairn et al., 2025a; Liston et al., 2014). Emerging studies highlight the integration of telerehabilitation and augmented reality, which offer scalable and remotely deliverable care models, especially vital in underserved regions (Gulline et al., 2025). However, real-world adoption remains inconsistent: many clinics continue to focus on generic exercise modules without adjusting for cognitive load, comorbidities, or patient lifestyle, indicating a need for stronger implementation frameworks.

Looking ahead, future directions must harness emerging technologies and methodological refinements to bridge existing gaps while meeting patient needs. Wearable biosensors and markerless motion analysis systems show promise for dynamic, real-time risk stratification. Advanced computational models integrating environment, physiology, and patient behavior may enable predictive analytics and personalized intervention pathways. Virtual reality solutions have recently become commercially available; however, their role is limited by default since they cannot facilitate walking exercises which are essential for the reestablishment of mobility.

Intensive research has been conducted using cutting-edge augmented reality technology within the context of three EU-funded projects (HOLOBALANCE, SMART BEAR, and the current TELEREHAB DSS). These projects project a holographic physiotherapist avatar in real-space, providing exercise programme guidance. These platforms also capture movements via body motion tracking sensors for providing real-time feedback on patients exercise performance and corrections. Preliminary work investigating these platforms' acceptability, feasibility and effectiveness has already been completed. The results have shown promise, in terms of cost-effectiveness, patient acceptability and usability among patients with MCI (Bovornratanaraks et al., 2024; Utoomprurkporn et al., 2023) and stroke (Nairn et al., 2025) in addition to preliminary feasibility using IMUs, pressure-sensitive wellness mats and the eHealth literacy application (Georgas et al.). Market analysis has also proven, that these telerehabilitation solutions fill many existing gaps and make rehabilitation more accessible and engaging, with TeleRehab DSS standing out as superior in terms of AI-decision support, objective data collection and real-time feedback (Nairn et al., 2025b).

Other pressing issues highlighted by Research Topic include the need for standardized outcome metrics. Currently, measures vary widely making study comparison difficult. A unified core outcome set would advance research coherence and meta-analytic capacity. Workforce development also requires attention: implementing multifactorial programs demands training physiotherapists in cognitive assessment and dual-task facilitation, in addition to the dedicated skills needed for balance physiotherapy which are not currently part of the relevant curricula, and creating multidisciplinary teams with clearly delineated roles while avoiding siloed delivery. Finally, equity considerations are paramount: older adults with neurological comorbidities or from socioeconomically disadvantaged backgrounds face the greatest fall risk, but are often excluded from trials. Future research must emphasize inclusion and access to ensure that interventions reach those most in need.

In summary, this Research Topic provides a timely and rigorous examination of multifactorial balance assessment and rehabilitation. By highlighting epidemiology, identifying intervention gaps, outlining current practices and trends, and charting future opportunities, this Research Topic offers a roadmap for translating science into sustainable, equitable fall prevention strategies.

Author contributions

DK: Writing – original draft, Writing – review & editing. BN: Writing – original draft, Writing – review & editing. CN: Writing – review & editing. MP: Writing – review & editing. NU: Conceptualization, Writing – review & editing. D-EB: Writing – review & editing.

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EDITED BY
Nattawan Utoomprurkporn,
Chulalongkorn University, Thailand

REVIEWED BY
Changhe Shi,
First Affiliated Hospital of Zhengzhou University, China
Matthew Swan,
Icahn School of Medicine at Mount Sinai, United States

*CORRESPONDENCE
Shengyuan Su
✉ sosheng@hotmail.com

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Risk factors for falls in Parkinson's disease: a cross-sectional observational and Mendelian randomization study

Yifan Zhang[1,2], Yuehui Zhang[1], Yuexin Yan[1], Xiangxu Kong[1] and Shengyuan Su[1]*

[1]Department of Intensive Care Medicine, ShenzhenBaoan People's Hospital, Shenzhen, China,
[2]Department of Neurological Center, ShenzhenBaoan People's Hospital, Shenzhen, China

Background: Patients with Parkinson's disease (PD) exhibit a heightened risk of falls and related fractures compared to the general population. This study aims to assess the clinical characteristics associated with falls in the patient with PD and to gain further insight into these factors through Mendelian randomization analysis.

Methods: From January 2013 to December 2023, we included 591 patients diagnosed with Parkinson's disease at Shenzhen Baoan People's Hospital. Using univariate and multivariate logistic regression analyses, we identified clinical variables associated with falls. We constructed a nomogram based on these variables and evaluated the predictive efficacy of the model. Additionally, we employed summary statistics from genome-wide association studies to conduct two-sample Mendelian randomization (MR) analyses on key variables influencing falls.

Results: Compared to the control group, we identified osteoporosis, motor dysfunction, higher Hoehn and Yahr scale as significant risk factors for falls in PD patients. Conversely, treatment with levodopa and a higher level of education exhibited a protective effect against the risk of falling. MR analysis further confirmed a causal relationship between osteoporosis, education level and falls in PD patients.

Conclusion: Osteoporosis and educational attainment are correlated with falls in Parkinson's disease.

KEYWORDS

Parkinson's disease, falls, clinical prediction, Mendelian randomization, osteoporosis

Introduction

Parkinson's Disease (PD) is a progressive neurodegenerative disorder predominantly characterized by motor dysfunctions such as tremors, rigidity, bradykinesia and issues with balance and coordination. These symptoms not only diminish the quality of life for patients but also substantially increase the risk of falls. Particularly in PD patients, the incidence of falls is higher compared to age-matched healthy individuals (Bloem et al., 2001), potentially leading to severe consequences such as restrictions in daily activities, heightened fear of falling, increased medical costs. and elevated care needs (Dahodwala et al., 2017; Fasano et al., 2017).

Studies have linked the propensity for falls in PD patients to diminished cholinergic activity, with degeneration of the Pedunculopontine Nucleus (PPN) being a primary cause of impaired postural control and gait dysfunction (Bohnen et al., 2009). Gait freezing and postural abnormalities are strongly associated prognostic factors for falls; gait freezing manifests as difficulty in turning and delayed limb coordination, thereby increasing the risk of falling (Murueta-Goyena et al., 2024). Postural abnormalities are primarily caused by impaired motor autonomy and reactive postural control (Bekkers et al., 2018).

In addition to assessments of balance and gait, current research also encompasses neuropsychological testing, non-motor symptoms, and disease-related variables, with demographic factors often serving as confounding factors in prognostic studies of falls. Although motor dysfunctions may compromise motor control and affect gait, they are frequently omitted in previous prognostic models for falls (Custodio et al., 2016). Furthermore, the predictive role of disease severity in falls remains contentious; the Hoehn and Yahr (H&Y) scale is a significant predictive tool (Kader et al., 2016), while the predictive capability of the Unified Parkinson's Disease Rating Scale (UPDRS) III scale still requires validation (Almeida et al., 2017; Kwon et al., 2021; Lindholm et al., 2021a).

PD patients are prone to fractures when they fall, associated with osteoporosis and reduced bone mass (Invernizzi et al., 2009). In addition to bone density reduction directly caused by PD, other factors such as reduced physical activity, vitamin D deficiency, malnutrition, duration and severity of the disease, old age and low body mass index contribute to the development of osteoporosis in PD patients (Pignolo et al., 2022). As the H&Y stage of PD patients increases, the decline in bone density becomes more pronounced (2023).

This study aims to analyze the clinical characteristics, motor disorder scores, disease stages and demographic data of PD patients to identify potential risk factors associated with falls. Moreover, using Genome-Wide Association Study (GWAS) data for Mendelian randomization (MR) analysis, this study further explores the correlation between relevant variables and falls.

Materials and methods

Study design and population

This study is a retrospective cross-sectional analysis of patients diagnosed with PD at Baoan People's Hospital from January 2013 to December 2023. Inclusion criteria were: (1) diagnosed with PD, (2) availability of data. Exclusion criteria included: (1) severe cognitive impairment, (2) history of orthopedic or spinal surgery or other chronic diseases of the musculoskeletal system, (3) history of Deep Brain Stimulation (DBS) surgery, (4) chronic renal failure or cancer, and (5) occurrence of stroke, myocardial infarction, severe liver disease, or cardiac disease within 3 months prior to study enrollment.

Clinical data collection

Patient data were collected from medical records, including basic demographic information (age, gender, and educational level), medical history (chronic diseases), motor function impairment scores (UPDRS III), H&Y staging, medication usage, laboratory tests, non-motor symptoms (including sleep disorders and anxiety), and personal history (smoking and alcohol consumption). The UPDRS III score was assessed during the medication-off period in patients. Anxiety refers to anxiety disorders and is diagnosed based on psychiatric evaluations using anxiety scales. A diagnosis of anxiety disorder is made when the Hamilton Anxiety Rating Scale (HAMA) score exceeds 7 points. Sleep disorders encompass difficulties in falling asleep and sleep maintenance issues, with the diagnostic criterion being a Pittsburgh Sleep Quality Index score of 8 or higher. Patients were divided into fallers and non-fallers based on whether they had fallen unintentionally onto the ground or another lower surface without overwhelming external force or significant internal events (Emerson, 2023). The study was approved by the Ethics Committee of Baoan People's Hospital in Shenzhen and conducted according to the Declaration of Helsinki standards, with an ethical approval number BYL20240403. This study has been successfully registered with the China Clinical Trial Registry under the registration number ChiCTR2400083288.

GWAS data sources

For the Mendelian randomization analysis, single nucleotide polymorphisms (SNPs) were used as instrumental variables, combining cross-sectional study results with previous research. Educational attainment and osteoporosis were considered exposure factors, with falls as the outcome variable. Data on educational attainment were derived from the Social Science Genetic Association Consortium (SSGAC), including 766,345 individuals of European descent (Lee et al., 2018). Osteoporosis data were derived from an extensive meta-analysis that identified genetic variants linked to Bone Mineral Density (BMD) at the Femoral Neck (FN), Forearm (FA), and Lumbar Spine (LS) in a cohort of 53,236 individuals of European ancestry (Zheng et al., 2015). Susceptibility to falls was determined using data from a UK Biobank study, which included 461,725 cases of falls.

Statistical analysis

The cross-sectional data of the included patients were described using frequencies and percentages for categorical data and continuous variables were expressed as mean ± standard deviation. The UPDRS- III and H&Y staging were transformed into dichotomous variables based on the optimal cutoff values corresponding to the maximum Youden Index on the receiver operating characteristic (ROC) curve. Educational level, a multicategory variable, was transformed into dummy variables. The Chi-square test was applied to categorical variables, while the Mann-Whitney U test was used to compare the continuous

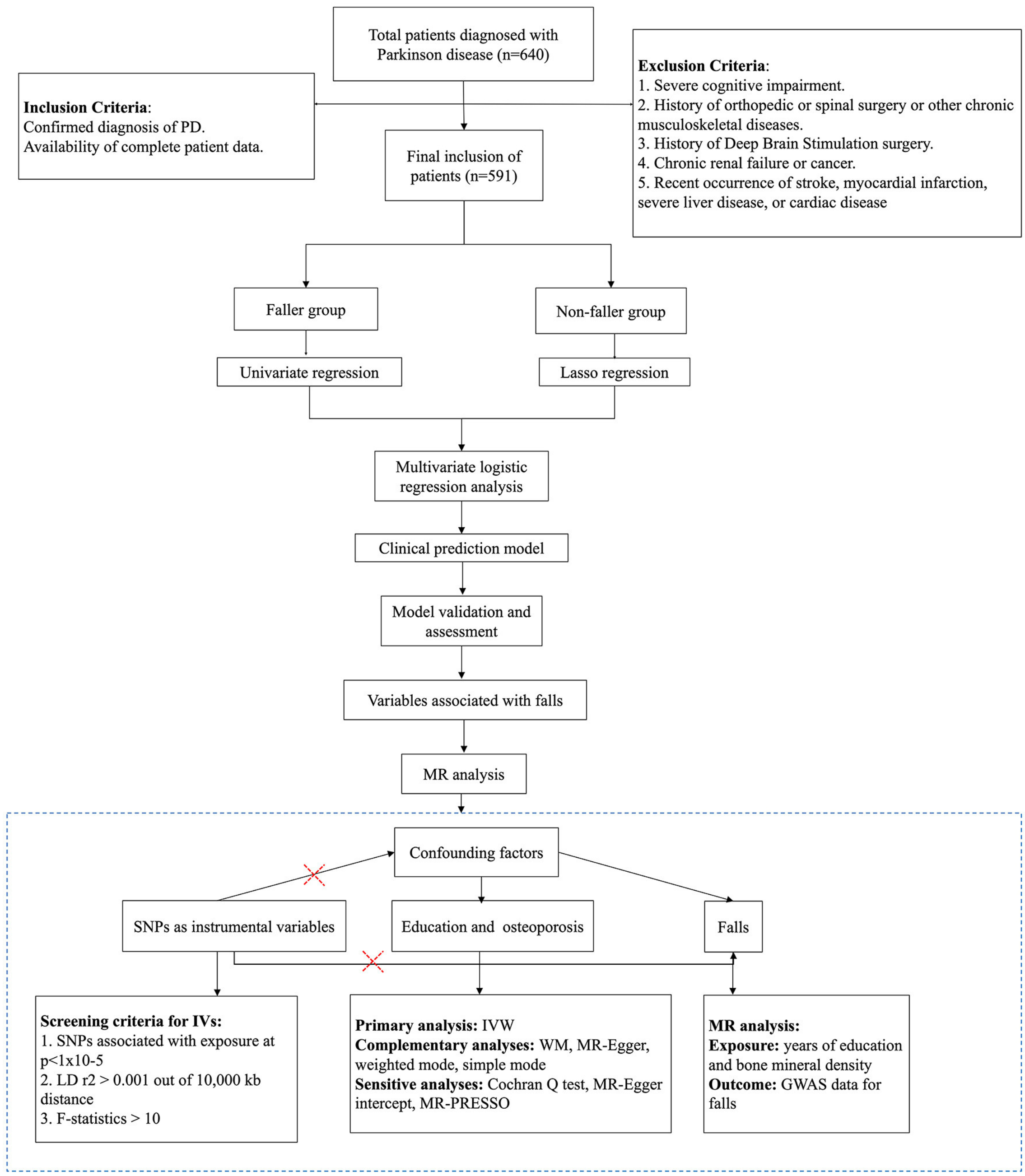

FIGURE 1
The flowchart of this study, Mendelian randomization (MR).

variables between the fallers and the control group. Univariate regression analysis and LASSO regression were utilized to select variables related to falls, followed by multivariate logistic regression analysis to identify clinical variables associated with falls. The model expressed the magnitude of associations using odds ratios (ORs) and 95% confidence intervals (CIs), with a significance level set at $p < 0.05$. Based on the multivariate analysis, a predictive model was constructed and internally validated using the concordance index (C-index), corrected C-index, calibration curves, clinical impact curve (CIC), decision curve analysis (DCA), and the ROC curve to assess the model's predictive accuracy and consistency. The fit of the model was evaluated with the Hosmer-Lemeshow test to check if the predicted probabilities matched the observed probabilities and a forest plot was created for a visual predictive analysis of the risk factors for falls.

MR analysis

In this study, MR analysis primarily utilized the Inverse Variance Weighted (IVW) method to assess the causal relationships

TABLE 1 Demographic characteristics and clinical features of fallers and non-fallers.

	Non-fallers ($n = 534$)	Fallers ($n = 57$)	*P* value
Demographics			
Age (years)	77 [69, 84]	78 [69, 84]	0.983
Gender (Male)	301 (56)	27 (47)	0.246
Motor features			
MDS-UPDRS III	28 [25, 32]	33 [25, 43]	0.007
Hoehn and Yahr staging	2.50 [2.00, 2.50]	2.50 [2.50, 2.70]	<0.001
Stage 2	169 (32)	4 (7)	
Stage 2.5	250 (47)	30 (53)	
Stage 3	99 (19)	21 (37)	
Stage 4	16 (3)	2 (4)	
Education			0.015
Below high school	265 (50)	31 (54)	
High school	159 (30)	23 (40)	
College or higher	110 (21)	3 (5)	
Medical history			
Osteoporosis	62 (12)	13 (23)	0.027
Hypertension	281 (53)	29 (51)	0.911
Diabetes	122 (23)	12 (21)	0.888
CAD	58 (11)	4 (7)	0.501
Stroke	158 (30)	25 (44)	0.039
Personal history			
Drinking	15 (3)	4 (7)	0.101
Smoking	11 (2)	2 (4)	0.362
Sleep and mental health			
Anxiety	88 (16)	7 (12)	0.528
Sleep disorders	26 (5)	5 (9)	0.208
Medication usage			
Levodopa treatment	332 (62)	27 (47)	0.042
Calcium_Supplement	38 (7)	3 (5)	0.787
Calcium_Phosphate	38 (7)	3 (5)	0.787
Calcium_Carbonate	150 (28)	22 (39)	0.132
Laboratory tests			
WBC ($\times 10^9$/L)	4.61 [3.55, 5.77]	6.35 [5.49, 7.63]	0.194
Neutrophils ($\times 10^9$/L)	4.08 [3.17, 4.79]	4.33 [3.02, 5.48]	0.159
Cholesterol (mmol/L)	0.99 [0.73, 1.3]	3.85 [3.09, 4.59]	0.337
Triglycerides (mmol/L)	2.55 [2.11, 3.08]	1.01 [0.77, 1.28]	0.795
Creatinine (mmol/L)	294.66 [235.05, 366.61]	66 [54.1, 83.1]	0.208
Uricacid (mmol/L)	79.98 [59.25, 84.08]	271.95 [230.4, 366]	0.335

For continuous variable "[ ]", the values represent quartiles, and for categorical variables "( )" indicate percentages. CAD, Coronary Artery Disease; WBC, White Blood Cell.

between genetically predicted osteoporosis, years of education and the risk of falls. Additionally, four complementary MR methods were employed to validate the results of IVW: MR Egger, weighted median, weighted mode, and MR-PRESSO for pleiotropic residuals and outliers. The potential pleiotropic effects in the causal estimates were addressed through sensitivity analyses due to the possibility of bias introduced by pleiotropic instrumental variables in the IVW estimate. Cochran's Q test was used to assess potential heterogeneity. Random-effects IVW analysis adjusted for measured heterogeneity. The MR-Egger intercept was used to estimate the level of pleiotropy among genetic variants ($p < 0.05$) was considered indicative of potential horizontal pleiotropy. MR-PRESSO was also utilized to evaluate the presence of pleiotropy by comparing the observed sum of squared residuals with the expected sum of squared residuals. Additionally, leave-one-out analysis was conducted to determine if the results were driven by individual variants. All statistical analyses were performed using R software version 4.1.2 (R Foundation, Vienna, Austria).

Results

Demographic characteristics

This study initially collected data on 640 patients. After excluding 8 cases due to DBS surgery, 27 due to joint surgery and 14 due to kidney disease, 591 patients met the inclusion criteria (the selection process is illustrated in Figure 1). These were divided based on the occurrence of falls into a fallers group of 57 patients and a non-fallers group of 534 patients. There were no significant differences in age and gender between the two groups. The educational levels of both groups were predominantly middle to high school, with college-level education or higher present in 21% of the non-fallers and only 5% of the fallers. No significant differences were observed in personal history or laboratory tests between fallers and non-fallers. There was a significantly higher prevalence of osteoporosis in the fallers compared to the non-fallers (faller vs. non-faller: 23% vs. 12%, $p = 0.027$). The proportion of Parkinson's Disease patients with a history of stroke was significantly higher in the fallers than in the non-fallers (faller vs. non-faller: 44% vs. 30%, $p = 0.039$). There was no significant difference in the incidence of hypertension between the two groups. Regarding the severity of motor dysfunction, the fallers had significantly higher UPDRS III scores compared to the non-fallers (faller vs. non-faller: 33 [25, 43] vs. 33 [25, 32], $p = 0.007$). Additionally, the fallers group was at a higher stage of the H&Y

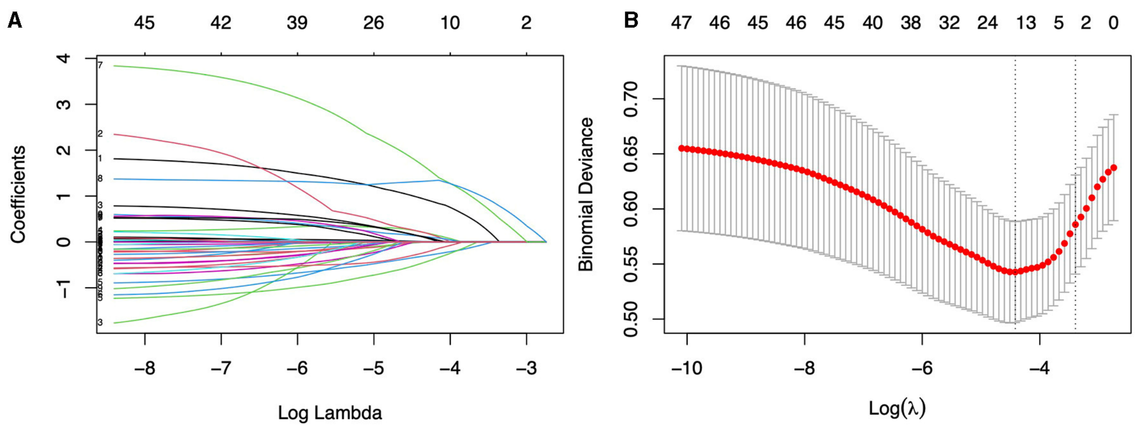

FIGURE 2
(A) Utilizing 10-fold cross-validation to screen for fall-related variables using LASSO regression model. **(B)** LASSO regression cross-validation curve, where the left dashed line represents the lambda value with the best metric evaluation, and the right dashed line represents the lamba value for the model with one standard error of the best value.

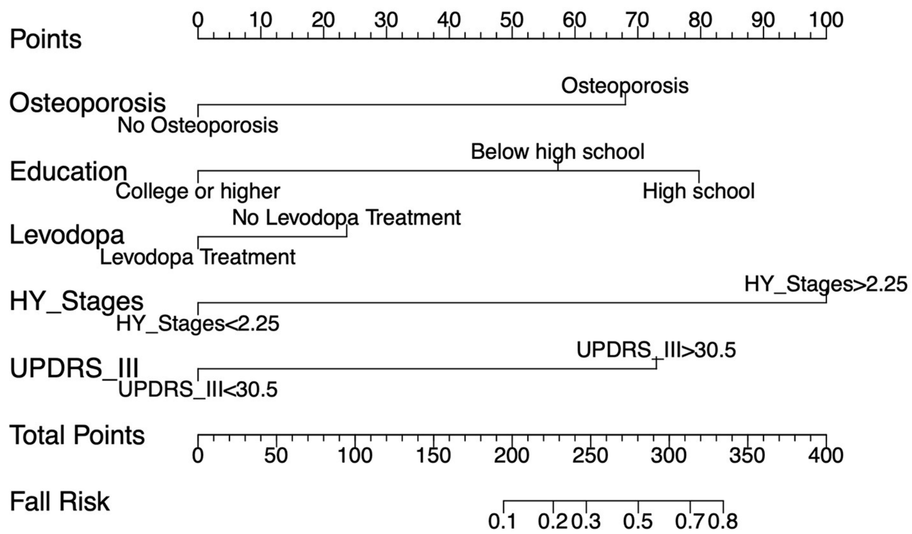

FIGURE 3
A nomogram illustrating the calculation of risk scores and prediction of fall risk. For each of the five predictive variables, draw a vertical line from the corresponding value to the "Points" line. The sum of these points is then plotted on the "Total Points" line, which correlates to the "Fall Risk" of indicated on the scale.

scale compared to the non-fallers group (faller vs. non-faller: 2.50 [2.5, 2.7] vs. 2.50 [2, 2.5], $p < 0.001$) (Table 1). In the gender subgroup analysis, males were younger than females, females were more susceptible to osteoporosis compared to males, with a higher intake of calcium supplements (Supplementary Table 1). In the educational level subgroup analysis, individuals with a high school diploma were the youngest, followed by those with a university degree, while those with less than a high school education were the oldest. Within this latter subgroup, the UPDRS III scores were the highest, and there was a greater prevalence of hypertension and coronary heart disease, as well as a higher number of drinkers. Compared to those with more than a high school education, those with less education consumed fewer calcium supplements, yet had lower blood cholesterol levels (Supplementary Table 2).

Factors affecting falls in PD

The ROC curve analysis reveals that the optimal cutoff value for predicting falls based on the UPDRS III score is 30.5, with an area under the curve (AUC) of 0.609 (95% CI, 0.520–0.698). Utilizing this threshold, the sensitivity for diagnosing falls is 59.6%, and the specificity is 74%. The best cutoff value for predicting falls using the H&Y staging is 2.25, with an AUC of 0.657 (95% CI, 0.597–0.717), yielding a sensitivity of 93% and a specificity of 31.6%. A univariate regression analysis was conducted on all demographic variables, clinical motor scores, disease staging, medical history, and medication usage, followed by LASSO regression analysis (Figure 2). Variables with a p-value < 0.05 in univariate regression, combined with those selected under the LASSO regression criterion λ-se (λ-se = 0.054), were included in a multivariable logistic regression analysis. Ultimately, the variables associated with falls include levodopa medication use, osteoporosis, educational level, H&Y stages and UPDRS III score. These five variables have been incorporated into the predictive model and depicted in a nomogram (Figure 3). Osteoporosis (OR = 5.56, 95% CI: 2.43–12.77, p = 5.10E-05) significantly increases the risk of falls. Conversely, a higher educational level significantly reduces the risk of falls (OR = 0.25, 95% CI: 0.068–0.90, $p = 0.034$), for individuals with a college education or higher, indicating that higher education acts as a protective factor. Both the H&Y staging (OR = 12.30, 95% CI: 4.14–36.50, $p = 6.19 \times 10^{-6}$) and UPDRS III scores (OR = 6.401, 95% CI: 3.44–11.94, $p = 5.07 \times 10^{-9}$) are identified as significant risk factors for falls, with increasing disease progression and motor dysfunction substantially elevating fall risk (Table 2).

Evaluation of the predictive performance of the nomogram

The performance of the nomogram model was assessed using the C-index, calculated through the Bootstrap method, resulting in a C-index of 0.821 (95% CI: 0.760, 0.883). Unadjusted and bias-adjusted C-indices were derived using the cross-validation validate method, with values of 0.815 and 0.804, respectively, indicating stable predictive performance in the absence of bias considerations. ROC curve analysis yielded an AUC of 0.821 (Figure 4A), demonstrating the model's excellent discriminative ability. The calibration curve, shown in Figure 4B, along with a Hosmer-Lemeshow goodness-of-fit test *p*-value of 0.078, confirms the model's good calibration. Decision Curve Analysis (DCA) indicates that employing the model (represented by the red solid line) for patient evaluation and intervention at appropriate risk thresholds (>0.1) yields a positive net benefit (NB), compared to scenarios without intervention (black solid line) and complete intervention (gray solid line) (Figure 4C). The Clinical Impact Curve (CIC) at a threshold probability >70% shows a high concordance between the predicted falls and the actual falls, confirming the high clinical efficacy of the predictive model (Figure 4D). Overall, the nomogram provides reasonable and clinically relevant predictions. In the male and female subgroup analyses, UPDRS III scores, H&Y staging, and osteoporosis were identified as risk factors for falls, but a high level of education, calcium supplementation and treatment with levodopa were protective factors only in the male subgroup. Age subgroup analysis showed that in patients with PD both older than 77 years and younger than 77 years, UPDRS III scores, H&Y staging, and osteoporosis remained risk factors for falls. However, treatment with levodopa was a protective factor in patients younger than 77 years (Supplementary Tables 3, 4).

MR analysis of education, osteoporosis, and falls

Given the significant correlations observed between osteoporosis, years of education and falls in the multivariable regression analysis, we proceeded with MR analysis to infer causal relationships. In the primary IVW analysis, a negative causal relationship was identified between osteoporosis and falls. Specifically, FA-BMD showed an association with falls (OR: 0.996, 95% CI: 0.994–0.998, SE: 0.00091, $p\_adjust < 0.001$); LS-BMD (OR: 0.897, 95% CI: 0.978–0.995, SE: 0.004, $p\_adjust = 0.016$) and FN-BMD (OR: 0.988, 95% CI: 0.977–0.998, SE: 0.005, $P = 0.027$, $p\_adjust = 0.134$). Additionally, years of education demonstrated a significant negative correlation with falls (OR: 0.962, 95% CI: 0.950–0.975, SE: 0.006, $p\_adjust < 0.001$) (Table 3). Notably, no evidence of pleiotropy or heterogeneity was detected using the MR-Egger intercept test or the Cochran Q test (both $p > 0.05$). These sensitivity analyses confirm the reliability and stability of the MR results. Supplementary Figure 1 includes funnel plots, leave-one-out SNP analysis and scatter plots to further substantiate these findings.

Discussion

Falls in patients with PD typically impose significant health, economic, and social burdens, particularly leading to decreased independence and reduced quality of life in the elderly (Xu et al., 2022). Patients with PD are more susceptible to injuries and have higher rates of emergency visits due to falls (Dahodwala et al., 2017), making the short-term identification of fall risks crucial for clinical assessments. Long-term, understanding the specific causes of falls in PD patients is vital for predicting and preventing falls, which aids in developing effective fall prevention strategies to mitigate the incidence and related consequences.

In this study, we analyzed clinical data from 591 PD patients to identify factors associated with the risk of falls. The results revealed multiple factors significantly correlated with fall risk in PD patients, including the motor disorder score (UPDRS III), disease staging (H&Y stages), osteoporotic status and years of education. However, given the retrospective nature of our study, causality could not be definitively established. To address this, we integrated a MR analysis using public databases. Although the two-sample MR analysis hinted at potential causal links between years of education, osteoporosis and falls, it is imperative to note that the MR analysis was derived from a European cohort beyond cross-sectional populations. Furthermore, it did not differentiate between Parkinson's and non-Parkinson's cohorts, thus offering a generalized insight into the plausible associations among education level, bone density and fall occurrences. Consequently, the applicability of MR results may be subject to limitations in broader contexts.

Falls and osteoporosis represent major health challenges in PD. More severe motor disorders increase the propensity for falls among PD patients, while osteoporosis heightens the risk of fractures post-fall (Tassorelli et al., 2017). In this study, postmenopausal female patients exhibited a significantly higher incidence of osteoporosis compared to males, with 59% of female patients affected vs. 29% of males. Nevertheless, our study found no gender differences in fall incidents, suggesting the presence of other more influential factors beyond gender. Moreover, the decrease in BMD in PD patients is associated not only with malnutrition and reduced muscle strength but also potentially with long-term levodopa use. Although levodopa is the primary

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TABLE 2 Predictors of falls in univariate and multivariate analysis.

	Univariate			Multivariate		
	OR	95%CI	*P* value	OR	95%CI	*P* value
Demographics						
Age (years)	0.967	0.98–1.03	0.82			
Gender (Male)	0.72	0.4–1.2	0.196			
Motor features						
UPDRS III (>30.5)	4.201	2.41–7.46	<0.001	6.407	3.437–11.943	5.07E-09
Hoehn and Yahr staging (>2.25)	6.130	2.46–20.51	<0.001	12.30	4.142–36.503	6.19E-06
Education						
Below high school	Ref.	Ref.	-	Ref.	Ref.	-
High school	1.243	0.69–2.19	0.469	1.760	0.916–3.381	0.090
College or higher	0.234	0.06–0.67	0.018	0.247	0.068–0.900	0.034
Medical history						
Osteoporosis	2.250	1.11–4.31	0.018	5.565	2.426–12.767	5.10E-05
Hypertension	0.932	0.54–1.62	0.802			
Diabetes	0.901	0.44–1.7	0.759			
CAD	0.621	0.18–1.58	0.372			
Stroke	1.862	1.06–3.23	0.029	1.580	0.846–2.952	0.152
Personal history						
Drinking	2.614	0.72–7.5	0.098			
Smoking	1.727	0.26–6.65	0.484			
Sleep and mental health						
Anxiety	0.711	0.29–1.52	0.414			
Sleep_Disorders	1.881	0.62–4.73	0.216			
Medication usage						
Levodopa treatment	0.553	0.31–0.95	0.031	0.518	0.279–0.964	0.038
Calcium_Supplement	0.728	0.17–2.09	0.602			
Calcium_Carbonate	1.614	0.9–2.81	0.099			

CAD, Coronary Artery Disease; Ref, reference.

medication improving motor symptoms in PD, it may cause hyperhomocysteinemia, thereby impacting BMD (Lee et al., 2010). Interestingly, despite the potential side effects of levodopa, our study indicates that it also plays a protective role in preventing falls to some extent.

Previous studies have shown that fall frequency is associated with BMD (Fink et al., 2005), a connection further corroborated by our MR analysis. Specifically, the BMD of the ankle and lumbar spine is closely linked to fall events. Consequently, we chose fall incidents occurring within the past year as the study outcome, indicating a possible correlation between recent falls and BMD. Although studies suggest that vitamin D and calcium supplementation can enhance BMD (Voulgaridou et al., 2023), our data revealed no significant differences in calcium supplementation between fallers and non-fallers. Due to the lack of comprehensive BMD data, we could not analyze the relationship between BMD and calcium supplementation in detail. For osteoporosis diagnosis, we relied on the dual-energy X-ray absorptiometry (DXA) measurements of T-scores, with a standard of T-scores lower than −2.5 (Aibar-Almazán et al., 2022). Additionally, we referenced clinical diagnoses by osteoporosis specialists, employing a comprehensive assessment approach to ensure accuracy and thoroughness in diagnoses.

While there is no direct evidence linking educational level with the risk of falls in PD patients, existing studies suggest that a higher educational degree correlates with less severe motor impairments in PD (Kotagal et al., 2015; Jeong et al., 2022). Furthermore, other research indicates that PD patients living in rural areas face a higher risk of falls, likely related to the relatively lower educational levels prevalent in these areas (Xu et al., 2022). MR analysis also supports the protective role of higher educational levels in reducing fall risk. Therefore, future research should further explore the relationship between educational level and fall risk in PD patients.

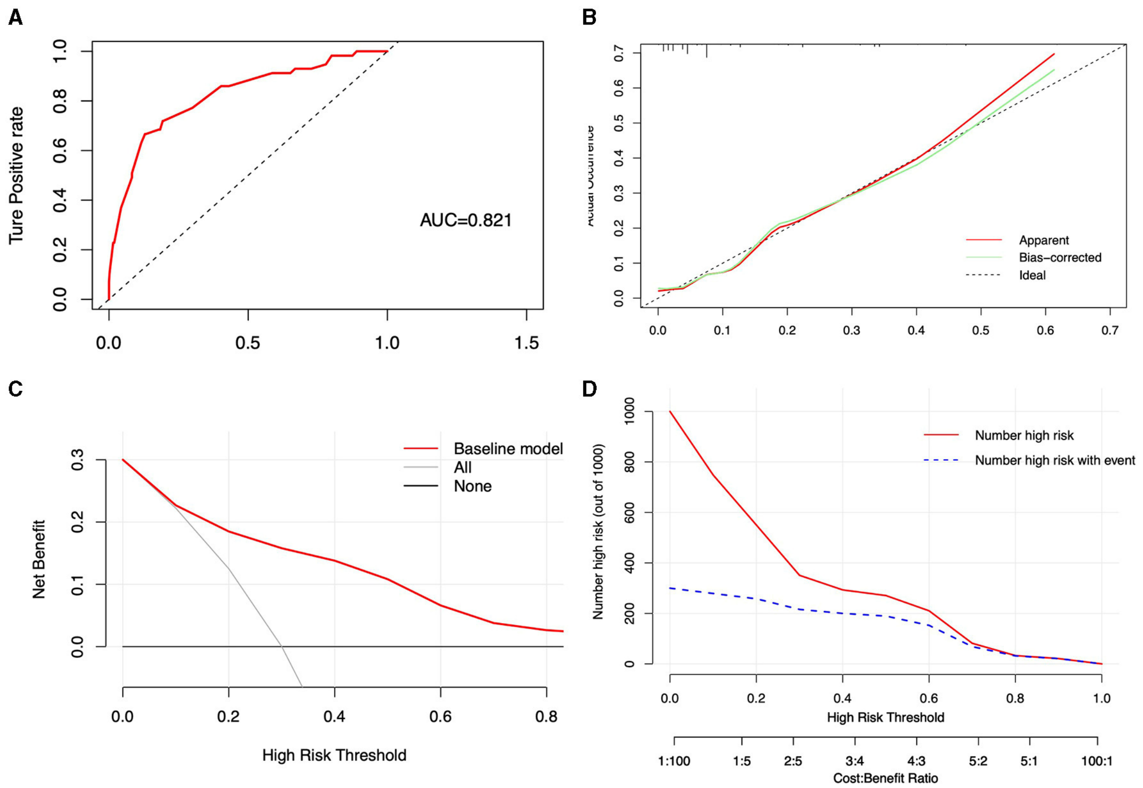

FIGURE 4
Visualization of the predictive model's performance and clinical impact. **(A)** ROC curve of the predictive model, displaying the area under the curve (AUC); **(B)** Calibration curve for the predictive model, with the current model's performance shown by the red solid line, the adjusted curve by the green solid line, and the ideal line by the black dashed line; **(C)** clinical decision curve of the model; **(D)** clinical impact curve of the model.

Studies have shown that the revised H&Y staging is related to the risk of falls in PD patients (Geroin et al., 2020). Although the motor disorder score is considered a crucial risk factor for assessing disease severity, some studies deem it lacks value as a predictive variable (Custodio et al., 2016). Additionally, compared to fall history, cognition, and retropulsion tests, the clinical utility of using UPDRS-III to predict falls appears limited (Lindholm et al., 2021a,b). This study delved into the accuracy of utilizing the UPDRS-III, which is generally reliable but lacks high sensitivity and clear specificity. This implies that while this threshold can adequately identify PD patients who haven't experienced falls, its ability to precisely pinpoint patients prone to falls is moderate. The H&Y staging similarly exhibited limited accuracy in predicting falls. Using 2.25 as the optimal cutoff value notably increased sensitivity but reduced specificity. These findings suggest that although the H&Y staging can identify most at-risk fallers with heightened sensitivity, its low specificity leads to misclassification of many non-fallers as high risk. This could potentially cause undue concern and over-intervention. The AUC analysis mentioned may be influenced by the study's patient count, indicating certain limitations in accurately predicting falls. These findings suggest that multiple factors should be considered in clinical practice to assess fall risk, rather than relying solely on a single assessment tool or disease stage.

This study has certain limitations in assessing non-motor symptoms, particularly the lack of detailed evaluation data on depression and cognitive function. Depression and cognitive impairment are common non-motor symptoms in neurodegenerative diseases like Parkinson's disease, significantly impacting patients' quality of life. Research has shown that higher cognitive reserves are associated with better cognitive function in Parkinson's disease (Gu and Xu, 2022), while significant cognitive deficits also increase the risk of falls in PD (Kim et al., 2013; Cheng et al., 2020). Additionally, PD patients prone to falls often exhibit more depressive symptoms with depression itself being a risk factor for falls in PD (Bryant et al., 2012; Li et al., 2023).

Nonetheless, this study is constrained by its retrospective design and reliance on data from a single regional hospital, leading to potential issues such as selection bias, challenges in establishing causality, and inadequate control of confounding factors. There are challenges such as selection bias, difficulty in establishing causality, and inadequate control of potential confounding factors. Future research should extend to a broader population and multiple centers to validate and deepen these findings. Further studies should also consider including other potential fall risk factors, such as cognitive impairments and visual disorders, BMI, and explore their interactions with the identified risk factors. Additionally, our study did not include patients who underwent orthopedic surgery or deep brain stimulation, lacking analysis for these groups. Overall, this study underscores the importance of comprehensive management of fall risks in PD patients, particularly regarding motor disorders and bone health, helping

TABLE 3 Mendelian randomization (MR) analysis of the relationship between years of education, bone mineral density (BMD), and falls.

Traits	Method	OR	95%CI	*P* value	*P* adjust
Years of schooling	MR Egger	1.000	0.952–1.051	0.997	0.997
Years of schooling	Weighted median	0.961	0.944–0.979	0.000	0.000
Years of schooling	Inverse variance weighted	0.963	0.951–0.975	0.000	0.000
Years of schooling	Simple mode	0.883	0.829–0.940	0.000	0.000
Years of schooling	Weighted mode	0.984	0.931–1.040	0.563	0.703
FA BMD	MR Egger	1.000	0.995–1.004	0.856	0.856
FA BMD	Weighted median	0.998	0.996–1.001	0.165	0.411
FA BMD	Inverse variance weighted	0.996	0.994–0.998	0.000	0.000
FA BMD	Simple mode	0.998	0.992–1.004	0.548	0.684
FA BMD	Weighted mode	0.998	0.993–1.004	0.543	0.684
FN BMD	MR Egger	1.025	0.963–1.090	0.456	0.570
FN BMD	Weighted median	0.989	0.974–1.004	0.150	0.250
FN BMD	Inverse variance weighted	0.988	0.977–0.999	0.027	0.134
FN BMD	Simple mode	0.976	0.950–1.004	0.110	0.250
FN BMD	Weighted mode	1.001	0.972–1.031	0.965	0.965
LS BMD	MR Egger	0.996	0.962–1.031	0.803	0.803
LS BMD	Weighted median	0.991	0.979–1.003	0.152	0.380
LS BMD	Inverse variance weighted	0.987	0.979–0.996	0.003	0.016
LS BMD	Simple mode	0.995	0.972–1.019	0.691	0.803
LS BMD	Weighted mode	0.994	0.974–1.015	0.590	0.803

FA, Forearm; FN, Femoral Neck; LS, Lumbar Spine.

us better understand and address this increasingly severe public health issue.

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 the Ethics Committee of Shenzhen Baoan People's 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

YiZ: Data curation, Investigation, Writing—original draft. YuZ: Methodology, Writing—review & editing. YY: Investigation, Writing—review & editing. XK: Resources, Validation, Writing—original draft. SS: Methodology, Resources, Writing—review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnagi.2024.1420885/full#supplementary-material

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Nattawan Utoomprurkporn,
Chulalongkorn University, Thailand

REVIEWED BY
Artur Francisco Schumacher-Schuh,
Federal University of Rio Grande do Sul, Brazil
Jacy Bezerra Parmera,
University of São Paulo, Brazil

*CORRESPONDENCE
Ying-Fang Lei
✉ hexhell2616@163.com
Xing-Zuan Jiang
✉ jiangxingzuan@126.com

†These authors have contributed equally to this work and share first authorship

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Mapping the research of nursing in Parkinson's disease: a bibliometric and quantitative analysis

Han-Bing Liao[1†], Yan-Lin Fang[1†], Shu-Yi Chen[1†], Yu-Shan Yin[2†], Jiao Li[1], Peng Zhou[2], Bin Li[2], Xing-Zuan Jiang[1]* and Ying-Fang Lei[1]*

[1]Department of Geriatrics, The Second Affiliated Hospital of Guangzhou Medical University, Guangzhou, China, [2]Department of Neurology, Institute of Neuroscience, Key Laboratory of Neurogenetics and Channelopathies of Guangdong Province and the Ministry of Education of China, The Second Affiliated Hospital, Guangzhou Medical University, Guangzhou, China

Background: Parkinson's disease (PD) is a chronic and progressive neurodegenerative disorder. Clinically, the therapeutic strategy of PD could only alleviate the symptoms. Nursing plays a crucial role in providing patient education, symptom management, and psychosocial support. This study aims to analyze the current state and prospects of research in the field of Parkinson's disease (PD) and its associated nursing care through bibliometric methods to explore the trends that May guide its future development.

Methods: Literature related to Parkinson's disease and nursing care was systematically searched by the Web of Science database from 1991 to 2023. Quantitative analysis of cooperative networks was conducted using bibliometric tools VOSviewer and CiteSpace.

Results: The analysis covered 2,649 publications in the field of PD and nursing care, authored by 12,576 researchers from 3,869 institutions across 94 countries. The number of articles has steadily increased over the past 20 years. In this research field, the United States and the United Kingdom emerged as leading countries, and Radboud Universiteit Nijmegen was positioned as an international hub. *Movement Disorders* was identified as the journal with the highest output and with the most co-citation. Prof. Bastiaan R. Bloem published the most papers in the area, and Prof. Per Odin had the highest average citation. The major fields of these publications are clinical neurology, geriatrics & gerontology, multidisciplinary sciences, and health care sciences & services. Hot topics in the field predominantly revolve around Parkinson's disease, quality of life, and dementia.

Conclusion: Research in Parkinson's disease and nursing care is experiencing a period of rapid growth, with continuous expansion in research scope and depth of investigation. One of the trends identified is the increasing focus on quality of life and the management of dementia in PD patients, reflecting the importance of these areas in research. The study further suggests that future advancements in the field May rely significantly on strengthening international collaborations and addressing global disparities in resource distribution, particularly by promoting research inclusivity and cooperation among low-resource countries.

KEYWORDS

Parkinson's disease, nursing care, bibliometric analysis, quality of life, dementia

1 Introduction

Parkinson's disease (PD) is a chronic and progressive neurodegenerative disorder that affects millions worldwide (1, 2). It is characterized by the loss of dopaminergic neurons in the substantia nigra pars compacta and the presence of Lewy bodies in the brain (3). PD manifests with motor symptoms such as tremors, bradykinesia, and rigidity, as well as non-motor symptoms including depression, anxiety, and cognitive decline (4, 5). PD is one of the common neurological diseases causing a huge hurt to the physical and psychological suffering of patients. With the development of disease, the patients will gradually lose their ability to work and daily life. Clinically, the therapeutic strategy of PD is limited and could only alleviate the symptoms (6, 7). The management of PD requires a multidisciplinary approach, in which nursing plays a crucial role in providing patient education, symptom management, and psychosocial support (8).

The importance of nursing research in PD is well recognized, as effective nursing interventions can significantly improve the quality of life of individuals living with the condition. Nurses are often the longest-serving healthcare professionals in the lives of individuals with PD, providing consistent and reliable care throughout the trajectory of the disease. However, the nursing research field in PD is vast and complex, with numerous studies published each year across multiple journals (9). To gain a comprehensive understanding of the current state of nursing research in PD, a bibliometric analysis is a useful tool. Bibliometric analysis is a quantitative approach that involves the use of mathematical and statistical methods to study the patterns and relationships in the production and utilization of literature. It allows for the identification of research trends, hotspots, and emerging areas within a specific field (10, 11).

In this study, we conducted a bibliometric analysis to map the research trends and hotspots of nursing research in PD. The objectives of this analysis were to identify the main research topics and trends in nursing research on PD, identify the main contributors to this research, and explore the international collaboration in this field. We also aimed to identify potential gaps in the literature that require further exploration.

2 Materials and methods

2.1 Data retrieval and collection

This article retrieves the relevant literature on nursing study in PD from the Web Science Core Collection database (WoSCC). The search formula is: (((AB = (Parkinson's disease)) OR AB = (paralysis agitans)) AND AB = (nursing OR Patient care OR Medical care)) OR (((TI = (Parkinson disease)) OR TI = (paralysis agitans)) AND TI = (nursing OR Patient care OR Medical care)). The search period is from 1991 to 2023, including all types of documents in this interval. The language is limited to English. The retrieval and extraction of data were performed by two independent researchers to avoid potential bias and improve the reliability of the results. The studies involving Parkinson's disease and nurse care were included, while those published informally or not published in English were excluded.

2.2 Data analysis and visualization

This study mainly used VOSviewer 1.6.19 and CiteSpace 6.2.R4 to analyze the relevant literature. Firstly, VOSviewer was used to build a thesaurus of synonyms and merge the synonyms in the literature (12–14). Subsequently, CiteSpace was used to process the data downloaded from WOSCC and create a new project for visualization analysis (15–17). The period was set from 1991 to 2023, and each time slice was set to 1. When analyzing, individual node types were selected, and the threshold was set to (top N per slice) = 50, top N% = 20%. Next, visualization analysis was conducted on key information such as authors, countries/regions, journals, and institutions of these studies.

3 Results

3.1 Overview of included literature

Following the above retrieval strategy, a total of 2,649 pieces of literature are obtained for WOSCC. These literature were written by 12,576 authors from 3,869 institutions of 94 countries and cited 78,761 papers from 15,161 journals.

3.2 Annual publications and trends

The total number of papers published in this field has shown an increasing trend over time (Figure 1). After 2005, the number of related studies has increased exponentially, with the highest number of publications in 2021, indicating that this field has attracted increasing attention from scholars in recent years.

3.3 Author influence analysis

Bibliometrics analysis of authors in the field helps in identifying representative scholars and core research forces in the field (18, 19). The 2,903 authors in this field were analyzed by VOSviewer. The top five authors in terms of publication output are listed in Supplementary Table S1. The author with the highest number of publications and citations is Prof. Bastiaan R. Bloem from Radboud Universiteit Nijmege. The author with the highest average citation is Prof. Per Odin from Radboud Universiteit Nijmegen. These results indicate that these authors have a high influence in the field of PD and nursing.

The authors who have published at least five articles were filtered to generate a co-authorship network map in the field, revealing information on representative scholars and their collaborations. It is evident from the map that there is a close connection among authors, with Bastiaan R. Bloem and Marten Munneke PT presenting the highest number of links (Figure 2).

3.4 Contributions of countries/regions

The contributions of nursing research in PD were accomplished by 52 countries. The majority of publications (83%, 2,191 papers) originated from the five top-ranking countries in this domain. To elucidate the contributions of individual countries more clearly, we employed the VOSviewer tool and visual analysis on countries with five or more publications, the findings of which are depicted in

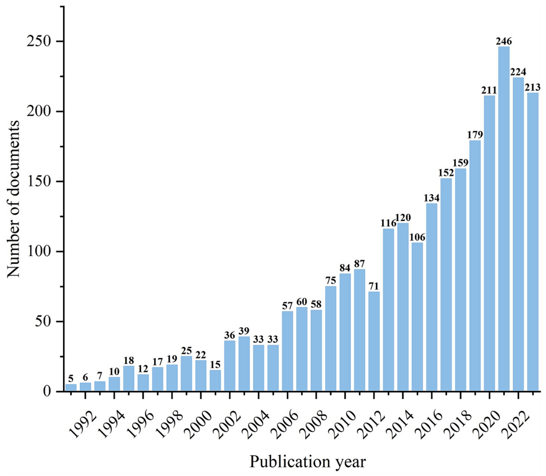

FIGURE 1
Analysis of the publication years of research literature related to PD and nursing.

Figure 3A. A compilation of the top ten prolific publishing countries has been presented in Supplementary Table S2. A considerable disparity of publication across countries was presented. The United States was the country with the highest number of published articles, far outpacing other countries as illustrated in Figure 3B. The list is dominated by developed countries, indicating a discrepancy in the level of emphasis placed on this research area by various nations. The average number of publications from low-and middle-income countries in Latin America, Africa, and Asia was 9.84, significantly lower than that of high-income countries. An extensive collaborative network exists between the leading countries, including the United Kingdom, the United States, Germany, and France, while collaboration between low-and middle-income countries and developed countries is not very close (Figure 3B).

3.5 Institutional influence analysis

So far, a total of 3,869 institutions have published literature in this field. Supplementary Table S2 presents the top ten institutions in terms of publication output. It can be observed that the institution with the highest number of publications is Radboud Universiteit Nijmegen (99 papers, 3.74% of the total), followed by the University of Pennsylvania (81 papers, 3.06% of the total) and the University of Toronto (75 papers, 2.83% of the total). From Supplementary Table S2 and

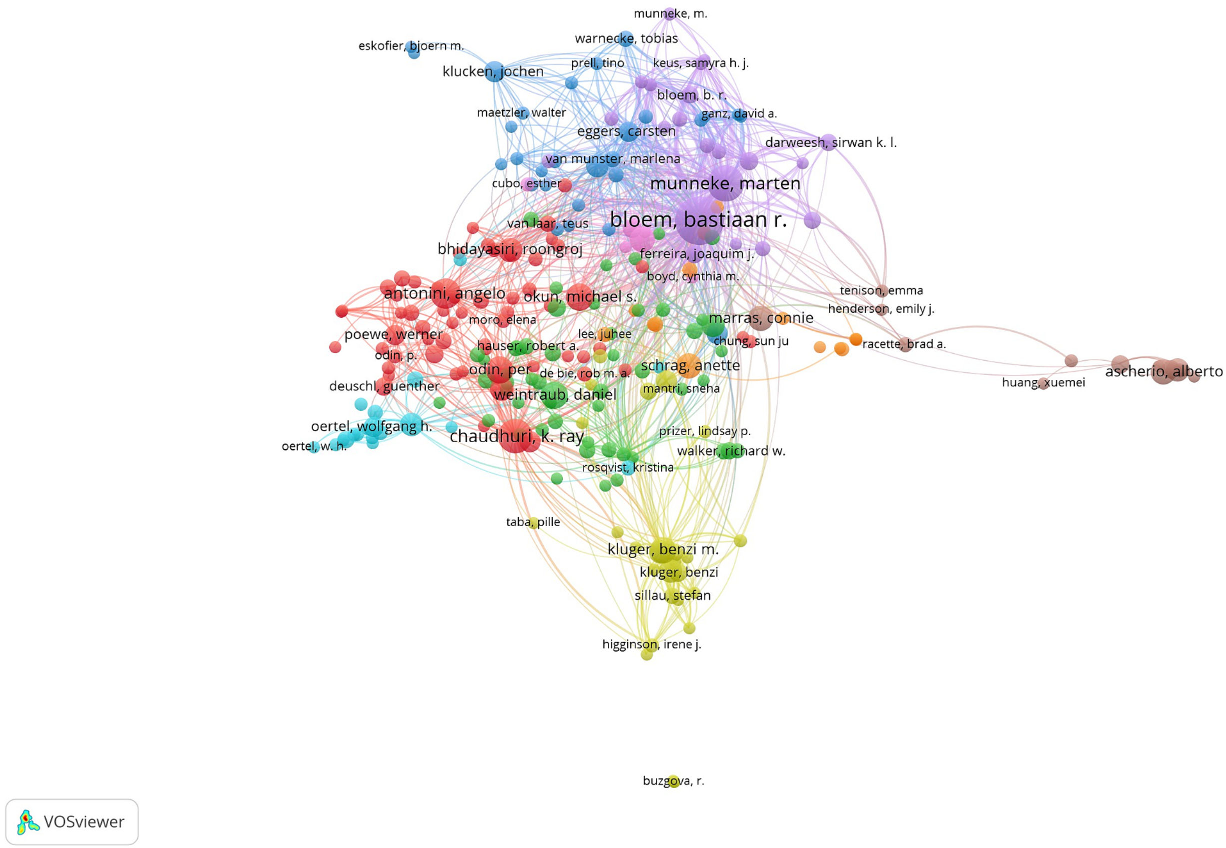

FIGURE 2
Author collaboration network for research related to Parkinson's and nursing. The color of the nodes indicates different clusters; the size of the nodes denotes the number of documents output, with larger nodes signifying a greater volume of documents; the thickness of the lines represents the strength of collaboration, with thicker lines indicating tighter connections between two authors.

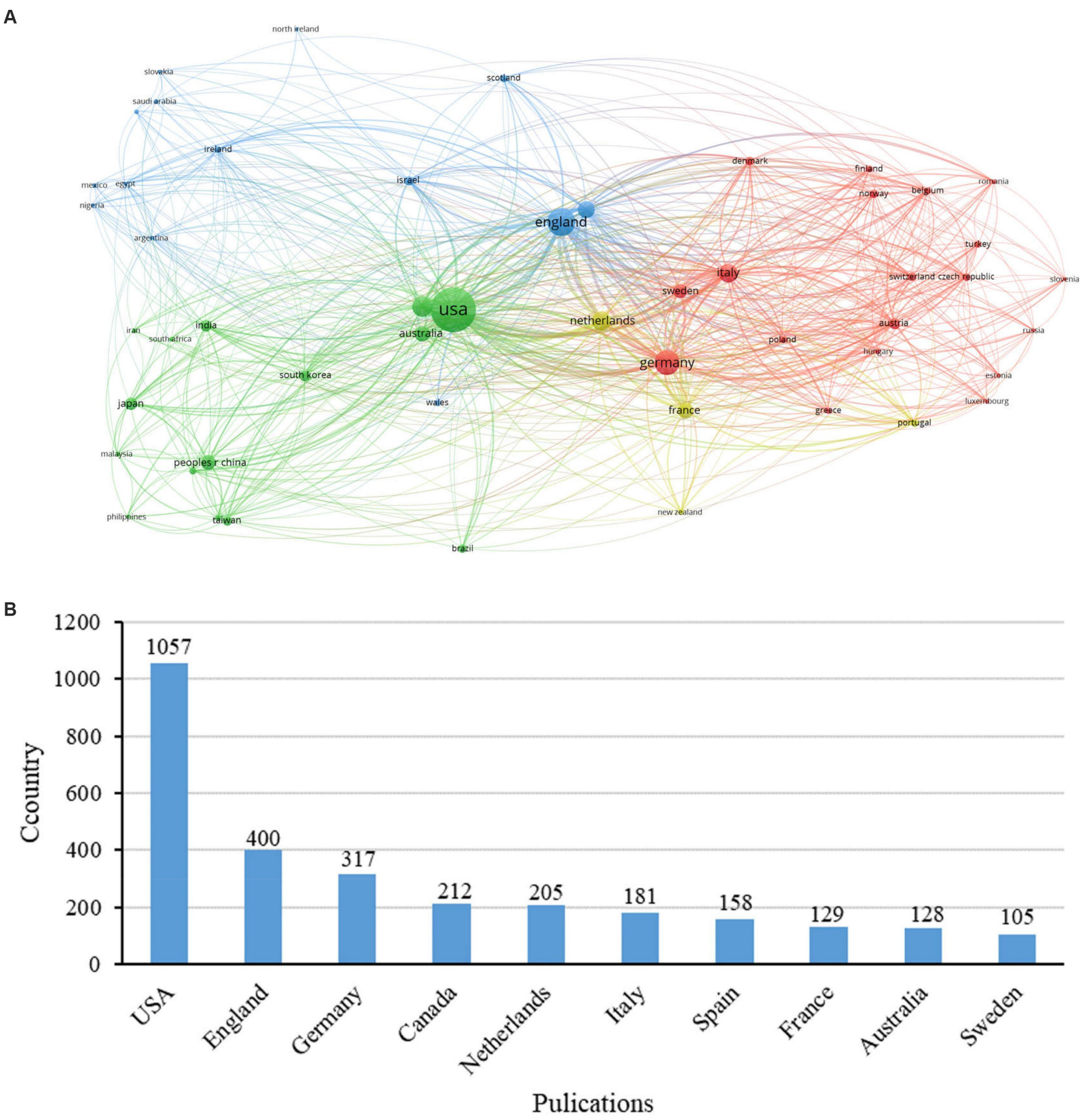

FIGURE 3
Schematic illustration of analysis of countries/regions. **(A)** Countries collaboration map; **(B)** Publication volume by regions in research on PD and nursing.

Figure 4, it can be found that the publication output of leading research institutions accounts for a small proportion of the overall publication output, and a head effect has not yet been formed (20).

3.6 Journal analysis for articles published in the field

The 2,649 papers in this field were published in 872 journals. The top ten journals have contributed 728 papers on the subject, accounting for 27.48% of this field. "*Movement Disorders*" (IF: 8.6, Q1) stands as the journal with the highest output, publishing 234 articles. According to JCR 2022 standards, the majority of the journals within the top ten are categorized as either Q1 or Q2, with "*The Lancet Neurology*" (IF: 48, Q1) being identified as the journal with the highest impact factor, featuring 17 articles that garner an average of 96 citations each. Notably, both aforementioned journals are prominent within the clinical neurology sector, signifying an escalating interest in PD and nursing research among professionals in this discipline.

3.7 Analysis of co-cited journals

As shown in Supplementary Table S4, the journal with the highest citation frequency is "*Movement Disorders*" (9,947 citations), followed by "*Neurology*" (6,816 citations) and "*Parkinsonism & related*

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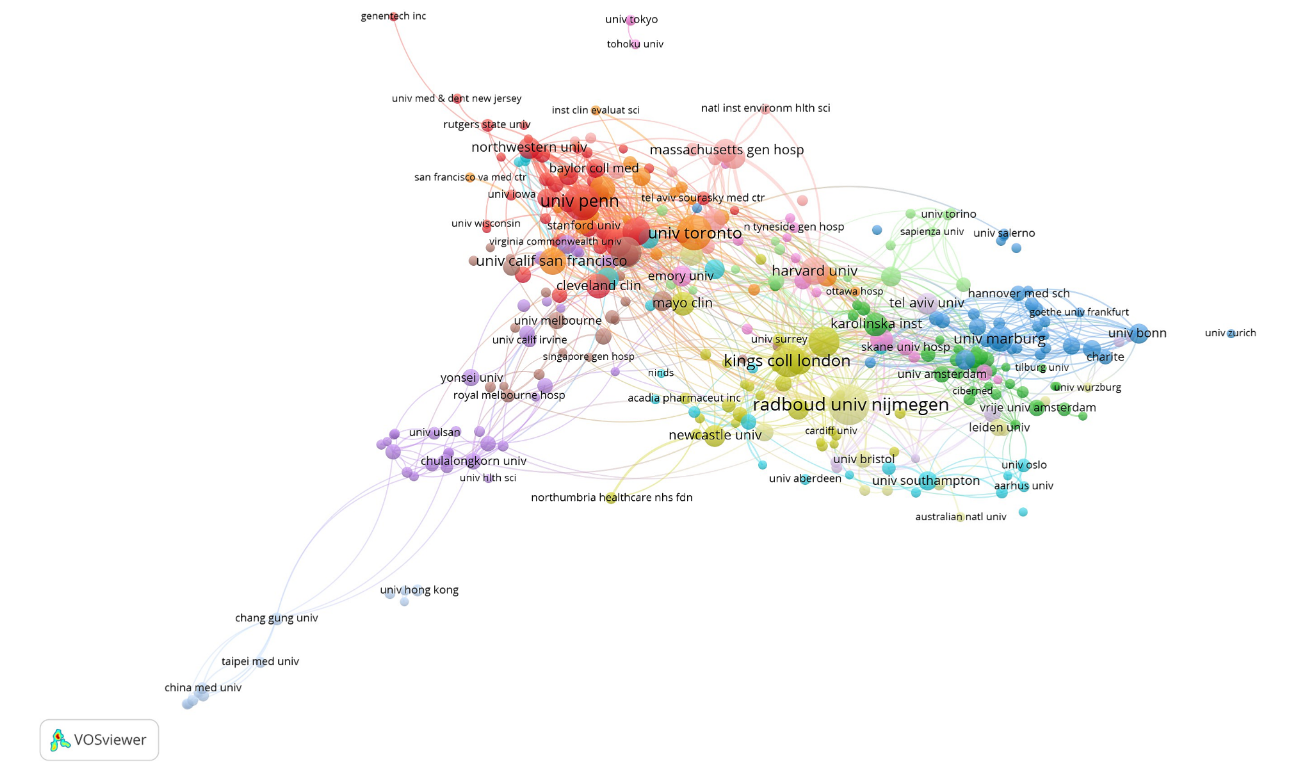

FIGURE 4
Collaboration network of institutions related to PD and nursing research.

disorders" (3,825 citations). Among the top 10 journals with the highest citation frequency, the proportion of Q1 journals is the highest, indicating that articles in this field have a high level of influence. Using VOSviewer software, 735 journals with a minimum of 20 citations were analyzed. The network is mainly divided into four main clusters: Clinical Neurology, Geriatrics & Gerontology, Multidisciplinary Sciences, and Health Care Sciences & Services (Figure 5).

3.8 Co-cited reference analysis

There are a total of 78,761 cited references in the field. *The Parkinsonism: onset, progression, and mortality* (21) has the highest number of citations, reaching 331. Figure 6A displays a visualization of the Co-cited density landscape, where areas closer to yellow indicate a higher influence of the literature, and those closer to blue suggest a lower influence. Figure 6B presents the top 10 co-cited references with the strongest citation bursts, with burst strength values ranging from 3.85 to 8.16. The literature with the highest burst strength (8.16) is *The health burdens of Parkinson's disease* (22).

3.9 Analysis of keyword

A keyword co-occurrence network view was constructed by utilizing VOSviewer, based on the analysis of 2,649 publications, to unveil the research hotspots and core concepts of a field (23). A total of 837 keywords that occurred at least five times were included for analysis. The top ten most frequent keywords were Parkinson's disease, quality-of-life, dementia, prevalence, people, depression, symptoms, quality of life, nonmotor symptoms, levodopa, and risk (Figure 7A; Supplementary Table S6). Figure 7B displays the top ten keywords with the highest burst strength, with the burst strength values ranging from 4.28 to 10.71. Notably, the two keywords with the highest burst are "population" (10.74) and "Alzheimer's disease" (10.71). Both the figure and table indicate that high-frequency keywords such as "Parkinson's disease", "quality-of-life", "dementia", "prevalence", "people", etc., form the representative academic terminologies of the field and denote its research hotspots.

4 Discussion

This study performed a bibliometric analysis on 2,649 publications related to PD care. Analysis indicated a steady annual growth rate of 14.6% since 1991, reflecting an increased volume of literature and heightened research activity in the field. This trend is likely associated with global population aging and lifestyle changes, leading to a rise in the incidence of PD and a correspondingly greater focus on its care and treatment research. Advances in medical technology and innovations in research methodologies are also identified as key drivers of scientific progress (24). Previous studies in this field focus on understanding and management of PD disease and improving the quality of life for individuals with PD. Future studies should aim to explore the impact of these trends on clinical practice and to identify potential areas for further research in PD care. This study provides a valuable resource for

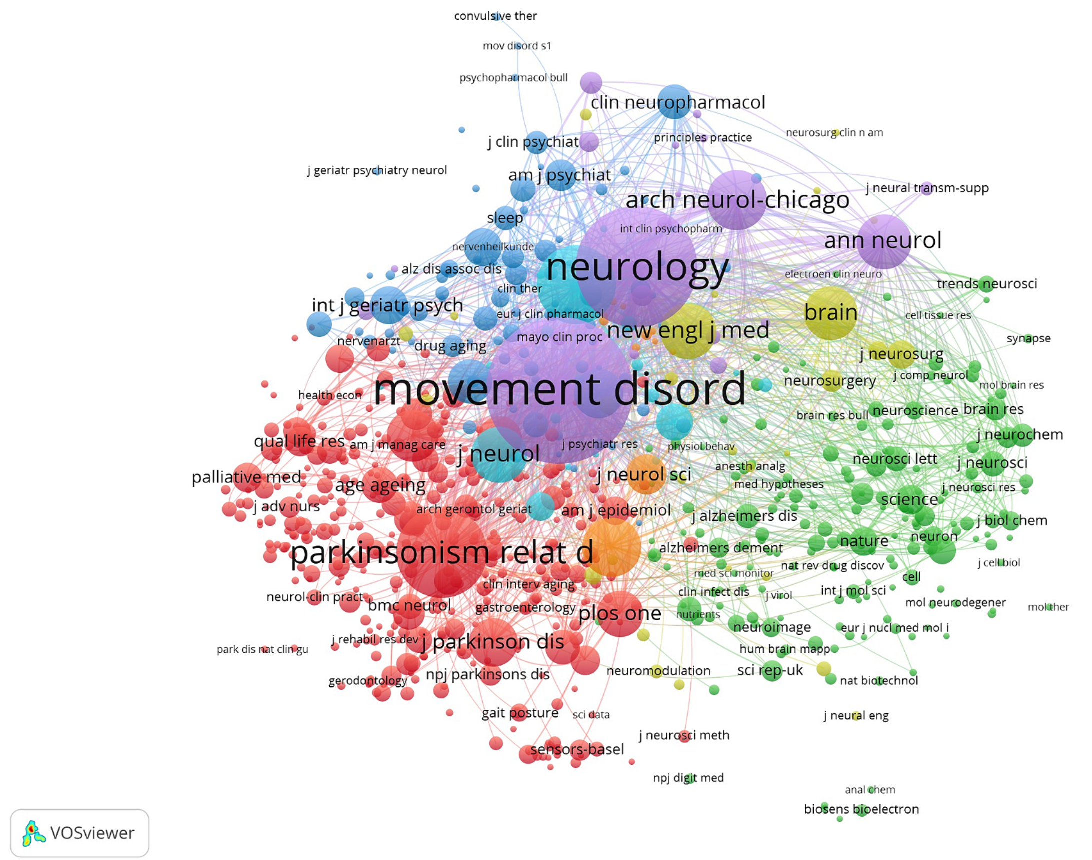

FIGURE 5
Co-cited map of journals in collaborative research related to Parkinson's and nursing.

researchers, clinicians, and policy-makers in the field of PD nursing, and would be helpful in guiding future research directions and enhancing understanding of current research trends and hotspots.

Analysis of the contributions of different countries/regions revealed that publications of nursing research in PD are predominantly concentrated in developed countries. The United Kingdom, with the majority of top institutions, led international collaborations. Studies on PD were weaker in lower-middle income countries, in which PD would be less common due to a low average lifetime. It was indicated that the international distribution of this field was imbalanced. The developed countries May have high investment in healthcare than the lower-middle income countries. It is necessary to increase the research investment of the lower-middle income countries and cooperation with the developed countries. Extensive collaboration were presented between the developed countries, while collaboration between low-and middle-income countries and developed countries is limited. Collaborative efforts between developed and developing countries in this field require strengthening. Enhanced international cooperation is pivotal for advancing knowledge sharing, technical exchanges, and further development in the field. Radboud University, alongside other leading institutions such as the University of Pennsylvania, maintains robust collaborative ties, positioning it as a significant academic hub. Professor Bastiaan R. Bloem has a notable publication and citation record in PD care research, influencing research directions and focal points in the field through exemplary practices and innovative methods.

Further analysis identified hotspots and emerging trends in this domain. Keyword and research hotspot analyses indicate "Parkinson's Disease", "Quality of Life", and "Dementia" as central themes, highlighting their significance in both research and clinical practice. Notably, the rising prominence of the keyword "Alzheimer's Disease" suggests a growing focus in PD research on comorbidities with neurodegenerative disorders and their effects on treatment and care strategies. These findings underscore the evolving nature of the field and the need for continued exploration of comorbidities and their impact on PD care.

The co-authorship network analysis reveals a strong pattern of collaboration among researchers, particularly evident in the connectivity of core authors (25). This finding highlights the importance of strengthening scientific capabilities through cross-institutional and cross-national collaborations for future scientific advancements. With the discovery of biomarkers in PD, the application of gene-editing technologies, the development of novel medications, the exploration of new therapeutic approaches, as well as the integration of telemedicine and digital health monitoring tools, the field is experiencing rapid growth. However, this study also highlights the global disparities in resource distribution, as low-resource countries face challenges in accessing

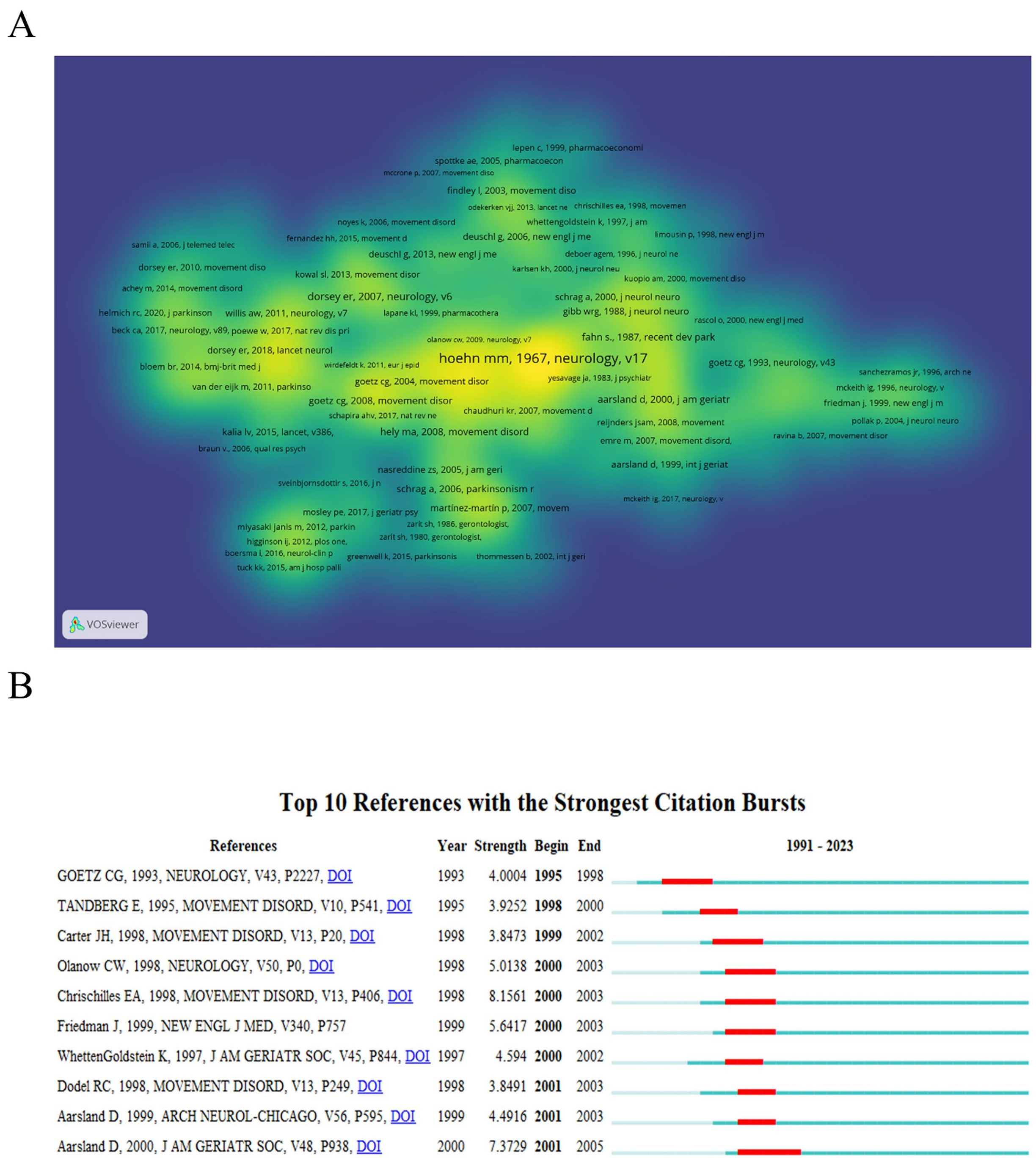

FIGURE 6
Schematic illustration of analysis of co-cited references. **(A)** The density visualization map of co-cited references based on VOSviewer. The color closer to yellow indicates a higher influence, while blue indicates a lower influence. **(B)** Burst strength and time duration of the top 10 references with the strongest citation bursts.

care resources, professional training, and research infrastructure. This emphasizes the need to address these imbalances through enhanced international cooperation and global sharing of scientific outputs.

This study has certain limitations. Firstly, our data is exclusively sourced from the WOSCC, which May not be comprehensive enough. Additionally, we only screened English articles, thus excluding articles published in other languages.

5 Conclusion

The study conducted a comprehensive bibliometric analysis of research literature in the field of Parkinson's disease (PD) care, revealing an increasing trend in research and care attention resulting from global population aging and shifts in lifestyle. Research priorities are focused on quality of life and dementia-related issues associated with PD. However, activities are predominantly concentrated in developed countries,

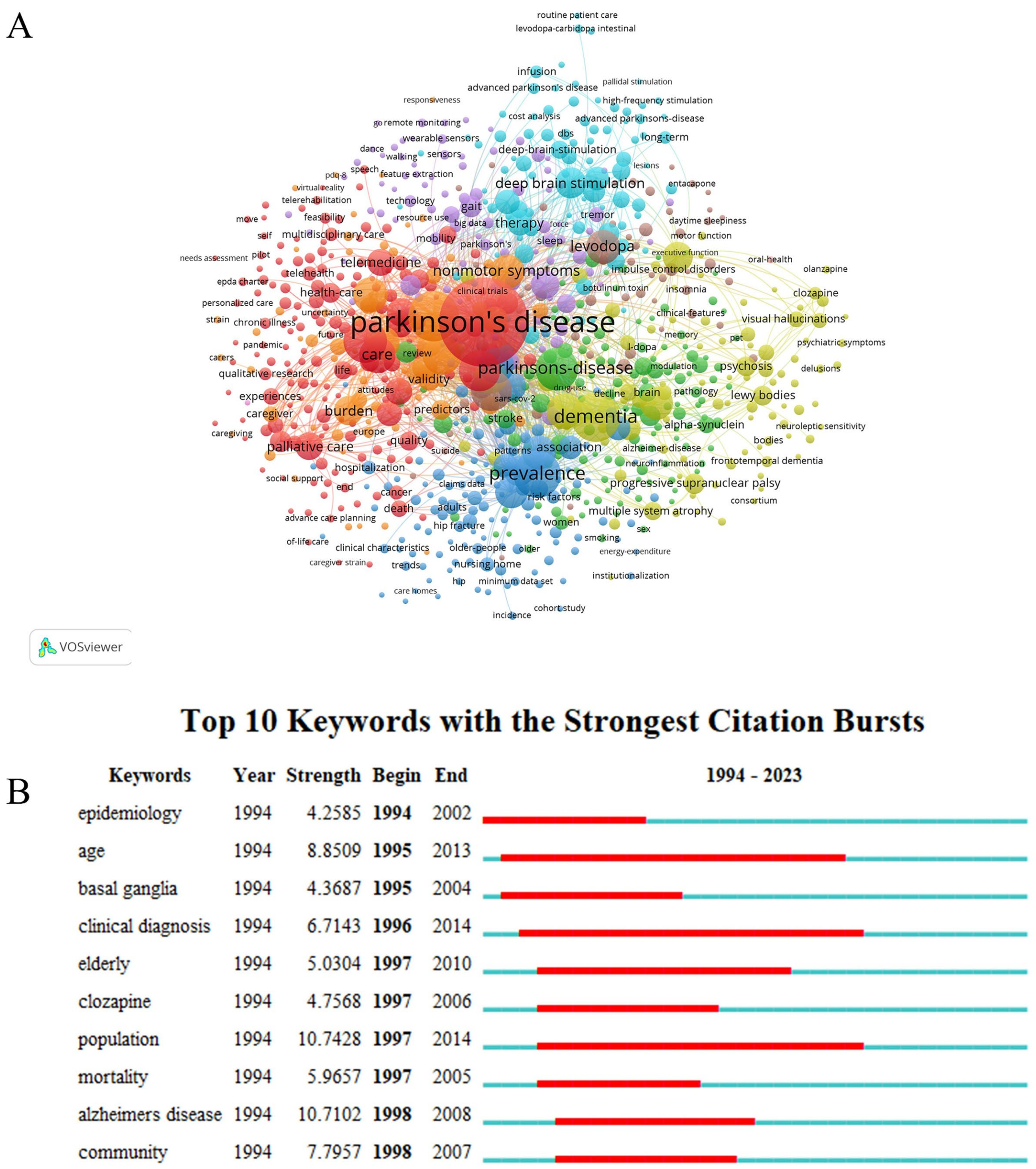

FIGURE 7
Schematic illustration of analysis of keywords. **(A)** Visualization map of keywords in PD and nursing research; **(B)** Burst strength and time duration of the top 10 keywords with the strongest citation bursts.

highlighting a deficiency in international collaboration. Future research should emphasize inclusivity and cooperation, especially in developing nations with uneven resource distribution and limited care capabilities, to promote balanced global advancement in PD care and research.

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

H-BL: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Y-LF: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. S-YC: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Y-SY: Writing – review & editing, Writing – original draft. JL: Writing – review & editing, Writing – original draft. PZ: Writing – review & editing, Writing – original draft. BL: Funding acquisition, Writing – review & editing. X-ZJ: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Y-FL: Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration.

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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/fneur.2024.1412158/full#supplementary-material

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EDITED BY
Dimitrios Kikidis,
National and Kapodistrian University of Athens, Greece

REVIEWED BY
Pasquale Mone,
University of Molise, Italy
Iokfai Cheang,
Nanjing Medical University, China

*CORRESPONDENCE
Jiyan Leng
✉ lengjy@jlu.edu.cn

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Association between arteriosclerosis, hemodynamic indices, and the risk of falls: receiver operating characteristic curve analysis for different indices in older individuals

Kexin Zhang, Yucen Ma, Di Yang, Mengyu Cao, Huijing Jin and Jiyan Leng*

Department of Cadre Ward, The First Hospital of Jilin University, Changchun, China

Objective: This study aimed to assess the risk factors for falls and evaluate the correlation between arteriosclerosis, hemodynamic indices, and the risk of falls in older individuals.

Method: This cross-sectional study included 920 individuals aged 60 and above from the cadre ward of the First Hospital of Jilin University. Data were obtained from the comprehensive geriatric assessment database of the cadre ward. Ankle-brachial indices (ABI) and brachial-ankle pulse wave velocity (baPWV) were measured using an OMRON arteriosclerosis detection device. Hemodynamic indices were assessed using the CSM3100 thoracic impedance hemodynamic detection system. Fall risk was evaluated with the fall risk assessment tool.

Results: Significant differences in age, weight, education, smoking status, alcohol consumption, cognitive impairment, malnutrition, daily living abilities, depressive state, baPWV, ABI (all $p < 0.001$), systolic pressure, heart rate, cardiac stroke volume, and systemic vascular resistance were observed among the three groups ($p = 0.011$, $p = 0.035$, $p = 0.005$, $p = 0.016$). Ordinal logistic regression analysis indicated that the probability of an increase in fall risk by one level was 2.069 times higher for each unit decrease in educational background. Additionally, fall risk increased by 2.492 times for each additional year of age, 55.813 times for each unit of weight, 3.208 times for smoking status, 3.610 times for alcohol consumption, 4.665 times for cognitive impairment, 2.247 times for malnutrition, 2.596 times for ABI, 2.092 times for heart rate, and 1.586 times for cardiac stroke volume. The receiver operating characteristic curve analysis for fall risk in older individuals demonstrated that ABI was superior to heart rate and systemic vascular resistance in predicting the occurrence of falls.

Conclusion: Our findings indicate that age, weight, educational background, smoking status, alcohol consumption, cognitive impairment, malnutrition, ABI, systolic blood pressure, heart rate, and cardiac stroke volume are associated with an increased risk of falls in older adults. Moreover, arteriosclerosis and hemodynamic parameters may aid in the early identification of fall risk among older individuals.

KEYWORDS

older adults, arteriosclerosis, hemodynamic, the risk of falls, comprehensive geriatric assessment

1 Introduction

Falls refer to a sudden and unconscious change in body position, resulting in a loss of balance and falling to the ground or a lower plane due to various risk factors (1). Annually, at least one-third of individuals aged 65 and above experience falls, with approximately 30% leading to physical injuries such as soft tissue damage, bleeding, fractures, and even death (2, 3). Falls are the leading cause of injury-related deaths among individuals aged 65 and older in China. According to the national disease surveillance system's 2018 data, the fall-related death rate for this age group in China is 63.83 per 100,000, accounting for 39.72% of all injury-related deaths in this demographic. Recent studies have indicated that the incidence of falls increases with age (3, 4), posing a significant threat to the safety of older adults (5).

Older individuals experience an increased incidence of falls due to various intrinsic factors, including skeletal muscle degradation, an unstable center of gravity, impaired balance and coordination, reduced ability to maintain body posture, and decreased vision and cognitive response. Additionally, certain medical conditions such as arteriosclerosis, hypertension, cardiac insufficiency, arrhythmia, and valvular disease contribute to this risk. Vision impairments, gait instability, and blood pressure abnormalities also play a significant role. Furthermore, many medications can affect mental and emotional states, thereby increasing fall risk. Older hospitalized patients with cardiovascular diseases and hemodynamic issues are particularly prone to falls due to the degradation of physiological functions, the influence of underlying diseases, and the effects of medications. These falls significantly impact the physical and mental health of older patients and have become one of the primary contributors to mortality among older patients with cardiovascular disease. Arteriosclerosis (AS) is a systemic cardiovascular disease characterized by the accumulation of lipids, inflammation, cells, and tissue fibrosis within the arterial wall, leading to the formation of plaques and emboli. This condition is a root cause of most clinical cardiovascular diseases (CVD) (6). Previous studies have shown that frailty is a strong predictor of both short-term and long-term mortality in patients with severe acute myocardial infarction. Conversely, cardiovascular-related diseases, particularly hypertension, increase the risk of frailty in older adults (7–10). This paper aims to investigate the risk factors for falls in older individuals and explore the correlation between arteriosclerosis, hemodynamic indices, and fall risk in this population.

2 Materials and methods

2.1 Participants and eligibility criteria

Participants in this study were individuals aged 60 years and older who were admitted to the cadre ward of the First Hospital of Jilin University between May 1, 2019, and December 31, 2023. The inclusion criteria were as follows: (1) age ≥ 60 years and (2) completion of the comprehensive assessment questionnaire and older adult-specific tests. Exclusion criteria included: (1) incomplete basic data or missing indicators in the comprehensive assessment questionnaire and (2) the presence of malignant tumors, immune system disorders, severe liver or kidney dysfunction, or other serious illnesses.

2.2 Measurement

In this study, we analyzed the medical records of all individuals who met the eligibility criteria at the First Hospital of Jilin University between May 1, 2019, and December 31, 2023. Collected medical data included height, weight, sex, age, educational background, smoking history, and drinking history. Ankle-brachial index (ABI) and brachial-ankle pulse wave velocity (baPWV) were measured using an OMRON arteriosclerosis detection device. Hemodynamic parameters were evaluated using the CSM3100 thoracic impedance hemodynamic detection system. Furthermore, participants were assessed with the Activities of Daily Living Scale (ADL and IADL), Mini-Mental State Examination (MMSE), Geriatric Depression Scale (GDS), Falls Risk Assessment (FRA), and Mini Nutritional Assessment (MNA; Part I and Part II).

2.3 Arteriosclerosis test

A Japan-made Omron arteriosclerosis detection device was utilized, operated by trained medical personnel. Patients were instructed to remove their shoes and socks, turn their feet outward, and rest quietly in a supine position for 5 min. In accordance with the standard measurement protocol, cuffs were placed at the antecubital fossa and ankle of the upper limbs to detect the pulsation of the brachial artery and posterior tibial artery and measure systolic blood pressure. ECG clips were attached to the wrists, and a phonocardiogram sensor was positioned along the left sternal border at the fourth intercostal space to detect ECG signals, phonocardiograms, and pulse waveforms. Each measurement was performed twice, and the average values were recorded. The average ABI and baPWV were calculated based on the measurements from both the left and right sides (11, 12). Pasquale Mone et al. (13) found that P-Wave Dispersion (PWD), an electrocardiogram (ECG) parameter defined as the difference between the longest and shortest P-wave durations, was significantly correlated with MMSE scores. Increased arterial stiffness impairs the buffering capacity of large arteries, leading to elevated systolic blood pressure, reduced diastolic blood pressure, and widened pulse pressure. This elevation in afterload on the heart diminishes blood supply during diastole and increases the risk of arrhythmia. Previous studies have demonstrated a positive correlation between baPWV and PWD. Additionally, increased arterial stiffness is associated with the severity of cerebral small-vessel disease (SVD) and may serve as a predictor for incident dementia. As hypothesized, Sae Yamagishi et al. (14) investigated the predictive value of brachial-ankle pulse wave velocity (baPWV) for dementia and cognitive decline, and found that baPWV was indeed associated with both.

2.4 Hemodynamic test

The CSM3100 thoracic impedance hemodynamic detection system (Shenzhen Qianfan Electronics Co., Ltd.) was utilized to measure the patients' hemodynamic parameters. Patients were instructed to lie flat and rest for at least 10 min. A blood pressure cuff was placed over the brachial artery pulsation site, and the skin of the neck and chest was disinfected with alcohol. Electrode sensors were attached to the bases of the left and right sides of the neck (below the earlobes) and along the midaxillary line (aligned with the sternal xiphoid process), with the larger head of the electrode facing proximally. The patients' sex, weight, and height were recorded on the monitoring device. Thoracic electrical bioimpedance was measured by placing electrodes, and impedance changes were calculated through data processing to derive the hemodynamic parameters. Ge Tian et al. (15) investigated the causal relationship between higher blood pressure, pulse pressure, and an increased risk of frailty, suggesting that controlling hypertension may reduce the risk of frailty. Based on preliminary experimental results, we included indices such as stroke volume, systemic vascular resistance index, and thoracic fluid conductivity, given their potential relevance to the study's objectives (16–19).

2.5 Fall risk assessment

The FRA tool was employed in this study. This scale, introduced in 2011 by the Ministry of Health of China (20), comprises 35 items, each scored from 1 to 3 points, with a maximum score of 53 points. Participants scoring ≤2 were classified as low risk, those scoring 3–9 as medium risk, and those scoring ≥10 as high risk. In 2014, Zhuge Yi et al. (21) referenced the revised Fall Efficacy Scale from abroad and applied the guideline scale to assess fall risk in the older adults (22). This scale has demonstrated high reliability and validity and is an effective tool for screening fall risk in older Chinese adults.

2.6 Other assessment

2.6.1 Activities of daily living scale

The ADL and IADL scales assess the fundamental aspects of daily life (23). Both scales consist of 14 items, categorized into four levels: (1) Can perform independently, (2) Some difficulty, (3) Requires assistance, and (4) Unable to perform. The total score ranges from 14 to 56 points (24). These scales are further divided into two subscales: Physical Activities of Daily Living (PADL) and Instrumental Activities of Daily Living (IADL), each comprising seven items.

2.6.2 Nutritional status

The MNA (25) has been widely used in prior studies to evaluate the nutritional status of older adults and serves as an evidence-based screening tool. An MNA score of less than 17 indicates malnutrition in participants.

2.6.3 Depression

The Geriatric Depression Scale (GDS) (26) was specifically developed for older adults. The GDS consists of 30 items, each assigned one point, with a maximum possible score of 30. Participants scoring ≤10 were classified as normal, those scoring 11–20 were categorized as having mild depression, and those scoring 21–30 were classified as having moderate-to-severe depression (27).

2.6.4 Cognitive function

The MMSE is a psychometric screening tool commonly used to evaluate cognitive function. The threshold for cognitive normality is determined by an individual's educational background: a score greater than 20 for those with primary school education, and greater than 24 for those with junior high school education or higher. Scores below these thresholds indicate cognitive impairment. Previous research (28–30) has shown that, while the sensitivity of the MMSE is slightly lower than that of the MoCA in detecting mild cognitive impairment (MCI) and MCI prevalence is higher when using the MoCA compared to the MMSE, both tools demonstrate excellent specificity. Both the MMSE and MoCA consistently identify modifiable factors associated with MCI, providing valuable evidence for the development of intervention strategies. Gao Mingyue et al. (31) evaluated the factors influencing MMSE scores and the validity of its normative values for screening. Their findings demonstrated that the MMSE exhibits high reliability and validity, making it a suitable tool for screening cognitive impairment in older Chinese adults.

2.7 Statistical methods

Statistical analyses were conducted using SPSS statistical software (version 26.0; IBM Corp., Armonk, NY, United States). Continuous variables are presented as mean ± standard deviation (SD) or median (interquartile range), depending on their distribution. Categorical variables are expressed as percentages. Comparisons of quantitative data between two groups were performed using t-tests, while comparisons across multiple groups were made using one-way ANOVA. Categorical variables, such as sex, were compared using chi-square (χ^2) tests. If the data did not follow a normal distribution, rank sum tests were applied. Ordinal logistic regression analysis was employed to examine the correlations between arteriosclerosis, hemodynamic indices, and fall risk. The area under the curve (AUC) was calculated by plotting the receiver operating characteristic (ROC) curve to assess the association between various indices and fall risk. The Youden index was applied to determine the optimal cutoff point. All statistical tests were two-sided, with $p < 0.05$ considered statistically significant.

3 Results

3.1 Baseline characteristics

As presented in Table 1, the study included a total of 920 participants. Statistically significant differences were observed among the three groups regarding age, weight, education level, smoking status, alcohol consumption, cognitive impairment, malnutrition, activities of daily living, and depressive state (all $p < 0.001$).

3.2 Comparison of arteriosclerosis and hemodynamic indices among low-, medium-, and high-risk group

As presented in Table 2, significant differences were observed among the three groups regarding baPWV, ABI, systolic blood pressure, heart rate, cardiac stroke volume, and systemic vascular resistance ($p < 0.05$). The high-risk group exhibited higher baPWV, systolic blood pressure, and systemic vascular resistance, as well as lower ABI, heart

TABLE 1 Comparison of demographic information of the individuals.

	All	Low risk group (*N* = 212)	Medium risk group (*N* = 358)	High risk group (*N* = 350)	*p*
Age (years)	75.1 ± 10.2	70.9 ± 9.1	76.0 ± 9.6[a]	76.7 ± 10.9[a]	<0.001*
Gender					0.159
Male	615 (66.8%)	146 (68.9%)	226 (63.1%)	243 (69.4%)	
Female	305 (33.2%)	66 (31.1%)	132 (36.9%)	107 (30.6%)	
Height (cm)	166.4 ± 7.8	167.3 ± 7.3	165.8 ± 8.1[a]	166.4 ± 7.8	0.072
Weight (kg)	68.0 ± 11.5	71.2 ± 10.6	66.8 ± 12.0[a]	67.2 ± 11.2[a]	<0.001*
Education					<0.001*
Illiteracy	111 (12.1%)	14 (6.6%)	22 (6.1%)	75 (21.4%)	
Primary School	277 (30.1%)	43 (20.3%)	81 (22.6%)	153 (43.7%)	
Middle School	25 (2.7%)	3 (1.4%)	17 (4.7%)	5 (1.4%)	
College Degree and Above	507 (55.1%)	152 (71.6%)	238 (66.5%)	117 (33.4%)	
Smoking					<0.001*
Yes	620 (67.5%)	169 (79.7%)	277 (77.9%)	174 (49.7%)	
No	298 (32.5%)	43 (20.3%)	79 (22.2%)	176 (50.3%)	
Alcohol					<0.001*
Yes	559 (60.8%)	152 (71.7%)	263 (73.5%)	144 (41.2%)	
No	361 (39.2%)	60 (28.3%)	95 (26.5%)	206 (58.9%)	
Cognitive Impairment					<0.001*
Yes	85 (9.2%)	4 (1.9%)	21 (5.9%)	60 (17.1%)	
No	835 (90.8%)	208 (98.1%)	337 (94.1%)	290 (82.9%)	
Malnutrition					<0.001*
Yes	177 (19.2%)	12 (5.7%)	76 (21.2%)	89 (25.4%)	
No	743 (80.8%)	200 (94.3%)	282 (78.8%)	261 (74.6%)	
Ability of Daily Living (score)	16.9 ± 5.6	14.5 ± 1.7	15.6 ± 3.6[a]	19.7 ± 7.4[a,b]	<0.001*
Depressive State (score)	18.5 ± 12.9	21.2 ± 9.3	22.1 ± 10.6	32.4 ± 9.5[a,b]	<0.001*

[a]indicates that the difference is statistically significant compared with the low-risk group.
[b]indicates that the difference is statistically significant compared with the medium-risk group.
*$p < 0.05$.

rate, and cardiac stroke volume compared to the other two groups. All of these differences were statistically significant ($p < 0.05$).

3.3 Ordinal logistic regression analysis of body composition and serological indices of the low-, medium-, and high-risk groups to predict the risk of falls

As shown in Table 3, the probability of fall risk increasing by one level was 2.069 times higher for each unit decrease in educational background (OR = 0.483, 95% CI: 0.862–3.333, p = 0.006). Furthermore, the probability of fall risk increasing by one level was 2.492, 55.813, 4.665, 2.596, 2.092, and 1.586 times higher for each additional unit of age, weight, cognitive impairment, ABI, heart rate, and cardiac stroke volume, respectively (OR = 2.492, 95% CI: 0.862–3.333, p < 0.001; OR = 55.813, 95% CI: 3.305–942.250, p = 0.005; OR = 4.665, 95% CI: 2.875–7.576, p < 0.001; OR = 2.596, 95% CI: 1.895–3.557, p < 0.001; OR = 2.092, 95% CI: 1.404–3.117, p < 0.001; OR = 1.586, 95% CI: 1.118–2.249, p = 0.010).

3.4 The association of different indices with the occurrence of falls

The correlation between various indices and the occurrence of falls in older adults was analyzed and compared. As shown in Table 4, the area under the curve (AUC) for ABI, heart rate, and systemic vascular resistance was greater than 0.5, with AUC values of 0.602, 0.565, and 0.529, and corresponding Youden's Indices of 21.02, 15.00, and 8.00, respectively. The analysis indicated that ABI was superior in predicting the occurrence of falls compared to heart rate and systemic vascular resistance. The corresponding ROC curve is displayed in Figure 1.

4 Discussion

Our study found that increased baPWV, systolic blood pressure, and systemic vascular resistance, along with decreased ABI, heart rate, and cardiac stroke volume, are significant risk factors for falls in older adults. Falls, a common and serious aspect

TABLE 2 Comparison of arteriosclerosis and hemodynamic indices among the low-, medium-, and high-risk groups.

	All	Low risk group	Medium risk group	High risk group	p
baPWV (right)(cm/s)	1766.5 ± 398.3	1632.7 ± 276.5	1802.1 ± 369.2[a]	1811.3 ± 466.8[a]	<0.001*
baPWV (left)(cm/s)	1766.8 ± 391.5	1631.6 ± 263.7	1784.6 ± 353.0[a]	1830.6 ± 467.7[a]	<0.001*
baPWV (cm/s)	1766.3 ± 366.7	1632.2 ± 263.4	1792.6 ± 344.3[a]	1820.6 ± 419.8[a]	<0.001*
ABI (right)	1.09 ± 0.15	1.13 ± 0.13	1.11 ± 0.14	1.05 ± 0.17[a,b]	<0.001*
ABI (left)	1.10 ± 0.45	1.12 ± 0.15	1.10 ± 0.14	1.10 ± 0.71	0.100
ABI	1.10 ± 0.26	1.12 ± 0.13	1.10 ± 0.13	1.08 ± 0.38[a]	0.011*
Systolic Pressure (mmHg)	138.1 ± 19.1	136.1 ± 17.8	138.7 ± 20.2[a]	138.8 ± 18.8[a]	0.035*
Diastolic Pressure (mmHg)	77.4 ± 11.2	78.7 ± 10.7	77.1 ± 11.3	76.8 ± 11.3[a]	0.475
Heart Rate (cpm)	72.5 ± 10.0	74.2 ± 10.0	72.6 ± 10.6	71.4 ± 9.1[a]	0.005*
Cardiac Stroke Volume (ml)	81.0 ± 22.3	79.7 ± 20.5	83.7 ± 21.6[a]	79.1 ± 23.8[b]	0.016*
Thoracic Fluid Conductivity (/kohm)	0.03 ± 0.07	0.03 ± 0.06	0.03 ± 0.07	0.03 ± 0.08	0.053
Systemic Vascular Resistance (Dyne sec/cm^{-5} m^2)	156.1 ± 55.3	159.8 ± 60.2	148.5 ± 42.9[a]	161.7 ± 62.2[b]	0.003*

baPWV, brachial-ankle pulse wave velocity. ABI, ankle-brachial indices.
[a]indicates that the difference is statistically significant compared with the low-risk group.
[b]indicates that the difference is statistically significant compared with the medium-risk group.
*$p < 0.05$.

TABLE 3 Ordinal logistic regression analysis of arteriosclerosis and hemodynamic indices to predict the risk of falls among older adults in the low-, medium-, and high-risk groups.

Indicators	B	SE	Wald	OR	95%CI	p
Age (year)	0.913	0.148	37.841	2.492	0.862–3.333	<0.001*
Weight (kg)	4.022	1.442	7.778	55.813	3.305–942.250	0.005*
Education	−0.727	0.201	13.033	0.483	0.326–0.717	0.006*
Cognitive Impairment (Yes)	1.540	0.247	38.895	4.665	2.875–7.576	<0.001*
baPWV (cm/s)	0.050	0.183	0.075	1.051	0.734–1.505	0.784
ABI	0.954	0.161	35.164	2.596	1.895–3.557	<0.001*
Systolic Pressure (mmHg)	0.182	0.123	2.180	1.200	0.942–1.528	0.140
Heart Rate (cpm)	0.738	0.203	13.169	2.092	1.404–3.117	<0.001*
Cardiac Stroke Volume (ml)	0.461	0.178	6.687	1.586	1.118–2.249	0.010*
Systemic Vascular Resistance (Dyne sec/cm^{-5} m^2)	0.292	0.157	3.449	1.339	0.984–1.822	0.063

Dependent Variable: the risk of falls. Independent Variable: age, weight, education, cognitive impairment, baPWV, ABI, systolic pressure, heart rate, cardiac stroke volume, systemic vascular resistance. baPWV, brachial-ankle pulse wave velocity. ABI, ankle-brachial indices. *$p < 0.05$.

of geriatric syndromes, are influenced by multiple factors, either independently or in combination. Preclinical cardiovascular disease (CVD) is also widespread among older adults. Recent treatment guidelines for CVD risk factors, such as hypertension, hypercholesterolemia, and procoagulant conditions (e.g., atrial fibrillation), have been expanded to include a larger proportion of older individuals (32–34). There is growing evidence suggesting a correlation between arteriosclerosis, hemodynamic abnormalities, and falls in older adults (Figure 2).

Ge Tian et al. (15) investigated the causal association between elevated blood pressure, pulse pressure, and an increased risk of frailty. Since arteriosclerosis and hemodynamic changes contribute to greater frailty and muscle weakness, which in turn reduce mobility, effectively managing these conditions can help mitigate the risk of falls.

Patients with cardiac insufficiency are prone to falls due to reduced cerebral perfusion, decreased cardiac output, unstable posture, and other symptoms during acute episodes (35, 36). Cardiovascular disease is prevalent among older adults (37, 38) and is linked to an elevated risk of falls (39–41). Left untreated, cardiovascular disease may theoretically increase the risk of falls. The cardiovascular system plays several critical roles in bodily function, such as ensuring an adequate blood supply to peripheral muscles during activity and maintaining the blood pressure required for cerebral perfusion to support balance (42). However, treatments aimed at preventing cardiovascular events in older adults, such as the initiation of antihypertensive medication, are associated with a heightened risk of falls in the short term. Arteriosclerosis, the primary cause of cardiovascular disease in

TABLE 4 Correlation between different indices and the occurrence of falls.

	AUC (95%CI)	p	Youden's index (%)	Sensitivity (%)	Specificity (%)
Cognitive Impairment (Yes)	0.452 (0.410–0.494)	0.035*	9.55	98.12	11.43
Malnutrition (Yes)	0.412 (0.371–0.452)	<0.001*	17.64	94.31	23.33
baPWV (cm/s)	0.365 (0.325–0.405)	<0.001*	0.47	97.63	2.84
ABI	0.602 (0.559–0.645)	<0.001*	21.02	60.81	60.21
Heart Rate (cpm)	0.565 (0.520–0.610)	0.004*	15.00	62.70	52.30
Systolic Pressure (mmHg)	0.464 (0.421–0.507)	0.111	1.12	97.21	4.01
Cardiac Stroke Volume (ml)	0.488 (0.445–0.532)	0.602	4.37	92.93	11.44
Systemic Vascular Resistance (Dyne sec/cm^{-5} m^2)	0.529 (0.485–0.572)	0.207	8.00	46.70	61.30

baPWV, brachial-ankle pulse wave velocity. ABI, ankle-brachial indices. *$p < 0.05$.

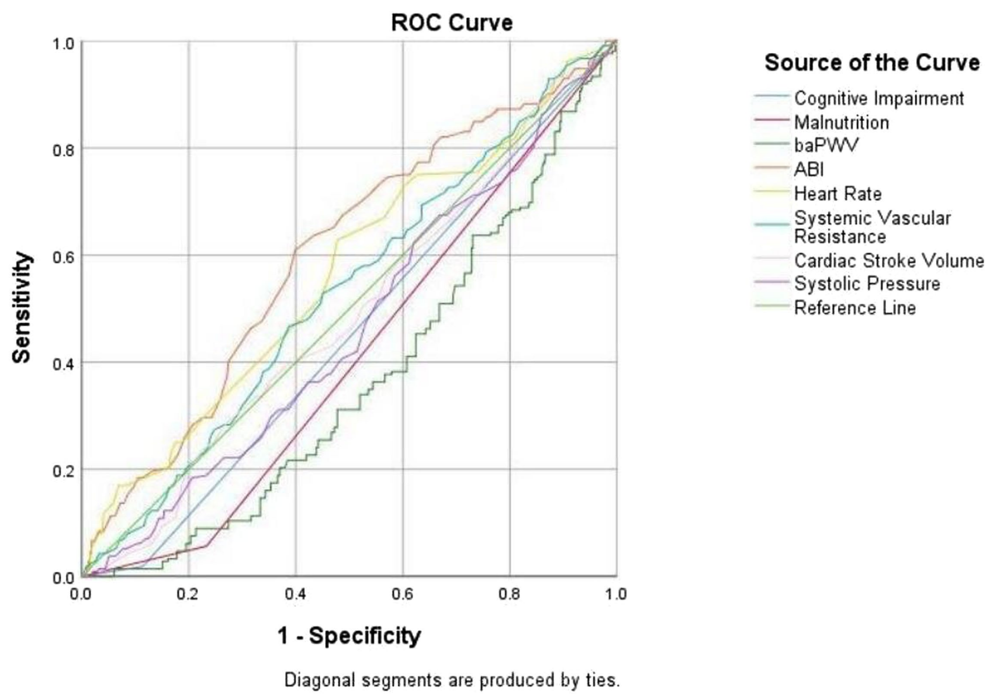

FIGURE 1
The receiver operating characteristics curve of different indices for the occurrence of falls.

older adults, is also closely linked to the risk of falls in this population (43, 44).

Studies have shown that subclinical cardiovascular disease increases the risk of falls. The causes of falls are multifactorial and include muscle weakness, impaired physical function during transitions (e.g., moving from sitting to standing or walking), and postural imbalance while standing (45, 46). The cardiovascular system plays a critical role in these basic functions, including increasing heart rate during positional changes, maintaining peripheral blood supply, and stabilizing blood pressure to counteract the effects of gravity while standing. These functions are essential for maintaining balance, which is mediated by the central nervous system (42, 47). Thus, functional pathway defects leading to falls may originate from cardiovascular conditions, even before these conditions present as clinical cardiovascular disease. The findings of this study support these conclusions.

This study found that fall risk is closely associated with age, education level, cognitive impairment, and daily living ability. Although falls can occur in any age group, the risk is significantly higher in older adults compared to younger individuals (48, 49). Our research suggests that fall occurrence is related to education level, potentially due to the stronger health awareness among individuals with higher educational attainment. Numerous studies have shown that older adults with cognitive impairment are more prone to falling (50, 51), likely because their ability to process and respond to external information is diminished, increasing the likelihood of falls.

Our research suggests that older adults should regularly monitor arteriosclerosis and hemodynamic parameters, including ABI, heart rate, and systemic vascular resistance. Assessing the extent of atherosclerosis, screening for cardiovascular diseases,

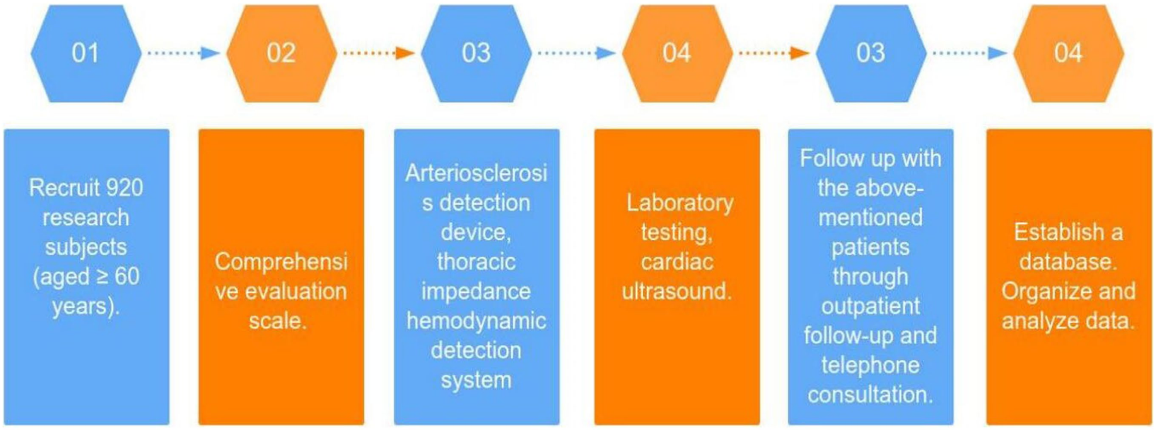

FIGURE 2
Study flow chart.

and implementing early detection and prevention strategies for falls are essential for improving the health outcomes of older adults.

5 Conclusion

Our findings indicate that age, weight, educational background, smoking status, alcohol consumption, cognitive impairment, malnutrition, ABI, systolic blood pressure, heart rate, and cardiac stroke volume are associated with an increased risk of falls in older adults. Moreover, arteriosclerosis and hemodynamic parameters may aid in the early identification of fall risk among older individuals.

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 the ethics committee of the First Hospital of Jilin University. 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

KZ: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. YM: Data curation, Methodology, Writing – review & editing. DY: Data curation, Writing – review & editing. MC: Data curation, Writing – review & editing. HJ: Data curation, Writing – review & editing. JL: 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.

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EDITED BY
Nattawan Utoomprurkporn,
Chulalongkorn University, Thailand

REVIEWED BY
Sunghoon Shin,
Yeungnam University, Republic of Korea
Semra Bulbuloglu,
Istanbul Aydın University, Türkiye

*CORRESPONDENCE
Samuel Teferi Chanie
✉ sami.ager21@gmail.com

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Cross-cultural adaptation, content validity, and reliability of the Amharic version of the modified John-Hopkins fall risk assessment scale among older adults who attend home health care services

Samuel Teferi Chanie[1]*, Moges Gashaw[1], Kassaw Belay Shiferaw[1], Fiseha Sefiwu Zinabu[1], Setegn Fentahun[2], Kassahun Cherkos[1], Alemu Kassaw Kibret[1], Ermias Solomon Yalew[1], Assefa Kebad Mengesha[3], Habtamu Semagne Ayele[3], Zufan Yiheyis Abriham[4] and Mihret Dejen Takele[1]

[1]Department of Physiotherapy, College of Medicine and Health Science, University of Gondar, Gondar, Ethiopia, [2]Department of Psychiatry, College of Medicine and Health Science, University of Gondar, Gondar, Ethiopia, [3]Department of Pharmacology, School of Pharmacy, College of Medicine and Health Science, University of Gondar, Gondar, Ethiopia, [4]Department of Medical Parasitology, School of Biomedical and Health Sciences, College of Medicine and Health Science, University of Gondar, Gondar, Ethiopia

Background: The modified John-Hopkins fall risk assessment tool (mJH-FRAT) is a comprehensive and multi-factor fall risk assessment tool used to screen and grade older adult's fall risk levels in home health care services. This can help to identify risky individuals early, establish prevention protocols, and reduce the occurrence of injury. Nevertheless, there is a dearth of contextually valid and reliable fall risk assessment tools among this population in the study area. The aim of this study is therefore to cross-culturally adapt and assess the content validity and reliability of the modified John-Hopkins fall risk assessment tool among older adults following home health care in Ethiopia.

Method: The English version of the mJH-FRAT underwent cross-cultural adaptation into Amharic. The final Amharic version was subjected to face validity and then content validity was computed. This community-based study was conducted from November 2023 to May 2024 with a total of 150 participants selected through convenience sampling. Data collection occurred through face-to-face interviews. Epi-Info 7 and Statistical Package for the Social Sciences software version 25 facilitated data entry and analysis, respectively. Reliability was assessed by employing intra-rater and inter-rater reliability using Cohen's kappa.

Result: The CVI based on the item level of all the items was between 0.8 and 1. The S-CVI based on average for domains such as general condition and clinical condition was 0.925 and 1, respectively, and the S-CVI (average) of the scale was 0.96. The S-CVI based on the universal agreement value for the overall 8 items was 0.75. The kappa statistic coefficient value was between 0.79 and 1. The intra-rater reliability and inter-rater reliability were 0.94 and 0.93, respectively.

Conclusion: The rigorous adaptation process, face and content validity, and reliability analyses demonstrated that the Amharic mJH-FRAT is a content valid and reliable tool for assessing the fall risk level in this population. Clinicians and researchers can utilize this tool for the advancement of both clinical practice and research work on this group of people in Ethiopia.

KEYWORDS

Amharic, content validity, cross-cultural adaptation, home health care service, modified John-Hopkins fall risk assessment scale, older adults

Introduction

Background and statement of the problem

Injuries are a significant public health concern worldwide (1, 2) and it became the fourth leading cause of death among older adults (3). According to data from Ethiopia's Health and Demographic Surveillance Sites, injuries constitute 6.4% of the 9,719 older adult deaths recorded in 3 years, with fall down injuries accounting for the majority (4). Now a days, fall down injuries have become one of the most prevalent and harmful injuries that affect older adults (5).

Age-related physical changes, pre-disposing comorbidities, and environmental factors like utilizing worn out shoes are usual causes of fall among the older adults (6). Regardless, a fall down injury might be fatal or non-fatal. Non-fatal fall injuries are highly correlated with a loss of independence (7) and it contributes to increased health care expenditures and a lower quality of life among older adults, and the expenses along with the health care services related to falls at older ages are rising dramatically on a global base (8).

Fall down injuries account for multiple complications, including fractures, among the older adult population (9). Comparably, it takes much longer for older adults to recover from fall-related injuries owing to diminishing functional capacity and physiological deterioration associated with age than adults (10, 11). Falls can lead to long-term disabilities and physical dependence (12). Falls cause not only physical injuries but also psychological repercussions such as a sense of unhappiness and discomfort (13).

Since falling exacerbates the chance of a recurrence of falling and is related to further detrimental health effects, including fear of falling (14, 15). Fear of falling, the level of certainty that someone feels in their ability to execute activities of daily living (ADL) without falling, by itself hinders the ability to perform routine activities for living, increasing the degree of dependence on assistance and reducing one's autonomous (16). Moreover, falling increases the likelihood of falling after a certain period of time and corresponds to deconditioning, fragility, and gait disturbance (17). Commonly, surgical management, physiotherapy, and psychotherapy interventions are included in managing fall complications (18).

There are a number of fall risk assessment tools to measure the incidence of falls among community-dwelling older adults; however, fall risk level assessment among older adults following home health care services is untouched in the country. The John-Hopkins fall risk assessment tool (JH-FRAT) was first developed by Stephanie S. et al. to examine multi-factor fall risks among older adults in acute health care settings (19).

To apply JH-FRAT in the community for older adults following home health care services, the modified John-Hopkins fall risk assessment tool (mJH-FRAT) was cross-culturally adapted and validated (20) and it has demonstrated high specificity and sensitivity and is easy to use (20). The tool has seven items that help predict an older adult's fall risk level. It has a total score of 35 and three categories, such as low risk (0–6), moderate risk (7–13), and high risk (14–34).

Taking into consideration the incidence of falls among older adults following home health care services and its negative impact on their ADL, psychological status, and quality of life, assessing their fall risk level with a valid and reliable measurement tool is a crucial step. Moreover, the measurement tool's psychometric properties should be evaluated contextually to avoid its varying nature in relation to cultural context, literacy level, and age. However, there is no cross-culturally adapted, valid, and reliable fall risk measurement tool in Amharic to use among such a population in Ethiopia. Therefore, the aim of the present study is to cross-culturally adapt and examine the content validity and reliability of the English version of the modified John-Hopkins fall risk assessment tool on this population in Ethiopia.

Method

Study procedure and period

This community-based cross-cultural adaptation, content validation and reliability study was conducted from November, 2023 to May, 2024. The current study followed a two-stage methodology to accomplish its objective. First, translation and cross-cultural adaptation of the English mJH-FRAT into Amharic, face and content validity were carried out. Next, the reliability of the Amharic version of mJH-FRAT was scrutinized. This study was carried out based on the Helsinki Declaration. The Institutional Review Board of the School of Medicine of the University of Gondar approved the study (ref no: SOM 575). The signed informed consent form was attained from

Abbreviations: Am-JHFRAT, Amharic Version of John Hopkins Fall Risk Assessment Tool; BT1, Back Translation One; BT2, Back Translation Two; CVI, Content Validity Index; CVR, Content Validity Ratio; I-CVI, Item-level Content Validity Index; mJH-FRAT, modified John-Hopkins fall risk assessment tool; S-CVI/Ave, Scale-level Content Validity Index based on the Average; S-CVI/UA, Scale-level Content Validity Index based on the Universal Agreement; SPSS, Statistical Package Social Science; T1, Translation one; T2, Translation two.

every participant after providing a verbal and written account. Stage one:

Translation and cross-cultural adaptation into Amharic

The translation and cross-cultural adaptation of the English mJH-FRAT into Amharic language occurred based on the cross-cultural adaptation and translation of measurement tool guideline stated by Beaton's (21). The detailed procedural steps are mentioned below.

Step 1: Two bilingual English-speaking forward translators who are fluent in both Amharic and English independently translated the original mJH-FRAT along with its specific instructions into Amharic (Am). As recommended, the first forward translator had a medical background, and he was from the department of physiotherapy at the school of medicine and health sciences at the University of Gondar, and he had information about the aim of the study. Whereas the second forward translator was an English language expert, and he is from the English language department, and he had no information about the aim of the study.

Step 2: The two forward translators and principal investigator combined the two forward translations (FT1 and FT2) into a common version (FT12) through consensus. This step resulted in a consensus translation of the Amharic version of mJH-FRAT (mJH-FRAT-Am I), and the principal investigator was there to mediate the synthesis of T12.

Step 3: Forward-translated Amharic version I of mJH-FRAT was translated back into English by two bilingual back translators independently. The two translators were neither aware nor informed about the concepts explored to avoid information bias and highlight unexpected meaning (22). Both the translators were from the department of English language, at the University of Gondar. They met and synthesized the back-translated English version of mJH-FRAT. This process was to make sure the content of the back-translated version was consistent with the content of the original version and spotting out possible imperfections.

Step 4: The expert panel was formed by five members: three physiotherapists (MSc), one from the language department (MSc), and one methodologist (PHD). The panel members, therefore, met and reviewed the translated version and discussed the clarity, understandability, and comprehensiveness of all the items in the questionnaire to reach a consensus on any possible discrepancy. Moreover, the panelists assessed the equivalence of the original and translated versions using four criteria: semantic equivalence, idiomatic equivalence, experiential equivalence, and conceptual equivalence (23). Finally, they proposed what would be considered the pre-final version of the questionnaire for further testing.

Step 5: The pre-testing of the pre-final Amharic version of mJH-FRAT was carried out using cognitive interviews with participants from the target population. The cognitive interview was carried out with a total of 30 older adults who follow home health care services in the study area. These participants were involved for the pre-testing purpose only. Hence, they did not participate in the reliability assessment. The clarity of instructions, language appropriateness, cultural suitability, and acceptability of the scale were evaluated as well. Lastly, the translated and cross-culturally adapted Amharic version of mJH-FRAT was prepared for face and content validation assessment.

Face validity

Face validation is performed to assure that lay experts easily understand the items of the scale in terms of their feasibility, formatting, readability, and/or clarity in language (24). The adapted modified John-Hopkins fall risk assessment tool was checked for face validity by 15 randomly selected lay experts with yes or no responses to indicate favorable and unfavorable evaluation criteria, respectively. Lay experts were health practitioners (physiotherapists and clinical nurses) who were providing health care services at home. They were asked if the format and items were clear, understandable, and contextual language selection.

Content validity

Content validity is also known as intrinsic validity, and it is a pre-request for further statistical validity. It is used to measure the comprehensiveness and representativeness of the content domain of items in a questionnaire (25). Moreover, it allows the researchers to obtain a clear picture of the limitations, dimensions, and components of the construct from the panel of experts (26). The content validity of the adapted mJH-FRAT was assessed by content validity determination and judgment quantification (27).

Two independent expert panels were formed for the content validity determination and quantification procedure. Each expert panel had 10 members from academia (physiotherapy, occupational therapy, and biostatistics departments). The criteria for panel member selection were expert's knowledge of the subject matter, specific training, and work experience over 5 years. A consent form was sent to all the experts, and they were notified that they were taking part in the study voluntarily and that they had the right to withdraw at any time. The adapted modified John-Hopkins fall risk assessment questionnaire was then sent to the members of the expert panels through email after their consent to participate was secured.

The first expert panel was responsible for content validity determination. Additionally, they were also responsible for adding, removing, or modifying the items and evaluating the scale's items for their representativeness, applicability, and feasibility in low-resource study settings. A scheduled face-to-face panel discussion was held to reach a consensus regarding their judgments to review and endorse the appropriate and feasible means of instruction.

The second expert panel was formed mainly to reduce over-or under-estimation of rating and judging. The panel members received the tool with a checklist to rate the preliminary scale's items in terms of their relevancy and essentiality for the content domain of the scale. The rating process took no more than 15 min.

Content validity determination

The content validity determination was conducted using both developmental and judgmental stage (28). The development stage comprises three steps, such as domain identification, item generation, and instrument construction (29, 30). The domain identification was done using a literature review, content analysis, and panel expert suggestions (31). One item was added during the item generation step. The items were then arranged in each domain, reworded as suggested, and refined by the panel experts for the final scale construction.

Content validity quantification

Content validity index based on item level (I-CVI), scale level content validity index based on average agreement (S-CVI/Ave), scale level content validity index based on universal agreement (S-CVI/UA), content validity ratio, and Kappa statistic coefficient (K) were employed for the quantification of the content validity of the adapted modified John-Hopkins fall risk assessment tool.

Content validity index (CVI)

It is the procedure that enables raters to independently review and score the relevance of the items to the content domain represented by the tool (27). The CVI for each individual item (I-CVI) as well as for the total scale (S-CVI) was computed. The relevance category has four points, such as: not relevant = 1, somewhat relevant = 2, quite relevant = 3, and highly relevant = 4. The CVI is the proportion of a score of 3 or 4 given to the items by the experts (27).

The content validity index value for individual items ranges from 0 to 1, and I-CVI > 0.79 is considered the item being relevant for the content domain of the scale (32, 33). The scale level content validity index has two approaches, such as based on the average (S-CVI/Ave) and based on universal agreement (S-CVI/UA). The acceptable value of scale level CVI based on average (S-CVI/Ave) and universal agreement (S-CVI/UA) values was set at 0.8 and 0.7, respectively (34).

Kappa statistic coefficient

The kappa statistic shows the percentage of agreement that remains after a chance agreement is taken out. The total amount is compared with the highest value that may be achieved, which allows for agreements that arise only by chance, considering the distribution of the marginal item ratings allocated by each expert (35, 36). The kappa statistic, a consensus index of inter-rater agreement, is added to CVI to ensure that the chance agreement has no effect on the expert agreement (31). Kappa's assessment criteria is that values above 0.74 are considered excellent (37).

Content validity ratio (CVR)

In accordance with Lawshe's principle, the content validity ratio is the ratio of the number of experts rating the items of the tool as essential to the total number of expert panel members. It assesses if the items of the tool are necessary to conduct a certain construct by observing a set of experts who rated each of the items in terms of a three-point scale, such as 1 = essential, 2 = useful but not essential, and 3 = not essential (38).

When an item is rated as "essential" by all experts, the CVR value will be equal to 1, the CVR value will be between 0 and 1 when the number of respondents who rate the item as "essential" is greater than half yet less than all, and the value of the CVR will be negative if less than 50 % of the experts rate the item as "essential" (39). The acceptable value of CVR was set at 0.6 and above (39).

Phase two: reliability assessment

Study setting

The present study was scrutinized to translate and cross-culturally adapt the English modified John Hopkins fall risk assessment tool into Amharic and assess the face validity, content validity, and inter-rater and intra-rater reliability of the Amharic version among older adults following home-based health care in Ethiopia. Although Ethiopia has multiple ethnic groups that speak different languages (40), Amharic is its official and national language, and it is also the first language in the study area, Gondar city. Gondar is the ancient and largely populated city, and it is located nearly 800 km north of Addis Ababa, the capital of Ethiopia. The city has six sub-cities with 25 Kebeles.

Study population, inclusion and exclusion criteria

This study included older adult individuals who follow home based health care service in Gondar city during the study period. The inclusion criteria were older adults who attend health care interventions at their home for at least two visits per week, who had a willingness to participate in the study, who can walk with or without assistive devices, and who are able to speak and understand Amharic. This study excluded bed-ridden older adults, who are medically diagnosed with psychological disorders or cognitive impairment, since they may not respond appropriately. The eligibility criteria screening began after the individual's willingness to participate in the study was secured.

Sample size and sampling technique

There is still a dearth of precise and universal sample size determination technique for the validity and reliability assessment (41). The sample size determination for the reliability assessment studies is usually between 20 individuals for the 3-point rating scale and 100 for the 7-point scale. The recommended minimal sample size for the 4, 5, and 6-point scales is 30, 50, and 75, respectively (42). This study assumed 150 older adults for the reliability assessment (75 for inter-rater and 75 for intra-rater reliability). The convenience sampling method was employed to select the study participants.

Data collection

Well-trained physical therapy professionals (MSc) were engaged in the data collection process. The signed informed consent form was obtained from every participant after providing a verbal and written account before proceeding with data collection. Additionally, the participants were given a concise explanation regarding the purpose of the study and that their personal information was going to be kept confidential.

One trained professional collected data twice from the same respondent with 2 weeks of duration in between one session and the other to avoid recall bias for the intra-rater reliability evaluation. On the other hand, two trained professionals collected data from the same respondent one after the other within 15 min of rest in between for the inter-rater reliability assessment. Data collectors who participated during the inter-rater reliability assessment had no access to the other collector's results to prevent bias. The principal investigator and other co-authors strictly reviewed the data for clarity, accuracy, and completeness.

Reliability analysis

Reliability evaluates how well a certain measurement tool has a consistent result. Additionally, reliability assessment aids in identifying mistakes in content sampling, variances in respondents' characteristics, and preferences for measurement scales (43). The reliability of the

Amharic version of mJH-FRAT was assessed by intra-rater and inter-rater reliability.

Intra-rater reliability examines the consistency of rating scores given by the same rater over time (44). On the other hand, inter-rater reliability is the degree to which various raters provide consistent estimates of the same construct. It assesses an agreement among two or more raters (45).

The intra-rater and inter-rater reliability assessments of Am-JHFRAT were computed using Cohen's kappa coefficient (K) since it is categorical. The value of kappa ranges from 0 to 1. A Cohen's kappa value of 0 indicates no agreement between the two rates. 0.01–0.20 indicates poor agreement, 0.21–0.40 indicates slight agreement, 0.41–0.60 indicates fair agreement, 0.61–0.80 indicates good agreement, 0.81–0.92 indicates very good agreement, 0.93–1.0 indicates excellent agreement, and 1.0 indicates perfect agreement between two rates (45).

Epi-Info 7 data program and Statistical Package Social Science (SPSS) version 25 software were used to enter and analyze the data, respectively. The participant's socio-demographic characteristics were reported by descriptive statistical analysis using counts (n) and percentages (%) through texts and tables.

Results

Translation and cross-cultural adaptation into Amharic

A robust procedure was followed to translate and cross-culturally adapt the original mJH-FRAT into Amharic. The forward and backward translations were carried out satisfactorily. Next, an in-person discussion was held by the expert committee to screen the establishment of equivalence between the translated and the original questionnaire based on the criteria mentioned earlier. Then, the committee approved that the translated questionnaire fulfilled all the equivalence criteria. Moreover, the instructional design was endorsed to be a face-to-face questionnaire administration method to make the tool feasible for the illiterate people. In conclusion, the translation and cross-cultural adaptation task was completed successfully.

Face validity

The present study involves 15 lay experts for face validity assessment, and they reported that all the items were easy to understand. Additionally, they also asserted that the domain frame of the questionnaire was logical. Moreover, the experts support that the scale format was relevant to the measuring tool. Conversely, they revealed a jargon phrase that would be difficult to understand by the study population. The phrase in the item (ሲራምዱ ሚዛንዎን ለመጠበቅ ይቸገራሉ) was replaced with more clear words (ሲራምዱ የመንገዳገድ ችግር አለብዎት ወይ) as lay experts have recommended. Generally, the Amharic mJH-FRAT demonstrates excellent face validity.

Content validity

The content validity assessment included a total of 20 panel experts in two different phases. All the experts approved the two identified domains and all the items in the first phase of the panel discussion. The panelists raised invaluable comments and added one item ("presence of fear of falling") that is evidenced to be related to the content domain of the questionnaire and a cause for falling (46). Moreover, there was some modification in terms of item relocation to another domain and reordering of items with their respective domains. Then, the revised and adjusted version was resubmitted via email to experts for approval. Finally, the preliminary Amharic version of the modified John-Hopkins fall risk assessment tool, composed of eight items with two domains, was prepared for content validity quantification.

The content validity quantification phase shows that the item level CVI of all the items in both domains ranged from 0.8 to 1 (Table 1). The S-CVI based on average for the overall items was 0.96. The S-CVI based on the universal agreement value for the overall 8 items was 0.75. The kappa statistic coefficient value was ranged from 0.79 to 1 (Table 1). The CVR result was between 0.8 and 1 (Table 1).

The above findings support that all the items are relevant and essential for the content domain of the questionnaire, and the expert's agreement was not affected by a chance agreement. This implies that the Am-JHFRAT is highly content valid to measure fall risk levels among older adults receiving home based health care services in Ethiopia.

Socio-demographic data for reliability analysis

The current study included a total of 150 older adult participants (75 for intra-rater reliability and 75 for inter-rater reliability) for the reliability assessment. The majority (43.4%) of the participant's ages were between 70 and 75 years old. Above half (67.4%) of them were male. Only a few (12%) of participants achieved a college or higher education level. Additionally, the majority (62.7%) of them were married. Over half (68%) of them were Orthodox Christians.

TABLE 1 Content validity quantification of the Amharic version of the modified John-Hopkins fall risk assessment tool among older adults following home-based health care service in Ethiopia, 2024.

Domain	Items	I-CVI	UA	Pc	K	CVR
General condition	Age	1	1	0.000976	1	1
	History of fall in the past 6 months	1	1	0.000976	1	1
	Fear of fall	1	1	0.000976	1	1
	Physical activity status	1	1	0.000976	1	1
Comorbidities	Medication	1	1	0.000976	1	1
	External appliance	0.9	0	0.00976	0.899	1
	Incontinence	0.8	0	0.044	0.79	0.8
	Alertness	1	1	0.000976	1	1

CVR, content validity ratio; I-CVI, item level content validity index; K, kappa statistic coefficient; Pc, probability of chance agreement and UA, universal agreement.

TABLE 2 Socio-demographic data of the participants for the reliability assessment of the Amharic version of John-Hopkins fall risk assessment tool among older adults following home-based health care service in Ethiopia, 2024.

Socio-demographic data	Category	Frequency (*n*)	Percentage (%)
Gender	Female	49	32.6
	Male	101	67.4
Age	65–70	62	41.4
	70–75	65	43.4
	>75	23	15.2
Educational status	Unable to read and write	64	42.7
	Primary school	37	24.7
	Secondary school	31	20.7
	College and above	18	12
Marital status	Married	94	62.7
	Divorced	29	19.3
	Widowed	27	18
Religion	Orthodox Christian	102	68
	Muslim	28	18.7
	Catholic	11	7.3
	Protestant	9	6

%, percentile; *n*, frequency.

Furthermore, the majority (46%) of them had a moderate level of fall risk. The detailed socio-demographic data is illustrated in the Table 2.

Reliability

The overall intra-rater reliability of the Amharic version of the modified John-Hopkins fall risk assessment scale was excellent ($K = 0.94$). In addition, the Cohen's kappa coefficient value for the intra-rater reliability of each domain was 0.90 and 0.86, respectively. The result reveals that the overall tool has excellent intra-rater reliability and at the domain level as well.

Similarly, the overall inter-rater reliability of the Amharic version of the modified John-Hopkins fall risk assessment scale was excellent ($K = 0.93$). Moreover, the Cohen's kappa coefficient values for the inter-rater reliability of each domain were 0.89 and 0.92, respectively, which supports the fact that the tool has excellent inter-rater reliability both at the scale and domain level.

Discussion

This study was carried out to translate and cross-culturally adapt the modified John-Hopkins fall risk assessment tool into Amharic and to evaluate the content validity and reliability of the Amharic modified John-Hopkins fall risk assessment tool in an Ethiopian context for use during home-based health care services. Fall risk level assessment among this population has been neglected so far, and no related study has been done before in the country. Hence, the current study addressed this particular gap for a comprehensive fall risk assessment and selective management.

During the cross-cultural adaptation process, additional words were included for further clarification of each item to make the instruction clear. Generally, the translators reached consensus later with a principal investigator as a mediator, and the overall adapting process was done satisfactorily. During the face validation, few rewordings were made on the specific item that resembled jargon words to enhance the item's understandability for the participants by adhering to the lay expert's suggestions. In conclusion, the questionnaire demonstrated satisfactory face validity.

The content validity assessment procedure was carried out in two independent phases to avoid expert's over-and under-estimation bias. Experts added one item ("the presence of fear of falling") that can be a cause for the incidence of falls among older adults (46, 47) during the first phase of the content validity procedure. Additionally, they also proposed and approved two domains, namely, general conditions and clinical conditions. Moreover, they reordered and arranged the items in their respective domains. Furthermore, the type of data collection method was suggested to be structured face-to-face questionnaire administration by considering the educational background of the majority of the study population.

Evidence asserts that there cannot be a single set of guidelines for establishing a defensible cut point for the scores of all tests (48). Thus, the one item added was made to hold its own score out of 2. Therefore, the total score was made out of 30, and the grade classification was established as follows: low fall risk (< 11 total points), moderate fall risk (11–22 total points), and high fall risk (>22 total points). Moreover, the content validity quantification finding supports that the Am-JHFRAT is highly content-valid in the Ethiopian context.

The values of the intra-rater and inter-rater reliability were 0.94 and 0.93, respectively, which together suggests that the Am-JHFRAT has excellent intra-rater and inter-rate reliability to assess the fall risk level of older adults who follow home-based clinical services in Ethiopia. This content valid and reliable scale is easy to use, and the items are well related to the content domain of the scale. Thus, it can be applied during home health care services for the early detection of older adult's fall risk levels and to proceed and apply targeted interventions to prevent post-complications secondary to fall injuries (19).

Strength and limitation of the study

The present study provides a contextual, content valid, and reliable fall risk assessment scale to apply during home-based health care services. The face validity was also evaluated, followed by a content validity examination. The study finding supports its use in the advancement of home based health care services and research work on this population to classify their fall risk level.

Despite this, the current study has a few limitations. To begin with, the study utilized a relatively small sample size with a convenient sampling technique, which may affect the representativeness of the result. Furthermore, due to the fact that there is no similar validated tool that measures the construction under consideration in an Ethiopian context, we were not able to scrutinize the tool's construct and criterion validity, suggesting a need for further psychometric assessment of this measurement tool in future studies for better evidence with a large sample size and probability random sampling technique.

Conclusion and clinical implication

The robust translation, cross-cultural adaptation process, face and content validity examination, and reliability examination support that the Amharic version of JH-FRAT is a content valid and reliable scale to assess the fall risk level of older adults following home-based health care services. This valid and reliable Am-JHFRAT is a time saver and easy to use for the advancement of home health care services and research works. This in turn helps health care providers detecting older adult's fall risk levels early, take specific and targeted interventions, and reduce the incidence of fall-down injury post-complications (49) (Supplementary File).

Generally, understanding older adult's fall risk level through a valid and reliable assessment tool and applying comprehensive prevention measurement promotes the older adult's quality of life and happy aging and reduces the individuals and public's economic burden. Further studies including disaggregated analysis are welcomed to solidify the finding on male and female participants.

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 carried out in line with the Helsinki Declaration. The University of Gondar School of Medicine Institutional Review Board approved this study (ref no: SOM 575). A verbal and written account was delivered, and a signed consent form was obtained. Moreover, the investigators and data collectors were strictly directed and ensured the privacy and confidentiality of participants' information.

Author contributions

SC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. MG: Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – review & editing. KS: Methodology, Software, Supervision, Validation, Writing – review & editing. FS: Software, Validation, Writing – review & editing. SF: Resources, Supervision, Validation, Writing – review & editing. KC: Data curation, Software, Supervision, Validation, Writing – review & editing. AK: Software, Supervision, Validation, Writing – review & editing. EY: Investigation, Software, Supervision, Validation, Writing – review & editing. AM: Supervision, Validation, Writing – review & editing. HS: Supervision, Validation, Writing – review & editing. ZA: Supervision, Validation, Writing – review & editing. MD: Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, 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.2024.1470517/full#supplementary-material

SUPPLEMENTARY FILE 1
The cross-culturally adapted and validated Amharic version of the modified John-Hopkins fall risk assessment questionnaire.

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Evaluating the effectiveness of evidence-based falls prevention programs: a study on participant risk levels and program congruency

Cathy S. Elrod* and Rita A. Wong

Center for Optimal Aging, Marymount University, Arlington, VA, United States

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EDITED BY
Nattawan Utoomprurkporn,
Chulalongkorn University, Thailand

REVIEWED BY
Tony Kuo,
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Rose Pignataro,
Emory and Henry College, United States
Carlo Lazzari,
International Centre for Healthcare and Medical Education, United Kingdom

*CORRESPONDENCE
Cathy S. Elrod
✉ celrod@marymount.edu

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Background: Falls are a leading cause of injury and injury-related deaths in older adults. A variety of community-delivered, evidence-based, fall risk-reduction programs have been developed and proven effective. These evidence-based fall prevention programs (EBFPP) have been classified along a fall-risk continuum, indicating the target fall-risk level of participants. The congruency between the program's targeted and enrolled fall-risk level of participants is unknown. This study creates a fall-risk classification index, places participants into one of three fall risk categories, and then examines congruency of actual vs. recommended fall-risk of participants, by program.

Methods: Data came from the Healthy Aging Programs Integrated Database, created by the National Council on Aging (NCOA) funded by the Administration for Community Living (ACL) for use by ACL falls prevention program grantees. Using data from a pre-participation survey designed by the ACDL for their grantees, a fall risk index was created. The fall risk levels of the participants were then compared to the fall risk profile of the EBFPPs as identified in NCOA's Evidence-based Falls Prevention Programs Risk Continuum Guidance for Program Selection in which they were enrolled.

Results: Between July 2016 and June 2022, 105,323 older adults participated in one of eight EBFPPs. Participant characteristics varied among programs. Applying the fall risk index to the fall risk sample (31,064 older adults), 29% of participants were identified as being at high risk, 41% at moderate risk, and 30% at low risk. When the fall risk level of participants, by program, was compared to the target risk profile of the associated EBFPP, programs that had a risk profile targeting individuals at moderate to low risk were found to enroll a larger percentage of adults at high risk than expected. All programs enrolled at least some participants at each of the three risk levels.

Conclusion: All eight EBFPPs enrolled participants across all three fall-risk levels with most programs being at least somewhat congruent with the fall-risk program continuum recommendations. More research is needed to better understand inconsistencies between risk-levels of program, target risk-levels, and actual participant risk-level, to guide either adaptations in the risk-level classification or program modifications to accommodate different risk-levels.

KEYWORDS

older adults, evidence-based programs, fall prevention, fall risk, health promotion, program evaluation, United States

1 Introduction

Falls are a significant public health issue for older adults, impacting morbidity and mortality. They are the leading cause of injury and injury-related deaths of older adults. Indeed, although the overall mortality rate in the United States decreased between 1999 and 2020, the death rate from falls increased (1). Fear of falling and sequalae of fall injuries affect quality of life and frequently lead to lowered physical activity and fitness as well as increased risk of future falls (2). Many conditions can contribute to falls, and most falls are caused by a combination of factors (2–4). As the number of risk factors increase, the likelihood of an older adult experiencing a fall also increases.

Well established risk-reduction programs, proven to decrease fear of falling, number of falls, and, in some cases, injuries from falls, in community-dwelling older adults, are available as community-delivered education, self-management, and/or exercise programs (5, 6). Despite their known effectiveness, community dissemination has been challenging (7). Insufficient numbers of volunteer or staff program leaders, limited funding to deliver programs affordably, and lack of public awareness and interest in pursuing fall prevention activities are frequently identified factors impacting reach and program sustainability (5, 6).

Since 2014, to stimulate community adoption, the Administration for Community Living (ACL) within the Department of Health and Human Services, has supported the community dissemination of evidence-based falls prevention programs (EBFPPs) through discretionary funding awards made through a competitive application process. Community-delivered fall prevention programs that are eligible for support through this grant program are approved by the ACL through a rigorous effectiveness review process. Criteria for receiving these cooperative agreement grants include a comprehensive review of the community needs with identification of fall risks, target audiences, and rationale for the chosen evidence-based fall prevention program (EBFPP) (8). Over $50 million has been awarded by the ACL through discretionary grants to grantees in support of fall prevention (9).

As of June 2022, 16 fall prevention programs were approved by the ACL as meeting the evidence-based standard of effectiveness for community-dwelling older adults. Each program has unique characteristics and differences in their approach to fall prevention. They also vary in fall risk level of the participants they target, tailoring intervention strategies (e.g., health education, self-management training, exercise) accordingly. The National Falls Prevention Resource Center at the National Council on Aging (NCOA) developed a falls risk continuum and recommends that fall prevention stakeholders consider fall risk along that continuum (low to high) to offer programming that addresses need across different levels of the risk continuum (10). This framework can be used to help service providers guide community members to the EBFPP most suited to address their individual fall risk.

Older adults generally self-enroll in one of these ACL grant supported programs based on availability, access, and interest, completing a standardized pre-participation survey documenting selected demographic, health, and fall history items. Awardees submit this data to a national fall prevention database (HAPID) that serves as a central data repository for all awardees and all programs. A 2021 article by Brach et al. provides an overview of the demographic characteristics and fall history of the nearly 89,000 older adults across all fall prevention programs with data submitted to this central repository between 2014 and 2019 (6). Brach reported that, in the aggregate, a higher proportion of participants were female, white, and college-educated than the general US population of older adults. The number self-reporting a recent fall was similar to national averages (30% of those responding to the question). The Brach study did not explore differences among programs or attempt to differentiate participants along fall risk levels.

We are unaware of any investigation exploring the demographic difference among participants across various EBFPPs in this large national dataset or congruency of the fall risk level of the participant and the choice of the EBFPP into which they enrolled. Thus, the goals of this project were to determine: (1) participant characteristics based on enrollment in an EBFPP; (2) the fall risk levels of individuals participating in each EBFPP, and (3) agreement between the fall risk levels of participants in each EBFPP with the NCOA identified targeted risk levels for each EBFPP.

2 Materials and methods

2.1 Research questions

Three primary research questions guided this study:

1. Are there differences among the ACL approved EBFPPs in terms of participant self-reported demographic background and health history? If yes, which differences are most pronounced?
2. For each EBFPP, what proportion of participants fall into each fall risk category, based on a fall risk index calculated from variables available in the HAPID database?
3. How consistent is the risk level for each EBFPP as visualized in the NCOA Risk Level Continuum as compared to the risk levels calculated from responses provided by actual participants?

2.2 Study participants and procedures

Data for this project came from a national falls database, Healthy Aging Programs Integrated Database (HAPID), created and managed by the NCOA and funded by the Administration for Community Living. ACL-funded fall prevention program grantees are required to submit program data into HAPID to help ACL monitor grantees' performance, describe participant demographics, and evaluate outcomes (11). Participants in these programs completed a standardized pre-participation survey documenting demographic and self-reported fall risk factors. Data were also collected about workshop leaders and organizations hosting programs. Data collection methods included paper and verbally administered questionnaires and electronic data capture. Workshop leaders, grant personnel, and organization staff entered data into the database. Marymount University's Institutional Review Board designated the project as exempt since the data from the database were de-identified.

Marymount University received permission to analyze data entered into the database between July 2016 and June 2022. During this period, 56 grantees supported 16 EBFPPs in 37 states with a range of organizations delivering the programs. These organizations included: Area Agencies on Aging, health care organizations, multipurpose social services organizations, educational institutions, state and county health departments, recreational organizations, senior and community centers, residential facilities, and faith-based organizations.

EBFPPs with the largest number of participants were examined for this project (Table 1): a Matter of Balance (MOB), Bingocize, Enhance Fitness, Otago Exercise Program (Otago), Stay Active and Independent for Life (SAIL), Stepping On, Tai Chi for Arthritis, and Tai Ji Quan.

2.3 Data and measures

2.3.1 Participant information

De-identified data from all participants above the age of 54 who enrolled in one of the eight targeted EBFPPs that started on or after July 1, 2016 and ended on or before June 30, 2022 were included in this study. The HAPID pre-participation survey that all participants were asked to complete at the start of each program provided the data used for the analysis. This survey includes demographic characteristics (e.g., age, sex, living arrangements, ethnicity, race, educational level, chronic conditions, and referral by a health care provider) and outcome measures (e.g., self-reported general health, fall history, fear of falling).

We anchored our risk level indicators in items supported by research and included or inferred in the Center for Disease Control and Prevention's Stopping Elderly Accidents, Deaths, and Injuries (STEADI) risk screening algorithm (Table 2). Although many factors contribute to risk of falling, the factors chosen to categorize older adults into fall risk levels are varied and reliant on available data (12–19). The items included in the pre-participation survey were not created to specifically assess risk level. However, several items provide insight into fall risk.

Given the information available on the pre-participation survey, we identified survey items associated with known fall risk factors to create an index to estimate fall risk level of participants at entry into the program. Six factors were identified and used to create a risk index (Figure 1). These factors included (1) falling in the last 3 months, (2) referred by a health care provider, (3) fear of falling, (4) fair or poor self-reported health status, (5) depression, and (6) age 75–84 years.

The STEADI initiative provides tools for older adults, caregivers and health care providers to reduce fall risk in older adults. The STEADI Algorithm for Fall Risk Screening, Assessment, and Intervention categorizes individuals into low, moderate or high risk for falls (20). It aligns with clinical practice guidelines, has been validated in adults aged 65 and older who participated in the National Health and Aging Trends Study, and has fair predictive validity (12–14). Lohman et al. (13) found STEADI fall risk categories were strong predictors of future falls. Individuals categorized as moderate risk were 2.6 times more likely to experience a future fall, and individuals categorized as high risk were 4.7 times as likely to experience a future fall as compared to individuals at low risk. The algorithm uses the STEADI Stay Independent checklist within the STEADI Stay Independent: Learn More about Fall Prevention brochure to determine an individual's risk for falling (20). The STEADI fall risk self-assessment tool was developed for adults 65 years or older who are ambulatory and living within the community. Its intended use is screening for fall risk, leading to awareness of an individual's own risk level and conversations about strategies to decrease risk (21). Rubenstein et al. compared the self-reported scores to a clinical assessment by geriatricians and found that the final 12 item questionnaire had good concurrent validity (21).

Two of the statements within the STEADI checklist assign 2 points for a yes answer, indicating a higher risk, when compared to the remaining 10 statements which assign 1 point (21). These two statements ask about fall history and gait deficiency. When comparing these two statements with ACL's pre-participation survey, two items captured similar information (Table 2). Both the STEADI question, asking if the individual had been advised to use an assistive device and the pre-participation question, asking if a health care provider recommended that they take an EBFPP, imply that a third party deemed the individual at sufficient risk of falling to recommend an active intervention. Thus, the item was included in our fall risk index with a score of 2 points if the participant answered yes (Table 2).

The remaining items in our fall risk index (fear of falling, depression, health status, and older age) received a score of 1 point. Fear of falling (22, 23) and depression (15–17, 24), have comparable

TABLE 1 Total number of participants in the eight targeted evidence-based fall prevention programs, and the subset of participants who responded to all fall risk index questions.

Program	All Participants *N* (%)	Participants who responded to all fall risk index questions *N*	Percentage of participants within each EBFPP who responded to all fall risk index questions
MOB	45,904 (43.6)	11,919	26%
Tai Chi for Arthritis	18,740 (17.5)	6,262	33%
Stepping On	14,117 (13.4)	4,279	30%
Enhance fitness	8,694 (8.3)	1,339	15%
Tai Ji Quan	8,578 (8.1)	2,641	31%
SAIL	6,863 (6.5)	3,268	48%
Bingocize	2,235 (2.1)	1,199	54%
Otago	462 (0.4)	157	34%
Total	105,323	31,064	30%

TABLE 2 Creating the fall risk index: fall risk indicators from STEADI, related resources, and the HAPID pre-participation survey.

STEADI survey items from the STEADI self-assessment fall risk checklist (20, 21) with the associated fall risk index score	Comparable survey items from the ACL pre-participation survey with the associated fall risk index score
I have fallen in the past year. Yes, I have fallen = 2 points No, I have not fallen = 0 points	In the past 3 months, how many times have you fallen? Fallen ≥ 1 = 2 points Fallen 0 times = 0 points
I use or have been advised to use a cane or walker to get around safely. Yes = 2 points No = 0 points	Did your doctor, nurse, physical therapist or other health care provider suggest that you take this program? Yes = 2 points No = 0 points
I am worried about falling. Yes = 1 point No = 0 points	How fearful are you of falling? A little, Somewhat, A lot = 1 point Not at all = 0 points
I often feel sad or depressed. Yes = 1 point No = 0 points	Has a health care provider ever told you that you have any of the following chronic conditions that lasted 3 months or more? For the health condition of Depression: Yes = 1 point No = 0 points
Literature supported	
Moreland et al. (18) found as self-reported health declined from excellent to poor, the percentage of falls increased.	In general, would you say that your health is _____ (poor to excellent)? Fair or poor = 1 point Excellent, very good, or good = 0 points
Although everyone over 65 years of age is at somewhat increased risk (thus the entire sample), Helsel et al. (19) identified 75–84 years of age as the period of highest risk of falls.	Age of participant 75–84 years of age = 1 point <75 or > 84 years of age = 0 points

STEADI questions (Table 2) and are regularly identified as risk factors. In terms of health status, the ACL survey asked participants "In general, would you say that your health is: excellent, very good, good, fair, poor." The STEADI checklist, although not directly asking about self-report health status, includes several items that are common indicators of impaired health status. Data from 2018 Behavioral Risk Factor Surveillance System showed that in adults aged 65 and older, as self-reported health declined from excellent to poor, the percentage of falls increased from 5 to 25% (18). Thus, a response of "fair or poor" health status received a score of 1 point.

In terms of age, Helsel et al. (19) reported that age of 75–84 years were significant predictors of falls over 4 years in community dwelling older adults. They also found that respondents over the age of 85 did not have an increased risk for falls as compared to those less than 70 years old. They hypothesized that decreased mobility and fewer risky activities could lead to a lower risk profile in individuals over 85 years of age. Thus, participants 75–84 years of age were assigned 1 point in the fall risk index.

2.3.2 Fall risk categories

The following categories were used for our fall risk index: low risk = 0–1 point, moderate risk = 2–3 points, high risk = 4 or more points. We based our categories on the STEADI risk algorithm which identified individuals as low, moderate, or high risk (20). For STEADI, individuals were categorized as low risk if they scored <4/14 on the Stay Independent questionnaire or indicated 'no' for their fall history. In order to capture a similar categorization, we identified low risk as scoring 0–1 points. For STEADI, a score of ≥4/14 or having a fall history puts an individual automatically into moderate or high risk with high risk reserved for individuals who have gait, strength or balance problems, ≥2 falls, or at least one fall resulting in injury. Given the limited questions on the pre-participation survey, it was not possible to mimic the STEADI risk classification for moderate and high risk. Thus, we reviewed the American Geriatrics Society/British Geriatrics Society (AGS/BGS) guidelines as many algorithms are based on them (25, 26). The screening questions are like those used by STEADI and support that as the number of fall risk factors increase, fall risk increases. We chose 2–3 points as moderate risk as a participant could have one significant risk factor (2 points) or 2–3 risk factors that were consistent with STEADI items that had a score of 1 point. If a participant scored 4 points or greater, indicating more items were scored as present, the risk level was deemed high.

2.3.3 NCOA's EBFPP risk continuum

The National Falls Prevention Resource Center at NCOA developed the Evidence-based Falls Prevention Programs Risk Continuum Guidance for Program Selection as a resource for stakeholders deciding which fall prevention program to implement (10). It provides the risk level associated with the targeted population for each approved EBFPP along a continuum from low risk to high risk (Figure 2).

2.4 Statistical analysis

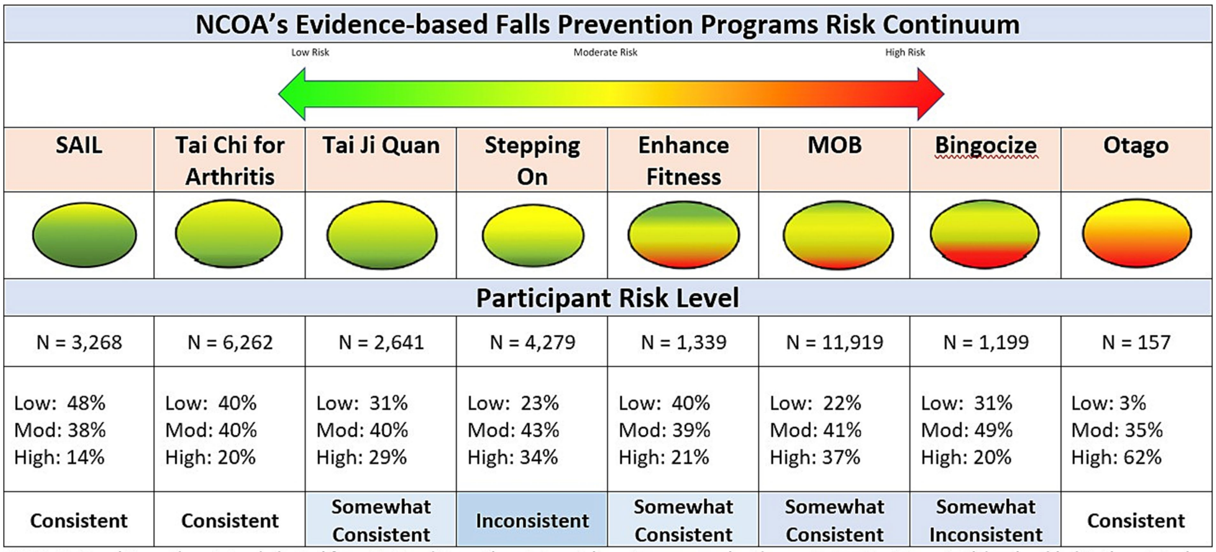
Descriptive statistics (frequencies, percentages) were used to capture participant characteristics. SPSS version 29 (IBM SPSS Statistics) was used for statistical analysis.

Fall Risk Index

	Points	
	Yes	No
Fell 1 or more times in last 3 months	2	0
Health provider suggest attendance	2	0
Fear of falling	1	0
Self-reported health status as fair or poor	1	0
Depression	1	0
75-84 years old	1	0

Scoring: 0-1= low risk; 2-3 = moderate risk; 4-8 = high risk

FIGURE 1
Fall risk index.



NCOA: National Council on Aging (adapted from National Council on Aging Risk continuum; used with permission. Participant risk levels added to the original

FIGURE 2
Consistency of participant risk level and programs risk continuum.

3 Results

3.1 Participant characteristics

3.1.1 Total sample

There were 105,323 participants within the 8 EBFPPs that either started or ended a workshop between July 1, 2016 and June 30, 2022. As the database does not follow a unique individual across or within programs, and all data available to us were fully de-identified, the same individual could be in the database more than once although that individual would only be included as a single participant within a specific workshop. The top five states in which these programs were located were Minnesota (12.4%), North Carolina (8.6%), Wisconsin (6.7%), Massachusetts (6.2%), and New York (5.9%). Thirteen states (Alaska, Delaware, Hawaii, Idaho, Indiana, Kansas, Kentucky, Louisiana, Nebraska, Nevada, Oregon, Pennsylvania, and West Virginia) did not host any programs.

Characteristics of participants within the total sample are shown in Table 3. Three quarters of the individuals were between the ages of 65 and 84 years old. Eighty-two percent (82%) were female, 85% were White, 95% were not Hispanic, 45% lived alone, and 43% were a college graduate. Overall, they self-reported good, very good, or excellent as their health status (84%), with 49% self-reporting they had arthritis, heart disease (19%), diabetes (18%), depression (13%), glaucoma (12%), and lung disease (7%). Twenty-seven percent (27%) had at least one fall in the last 3 months and 85% were fearful of falling.

When comparing participant characteristics across all EBFPPs there were differences based on enrollment in a specific program (Table 4).

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TABLE 3 Baseline characteristics of participants within the total sample; and those who completed all six fall risk index questions compared to those who did not.

Baseline characteristic	Total sample *n* = 105,323	Completed all 6 fall risk index questions *n* = 31,064	Did not complete all 6 fall risk index questions *n* = 74,259	
	Mean +/− SD or %	Mean +/− SD or %	Mean +/− SD or %	*p* value
Age, y	75.5 +/− 8.3	74.6 +/− 8.2	75.9 +/− 8.3	<0.001
55–64	9.1	10.6	13.5	
65–74	37.6	40.8	36.3	
75–84	38.0	36.0	38.9	
85 and above	15.3	12.6	16.4	
Sex	101,859	30,302	71,557	0.011
Female	81.9	82.3	81.7	
Lives alone	98,541	30,265	68,276	0.281
Yes	45.0	44.8	45.2	
Hispanic	96,901	30,002	66,899	<0.001
Yes	4.9	3.7	5.5	
Race	98,415	30,035	68,380	<0.001
American Indian or Alaska Native	1.2	0.7	1.4	
Asian	3.8	2.7	4.2	
Black or African American	8.3	9.1	8.0	
Native Hawaiian or Pacific Islander	0.1	0.1	0.1	
White	85.7	86.3	85.5	
More than one race	0.9	1.1	0.8	
Education	95,357	29,993	65,364	<0.001
Some elementary, middle, or high school	6.4	5.8	6.7	
High school graduate or GED	21.0	19.6	21.6	
Some college or technical school	29.7	29.8	29.7	
College (4 years or more)	42.9	44.8	42.0	
General health	89,266	31,064	58,202	<0.001
Excellent or very good	38.6	37.3	39.2	
Good	45.8	45.0	46.2	
Fair or poor	15.6	17.3	14.6	
Chronic conditions	105,323	31,064	74,259	
Arthritis	48.7	59.5	44.2	<0.001
Breathing/lung disease	7.1	12.6	4.7	<0.001
Depression	28.8	32.3	5.2	<0.001
Diabetes	17.8	21.2	16.4	<0.001
Glaucoma	31.2	13.8	11.4	<0.001
Heart disease	19.3	22.0	18.1	<0.001
Fall history	76,690	31,064	45,626	<0.001
At least one fall in last 3 months	27.3	28.4	26.6	
How fearful of falling	88,368	31,064	57,304	<0.001
Not at all	14.9	15.4	14.7	
A little	39.0	38.1	39.5	
Somewhat	32.6	31.8	33.0	
A lot	13.5	14.7	12.9	
Referred by health care provider	81,948	31,064	50,884	
Yes	16.4	16.7	16.1	0.016

TABLE 4 Characteristics of participants in total sample.

	Total Sample	Bingocize	Enhance Fitness	MOB	Otago	SAIL	Stepping On	Tai Chi Arthritis	Tai Ji Quan
	n (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)
	105,323	2,235	8,694	45,904	462	6,863	14,117	18,470	8,578
Age	105,323	2,235	8,694	45,904	462	6,863	14,117	18,470	8,578
55–64	9,560 (9.1)	322 (14.4)	845 (9.7)	3,249 (7.1)	32 (6.9)	548 (8.0)	917 (5.8)	2,628 (14.2)	1,119 (13.0)
65–74	39,614 (37.6)	878 (39.3)	3,956 (45.5)	14,793 (32.2)	127 (27.5)	2,966 (43.2)	4,376 (31.0)	8,723 (47.2)	3,795 (44.2)
75–84	40,050 (38.0)	740 (33.1)	3,209 (36.9)	18,752 (40.9)	185 (40.0)	2,638 (38.4)	6,168 (43.7)	5,641 (30.5)	2,717 (31.7)
85 and above	16,099 (15.3)	295 (13.2)	684 (7.9)	9,110 (19.8)	118 (25.5)	711 (10.4)	2,756 (19.5)	1,478 (8.0)	947 (11.0)
Sex	101,859	2,000	8,293	44,721	452	6,176	13,746	18,146	8,325
Male	18,486 (18.1)	394 (19.7)	1,337 (16.1)	8,637 (19.3)	119 (26.3)	763 (12.4)	2,788 (20.3)	2,929 (16.1)	1,519 (18.2)
Female	83,373 (81.9)	1,606 (80.3)	6,956 (83.9)	36,084 (80.7)	333 (73.7)	5,413 (87.6)	10,958 (79.7)	15,217 (83.9)	6,806 (81.8)
Living alone	98,541	2,124	7,570	43,816	370	6,403	12,867	17,306	8,085
No	54,157 (55.0)	1,104 (52.0)	4,666 (61.6)	21,883 (49.9)	218 (58.9)	3,955 (61.8)	6,833 (53.1)	10,738 (62.0)	4,760 (58.9)
Yes	44,384 (45.0)	1,020 (48.0)	2,904 (38.4)	21,933 (50.1)	152 (41.1)	2,448 (38.2)	6,034 (46.9)	6,568 (38.0)	3,325 (41.1)
Hispanic	96,901	1.928	7,311	43,275	355	5,646	13,356	17,359	7.671
No	92,150 (95.1)	1,605 (83.2)	6,932 (94.8)	40,608 (93.8)	339 (95.5)	5,508 (97.6)	13,165 (98.6)	16,596 (95.6)	7,397 (96.4)
Yes	4,751 (4.9)	323 (16.8)	379 (5.2)	2,667 (6.2)	16 (4.5)	138 (2.4)	191 (1.4)	763 (4.4)	274 (3.6)
Race	98,415	1,952	7,169	43,476	424	6,315	13,415	17,433	8,231
White	84,368 (85.7)	1,230 (63.0)	6,476 (90.3)	36,292 (83.5)	375 (88.4)	5,559 (88.0)	12,318 (91.8)	15,145 (86.9)	6,974 (84.7)
Black or African American	8,205 (8.3)	601 (30.8)	453 (6.3)	4,457 (10.3)	37 (8.7)	330 (5.2)	695 (5.2)	1,305 (7.5)	327 (4.0)
Asian	3,691 (3.8)	81 (4.1)	211 (2.9)	1,786 (4.1)	5 (1.2)	327 (5.2)	172 (1.3)	521 (3.0)	588 (7.1)
American Indian or Alaska Native	1,149 (1.2)	16 (0.8)	19 (0.3)	490 (1.1)	2 (0.5)	31 (0.5)	154 (1.1)	230 (1.3)	207 (2.5)
Native Hawaiian or other Pacific Islander	117 (0.1)	7 (0.4)	11 (0.2)	49 (0.1)	0 (0.0)	7 (0.1)	8 (0.1)	29 (0.2)	6 (0.1)
More than one race	885 (0.9)	17 (0.9)	0.0 (0)	402 (0.9)	5 (1.2)	1.0 (61)	68 (0.5)	203 (1.2)	129 (1.6)
Education level	95,357	1,961	7,438	40,452	422	5,948	13,514	17,572	8,050
Some elementary, middle, or high school	6,104 (6.4)	377 (19.2)	87 (1.2)	3,732 (9.2)	17 (4.0)	212 (3.6)	534 (4.0)	524 (3.0)	621 (7.7)
High school graduate or GED	19,995 (21.0)	567 (28.9)	1,102 (14.8)	9,609 (23.8)	68 (16.1)	1,046 (17.6)	3,652 (27.0)	2,738 (15.6)	1,213 (15.1)
Some college or technical school	28,344 (29.7)	545 (27.8)	2,405 (32.3)	12,235 (30.2)	97 (23.0)	1,756 (29.5)	4,169 (30.8)	4,960 (28.2)	2,177 (27.0)
College (4 years or more)	40,914 (42.9)	472 (24.1)	3,844 (51.7)	14,876 (36.8)	240 (56.9)	2,934 (49.3)	5,159 (38.2)	9,350 (53.2)	4,039 (50.2)
General health	89,266	2,044	2,023	39,852	411	6,226	13,144	17,476	8,090
Excellent or very good	34,501 (38.6)	566 (27.7)	801 (39.6)	13,441 (33.7)	129 (31.4)	3,145 (50.5)	4,701 (35.8)	8,175 (46.8)	3,543 (43.8)

(Continued)

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TABLE 4 (Continued)

	Total Sample	Bingocize	Enhance Fitness	MOB	Otago	SAIL	Stepping On	Tai Chi Arthritis	Tai Ji Quan
	n (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)	*n* (%)
Good	40,872 (45.8)	981 (48.0)	897 (44.3)	18,917 (47.5)	184 (44.8)	2,552 (41.0)	6,435 (49.0)	7,540 (43.1)	3,366 (41.6)
Fair or poor	13,893 (15.6)	497 (24.3)	325 (16.1)	7,494 (18.8)	98 (23.8)	529 (8.5)	2,008 (15.3)	1,761 (10.1)	1,181 (14.6)
Chronic conditions	105,323	2,235	8,694	45,904	462	6,863	14,117	18,470	8,578
Arthritis	51,269 (48.7)	968 (43.3)	2,104 (24.2)	24,041 (24.2)	226 (48.9)	2,595 (37.8)	7,177 (50.8)	10,403 (56.3)	3,755 (43.8)
Breathing/lung disease	7,447 (7.1)	339 (15.2)	500 (5.8)	2,749 (6.0)	49 (10.6)	726 (10.6)	994 (7.0)	1,398 (7.6)	692 (8.1)
Depression	13,895 (13.2)	386 (17.3)	615 (7.1)	6,600 (14.4)	78 (16.9)	726 (10.6)	1,969 (13.9)	2,318 (12.6)	1,212 (14.1)
Diabetes	18,717 (17.8)	616 (27.6)	711 (8.2)	9,544 (20.8)	81 (17.5)	878 (12.8)	2,706 (19.2)	2,834 (15.3)	1,347 (15.7)
Glaucoma	12,724 (12.1)	109 (4.9)	466 (5.4)	6,813 (14.8)	80 (17.3)	915 (13.3)	1,730 (12.3)	1,802 (9.8)	809 (9.4)
Heart disease	20,296 (19.3)	396 (17.7)	674 (7.8)	10,425 (22.7)	114 (24.7)	930 (13.6)	2,985 (21.1)	3,401 (18.4)	1,371 (16.0)
Fall history	76,690	1,699	1,974	34,095	387	5,430	11,905	14,485	6,715
No	55,728 (72.7)	1,379 (81.2)	1,586 (80.3)	23,059 (67.6)	229 (59.2)	4,611 (84.9)	7,941 (66.7)	11,718 (80.9)	5,205 (77.5)
At least one fall in last 3 months	20,962 (27.3)	320 (18.8)	388 (19.7)	11,036 (32.4)	158 (40.8)	819 (15.1)	3,964 (33.3)	2,767 (19.1)	1,510 (22.5)
How fearful of falling	88,368	1,961	1,824	39,567	349	6,092	13,147	17,377	8,051
Not at all	13,176 (14.9)	509 (26.0)	410 (22.5)	4,338 (11.0)	46 (13.2)	1,565 (25.7)	1,008 (7.7)	3,866 (22.2)	1,434 (17.8)
A little	34,456 (39.0)	693 (35.3)	742 (40.7)	14,380 (36.3)	105 (30.1)	2,845 (46.7)	4,558 (34.7)	7,550 (43.4)	3,583 (44.5)
Somewhat	28,793 (32.6)	520 (26.5)	509 (27.9)	14,391 (36.4)	129 (37.0)	1,364 (22.4)	5,075 (38.6)	4,644 (26.7)	2,161 (26.8)
A lot	11,943 (13.5)	239 (12.2)	163 (8.9)	6,458 (16.3)	69 (19.8)	318 (5.2)	2,506 (19.1)	1,317 (7.6)	873 (10.8)
Referral	81,948	1,833	3,674	37,187	306	4,829	12,401	15,558	6,160
No	68,548 (83.6)	1,542 (84.1)	2,788 (75.9)	31,107 (83.7)	168 (54.9)	4,179 (86.5)	10,701 (86.3)	13,086 (84.1)	4,977 (80.8)
Yes	13,400 (16.4)	291 (15.9)	886 (24.1)	6,080 (16.3)	138 (45.1)	650 (13.5)	1,700 (13.7)	2,472 (15.9)	1,183 (19.2)

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- Bingocize participants were more likely to be non-White (63%), Hispanic (16.8%), living alone (48%), no more than a high school graduate (48.1%), in fair or poor health (24.4%), and not fearful of falling (26%).
- Enhance fitness participants were more likely to be a high school graduate with at least some college or technical school education (84%), referred by a health care professional (24.1%), and not fearful of falling (22.5%).
- Matter of balance participants were more likely to be living alone (50.1%), depressed (34.7%), a previous faller (32.45%), and fearful of falling (89%).
- Otago exercise program participants were more likely to be male (26.35%), at least 85 years or older, graduated college (56.9%), in fair or poor health (23.8%), previous faller (40.8%), and referred by a health care professional (45.1%).
- Stay Active and Independent for Life participants were more likely to be female (87.6%), in excellent or very good health (50.5%), and not fearful of falling (25.7%).
- Stepping On participants were more likely to be living alone (46.9%), previous faller (33.3%), and fearful of falling (92.3%).
- Tai Chi Arthritis participants were more likely to be in excellent or very good health (46.85%) and not fearful of falling (22.2%).
- Tai Ji Quan participants did not trend toward any unique characteristics when compared to the general participant profile.

3.1.2 Fall risk sample

Of the 105,323 participants in the dataset, 31,064 answered all six pre-participation questions that made up the fall risk index and, thus, were included in the calculations of fall risk levels. All other participants were excluded from the calculation of risk level. Table 3 displays the response by group (those included vs. those excluded from calculation of fall risk index) and Chi Square analyses for group differences. A $p < 0.01$ level of significance was chosen given the large number of variables that increase the risk of a Type I error. Statistically significant differences were reported for all variables except, sex, living situation, and referral from a healthcare provider. Demonstrating statistically significant differences was not surprising given the large dataset. As seen in the table, for most variables, the actual differences were small and unlikely to represent clinically important differences.

Notable differences include more individuals with poor to fair health in the inclusion group and fewer in excellent to good health as well as more individuals in every category of chronic condition in the inclusion group than the exclusion group. This was particularly evident for depression with large differences between the groups (32.3% vs. 13.2%). Differences in those reporting arthritis (60% vs. 44%) and breathing/lung issues (13% vs. 5%) are also notable.

3.1.3 Fall risk level

Using the fall risk index within the fall risk sample (31,064 older adults), 29% of participants were identified as being at high risk, 41% at moderate risk, and 30% at low risk. Figure 3 provides the breakdown of the fall risk level of participants by each evidence-based fall prevention program. Stay Active and Independent for Life (SAIL) had the largest percentage of individuals at low risk (48.5%) and Otago had the lowest (19%). Whereas, Otago had the largest percentage at high risk (47%) and SAIL with the lowest (14%).

3.2 Congruency of targeted risk profiles

Congruency was examined between the targeted risk levels of participants as depicted on the NCOA visual continuum and the risk levels derived from our fall risk index. In general, greater congruency was observed in programs at either end of the continuum (high or

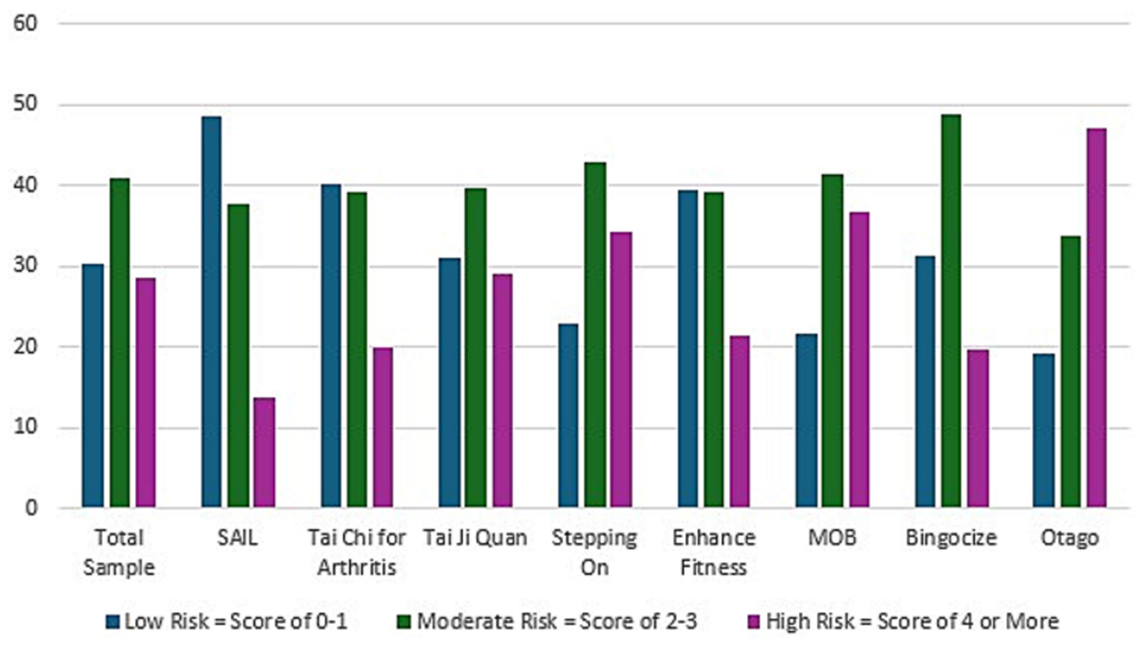

FIGURE 3
Fall risk level of participants by evidence-based falls prevention program.

low ends) than midrange. As depicted in Figure 2, the NCOA fall risk continuum visually illustrates each EBFPP's targeted participant risk level (green = low risk, yellow = medium risk, red = high risk). For each program targeting only two of the three fall risk categories, we operationally defined 'Consistent' as having at least 80% of participants classified within the target risk level, 'Somewhat Consistent' if between 70 and 79% of participants were classified within the two risk categories, and 'Inconsistent' if less than 70% of participants were classified within the two risk levels. For programs targeting participants across all three risk levels, we examined differences between the visually estimated relative proportions in each category and the proportions calculated using the fall risk index.

Five of the eight EBFPPs indicated the program targets only two of the three possible risk categories. Four programs (SAIL, Tai Chi for Arthritis, Tai Ji Quan, Stepping On) targeted only low or moderate risk individuals and one program (Otago) targeted only moderate to high-risk participants. SAIL, Tai Chi for arthritis and Otago meet the 80% criteria and were classified as 'Consistent'. Tai Ji Quan, with 71% of participants in the target risk levels was classified as 'Somewhat Consistent'. Stepping On with only 66% of participants within the target risk levels, was classified as 'Inconsistent'.

Three EBFPPs (Enhance fitness, MOB, Bingocize) included all three risk levels in their target population with slightly different proportions visually depicted for each along the NCOA continuum. All three enrolled participants across all three risk levels. All three were classified as 'Somewhat Consistent' given variations from the NCOA visual depiction. Enhance Fitness and Bingocize, visually depicted as targeting participants fairly equally across all three levels, attracted fewer participants at high risk than visually illustrated. MOB, depicted as targeting predominantly moderate and low risk participants, enrolled a high proportion of high-risk participants.

4 Discussion

Using data from the ACL-NCOA Healthy Aging Programs Integrated Database (HAPID) between July 2016 and June 2022, we examined the characteristics of a broad national sample of older adults attending a variety of evidence-based fall prevention programs (EBFPPs) offered by a range of older adult-community serving agencies within 37 of the 50 states within the United States. The characteristics of the 105,323 participants displayed in Table 4 indicate that participants were primarily: white; female; with at least some fear of falling; between 65 and 84 years of age; had completed at least some college; described their health as good, very good, or excellent; and self-enrolled in the EBFPP (were NOT referred to the program by a health care provider). These findings are similar to the demographic trends identified in earlier studies by Smith et al., based on 2014–2017 HAPID data and Brach, based on 2014–2019 HAPID data (6, 27). Of particular concern is the continued low enrollment of men and participants who are non-white.

We used data available in the pre-participation survey inputted into the national HAPID database to create a fall risk score for each participant in the eight ACL-supported fall prevention programs and categorized risk into three levels. As such, 29% of participants were classified at high fall risk, 41% at moderate fall risk, and 30% at low fall risk. The proportion of individuals at moderate to high risk (70%) was higher than the 48% of individuals identified as moderate or high risk in the 2011 National Health and Aging Trends Study (NHATS) of the general older adult population (13). Additionally, 85% of subjects in our sample expressed at least some fear of falling compared to only 25.6% of subjects in the 2011 NHATS survey (19). These findings support the assumption that individuals at higher fall risk and with at least some concern about falling are more likely to enroll in a fall prevention program than those at low risk and low concern about falling.

In creating the fall risk index, we were limited to the variables included in the pre-participation survey and reported in the HAPID dataset. This fall risk index is not intended for generalization beyond the HAPID dataset. The CDC STEADI checklist was chosen as the primary tool against which to base risk level. The STEADI fall risk checklist was specifically designed for community-dwelling older adults, to be understandable to older adults, and to include modifiable fall risk factors. Rubenstein et al. all reported high consistency between self-reported STEADI checklist scores and clinically assessed scores (21). Future studies are needed to examine concurrent validity of responses on this fall risk index against the comparable items on the STEADI checklist and criterion-related validity by assessing the consistency of the self-reported responses with clinician assessment.

When examining each EBFPP separately (Figure 2), we see that each program enrolled participants across all three risk levels with most programs being at least somewhat consistent with their targeted level along the NCOA risk continuum. There was more congruence for programs tailored for participants at the ends of the risk level (low risk or high risk). Two programs (Stepping On and Matter of Balance), that focused more on adult education and encouraging behavior change than on active exercise participation, had very similar risk profiles with a tendency toward enrolling more participants at high-risk levels than other programs, except Otago. Stepping On, Otago, and Matter of Balance each demonstrated a higher percentage of participants who had fallen in the past 3 months (33.3, 40.8, 32.4%, respectively) and had the highest number of subjects expressing at least a little concern about falling (92, 87, 89%, respectively) than the other programs. This is consistent with the finding that these three programs enrolled the most subjects in the high-risk category.

Both Matter of Balance (MOB) and Stepping On are workshop-based programs focusing primarily on adult education, self-efficacy, and behavior change rather than on physical exercise. We speculate that older adults at higher fall risk may gravitate more toward workshop-based programs than exercise and physical activity programs. For MOB, this risk profile was somewhat consistent with their target population along the risk continuum. However, participants in Stepping On did not reflect the risk profile in NCOA's risk continuum that identifies the program as more suitable for low-risk individuals. Future investigation of outcomes for Stepping On by risk level may help determine if the NCOA risk continuum for Stepping On should be adjusted or if high-risk participants should be recommended to an alternative program tailored more directly for high fall-risk. Otago, an exercise program targeting high-risk individuals, is unique in that it is typically, although not exclusively, led by a health professional and delivered in an individualized 1–1 format.

Interestingly, Bingocize, the only other EBFPP in our review that is primarily workshop focused, had a relatively low proportion of participants in the high-risk category despite high-risk being a substantial target group according to the NCOA risk continuum. Bingocize also had the highest proportion of participants who were non-white (37%), and had diabetes (27.6%) or breathing/lung disease (15.2%). Bingocize and Otago had the highest proportion of participants defining their overall health as 'fair or poor'. Combining the benefit of a familiar and popular game, bingo, with adult health education, seems to capture interest across a broad fall risk level and wider-range of demographics than other EBFPPs. Future examination, by risk level, of the ability to achieve positive behavior change across risk levels will help determine the ideal risk continuum target for this program.

All EBFPPs with a primary focus on physical exercise participation (Tai Chi for Arthritis, Tai Ji Quan, Enhance Fitness, and SAIL) had fewer individuals at high risk than those enrolled in workshop-based programs (MOB and Stepping On). This was generally consistent with expectations as visualized along the NCOA risk continuum.

Evidence-based falls prevention programs have different ways of addressing fall prevention risk factors and different attractors for participants. Although subjects self-enroll in programs, program availability varies widely. Most communities are unable to offer a range of fall prevention programs. Thus, participants seeking fall prevention programs are limited to the programs available in their community even if the program is not ideally suited to their risk level. Host organizations must consider their mission, target audience, location of classes, and needs of their community in determining which programs to offer. Leaders delivering programs must be sensitive to the range of participant risk levels and strategies to adapt the program while remaining within the program's fidelity requirements.

Limitations of this study include the limited availability of risk-factor indicators for calculation of risk level, the low number of participants completing all 6 risk-factor indicators thus included in risk factor calculation, and the non-random nature of subjects enrolled in the programs. Only 30% of subjects in the HAPID database completed all 6 questions contributing to the fall risk index, required to be included in the fall-risk level categorization. Thus, our fall risk index represents a 'best-available' estimate of risk level from the subset of program participants who completed all 6 risk factor questions. A comparison of key characteristics of those included vs. not-included in the risk level calculations illustrated small but statistically significant differences between the two groups on most variables which could have impacted the risk-level scores.

The sample population for the HAPID dataset was not randomly chosen from the general population of older adults seeking fall prevention programs. All programs were supported by an ACL grant. Grantees were chosen based on a highly competitive application process in which they provided compelling evidence for the need in their community, the target region, delivery processes, and participants. Examining variability by target geographic area, type of delivery, or target populations is beyond the scope of this study. However, future examinations of these factors could provide additional insights into the link between choice of programs, risk level of participants, and characteristics of attendees.

5 Conclusion

The community-delivered EBFPPs supported by grants from ACL have enrolled a wide range of older adults. At least 80% of individuals enrolling in the community-delivered EBFPPs supported by ACL were white, female, have at least some fear of falling, and identify their general health as good, very good, or excellent. Overall, the proportion of participants who had fallen at least once was similar to that found in the general population. However, this rate varies by program. Programs focused more on training and education enrolled more participants who have fallen than EBFPPs focused more on exercise interventions.

All programs enroll participants across all three risk levels with variability across programs. The risk levels of participants in most programs are at least somewhat consistent with the NCOA risk continuum that serves as a guideline for choosing programs to match the target audience in a given community. As only 3 programs enrolled participants that were in agreement with their targeted risk profile, further examination of the remaining programs' identified risk level is indicated.

The enrollment of men and minority participants continues to be low, without substantial improvement from earlier studies using the same database. The findings suggest a need to tailor programs and improve recruitment to enhance reach to these under-represented populations. These findings also serve as a reminder that the characteristics of program participants vary across each of the three risk levels. This supports the NCOA recommendation to offer a range of programs targeting individuals at various risk levels. Program leaders must also be sensitive to the varied risk levels of their participants as it became clear in this study that not all older adults are enrolling in programs that are consistent with their fall risk profile.

It is crucial that programming to reduce fall risk is available for all older adults. The results of this study help to inform older-adult-focused organizations who wish to meet the needs of their community by recognizing populations who have had less access to EBFPPs and ensuring that the fall risk profile of the chosen EBFPP is congruent with the level of fall risk of their targeted audience.

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 below: data for this research was sourced from the Healthy Aging Programs Integrated Database (HAPID), which is publicly available upon request and funded by ACL/HHS. Interested researchers must email HAPIDHelp@ncoa.org, submit a Data Use Agreement, and meet with data management at the National Council on Aging to access a data codebook and understand the appropriateness of the data for the proposed research.

Ethics statement

This secondary data set was received in a format fully stripped of any data that would allow the identification of specific participants through direct or indirect identifiers. Thus, the study did not fall within the regulatory definition of research involving human subjects and did not require IRB review.

Author contributions

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EDITED BY
Nattawan Utoomprurkporn,
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Barrow Neurological Institute (BNI),
United States
Mohammad Faraj,
University of Anbar, Iraq

*CORRESPONDENCE
Min Cheol Chang
✉ wheel633@gmail.com

†These authors have contributed equally to this work and share first authorship

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Falls in a single brain rehabilitation center: a 3-year retrospective chart review

Yoo Jin Choo[1†], Jun Sung Moon[2†], Gun Woo Lee[3], Wook-Tae Park[3] and Min Cheol Chang[1*]

[1]Department of Physical Medicine and Rehabilitation, College of Medicine, Yeungnam University, Daegu, Republic of Korea, [2]Division of Endocrinology and Metabolism, Department of Internal Medicine, College of Medicine, Yeungnam University, Daegu, Republic of Korea, [3]Department of Orthopaedic Surgery, College of Medicine, Yeungnam University, Daegu, Republic of Korea

Objective: Falls in brain rehabilitation centers can negatively impact patient recovery, increase injury risk, and adversely affect rehabilitation outcomes. This study aimed to analyze the incidence of falls and identify associated risk factors among patients with brain lesions in a tertiary hospital's brain rehabilitation center from June 2021 to May 2024.

Methods: A retrospective chart review was conducted to examine patient characteristics, fall-related risk factors, functional assessments, and circumstances surrounding falls.

Results: Among 316 patients, 10 (3.2%) experienced falls, with a mean age of 61.3 ± 11.9 years. Most patients demonstrated walking and cognitive impairments. Seven falls (70%) occurred during attempts to get out of bed, with five of these incidents occurring at night. Falls were observed despite the presence of caregivers and bed rails. Additionally, all 10 patients were administered medications that may increase fall risk, such as somnifacients or tranquilizers. The occurrence of falls appeared to be associated with multiple factors, including physical limitations (e.g., impaired mobility, visual disturbances, and medication side effects), environmental conditions (e.g., inadequate lighting and medical staff shortages), and behavioral aspects (e.g., unassisted movement).

Conclusion: To mitigate fall risk, a comprehensive approach that includes improved nighttime lighting, education on assistive device use and medication management, caregiver training, and personalized rehabilitation programs may be beneficial.

KEYWORDS

fall, brain lesion, stroke, brain tumor, risk factor

1 Introduction

Brain rehabilitation centers serve as critical medical institutions for the recovery and rehabilitation of patients with brain injuries. These centers function as an essential intermediary stage to help patients in their transition to daily life by facilitating the recovery of both physical and cognitive functions, thereby enabling them to achieve the highest possible level of independence (1). In particular, brain rehabilitation requires a comprehensive approach that involves not only physical recovery but also cognitive recovery, sensory integration, and emotional well-being (2). However, patients with brain injuries face numerous challenges throughout the rehabilitation process; one such challenge is the risk of falls (3).

Falls occurring within rehabilitation centers are a significant issue because they can negatively impact the safety and recovery of patients. Patients with brain injuries are at an elevated risk of falls because of various factors, such as physical weakness, impaired balance, and medication use (4). This risk is particularly pronounced during rehabilitation, when patients may not have fully regained their physical abilities (5). Furthermore, a combination of cognitive impairments and motor dysfunction resulting from acquired brain injury increases the risk of falls. The incidence of falls in inpatient rehabilitation facilities has been reported to be as high as 15.9 per 1,000 days, whereas in general hospitals, the maximum rate is 3.73 per 1,000 days, thereby indicating a substantially higher fall rate in rehabilitation wards (6). Furthermore, a study by Callaly et al. (7) reported that approximately 24% of stroke patients experienced at least one fall within 2 years. Additionally, Teasell et al. (8) documented 180 fall incidents among 88 (37%) of 238 patients hospitalized in a rehabilitation ward over a 5-year period. Among these 88 patients, 45 experienced a single fall, 25 fell twice, 9 fell three times, and another 9 experienced four or more falls, thereby underscoring the prevalence of recurrent falls. Similarly, Lee et al. (9) reported that 34 (20.48%) of 166 patients hospitalized in a rehabilitation ward over the course of 1 year experienced falls. Falls within rehabilitation centers are more than mere accidents; they can lead to serious complications, including physical injury, delayed recovery, increased treatment costs, and worsened rehabilitation outcomes (10). These issues hinder the recovery process and may have detrimental effects on the psychological well-being of patients.

Therefore, fall prevention in rehabilitation centers should be addressed as a crucial matter requiring customized approaches that consider the unique characteristics and conditions of each patient (11). It is essential to perform comprehensive evaluations that encompass various factors, including physical weakness, psychological state, and emotional state, and develop appropriate preventive strategies accordingly (12). Such personalized approaches can reduce the risk of falls in individual patients and contribute to more successful rehabilitation outcomes.

The objective of this study was to propose practical solutions to reduce fall rates in rehabilitation centers and enhance patient recovery and rehabilitation outcomes. To this end, we conducted a 3-year analysis of fall incidence and associated risk factors among patients admitted to a rehabilitation center. Furthermore, we identified the underlying causes of falls and discussed strategies for mitigating fall risks.

2 Methods

A retrospective database review was conducted for patients admitted to the brain rehabilitation center at Yeungnam University Hospital over 3 years, from June 2021 to May 2024. The registered patients were hospitalized for brain rehabilitation due to stroke, traumatic brain injury, or brain tumors. There were no specific inclusion or exclusion criteria, and all cases of falls occurring during hospitalization were included in the analysis. This study was approved by the Institutional Review Board of Yeungnam University Hospital, and written informed consent was waived due to the retrospective nature of the study. This study conforms to all STROBE guidelines and reports the required information accordingly.

2.1 Patient characteristics and clinical assessment

Data regarding the general characteristics of the patients were collected. The collected data included age, sex, medical history, medical condition at the time of the fall, fall risk status, type of rehabilitation therapy performed at the time of the fall, gait and cognitive function assessed on the day of or the day before the fall, and use of medications that might increase fall risk (e.g., somnifacients, tranquilizers, or agents for benign prostatic hyperplasia). Individuals with a Morse Fall Scale score of 51 or higher were considered to have a high risk of falls (13). The Morse Fall Scale is a tool used to assess fall risk by evaluating various factors, such as the patient's fall history, walking status, and mental status (13). Typically, a score below 25 indicates low risk, a score ranging from 25 to 50 indicates moderate risk, and a score of 51 or higher indicates high risk. Gait function was assessed using the Functional Ambulation Categories (FAC) (14), and cognitive function was evaluated using the Mini-Mental State Examination (MMSE) (15). The FAC is a tool for assessing independent walking ability; the FAC score is categorized into six levels: 0, unable to walk independently and requires the assistance of two or more people; 1, requires continuous and significant assistance from one person to maintain weight shift and balance; 2, requires intermittent assistance from one person to maintain balance; 3, requires verbal correction without physical contact; 4, capable of walking independently indoors but requires assistance on stairs or uneven surfaces; and 5, capable of walking independently both indoors and outdoors. The MMSE is a tool for assessing cognitive function after acquired brain injury; it consists of 11 domains. An MMSE score of 24 or higher is considered normal, a score from 20 to 23 indicates mild cognitive impairment, and a score below 20 indicates moderate to severe cognitive impairment.

2.2 Definition and classification of falls

In this study, a fall was defined as an incident in which a patient descends to the floor from a sitting or standing position, unexpectedly falls to the floor while walking, or descends from a bed and falls to the ground. Falls were identified through self-reports by patients, reports from caregivers, or observations by medical staff. When a fall occurred, the medical staff documented the circumstances and the patient's condition at the time of the fall in the electronic medical record. The fall-related data collected in this study included the time of the fall, presence of a caregiver during the fall, location of the fall, presence of bed rails, patient's level of consciousness during the fall, and resulting injuries. The time of the fall was categorized into daytime and nighttime (9:30 p.m. to 6:30 a.m.). The location was classified as occurring in bed, during ambulation, or while using a wheelchair. The level of consciousness during the fall was categorized as alert, drowsy, stuporous, confused, or comatose. If any patient reported pain, indicated that they had struck a part of their body, or exhibited a visible abnormality, imaging studies, such as computed tomography scans or X-rays, were recommended. Imaging was performed with the consent of the patient or caregiver; if they declined, it was not performed.

2.3 Injury classification

The information regarding injuries, as documented in the medical records, was descriptive in nature and did not follow a standardized format. Based on previous studies (16), the severity of injuries was classified as follows: (1) no injury; (2) mild injury: minor cuts, minor bleeding, skin abrasions, swelling, pain, and minor contusions; (3) moderate injury: excessive bleeding, lacerations requiring sutures, temporary loss of consciousness, and moderate head trauma; and (4) severe injury: fractures, subdural hematomas, other major head trauma, cardiac arrest, and death.

2.4 Statistical analysis

The patients' age, FAC scores, and MMSE scores were described using means and standard deviations, and the data were analyzed using jamovi software, version 2.3.

3 Results

Of the 316 patients admitted to the brain rehabilitation center over the past 3 years, 10 patients (3.2%) experienced falls during hospitalization. The average age of these 10 patients was 61.3 ± 11.9 years (range: 39 to 82 years); six patients were male (60%) and four were female (40%). Nine patients (90%) had been diagnosed as having a stroke, while one patient (10%) had a brain tumor. Four patients (40%) had hemiplegia, and six patients (60%) had quadriplegia. Three patients (30%) had a history of hypertension, and three patients (30%) had a history of diabetes. All patients were undergoing both physical and occupational therapies. The mean FAC score was 2.4 ± 1.1 (range: 1–4), indicating significant impairment in independent walking. The mean MMSE score was 17.6 ± 7.2 (range: 10–29), indicating moderate to severe cognitive impairment (Table 1). All 10 patients were taking some medications that could increase the risk of falls, e.g., somnifacients, tranquilizers, or agents for benign prostatic hyperplasia, on the day of or the day before the fall (Table 2).

The 10 patients who experienced falls were classified as having a high risk of falls at the time of admission. Four of these patients (40%) fell during the day, while six (60%) fell at night. In five cases, a caregiver was present during the fall. On the other hand, no caregiver was present in the other five cases. Seven patients (70%) fell while getting out of bed, two patients (20%) fell while walking, and one patient (10%) fell during transfer from a wheelchair. Among the seven falls that occurred while getting out of bed, bed rails were raised in three cases and lowered in two cases. The status of the rails was unknown in two cases. Moreover, five out of these seven falls (71.4%) occurred at night.

Regarding the consciousness level during the fall, eight patients (80%) were alert, one patient was drowsy, and one patient was in a state of confusion. After the fall, seven patients (70%) did not report any injuries, while three patients (30%) had minor injuries with no abnormalities on imaging studies (Table 3).

4 Discussion

In this study, among the 316 patients admitted during the study period, 10 patients (3.2%) experienced falls. This figure was lower than those reported in previous studies on fall rates in rehabilitation wards. For instance, Suzuki et al. (17) reported that 121 out of 256 patients (47.3%) admitted to a rehabilitation ward over a 21-month period experienced at least one fall, while Lee and Stokic (18) reported that 140 out of 1,472 patients (9.5%) admitted to a tertiary medical rehabilitation center over an 18-month period experienced at least one fall. Campanini et al. (19) documented falls in 11 out of 147 patients (7.5%) admitted to orthopedic, pulmonary, and neurological rehabilitation wards over a 6-month period. Several factors may have contributed to these discrepancies in study findings. The study periods ranged from 6 to 18 months; however, because the annual fall incidence rates were not standardized, direct comparisons between studies were limited. Moreover, Suzuki et al. (17), who reported a high

TABLE 1 Demographic characteristics of patients who experienced falls.

	Age	Sex	Disease	Vector	The types of paralysis	History	Rehabilitation	FAC	MMSE
Patient 1	82	Male	ICH	Trauma	Hemiplegia	DM	PT, OT, FES	2	–
Patient 2	70	Male	SDH	Trauma	Quadriplegia	–	PT, OT, CT, GT	3	26
Patient 3	49	Male	ICH	Spontaneous	Quadriplegia	DM	PT, OT, GT, FES	1	16
Patient 4	63	Female	SDH	Trauma	Quadriplegia	–	PT, OT, GT, FES	2	10
Patient 5	62	Male	SDH	Unknown	Quadriplegia	HTN	PT, OT, GT, FES	3	11
Patient 6	39	Female	SAH, ICH	Trauma	Quadriplegia	–	PT, OT, GT	4	29
Patient 7	53	Female	SDH	Spontaneous	Quadriplegia	DM	PT, OT, CT, GT, FES	1	16
Patient 8	62	Male	Tumor	Spontaneous	Hemiplegia	–	PT, OT, CT, GT, FES	4	–
Patient 9	68	Female	ICH, infarction	Spontaneous	Hemiplegia	HTN	PT, OT, CT, GT, FES	2	15
Patient 10	65	Male	ICH	Spontaneous	Hemiplegia	HTN	PT, OT, GT, FES	2	–

FAC, functional ambulation category; MMSE, mini-mental state examination; ICH, intracerebral hemorrhage; DM, diabetes mellitus; PT, physical therapy; OT, occupational therapy; FES, functional electrical stimulation; SDH, subdural hemorrhage; CT, cognition therapy; GT, gait training; HTN, hypertension; SAH, subarachnoid hemorrhage.

TABLE 2 Types and dosages of medications administered on the day before and the day of the fall.

	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5	Patient 6	Patient 7	Patient 8	Patient 9	Patient 10
Day before the fall										
Somnifacient										
Circadin PR							2 mg*1			2 mg*1
Noiromin	300 mg*3	300 mg*3	300 mg*2	300 mg*3	300 mg*3					
Tranquilizer										
Buspirone HCl						15 mg*3				
Quetapin		25 mg*1	25 mg*1							
Razepam		1 mg*1		1 mg*1						
Rivotril			0.5 mg*1		0.5 mg*1	0.5 mg*4	0.25 mg*1			
Agent for benign prostatic hyperplasia										
Harnal-D									0.2 mg*1	
Proscar										5 mg*1
Tams	0.4 mg*1							0.4 mg*1		
Xatral XL										10 mg*1
Day of the fall										
Somnifacient										
Circadin PR							2 mg*1			2 mg*1
Noiromin	300 mg*3	300 mg*3	300 mg*2	300 mg*3	300 mg*3					
Tranquilizer										
Buspirone HCl						15 mg*3				
Quetapin		25 mg*1	25 mg*1							
Razepam		1 mg*1		1 mg*1						
Rivotril			0.5 mg*1		0.5 mg*1	0.5 mg*4	0.25 mg*1			
Agent for benign prostatic hyperplasia										
Harnal-D									0.2 mg*1	
Proscar										5 mg*1
Tams	0.4 mg*1							0.4 mg*1		
Xatral XL										10 mg*1

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TABLE 3 Fall-related characteristics.

	Time at fall	Presence of a caregiver at the time of the fall	Location	Presence of side rail	Consciousness state at the time of the fall	Presence of injury after the fall
Patient 1	Night	N	Bed	N	Drowsy	N
Patient 2	Night	Y	Bed	Y	Alert	Mild
Patient 3	Night	Y	Bed	Y	Alert	N
Patient 4	Day	N	Bed	Unknown	Confusion	Mild
Patient 5	Day	N	Bed	N	Alert	N
Patient 6	Night	Y	Bed	Y	Alert	N
Patient 7	Day	N	Walking	-	Alert	N
Patient 8	Night	Y	Walking	-	Alert	N
Patient 9	Day	N	Wheelchair	-	Alert	N
Patient 10	Night	Y	Bed	Unknown	Alert	Mild

N, no; Y, yes.

fall rate, studied patients with a mean age of 68.6 ± 11.5 years—over 7 years older than the mean age of 61.3 ± 11.9 years in the present study. Given that age is a well-established risk factor that significantly influences fall incidence (20), differences in the age distribution of study participants may have contributed to the observed variations in results. Furthermore, fall incidence in rehabilitation wards was determined based on incident reports documented by medical staff, and variations in the institutional definitions of falls may have led to underreporting of similar events across studies. It is also important to consider that falls may have been underreported in cases where clinical supervision was not in place at the time of the incident or when patients or caregivers failed to report the fall. Consequently, the actual number of falls may have been higher than what was recorded in clinical reports.

The objective of this study was to investigate fall incidents that occurred in a single brain habilitation center over the past 3 years and to identify risk factors associated with falls. Additionally, this study aimed to provide practical solutions for fall prevention and suggest future research directions to support clinicians in developing effective preventive strategies. According to the findings of this study, multiple factors contributing to falls were identified.

Falls predominantly occurred during mobility, with seven out of 10 patients (70%) falling while attempting to get out of bed. Notably, five (71.4%) of these falls occurred at night, while two (28.6%) occurred during the day. This finding aligns with the finding of a previous study, in which over 60% of falls among patients with acquired brain injury occurred at night (21). The increased frequency of falls at night suggests that physical factors, such as impaired vision or medication-induced sleep disorders; environmental factors, such as dark lighting or a reduction in nursing staff during nighttime hours; and behavioral factors, such as the tendency of patients to move independently, can heighten fall risk. Visual impairment and sleep disorders are common symptoms in patients with acquired brain injury. In particular, 12 to 84% of patients with stroke experience visual deficits, such as visual loss or blurred vision, and over 50% experience sleep disturbances (22–24). Impaired vision can complicate the identification of surrounding obstacles and disrupt distance perception. Difficulties in clearly perceiving the environment and surrounding areas can increase the risk of falls (25). Moreover, in patients with stroke, sleep disorders often arise because of anxiety or depression, leading to the use of somnifacients or tranquilizers (22). These medications depress the central nervous system and induce sedation, which may result in muscle relaxation, impaired balance, or confusion (26). In particular, when patients who take somnifacient get up at night, they may experience increased confusion in the dark, increasing the risk of falls when getting out of bed or navigating to the bathroom. Furthermore, the residual effects of somnifacient can slow reaction times and reduce attention, increasing the risk of tripping during movement (27). Tranquilizers act on the central nervous system to suppress anxiety, tension, and agitation. However, they may also lead to muscle relaxation and impaired motor coordination (28, 29). Consequently, tranquilizers may diminish a patient's ability to recognize and correct their body posture when feeling unsteady, making them more susceptible to falls (30, 31). These clinical findings support our hypothesis. In particular, among the 10 patients included in our study, nine had experienced a stroke. The five patients who fell around their beds at night were also stroke patients. All stroke patients were taking somnifacients and tranquilizers, which may have increased their risk of falls. In addition to physical factors, environmental or behavioral factors can play a significant role in increasing a patient's risk of falls. Typically, hospital wards turn off all lights at night, creating a dark environment. However, at Yeungnam University Hospital—where this study was conducted—the lights in the ward hallway remain on at night to facilitate the movement of patients and medical staff. In contrast, hospital rooms are usually kept completely dark, with doors closed during sleeping hours. Additionally, patients frequently draw the curtains while sleeping, further diminishing visibility. Under such low-light conditions, patients may struggle to maintain adequate peripheral vision, making it difficult to locate and grasp safety handrails or determine where to place their feet (32). Moreover, staffing levels can influence patient safety. At Yeungnam University Hospital's rehabilitation ward, the ratio of nursing staff to patients increases from 1 nurse per 8 patients during the day (6:30 a.m. to 9:30 p.m.) to 1 nurse per 13.3 patients at night (9:30 p.m. to 6:30 a.m.). This reduction in staffing may exacerbate safety risks, particularly in preventing falls during the night. Under these circumstances, more frequent monitoring of patient conditions becomes necessary during nighttime hours; however, the increased workload may lead to fatigue and stress among staff, potentially compromising the overall quality of patient care. Thus, optimizing staffing during critical hours, along with targeted environmental modifications, could be essential in reducing fall risks. Furthermore, in previous studies, patients who experienced falls were found to often refrain from seeking assistance before the fall because of reluctance to disturb family members or healthcare staff (5, 32). Moreover, patients undergoing rehabilitation after acquired brain injury may overestimate their physical capabilities and attempt movement without seeking help (33). To address this issue, hospitals can improve the environment by installing sensor lights to ensure safe navigation during sudden movements at night. Continuous education is also essential to encourage patients to refrain from wandering alone and to seek assistance when moving, thereby enhancing their safety.

Another noteworthy observation is that falls occurred despite the presence of caregivers and the presence of bed rails as environmental precautions. Among the 10 cases of falls, five cases (50%) occurred in the presence of caregivers. Regarding falls occurring around the bed, three out of seven cases (42.9%) occurred even with bed rails. These results suggest that falls could have occurred when the caregiver's attention was diverted, the assistance provided was insufficient, the caregiver was unable to offer help, or the patient attempted to climb over the bed rails (32). Caregivers must pay close attention to patients with acquired brain injury, who have a high risk of falls. However, realistic limitations exist. For instance, the caregiver may occasionally step away without handing the patient over to medical staff or the caregiver may sleep at night, making continuous vigilance difficult. Moreover, if a patient falls toward the caregiver, the caregiver may be unable to counter the force. Consequently, both the patient and caregiver may collapse. To avoid these situations, it is crucial to conduct regular fall prevention training for caregivers to help them recognize and respond quickly to risky situations (34, 35). Furthermore, the introduction of monitoring equipment that enables real-time observation of a patient's movements can facilitate immediate responses even if the caregiver's attention is diverted (36, 37). The occurrence of falls even in the presence of bed rails suggests that such assistive devices alone may not ensure fall prevention. Several studies have revealed that bed rails do not guarantee patient safety (38–40). While bed rails can serve as a physical barrier against falls, attempts by patients to climb over or lean on them may pose a greater risk. Therefore, rather than simply installing assistive devices, it is vital to educate both patients and caregivers on the correct usage of these devices and to implement additional measures tailored to each patient's physical condition. For instance, adjusting the height of beds for patients having a high risk of falls can create a safer environment when patients attempt to rise. Furthermore, placing frequently used items within easy reach of patients with mobility limitations can minimize unnecessary movements.

Finally, the fact that falls frequently occurred even among alert patients (80%) indicates that falls are not solely attributable to confusion or drowsiness. This suggests that even when a patient's consciousness is intact, falls can occur due to physical limitations, impaired balance, misjudgment, or the side effects of medications. Among the 10 patients included in this study, eight patients (80%) had difficulty walking independently (FAC score < 4), four patients (40%) had hemiplegia, and six patients (60%) had quadriplegia. Furthermore, five patients (50%) exhibited impaired cognitive function (MMSE score < 24), and four patients (40%) were taking medications, such as those for benign prostatic hyperplasia, in addition to somnifacients and tranquilizers. Motor dysfunctions make it challenging to maintain stability or balance during processes like getting in or out of bed or during movement. Damage to neural pathways following acquired brain injury often reduces muscle strength in certain body parts (41). In particular, weakened muscles in the legs or torso can make it difficult to adequately support body weight when rising from a bed, leading to a higher risk of imbalance (42, 43). Insufficient muscle strength can impair the ability to stabilize the body during weight-bearing activities, such as standing or moving, thereby increasing the risk of falls (44). Moreover, when paralysis occurs as a result of acquired brain injury, patients can face even greater difficulties in maintaining body balance (45). For example, when rising from a bed, if one leg cannot adequately support weight or if balance cannot be maintained with one arm, the risk of falling is heightened. Severe muscle weakness or paralysis can also lead to asymmetric gait patterns, complicating normal walking (46). Furthermore, a decline in motor coordination, which facilitates smooth and accurate movements through the simultaneous control of multiple muscles, may result in uncoordinated and inaccurate movements (47). Excessive or diminished muscle tone following acquired brain injury can further degrade balance and stability, increasing the risk of falls (48). Therefore, to reduce the risk of falls, it may be beneficial for rehabilitation therapies to emphasize tailored interventions that specifically address fall prevention (49). Strength training could target the most affected muscle groups, such as lower limb and core muscles, to enhance postural control and improve weight-bearing capacity. Balance training might be optimized by incorporating exercises such as marching in place, single-leg standing, and weight-shifting movements, which could help improve stability during daily activities (50). Additionally, functional electrical stimulation might be considered to help activate weakened muscles, thereby supporting both mobility and stability (51). Furthermore, educating patients on the proper use of assistive devices, such as walkers, canes, or crutches, can help maintain balance and enhance stability during movement (48). Cognitive decline following acquired brain injury can also increase the risk of falls. Cognitive impairment is recognized as an independent risk factor for falls. The risk of falling is approximately 2.7 times higher in individuals with cognitive impairment than in those without it (52). Impaired cognitive function slows down behavior and reaction times, leading to delayed responses in unexpected situations and a resultant higher risk of falls (53). Furthermore, cognitive decline can reduce spatial awareness and attention, making it challenging to accurately assess the surrounding environment (54). This impairment affects critical abilities needed to maintain balance or avoid obstacles, thereby increasing the risk of falls. To alleviate the risk of falls associated with cognitive decline, various therapeutic approaches can be employed. Cognitive training programs can enhance attention, judgment, and spatial awareness, helping patients to safely navigate and respond to hazardous situations (55). Moreover, occupational therapy can reduce errors and inattention related to cognitive impairment by repeatedly practicing daily living activities (27). Psychological support and education can also play a significant role in fall prevention by alleviating patients' fears of falling and enhancing their awareness of fall risks (56). Medications are a modifiable risk factor that can increase the risk of falls. The agents for benign prostatic hyperplasia used by the participants in this study included alpha-blockers, which relax the muscles of the prostate and bladder neck, and 5-alpha reductase inhibitors, which reduce the size of the prostate. These drugs can alleviate urinary difficulties caused by prostate enlargement; however, they can also affect blood vessels and lower blood pressure (57, 58). This action can lead to orthostatic hypotension, increasing the risk of sudden dizziness and falls on standing up (59). Alpha-blockers can also reduce muscle tone by blocking alpha-1 receptors, potentially decreasing stability and making it harder to maintain balance during walking or other daily movements (60). Therefore, when prescribing medications to patients having a high risk of falls following acquired brain injury, it is preferable to avoid drugs that can further increase the risk of falls. However, if the use of such medications is unavoidable, they should be administered at the lowest effective dose for the shortest duration possible (61). Moreover, providing thorough education to patients and caregivers about the potential side effects of these medications is crucial to help mitigate the risk of falls.

This study has several limitations. First, we did not identify which factors are independent risk factors for falls by comparing patients who experienced falls with those who did not. Second, the analysis was based on a small sample from a single institution. Therefore, future research should combine data from multiple institutions to establish and analyze a large-scale database of falls. This would provide a more comprehensive understanding of the risk factors for falls and contribute to the development of more effective fall prevention and management strategies.

5 Conclusion

This study investigated fall incidents that occurred in a single brain rehabilitation center and identified the associated risk factors and prevention strategies. The results indicated that falls primarily occurred during patient mobility from the bed, particularly at night. Moreover, frequent falls occurred even when patients were in a state of clear consciousness. This suggests that physical factors, such as visual impairments and side effects of medication; environmental factors, such as dark lighting or insufficient nursing staff coverage; and behavioral factors, such as patients' attempts to move without assistance, could contribute to falls. Falls even occurred despite the presence of caregivers and bed rails, highlighting the practical limitations of caregiver and assistive device roles. In conclusion, a multifaceted approach that considers physical, environmental, and behavioral factors is necessary for fall prevention. The implementation of various measures—including nighttime lighting, comprehensive training on the use of assistive devices, ongoing education for caregivers, the integration of monitoring equipment, patient-specific rehabilitation programs, and meticulous management of medications that may increase fall risk—could prove effective in reducing falls. These strategies may help create a safer environment and support fall prevention efforts. Additionally, future research could focus on identifying independent risk factors for falls by employing a multivariate approach that compares patients who experienced falls with those who did not. Moreover, expanding studies to multiple institutions with larger sample sizes could enhance the generalizability of findings and provide a more comprehensive understanding of fall risk factors across diverse healthcare settings. Furthermore, exploring emerging technologies, such as real-time monitoring systems and artificial intelligence-based fall prediction models, holds the potential to offer innovative solutions for proactive fall prevention in rehabilitation environments. By addressing these areas, future research may contribute to more effective and data-driven fall prevention strategies, ultimately supporting improvements in patient safety and rehabilitation outcomes.

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 the Institutional Review Board of Yeungnam University Hospital. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin due to the retrospective nature of the study.

Author contributions

YC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. JM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. GL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. W-TP: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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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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EDITED BY
Dimitrios Kikidis,
National and Kapodistrian University of Athens, Greece

REVIEWED BY
Francesco Lena,
Mediterranean Neurological Institute Neuromed (IRCCS), Italy
Guotuan Wang,
Henan University, China
Junxiao Xie,
Xi'an Jiaotong University, China

*CORRESPONDENCE
Yue Cheng
✉ 1194206427@qq.com

†These authors share first authorship

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Effects of different exercises on improving gait performance in patients with Parkinson's disease: a systematic review and network meta-analysis

Ying Li[1†], Jieling Huang[2†], Jinguo Wang[1] and Yue Cheng[3]*

[1]College of Sports Science, Jishou University, Jishou, China, [2]Faculty of Health Sciences and Physical Education, Macao Polytechnic University, Macao, Macao SAR, China, [3]Department of Neurology, People's Hospital of Changshou, Chongqing, China

Objective: Gait disorder represents a characteristic symptom of Parkinson's disease (PD), and exercise has been established as an effective intervention for gait management in PD. However, the relative efficacy of various exercise types in improving gait among PD patients remains unclear. This study aimed to compare the effectiveness of different movement-based interventions in enhancing gait for individuals with PD through a network meta-analysis.

Methods: A comprehensive search was conducted across multiple databases, including PubMed, Cochrane Library, Embase, Web of Science, and CNKI. The methodological quality of included studies was evaluated using the Cochrane Bias risk tool. Data was extracted from these studies to compare the efficacy of 29 distinct exercise interventions on gait performance in patients with PD.

Results: The analysis encompassed 68 randomized controlled trials (RCTs), involving a total of 3,114 participants. The results of the network meta-analysis showed that DE is higher than CON (SMD, 2.11; 95% CI 1.07 to 3.15), WE (SMD, 2.16; 95% CI 0.90 to 3.43), HE (SMD, 2.19; 95% CI 0.95 to 3.44), OE (SMD, 2.66; 95% CI 1.16 to 4.16), TR (SMD, 2.62; 95% CI 1.45 to 3.79) to better improve Gait velocity in patients with Parkinson's disease. DE is superior to CON (SMD, 2.08; 95% CI 0.04 to 4.13) in improving Step length. FAE is superior to CON (SMD, 1.01; 95% CI 0.04 to 1.98), BDJ (SMD, 1.20; 95% CI 0.15 to 2.25), RAGT (SMD, 1.29; 95% CI 0.07 to 2.52), DE (SMD, 1.57; 95% CI 0.36 to 2.77), TR (SMD, 1.62; 95% CI 0.48 to 2.76), OE (1.76, 95% CI 0.57 to 2.94) in improving Gait velocity. RAGT is superior to CT (MD, 2.02; 95% CI 0.41 to 3.63), TR (MD, 2.51; 95% CI 1.17 to 3.84), AE (MD, 2.66; 95% CI 0.45 to 4.88), BDJ (MD, 2.77; 95% CI 0.93 to 4.61), CON (MD, 2.83; 95% CI 1.30 to 4.36), DTT (MD, 12.84; 95% CI 10.05 to 15.63) in improving 6MWT.

Conclusion: Our study found that DE improved gait speed and step length in patients with Parkinson's disease better than other forms of exercise. FAE and RAGT were more effective than other exercises in improving step length and 6MWT in patients with Parkinson's disease.

KEYWORDS

Parkinson's disease, gait, 6MWT, network meta-analysis, systematic review

Introduction

PD is the second most prevalent neurodegenerative disorder characterized by motor activity deterioration, resulting from damage to the dopaminergic nigrostriatal system (Pajares et al., 2020; Simon et al., 2020). The incidence of PD correlates directly with age (Hallett et al., 2019). PD diagnoses are projected to double from 6 million in 2015 to 12 million in 2040, coinciding with approximately 1% of the global population exceeding 60 years of age (Ascherio and Ma, 2016; Tysnes and Storstein, 2017; Dorsey and Bloem, 2018). Gait abnormality represents a primary cause of motor dysfunction in PD patients (Frazzitta et al., 2009). These gait abnormalities manifest primarily as postural irregularities, diminished muscle strength in major limb and trunk muscle groups, reduced balance function, initiation difficulties, decreased stride length, inability to halt at will, turning challenges, and bradykinesia. This walking dysfunction in PD patients elevates fall risk and significantly impairs daily living capabilities.

Current PD treatment strategies aim to alleviate symptoms and decelerate disease progression (Raza et al., 2019). The prevailing PD treatment model involves anti-Parkinson's medications or Deep Brain Stimulation, which often prove inadequate, yielding minimal or no long-term patient improvement (Scelzo et al., 2019). Adjunctive and complementary treatments, such as exercise, can mitigate side effects of anti-Parkinson's drug therapy and have demonstrated efficacy in improving movement disorders including balance, gait, fall risk, and physical function while reducing fall incidence (Feng et al., 2020; Mak and Wong-Yu, 2019). An increasing body of evidence supports the crucial role of exercise therapy (Tomlinson et al., 2013; Abbruzzese et al., 2016). Dance exercise (DE) can down-regulate α-Syn protein level to a certain extent, inhibit neuronal apoptosis, improve mitochondrial dysfunction, and thus restore the motor function of early patients (Koo et al., 2017). Resistance training (RT) is a strength exercise that can enhance muscle strength by overcoming resistance in local muscle groups. It can also improve the body's neuroplasticity, up-regulate the expression level of dopaminergic neurotransmitters and receptors, promote the release of non-dopaminergic transmitters such as norepinephrine and 5-hydroxytryptamine (Qian et al., 2024), and improve the motor symptoms of Parkinson's patients. Aerobic exercise (AE) can improve motor function in patients with Parkinson's disease by regulating neurotrophic factors to support synaptic formation and angiogenesis, inhibit oxidative stress and improve mitochondrial function (Feng et al., 2020). However, the optimal exercise type for treating gait in PD patients remains unclear. According to Jiang's traditional meta-analysis, Robotic Assisted Gait Training (RAGT) can effectively enhance PD patients' walking function and gait performance (Jiang et al., 2024). In a conventional meta-analysis, Bishnoi found that Treadmill Training improved step and stride lengths in PD patients (Bishnoi et al., 2022). Nevertheless, a direct comparison between RAGT and Treadmill Training is currently lacking.

Network meta-analysis (NMA) has gained prominence in evaluating medical interventions due to its capacity to estimate the relative effectiveness and ranking of interventions, even in the absence of direct comparisons (Bafeta et al., 2014). Although Yang explored the influence of exercise patterns on Parkinson's patients, the exercise was classified into 24 categories, and there was a lack of research on six-minute walk test (6MWT) and Step-length outcome indicators (Yang et al., 2022). Victor explored the intervention measures to improve gait in Parkinson's disease, but there was a lack of studies on Stride length, 6MWT, and Step length (Hvingelby et al., 2022). Therefore, our study made a detailed division of movement modes, compared the gait forms of more PD patients, determined the best exercise mode to improve the gait of PD patients, and guided PD patients to choose the best exercise mode.

Methods and analysis

Registration

This network meta-analysis was designed according to the guidelines for Preferred Reporting Items of Systems Review and Network Meta-Analysis (PRISMA-NMA) (Hutton et al., 2015).

Search strategy

The computer searched PubMed, Web of Science, Embase, Cochrane Library, CNKI, and other databases, and the search period was established until August 20, 2024. The search takes the way of combining subject words and free words. The search strategy uses Pubmed as an example, as shown in Appendix 1.

Study selection

The inclusion criteria for study selection were based on the PICOS methodology (Participants, interventions, comparators, outcomes, and study design) (Hutton et al., 2015), shown in Table 1. In addition, we provide detailed definitions of 29 intervention terms. Each intervention is defined in Appendix 2.

Data extraction

The following data were extracted independently by two reviewers: first author, year of publication, country, sample size, intervention mode, intervention time, and intervention period. Data are expressed as mean ± standard deviation (mean ± SD). If the outcome indicator reports multiple points, we extract data for the most recent time.

Risk of bias assessment

The risk of bias was assessed independently by two reviewers and by a third reviewer using the tools provided by the Cochrane Collaboration (Higgins et al., 2011), including sequence generation, hidden assignment, blinking, incomplete outcome data, non-selective reporting of results, and other sources of bias. Each criterion was judged to have a low, unclear, or high risk of bias.

Data analysis

The netmeta package of R-4.2.1 software was used to perform mesh meta-analysis. Use the STATA 15.1 "networkplot" feature to

TABLE 1 Inclusion and exclusion criteria.

Category	Inclusion criteria	Exclusion criteria
Population	Parkinson's disease was diagnosed in patients >18 years of age	Patients with severe comorbidities such as severe hypertension, heart disease, or other serious systemic diseases
Interventions	Aerobic exercise (AE), Aquatic Exercise (AQE), Whole body vibration training (WBV), Virtual reality (VR), Treadmill training (TT), Resistance training (RT), Tai Chi (TC), Power Training (PT), Biofeedback Balance and Gait Training (BGT), Walking exercise (WE), Dance exercise (DE), Balance training (BT), Game training (GT), Baduanjin (BDJ), Home exercise (HE), Yoga (YG), Boxing exercise (BE), Robotic Assisted Gait Training (RAGT), Combined therapy (CT), Dual task training (DTT), Stretch exercise (SE), Five animal exercises (FAE), Other exercise (OE), Fitness exercise (FE), Qigong (QG), Virtual reality balance training (VRB), Core strength training (CST).	
Comparisons	Traditional Rehabilitation (TR), Control group (CON)	
Outcomes	Stride length, Gait velocity, 6 Minutes Walking Test (6MWT), Step length	
Study	Randomized controlled trial; published in English or Chinese	

draw and generate a network diagram that describes and presents different forms of exercises. We use nodes representing various interventions and edges representing head-to-head comparisons between interventions. Node splitting assesses inconsistencies between direct and indirect comparisons (Rücker and Schwarzer, 2015). The combined estimates and their 95% confidence intervals (95% CI) were calculated using random effects network analysis. When we are interested in results using the same unit of measure in a study, consider analyzing the results as a therapeutic effect by means difference (MD) or evaluating standardized mean difference (SMD). A pair-to-pair random-effects meta-analysis was used to compare various exercise therapies. The heterogeneity of all pair-to-pair comparisons was assessed using the I^2 statistic, and publication bias was evaluated using the p-value of Egger's test and the funnel plot.

Results

Literature selection

After deleting duplicates, 1,115 records were retrieved, 123 duplicates were removed, 891 articles with inconsistent titles were deleted, 33 articles with inconsistent titles were removed after reading the full text, and 68 articles were finally included (Appendix 3). The research flow chart is shown in Figure 1.

Study and participant characteristics

The included studies, published between 2007 and 2024, compared the effects of 29 different forms of exercise on people with Parkinson's disease. The duration of intervention ranged from 3 to 48 weeks. A total of 3,114 patients were reported. Of all the included studies, 33 reported Gait velocity, 16 reported Step length, 19 reported Stride length and 35 reported 6MWT. The characteristics of the studies and participants are shown in Table 2 and Appendix 3. The risk of bias assessment for each study is summarized in Appendix 4 and Figure 2.

Gait velocity

A total of 33 studies evaluated Gait velocity, involving 1,574 participants. We included the following 23 exercise measures in our network meta-analysis (Figure 3A):

Aerobic exercise (AE), Virtual reality (VR), Treadmill training (TT), Tai Chi (TC), Power Training (PT), Biofeedback Balance and Gait Training (BGT), Control group (CON), Walking exercise (WE), Dance exercise (DE), Balance training (BT), Baduanjin (BDJ), Home exercise (HE), Boxing exercise (BE), Robotic Assisted Gait Training (RAGT), Combined therapy (CT), Traditional Rehabilitation (TR), Dual task training (DTT), Stretch exercise (SE), Five animal exercises (FAE), Other exercise (OE), Qigong (QG), Virtual reality balance training (VRB), Core strength training (CST). Our results show that DE is higher than CON (SMD, 2.11; 95% CI, 1.07 to 3.15), WE (SMD, 2.16; 95% CI 0.90 to 3.43), HE (SMD, 2.19; 95% CI 0.95 to 3.44), AE (SMD, 2.42; 95% CI 1.05 to 3.80), OE (SMD, 2.66; 95% CI 1.16 to 4.16), BE (SMD, 2.74; 95% CI 1.24 to 4.23), TR (SMD2.62; 95% CI 1.45 to 3.79) to better improve Gait velocity in patients with Parkinson's disease (Figure 4A). In addition, we performed the Egger's test to assess publication bias (p = 0.325) (Appendix 5.1). The included studies did not show publication bias. Heterogeneity and inconsistencies in the mesh meta-analysis were also evaluated (Appendix 6). The most direct comparisons are CON VS QG (Appendix 7.1).

Step length

A total of 15 studies evaluated GUT, involving 802 participants. We included the following 14 exercise measures in the network meta-analysis (Figure 3B): Virtual reality (VR), Tai Chi (TC), Control group (CON), Dance exercise (DE), Balance training (BT), Baduanjin (BDJ), Robotic Assisted Gait Training (RAGT), Combined therapy (CT),

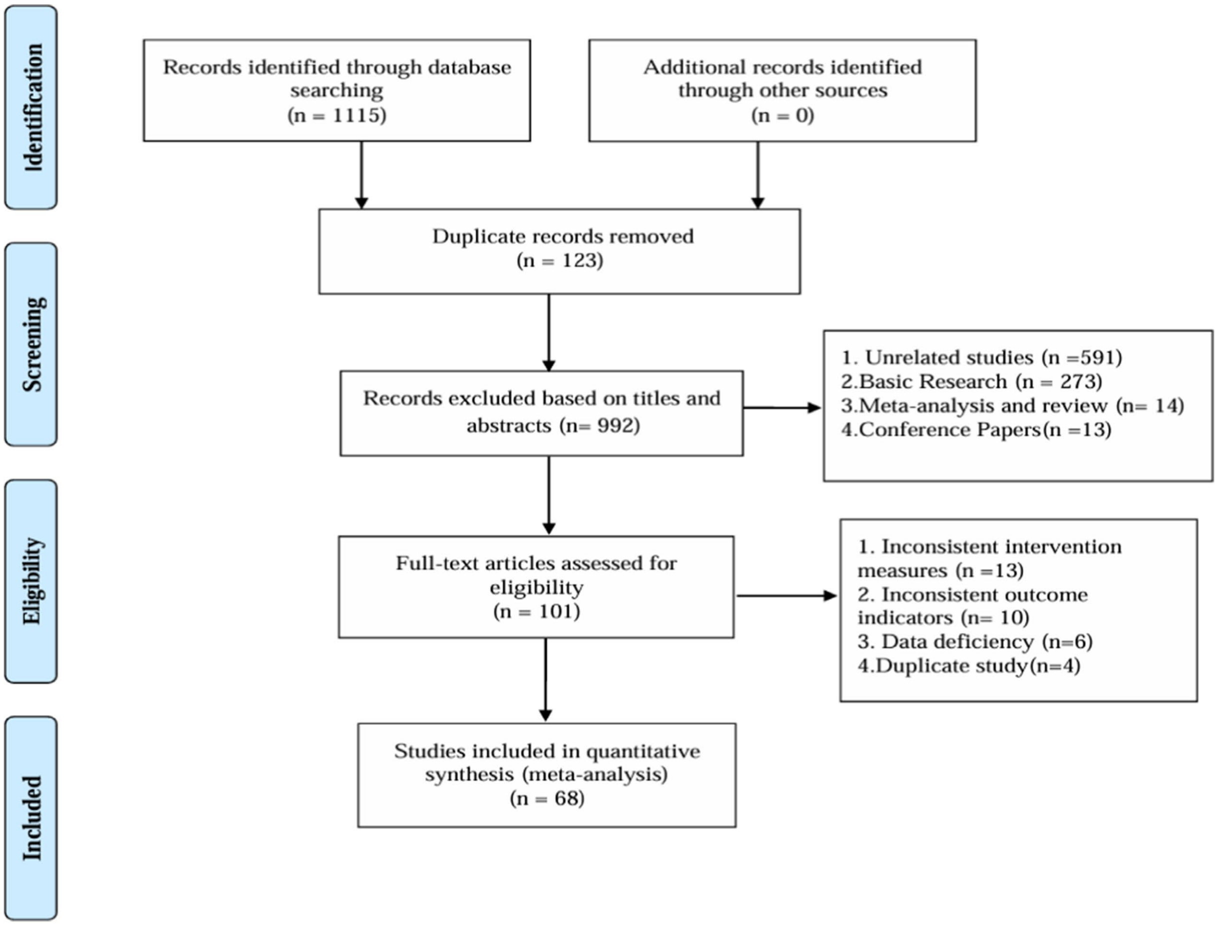

FIGURE 1
Flow chart.

Traditional Rehabilitation (TR), Dual task training (DTT), Stretch exercise (SE), Qigong (QG), Virtual reality balance training (VRB), Core strength training (CST). The results show that DE is superior to CON (SMD, 2.08; 95% CI 0.04 to 4.13) (Figure 4B). In addition, we performed the Egger test to assess publication bias ($p = 0.239$) (Appendix 5.2). The included studies did not show publication bias. We also evaluated the heterogeneity and inconsistencies of the mesh meta-analysis (Appendix 6). We made a direct comparison of exercise interventions (Appendix 7.2).

Stride length

A total of 19 studies evaluated, involving 741 participants. We included the following 16 exercise measures in the network meta-analysis (Figure 3C): Aerobic exercise (AE), Treadmill training (TT), Tai Chi (TC), Control group (CON), Walking exercise (WE), Dance exercise (DE), Baduanjin (BDJ), Yoga (YG), Robotic Assisted Gait Training (RAGT), Combined therapy (CT), Traditional Rehabilitation (TR), Dual task training (DTT), Stretch exercise (SE), Five animal exercises (FAE), Other exercise (OE), Qigong (QG). The results show that: FAE is superior to CON (SMD, 1.01; 95% CI 0.04 to 1.98), SE (SMD, 1.08; 95% CI 0.42, 1.74), BDJ (SMD, 1.20; 95% CI 0.15 to 2.25), RAGT (SMD, 1.29; 95% CI 0.07 to 2.52), TT (SMD, 1.35; 95% CI 0.22 to 2.48), DE (SMD, 1.57; 95% CI 0.36 to 2.77), TR (SMD, 1.62; 95% CI 0.48 to 2.76), AE (SMD, 1.72; 95% CI 0.74 to 2.70), OE (SMD, 1.76, 95% CI 0.57 to 2.94) in improving Gait velocity (Figure 4C). In addition, we assessed publication bias using the Egger test ($p = 0.659$) (Appendix 5.3). The included studies did not show publication bias. We also evaluated heterogeneity and inconsistencies in the mesh meta-analysis (Appendix 6). We made a direct comparison of exercise interventions (Appendix 7.3). The most direct comparisons are CON vs. QG and BDJ vs. CON.

6MWT

A total of 35 studies evaluated, involving 1,616 participants. We included the following 20 exercise measures in the network metaanalysis (Figure 3D): Aerobic exercise (AE), Aquatic Exercise (AQE), Whole body vibration training (WBV), Treadmill training (TT), Resistance training (RT), Tai Chi (TC), Control group (CON), Walking exercise (WE), Dance exercise (DE), Balance training (BT), Game training (GT), Baduanjin (BDJ), Boxing exercise (BE), Robotic Assisted Gait Training (RAGT), Combined therapy (CT), Traditional Rehabilitation (TR), Dual task training (DTT), Stretch exercise (SE), Other exercise (OE), Fitness exercise (FE). The results show that: RAGT is superior to CT (MD, 2.02; 95% CI 0.41 to 3.63), RT (MD,

TABLE 2 General characteristics of patients.

Characteristics	Gait velocity	Step length	Stride length	6MWT
Publication characteristics				
Total number of unique studies included	33	15	19	35
Publication year				
2001–2010	2	0	3	2
2011–2020	18	6	10	23
2021–2024	13	9	6	10
Study design characteristics				
Range of study sample size				
1–50	22	7	15	23
51–100	10	8	4	9
101–150	1	0	0	3
151–200	0	0	0	0
No. of intervention arms included				
2	32	15	17	31
3	1	0	2	4
No. of studies containing the following treatment nodes				
Aerobic exercise (AE)	1	0	1	1
Aquatic Exercise (AQE)	0	0	0	3
Whole body vibration training (WBV)	0	0	0	1
Virtual reality (VR)	2	1	0	0
Treadmill training (TT)	1	0	3	5
Resistance training (RT)	0	0	0	2
Tai Chi (TC)	3	1	2	5
Power Training (PT)	2	0	0	0
Biofeedback Balance and Gait Training (BGT)	1	0	0	0
Control group (CON)	16	4	11	16
Walking exercise (WE)	2	0	3	5
Dance exercise (DE)	1	1	1	6
Balance training (BT)	4	3	0	1
Game training (GT)	0	0	0	1
Baduanjin (BDJ)	2	1	3	2
Home exercise (HE)	2	0	0	0
Yoga (YG)	0	0	1	0
Boxing exercise (BE)	1	0	0	1
Robotic Assisted Gait Training (RAGT)	1	1	1	2
Combined therapy (CT)	2	2	1	6
Traditional Rehabilitation (TR)	9	9	2	11
Dual task training (DTT)	3	2	3	1
Stretch exercise (SE)	2	1	2	2
Five animal exercises (FAE)	2	0	1	0
Other exercise (OE)	2	0	2	2
Fitness exercise (FE)	0	0	0	1
Qigong (QG)	6	3	3	0
Virtual reality balance training (VRB)	1	1	0	0

(Continued)

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TABLE 2 (Continued)

Characteristics	Gait velocity	Step length	Stride length	6MWT
Core strength training (CST)	1	1	0	0
Time of intervention				
Unclear	1	0	1	1
3 weeks	2	1	1	0
4 weeks	3	3	3	3
5 weeks	1	0	1	0
6 weeks	2	1	3	2
8 weeks	5	3	1	7
10 weeks	1	1	0	5
11 weeks	1	0	0	0
12 weeks	13	4	7	12
16 weeks	1	1	1	2
24 weeks	2	1	1	3
48 weeks	1	0	0	0

2.00; 95% CI 0.08, 3.92), TC (MD, 2.15; 95% CI 0.42, 3.88), OE (MD, 2.30; 95% CI 0.37 to 4.23), SE (MD, 2.30; 95% CI 0.35 to 4.25), WE (MD 2.37; 95% CI 0.68 to 4.07), TR (MD, 2.51; 95% CI 1.17 to 3.84), AE (MD2.66; 95% CI 0.45 to 4.88), FE (MD, 2.67; 95% CI 0.43 to 4.91), BDJ (MD, 2.77; 95% CI 0.93 to 4.61), BE (MD, 2.87; 95% CI 0.45 to 5.30), CON (MD, 2.83; 95% CI 1.30 to 4.36), BT (MD, 3.19; 95% CI 0.68 to 5.70), WBV (MD, 5.42; 95% CI 2.71 to 8.21), DTT (MD, 12.84; 95% CI 10.05 to 15.63) in improving 6MWT (Figure 4D). In addition, we assessed publication bias using the Egger test ($p = 0.688$) (Appendix 5.3). The included studies did not show publication bias. We also evaluated heterogeneity and inconsistencies in the mesh meta-analysis (Appendix 6). We made a direct comparison of exercise interventions (Appendix 7.3). The most direct comparisons are CON VS DE.

Discussion

Gait disorder is one of the common manifestations of motor symptoms in PD patients, which often leads to loss of motor ability and increased mortality. It is one of the essential reasons for the decline in quality of life in PD patients. Therefore, it is of great significance to improve the movement mode of PD patients with gait disorders clearly. A total of 3,114 PD patients were included in our study, and 29 exercise methods were explored to enhance the improvement of gait disorders in PD patients.

Gait velocity and step length are frequently utilized as indicators to monitor the progression of gait disorders and treatment efficacy in patients with PD (Chien et al., 2006). Our study revealed that DE demonstrated superior efficacy compared to the Control group (CON), Walking exercise (WE), Home exercise (HE), Aerobic exercise (AE), Other exercise (OE), Boxing exercise (BE), and Traditional Rehabilitation (TR) in enhancing gait velocity among PD patients. Dance, as an art form, integrates aesthetic imagery, musicality, and goal-setting. It typically begins with a gradual warm-up, potentially improving strength, flexibility, and coordination. Furthermore, improvisation, co-creation, and aesthetic interpretation stimulate participants' creativity and imagination. The music incorporated in dance provides essential auditory cues for movement through rhythmic and speed variations (Batson et al., 2016). Tactile feedback can also facilitate movement. For instance, when partnered with a submissive individual, rhythmic auditory cues and attention strategies prove more advantageous in improving walking speed during dual tasks (Baker et al., 2007; Westheimer, 2008). Research indicates that DE can mitigate progressive neuronal axon degeneration, promote dendritic formation of new synapses, establish novel neural connections, activate or create new neural pathways, enhance the brain's regulatory role on limbs, improve joint flexibility, and alleviate movement disorders (Huang and He, 2016). Ashoori et al. (2015) suggested that basal ganglia lesions in PD patients may be associated with reduced internal rhythm, leading to impaired motor initiation and rhythm control. Basal ganglia activity increases during dance, particularly in the core-shell region (Brown et al., 2006). This suggests that dance may beneficially stimulate the basal nucleus in PD patients, enabling them to execute relatively complex movements and enhance their motor abilities. Our meta-analysis demonstrated that exercise interventions can improve step length in PD patients. Interestingly, our study only found DE to be superior to CON in improving step length in PD patients. This implies that most intervention studies in this meta-analysis had negligible or statistically insignificant effects on the step length parameter. Consequently, we recommend that future studies increase their focus on step length in PD research. In addition, our study also found that DE was better than CON in improving step length, but the results may be unstable. Considering that we may have many dances (tango, waltz, samba, Irish dance, ballroom dance, etc.), we suggest a detailed division of dance types for future research. Exploring which kind of dance improves stride length in patients with Parkinson's disease.

Our results indicate that FAE is superior to Control group (CON), Stretch exercise (SE), Baduanjin (BDJ), Robotic Assisted Gait Training (RAGT), Treadmill training (TT), Dance exercise (DE), Traditional Rehabilitation (TR), Aerobic exercise (AE), and Other exercise (OE)

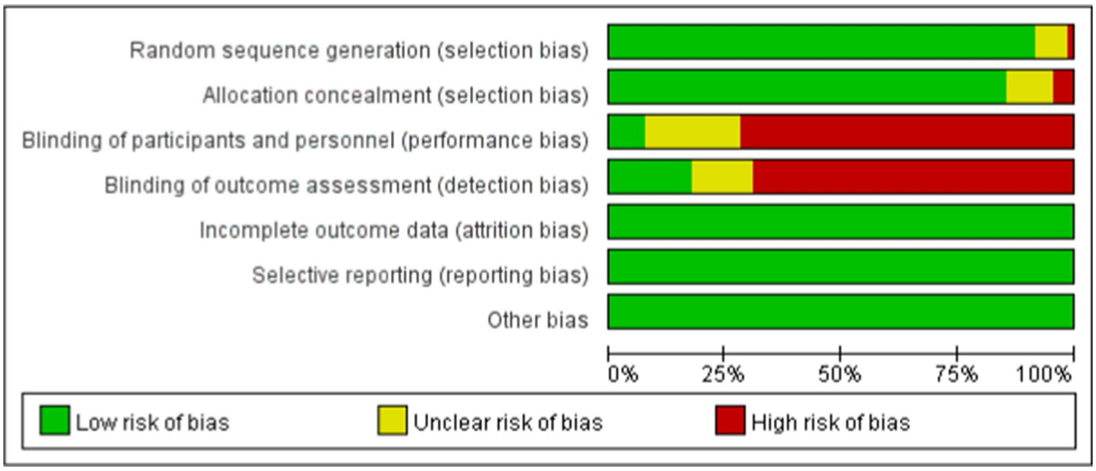

FIGURE 2
Percentage of studies examining the efficacy of exercise training in patients with non-specific chronic low back pain with low, unclear, and high risk of bias for each feature of the Cochrane risk of bias tool.

in improving Gait velocity. FAE, a traditional Chinese exercise, primarily emulates the movements of tigers, deer, bears, apes, and birds. This practice effectively stretches muscles and joints, engages various muscle groups, and involves alternating the body's center of gravity from front to back and left to right, thereby improving movement ability, balance, and coordination. Patients with PD typically exhibit a stooped posture, reduced arm swing, decreased lower limb motion range, slower stride speed, shorter stride length, reduced ground clearance, and prolonged double support period, increasing their susceptibility to falls (Cc and Rc, 2018; Wassom et al., 2015). FAE's efficacy in improving stride length for PD patients may be attributed to its emphasis on forward stride movements. The exercise requires patients to lift their hips while stepping forward, lunge, swing their arms, and shift their center of gravity between stride types, effectively enhancing their ability to take longer strides and mitigating stride ability decline (Xiaofei and Jinggang, 2018). Given its distinct cultural characteristics, promoting FAE warrants consideration. Strategies for promotion could include organizing basic FAE courses, offering accessible introductory sessions, and providing easily comprehensible multi-language or online courses through digital platforms.

6MWT is a 6-min walking test for patients, which can well reflect the walking endurance and cardiopulmonary function level of patients. Our NMA found that Robotic Assisted Gait Training (RAGT) was superior to Combined therapy (CT), Tai Chi (TC), Other exercise (OE), Stretch exercise (SE), Walking exercise (WE), Traditional Rehabilitation (TR), Aerobic exercise (AE), Fitness exercise (FE), Baduanjin (BDJ), Boxing exercise (BE), Control group (CON), Balance training (BT), Whole body vibration training (WBV), Dual task training (DTT) in improving 6MWT in PD patients. RAGT intervention is grounded in the theory of central nervous system plasticity and functional reorganization. Repetitive, purposeful weight-bearing walking training can enhance balance, facilitating gait automation and improved step speed (Aprile et al., 2019; Toole et al., 2005). Janssen's study found that enhancing patients' attention through sensory stimulation increased their walking speed in a straight line (Janssen et al., 2017). RAGT provides diverse sensory stimulation and continuous treatment (Mehrholz et al., 2017), promoting comprehensive motor function recovery and increasing motor ability in PD patients. Furthermore, external rhythm can compensate for defective internal rhythm in the basal ganglia, serving as proprioceptive cues (Nieuwboer et al., 2009), This allows for earlier, more targeted balance training, improving balance and subsequently increasing PD patients' motor ability (Capecci et al., 2019). Ongoing robot research optimization, exemplified by the new Lokomat robot integrating weight reduction, platform running, and gait correction, enhances timely feedback and evaluation. This enables patients to simulate normal walking under weight reduction conditions (Zhao et al., 2024). Suspension weight reduction maintains patients' upright posture for balance and reduces walking effort. The WalkBotS robot, supplemented with virtual reality games, achieves direct human-environment interaction. Virtual reality technology provides visual stimulation, better approximating real-life conditions, improving training engagement, and enhancing patient compliance (You et al., 2022). Future research will further explore the effectiveness of this robot-assisted gait training.

Strengths and limitations

This study represents the most comprehensive and systematic comparative meta-analysis of exercise effects on gait in individuals with PD. With a substantial sample size of 68 studies and 3,114 patients, encompassing 29 exercise interventions, it provides direct and indirect comparisons to offer new, comprehensive, evidence-based recommendations. The study holds significant clinical relevance, demonstrating that DE, FAE, and RAGT can markedly improve gait in PD patients. However, it is important to acknowledge potential limitations of network meta-analysis, such as reliance on indirect comparisons and variability in comparator groups. Notably, exercise emerges as an effective non-pharmacological intervention for PD management. Despite these findings, caution is warranted in interpreting the results due to relatively small sample sizes for each intervention, which may influence outcomes. Gait problems in PD

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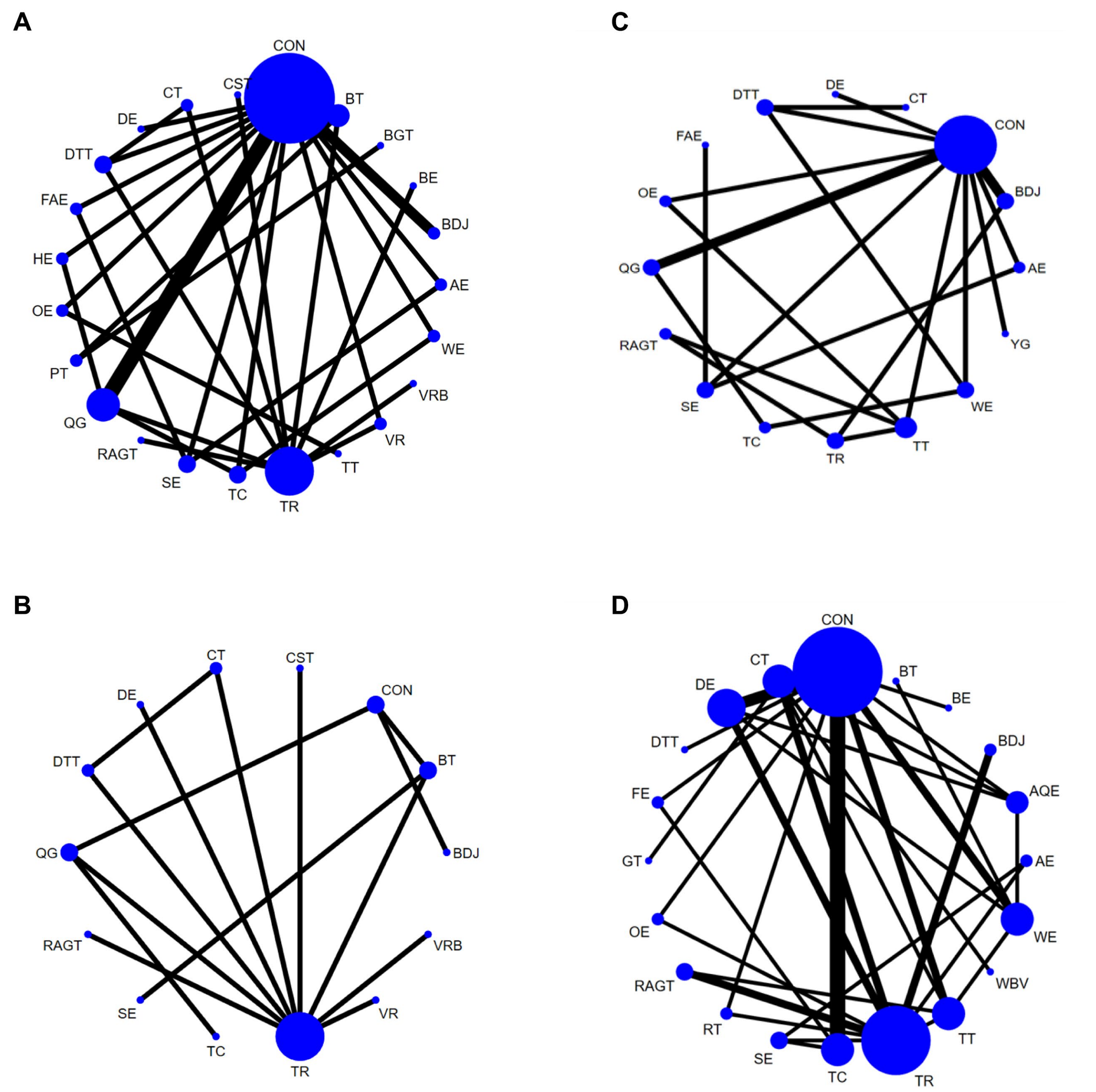

FIGURE 3
Network diagram of Gait velocity **(A)**, Step length **(B)**, Gait velocity **(C)**, and 6MWT **(D)**, in patients with Parkinson's disease. The node size represents the number of times the exercise appears in any comparison about that treatment, and the width of the edge represents the total sample size in the comparison it connects. Aerobic exercise (AE), Aquatic Exercise (AQE), Whole body vibration training (WBV), Virtual reality (VR), Treadmill training (TT), Resistance training (RT), Tai Chi (TC), Power Training (PT), Biofeedback Balance and Gait Training (BGT), Control group (CON), Walking exercise (WE), Dance exercise (DE), Balance training (BT), Game training (GT), Baduanjin (BDJ), Home exercise (HE), Yoga (YG), Boxing exercise (BE), Robotic Assisted Gait Training (RAGT), Combined therapy (CT), Traditional Rehabilitation (TR), Dual task training (DTT), Stretch exercise (SE), Five animal exercises (FAE), Other exercise (OE), Fitness exercise (FE), Qigong (QG), Virtual reality balance training (VRB), Core strength training (CST).

patients worsen with the progression of the disease, and patients have significant individual differences in gait performance (Zhang et al., 2021; Macht et al., 2007). Future studies can focus specifically on each stage of the disease to further reveal the impact of exercise intervention in different disease stages on gait in PD patients. Additionally, natural polyphenols may alleviate bradykinesia, enhance balance and coordination, and reduce turn time in PD patients, possibly due to their anti-striatal oxidative damage properties, inhibition of microglial activation and inflammatory factor secretion, and enhancement of neurotrophic factor expression (Kujawska and Jodynis-Liebert, 2018). Therefore, while focusing on movement interventions for PD patients, it is crucial to consider other factors influencing gait in this population. Previous research has highlighted exercise intensity as a crucial factor influencing exercise effectiveness (Borde et al., 2015; Milanović et al.,

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2015). However, different exercise modalities used different intensity criteria and intervention duration, which are significant limitations. Some studies included in this analysis failed to report exercise intensity and intervention duration. Future studies should prioritize detailed reporting of exercise intensity and intervention duration and a comparative analysis of gait improvement in PD patients at different intensity levels and intervention times. This approach will help determine the optimal exercise intensity to enhance gait function in PD patients.

Conclusion

Our study revealed that DE demonstrated superior efficacy in improving gait speed and step length among PD patients compared to other exercise modalities. Furthermore, FAE and RAGT exhibited greater effectiveness in enhancing step length and 6MWT performance, respectively, in individuals with PD. Overall, exercise interventions show significant benefits in improving gait parameters in PD patients. While exercise demonstrates a substantial impact on ameliorating PD symptoms, further investigation is needed to elucidate the underlying molecular mechanisms and neural circuit connections and regulation. Additionally, our quality evaluation highlighted that many studies lacked blinding procedures and randomized grouping, resulting in generally low certainty of evidence. Consequently, we recommend stricter quality control measures in future research, along with increased sample sizes, to further validate the findings of this study. While our study identifies the best form of exercise, safety is a critical consideration for people with Parkinson's when choosing a form of exercise. To ensure safety, the condition of patients with Parkinson's disease can be comprehensively considered when choosing exercise methods.

A

DE																**2.11 (1.07, 3.15)**						
0.29 (-1.02, 1.60)	FAE									**1.39 (0.48, 2.31)**						**1.86 (0.86, 2.87)**						
0.98 (-0.56, 2.52)	0.69 (-0.70, 2.08)	RAGT																				**1.63 (0.63, 2.63)**
1.13 (-0.22, 2.48)	0.84 (-0.34, 2.01)	0.15 (-1.08, 1.37)	CT	-0.53 (-1.61, 0.54)																		**1.92 (1.07, 2.78)**
1.28 (0.01, 2.55)	0.99 (-0.09, 2.06)	0.30 (-0.87, 1.46)	0.15 (-0.61, 0.92)	DTT												0.12 (-1.17, 1.40)						**1.25 (0.49, 2.00)**
1.39 (0.27, 2.52)	**1.10 (0.20, 2.00)**	0.41 (-0.76, 1.57)	0.26 (-0.64, 1.17)	0.11 (-0.68, 0.90)	QG								0.21 (-0.84, 1.26)			**0.68 (0.15, 1.21)**		**0.94 (0.05, 1.82)**	.			**1.41 (0.47, 2.35)**
1.53 (0.15, 2.92)	**1.24 (0.03, 2.45)**	0.55 (-0.84, 1.94)	0.40 (-0.78, 1.58)	0.25 (-0.84, 1.35)	0.14 (-0.85, 1.13)	PT		0.17 (-0.60, 0.95)			0.20 (-0.64, 1.04)											
1.54 (-0.30, 3.38)	1.24 (-0.47, 2.95)	0.55 (-1.34, 2.45)	0.41 (-1.33, 2.15)	0.26 (-1.42, 1.94)	0.15 (-1.43, 1.72)	0.00 (-1.77, 1.77)	TT													**1.12 (0.06, 2.19)**		
1.71 (0.56, 2.86)	**1.42 (0.48, 2.35)**	0.73 (-0.42, 1.87)	0.58 (-0.31, 1.47)	0.43 (-0.35, 1.20)	0.32 (-0.30, 0.93)	0.17 (-0.60, 0.95)	0.17 (-1.42, 1.76)	BT								0.62 (0.06, 1.19)						0.51 (-0.23, 1.26)
1.69 (0.30, 3.08)	**1.40 (0.18, 2.62)**	0.71 (-0.55, 1.96)	0.56 (-0.47, 1.59)	0.41 (-0.55, 1.37)	0.30 (-0.66, 1.26)	0.16 (-1.06, 1.38)	0.15 (-1.62, 1.93)	-0.02 (-0.96, 0.92)	VRB													**0.93 (0.18, 1.68)**
1.73 (0.44, 3.02)	**1.44 (0.68, 2.20)**	0.75 (-0.62, 2.11)	0.60 (-0.55, 1.75)	0.45 (-0.61, 1.50)	0.34 (-0.54, 1.21)	0.20 (-1.00, 1.39)	0.19 (-1.51, 1.89)	0.02 (-0.89, 0.93)	0.04 (-1.16, 1.24)	SE						0.34 (-0.59, 1.26)			0.67 (-0.26, 1.61)	.		
1.73 (0.11, 3.35)	1.44 (-0.04, 2.91)	0.75 (-0.87, 2.37)	0.60 (-0.85, 2.05)	0.45 (-0.93, 1.83)	0.34 (-0.96, 1.64)	0.20 (-0.64, 1.04)	0.19 (-1.77, 2.15)	0.02 (-1.12, 1.16)	0.04 (-1.44, 1.52)	0.00 (-1.46, 1.46)	BGT											
1.88 (0.69, 3.07)	**1.59 (0.61, 2.56)**	0.90 (-0.26, 2.06)	0.75 (-0.16, 1.66)	0.60 (-0.20, 1.40)	0.49 (-0.18, 1.16)	0.35 (-0.69, 1.38)	0.34 (-1.28, 1.96)	0.17 (-0.51, 0.86)	0.19 (-0.77, 1.15)	0.15 (-0.80, 1.11)	0.15 (-1.18, 1.48)	VR				0.19 (-0.51, 0.89)						**0.78 (0.02, 1.53)**
1.91 (0.70, 3.12)	**1.61 (0.61, 2.62)**	0.92 (-0.35, 2.20)	0.78 (-0.27, 1.82)	0.63 (-0.31, 1.56)	0.52 (-0.15, 1.18)	0.37 (-0.73, 1.47)	0.37 (-1.27, 2.00)	0.20 (-0.58, 0.98)	0.22 (-0.88, 1.31)	0.18 (-0.81, 1.16)	0.18 (-1.21, 1.56)	0.03 (-0.80, 0.86)	TC			-0.08 (-1.00, 0.84)	0.29 (-0.43, 1.01)					
1.99 (0.78, 3.20)	**1.70 (0.69, 2.70)**	1.01 (-0.28, 2.30)	0.86 (-0.20, 1.92)	0.71 (-0.24, 1.66)	0.60 (-0.15, 1.35)	0.46 (-0.65, 1.56)	0.45 (-1.18, 2.09)	0.28 (-0.51, 1.07)	0.30 (-0.81, 1.41)	0.26 (-0.72, 1.24)	0.26 (-1.13, 1.65)	0.11 (-0.73, 0.95)	0.08 (-0.79, 0.96)	BDJ		0.12 (-0.50, 0.73)						
2.14 (0.74, 3.53)	**1.84 (0.62, 3.07)**	1.15 (-0.11, 2.41)	1.01 (-0.04, 2.05)	0.85 (-0.12, 1.82)	0.74 (-0.23, 1.71)	0.60 (-0.62, 1.83)	0.60 (-1.18, 2.38)	0.43 (-0.52, 1.38)	0.45 (-0.63, 1.52)	0.41 (-0.80, 1.61)	0.40 (-1.08, 1.89)	0.26 (-0.71, 1.22)	0.23 (-0.87, 1.33)	0.15 (-0.97, 1.26)	CST							0.48 (-0.28, 1.25)
2.11 (1.07, 3.15)	**1.81 (1.02, 2.61)**	1.12 (-0.01, 2.26)	**0.98 (0.12, 1.84)**	**0.83 (0.10, 1.55)**	**0.71 (0.29, 1.14)**	0.57 (-0.34, 1.49)	0.57 (-0.95, 2.08)	0.40 (-0.09, 0.89)	0.42 (-0.51, 1.34)	0.38 (-0.39, 1.14)	0.38 (-0.87, 1.62)	0.23 (-0.34, 0.80)	0.20 (-0.42, 0.82)	0.12 (-0.50, 0.73)	-0.03 (-0.96, 0.90)	CON	0.00 (-1.00, 1.00)	-0.07 (-1.02, 0.88)	0.34 (-0.60, 1.27)	0.55 (-0.52, 1.63)		
2.16 (0.90, 3.43)	**1.87 (0.80, 2.94)**	1.18 (-0.15, 2.51)	1.03 (-0.07, 2.14)	0.88 (-0.12, 1.89)	0.77 (-0.01, 1.55)	0.63 (-0.53, 1.79)	0.63 (-1.05, 2.30)	0.46 (-0.41, 1.32)	0.47 (-0.68, 1.63)	0.44 (-0.61, 1.48)	0.43 (-1.00, 1.86)	0.28 (-0.62, 1.19)	0.26 (-0.37, 0.88)	0.17 (-0.77, 1.12)	0.03 (-1.14, 1.19)	0.06 (-0.66, 0.77)	WE					
2.19 (0.95, 3.44)	**1.90 (0.85, 2.95)**	1.21 (-0.09, 2.51)	1.06 (-0.01, 2.14)	0.91 (-0.06, 1.89)	**0.80 (0.12, 1.48)**	0.66 (-0.48, 1.80)	0.65 (-1.01, 2.32)	0.48 (-0.35, 1.32)	0.50 (-0.62, 1.63)	0.46 (-0.57, 1.49)	0.46 (-0.95, 1.87)	0.31 (-0.56, 1.19)	0.29 (-0.60, 1.18)	0.20 (-0.72, 1.13)	0.06 (-1.08, 1.19)	0.09 (-0.60, 0.77)	0.03 (-0.94, 1.00)	HE				
2.42 (1.05, 3.80)	**2.13 (1.07, 3.19)**	1.44 (-0.01, 2.88)	**1.29 (0.05, 2.54)**	1.14 (-0.02, 2.29)	**1.03 (0.03, 2.02)**	0.89 (-0.40, 2.17)	0.88 (-0.88, 2.64)	0.71 (-0.31, 1.74)	0.73 (-0.56, 2.02)	0.69 (-0.21, 1.59)	0.69 (-0.84, 2.22)	0.54 (-0.52, 1.60)	0.51 (-0.58, 1.61)	0.43 (-0.66, 1.52)	0.29 (-1.01, 1.58)	0.31 (-0.58, 1.21)	0.26 (-0.89, 1.40)	0.23 (-0.90, 1.36)	AE			
2.66 (1.16, 4.16)	**2.37 (1.03, 3.71)**	**1.68 (0.11, 3.24)**	**1.53 (0.15, 2.91)**	**1.38 (0.08, 2.68)**	**1.27 (0.11, 2.43)**	1.13 (-0.29, 2.54)	**1.12 (0.06, 2.19)**	0.95 (-0.23, 2.14)	0.97 (-0.45, 2.39)	0.93 (-0.39, 2.25)	0.93 (-0.71, 2.57)	0.78 (-0.44, 2.00)	0.75 (-0.49, 2.00)	0.67 (-0.57, 1.91)	0.53 (-0.90, 1.95)	0.55 (-0.52, 1.63)	0.50 (-0.79, 1.79)	0.47 (-0.81, 1.75)	0.24 (-1.16, 1.64)	OE		
2.74 (1.24, 4.23)	**2.44 (1.11, 3.78)**	1.75 (0.39, 3.12)	1.61 (0.44, 2.78)	1.46 (0.35, 2.56)	1.35 (0.24, 2.45)	1.20 (-0.13, 2.54)	1.20 (-0.66, 3.05)	1.03 (-0.06, 2.12)	1.05 (-0.15, 2.24)	1.01 (-0.31, 2.33)	1.01 (-0.57, 2.58)	0.86 (-0.24, 1.96)	0.83 (-0.39, 2.05)	0.75 (-0.49, 1.98)	0.60 (-0.60, 1.80)	0.63 (-0.44, 1.70)	0.57 (-0.70, 1.85)	0.54 (-0.70, 1.79)	0.32 (-1.08, 1.72)	0.08 (-1.44, 1.59)	BE	-0.12 (-1.05, 0.81)
2.62 (1.45, 3.79)	**2.32 (1.37, 3.28)**	1.63 (0.63, 2.63)	1.49 (0.78, 2.20)	1.34 (0.74, 1.94)	1.23 (0.63, 1.82)	1.08 (0.13, 2.04)	1.08 (-0.53, 2.69)	0.91 (0.34, 1.47)	0.93 (0.18, 1.68)	0.89 (-0.05, 1.82)	0.89 (-0.39, 2.16)	0.74 (0.15, 1.33)	0.71 (-0.09, 1.51)	0.63 (-0.19, 1.44)	0.48 (-0.28, 1.25)	0.51 (-0.02, 1.05)	0.45 (-0.42, 1.33)	0.43 (-0.41, 1.26)	0.20 (-0.85, 1.24)	-0.04 (-1.24, 1.16)	-0.12 (-1.05, 0.81)	TR

B

DE											1.35 (-0.12, 2.82)		
0.60 (-1.26, 2.46)	CT		-0.37 (-1.92, 1.17)								1.22 (-0.16, 2.60)		
0.58 (-1.41, 2.57)	-0.02 (-1.78, 1.74)	VRB									0.77 (-0.57, 2.11)		
0.81 (-1.04, 2.66)	0.21 (-0.99, 1.42)	0.23 (-1.52, 1.98)	DTT								0.10 (-1.23, 1.43)		
0.83 (-1.16, 2.83)	0.23 (-1.53, 2.00)	0.25 (-1.65, 2.16)	0.02 (-1.73, 1.78)	CST							0.52 (-0.83, 1.87)		
0.99 (-1.33, 3.31)	0.39 (-1.74, 2.52)	0.41 (-1.83, 2.65)	0.18 (-1.94, 2.29)	0.16 (-2.09, 2.40)	SE	0.08 (-1.28, 1.43)							
1.07 (-0.81, 2.95)	0.47 (-1.17, 2.11)	0.49 (-1.29, 2.27)	0.26 (-1.37, 1.88)	0.24 (-1.55, 2.02)	0.08 (-1.28, 1.43)	BT					0.04 (-1.29, 1.37)	1.31 (-0.14, 2.75)	
1.08 (-0.98, 3.14)	0.48 (-1.36, 2.32)	0.50 (-1.47, 2.47)	0.27 (-1.56, 2.09)	0.24 (-1.73, 2.22)	0.09 (-2.21, 2.39)	0.01 (-1.85, 1.87)	RAGT				0.27 (-1.17, 1.72)		
1.12 (-0.80, 3.04)	0.52 (-1.16, 2.20)	0.54 (-1.28, 2.36)	0.31 (-1.35, 1.97)	0.29 (-1.54, 2.11)	0.13 (-1.83, 2.09)	0.05 (-1.36, 1.47)	0.04 (-1.85, 1.94)	QG		0.27 (-1.26, 1.81)	0.51 (-0.91, 1.93)	0.67 (-0.79, 2.12)	
1.17 (-0.82, 3.17)	0.58 (-1.18, 2.34)	0.59 (-1.30, 2.49)	0.36 (-1.38, 2.11)	0.34 (-1.56, 2.24)	0.18 (-2.05, 2.42)	0.11 (-1.67, 1.89)	0.10 (-1.87, 2.07)	0.05 (-1.77, 1.87)	VR		0.18 (-1.16, 1.52)		
1.40 (-1.06, 3.85)	0.80 (-1.48, 3.07)	0.82 (-1.56, 3.20)	0.58 (-1.68, 2.85)	0.56 (-1.82, 2.95)	0.41 (-2.08, 2.89)	0.33 (-1.76, 2.41)	0.32 (-2.12, 2.76)	0.27 (-1.26, 1.81)	0.22 (-2.16, 2.60)	TC			
1.35 (-0.12, 2.82)	0.75 (-0.39, 1.89)	0.77 (-0.57, 2.11)	0.54 (-0.58, 1.66)	0.52 (-0.83, 1.87)	0.36 (-1.43, 2.15)	0.28 (-0.89, 1.46)	0.27 (-1.17, 1.72)	0.23 (-1.00, 1.46)	0.18 (-1.16, 1.52)	-0.05 (-2.01, 1.92)	TR		
2.08 (0.04, 4.13)	1.48 (-0.33, 3.30)	1.50 (-0.44, 3.45)	1.27 (-0.53, 3.07)	1.25 (-0.70, 3.20)	1.09 (-0.74, 2.93)	1.02 (-0.23, 2.26)	1.01 (-1.01, 3.03)	0.96 (-0.29, 2.21)	0.91 (-1.04, 2.86)	0.69 (-1.29, 2.66)	0.73 (-0.68, 2.15)	CON	0.27 (-1.10, 1.63)
2.35 (-0.11, 4.81)	1.75 (-0.52, 4.03)	1.77 (-0.61, 4.15)	1.54 (-0.73, 3.80)	1.52 (-0.87, 3.90)	1.36 (-0.93, 3.65)	1.28 (-0.57, 3.13)	1.27 (-1.17, 3.71)	1.23 (-0.62, 3.08)	1.18 (-1.20, 3.56)	0.95 (-1.45, 3.36)	1.00 (-0.97, 2.97)	0.27 (-1.10, 1.63)	BDJ

FIGURE 4 (Continued)

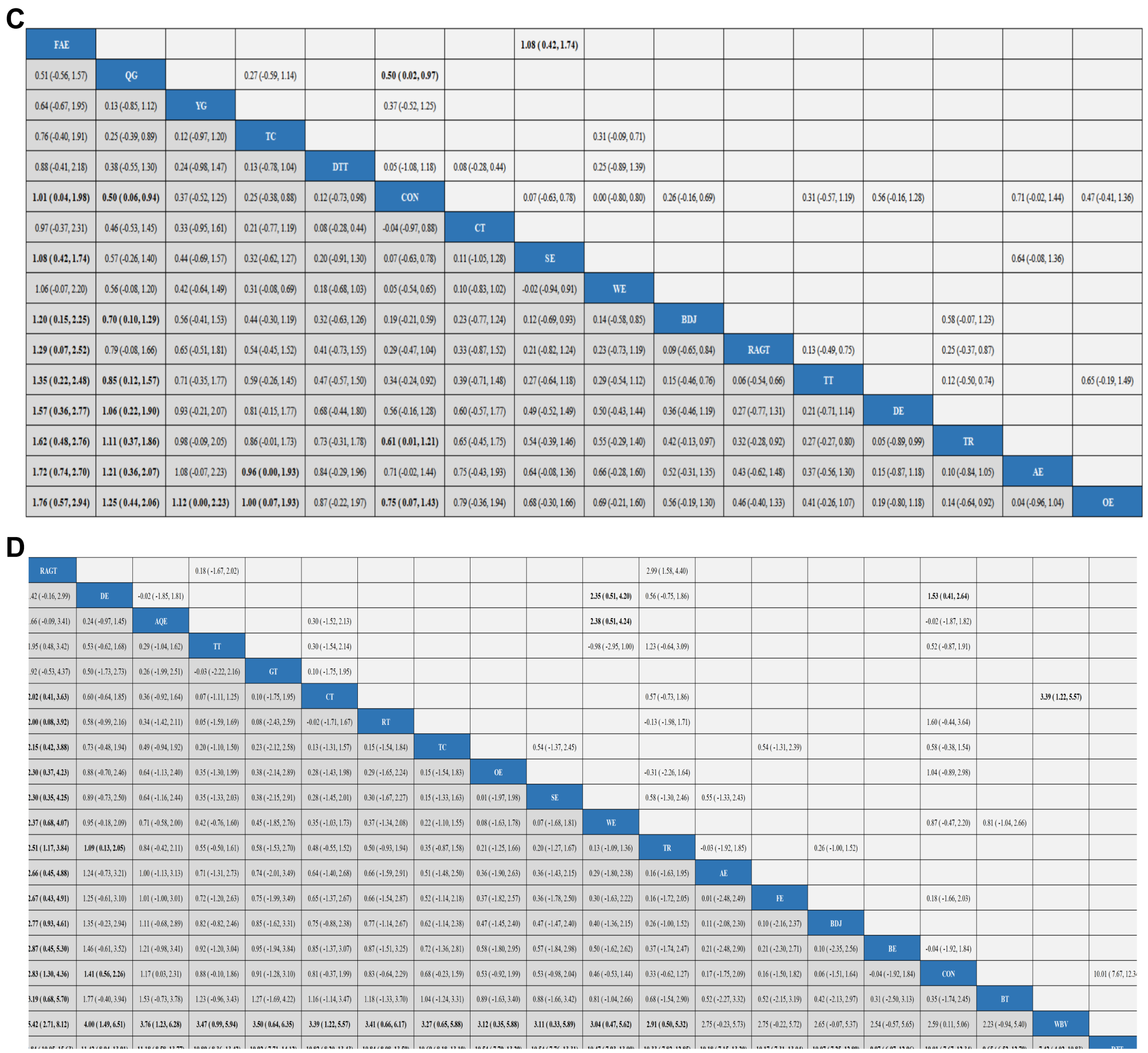

FIGURE 4
Results analysis league chart. Gait velocity **(A)**, Step length **(B)**, Gait velocity **(C)**, and 6MWT **(D)**. The data are the mean difference and 95% confidence interval of continuous data. Aerobic exercise (AE), Aquatic Exercise (AQE), Whole body vibration training (WBV), Virtual reality (VR), Treadmill training (TT), Resistance training (RT), Tai Chi (TC), Power Training (PT), Biofeedback Balance and Gait Training (BGT), Control group (CON), Walking exercise (WE), Dance exercise (DE), Balance training (BT), Game training (GT), Baduanjin (BDJ), Home exercise (HE), Yoga (YG), Boxing exercise (BE), Robotic Assisted Gait Training (RAGT), Combined therapy (CT), Traditional Rehabilitation (TR), Dual task training (DTT), Stretch exercise (SE), Five animal exercises (FAE), Other exercise (OE), Fitness exercise (FE), Qigong (QG), Virtual reality balance training (VRB), Core strength training (CST).

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

YL: Conceptualization, Data curation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. JH: Conceptualization, Resources, Software, Writing – original draft. JW: Methodology, Resources, Software, Writing – original draft. YC: Funding acquisition, Investigation, Methodology, 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

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Glossary

AE - Aerobic exercise

AQE - Aquatic exercise

WBV - Whole body vibration training

VR - Virtual reality

TT - Treadmill training

RT - Resistance training

TC - Tai Chi

PT - Power training

BGT - Biofeedback balance and gait training

CON - Control group

WE - Walking exercise

DE - Dance exercise

BT - Balance training

GT - Game training

BDJ - Baduanjin

HE - Home exercise

YG - Yoga

BE - Boxing exercise

RAGT - Robotic assisted gait training

CT - Combined therapy

TR - Traditional rehabilitation

DTT - Dual task training

SE - Stretch exercise

FAE - Five animal exercises

OE - Other exercise

FE - Fitness exercise

QG - Qigong

VRB - Virtual reality balance training

CST - Core strength training

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EDITED BY
Dimitrios Kikidis,
National and Kapodistrian University of Athens, Greece

REVIEWED BY
Xiang Li,
The First Affiliated Hospital of Ningbo University, China
Zhiqin Xie,
The First Affiliated Hospital of Nanchang University, China
Shuqi Jia,
Shanghai University of Sport, China

*CORRESPONDENCE
Fu Jie Jing
jingfujie@126.com

†These authors have contributed equally to this work and share first authorship

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Burden of falls in China, 1992–2021 and projections to 2030: a systematic analysis for the global burden of disease study 2021

Liang Sui†, Yueming Lv†, Kai Xin Feng and Fu Jie Jing*

School of Acupuncture-Tuina, Shandong University of Traditional Chinese Medicine, Jinan, Shandong, China

Background: The escalating burden of falls in China necessitates a detailed examination to elucidate its dynamics and trends. Using data from the Global Burden of Disease Study (GBD) 2021, this research assessed the burden of falls in China.

Methods: Data from GBD 2021 were analyzed using Joinpoint regression to identify long-term trends. The impact of mortality and disability-adjusted life years (DALYs) rate for falls was investigated through the age-period-cohort model. Additionally, a decomposition analysis was performed to ascertain the distinct impacts of population growth, aging, and epidemiological changes on the burden of falls from 1992 to 2021. Furthermore, this study employed both the BAPC and Nordpred models to project future burdens of falls.

Results: From 1992 to 2021 in China, the age-standardized rates of falls showed divergent trends. Prevalence and incidence rates increased, while mortality rates generally decreased. Males consistently exhibited higher rates than females. The rates of prevalence, incidence, and mortality exhibit a sharp increase beyond the age of 75 in 2021. Decomposition analysis identified aging as the primary driver of increased prevalence and mortality, particularly in females. Joinpoint regression analysis revealed fluctuating trends in prevalence and incidence with periods of increase and decline, and a general decrease in mortality except during brief intervals. DALYs and years of life lost (YLLs) rates generally decreased, with intervals of stabilization and minor increases, while years lived with disability (YLDs) showed significant fluctuations. By 2030, the projected DALYs rate for falls is expected to rise to approximately 547.4 per 100,000. Fractures of the lower extremity predominated as the leading cause of disability post-fall, with hip fractures increasingly contributing to disability among the older adult. Additionally, from 1992 to 2021, the population attributable fraction (PAF) of low bone mineral density for DALYs due to falls increased to 23.2%, with the PAF reaching 33.3% among women in 2021.

Conclusion: Falls continue to significantly burden public health in China. Our findings highlight the urgent need to develop targeted prevention and intervention strategies that cater to the country's unique demographic characteristics, aiming to mitigate the growing public health impact of falls.

KEYWORDS

falls, epidemiology, global burden of disease study, gender disparities, China

1 Introduction

The World Health Organization characterizes falls as incidents that unintentionally bring a person to the ground, floor, or a lower level, and they rank as the second leading cause of accidental death worldwide (1, 2). Falls rank among the most frequent injury mechanisms and consistently present a threat to health and longevity across various age groups. In younger, otherwise healthy individuals, falls can result in lifelong disabilities, including spinal cord damage or traumatic brain injuries, and often result in critical injuries that necessitate sophisticated surgical treatments, such as complex bone fractures or repair of intra-abdominal organ injuries (3). In older adults, the adverse effects of falls are often intensified by concurrent conditions such as reduced bone density, osteoporosis, or the administration of antiplatelet or anticoagulant therapies (4, 5). Falls represent a significant global public health challenge, heavily impacting health and medical care costs (6). Annually, an estimated 37.3 million severe falls occur worldwide, resulting in approximately 17 million disabling injuries and 684,000 fatalities due to falls, with over 80% of these incidents taking place in low- to middle-income countries (1).

Falls pose a significant threat to the health and well-being of people in China. In 2019, around 9.76 million severe falls were recorded among individuals aged 60 and older, leading to a cumulative loss exceeding 3.18 million disability-adjusted life years (DALYs) (7). This number is expected to rise as the population continues to age. National statistics indicate that around 40 million older adult individuals in China experience at least one fall annually, with direct medical costs exceeding 5 billion yuan each year (8). Despite the growing burden, research on falls among the population in China remains limited, although existing studies highlight the substantial health and economic impact of falls (1, 7, 9).

This study aims to comprehensively analyze the burden and trends of falls in China from 1992 to 2021. Specifically, we seek to examine the changes in the burden of falls over the past three decades. Analyze the 2021 data to identify which age and gender groups are most vulnerable. Apply joinpoint regression to assess trends and perform a decomposition analysis to explore contributing factors. Investigate the nature of injuries caused by falls to understand the specific health impacts. Conduct age-period-cohort analyses to understand temporal and generational shifts in fall-related mortality and DALYs rates. Project future trends up to 2030. Investigate associated risk factors to identify potential areas for intervention. By addressing these objectives, this study will provide critical insights into the epidemiology of falls in China, supporting targeted prevention and intervention efforts to mitigate this growing public health concern.

2 Methods

2.1 Data source

The study utilized data from the Global Burden of Disease (GBD) 2021 study, providing comprehensive health metrics categorized by sex, age, and region, updated annually through international cooperation. The report details 88 risk factors, 371 diseases, and 288 causes of death and injuries across 204 nations (10). Extensive methodological details of the GBD 2021 study have been described in prior research (10, 11). In China, primary data were derived from censuses, Disease Surveillance Points, population surveys, and the Chinese CDC's Cause of Death Reporting System, and systematic reviews assessing disease incidence and prevalence (12). Data regarding the incidence, prevalence, mortality, and DALYs, including years lived with disability (YLDs) and years of life lost (YLLs), and their age-standardized rates (ASRs) for falls were sourced from the Global Health Data Exchange (https://vizhub.healthdata.org/gbd-results/). Concept Definition and Retrieval Strategy related to disease burden in this study can be found in the Supplementary material.

2.2 Join-point

Long-term trends in the burden of falls, were analyzed by assessing average annual percent changes (AAPC) with 95% confidence intervals (CIs) using a joinpoint regression model (version 5.2.0; National Cancer Institute, USA). This model divides the time series into distinct segments and detects significant trends within each segment (13, 14). The AAPC is calculated by weighting the regression coefficients from each segment's annual percent changes. A positive AAPC, with a 95% CI that does not include zero, suggests an increasing age-standardized rate (ASR). Conversely, a negative AAPC, with a 95% CI that remains below zero, indicates a declining ASR.

2.3 Decomposition analysis

To clarify the key factors driving changes in the burden of falls from 1992 to 2021, a decomposition analysis was utilized. This method aimed to assess the distinct impacts of epidemiological shifts, aging and population growth (15, 16). The analysis involved estimating the impact of each factor while holding the other two constant.

2.4 Age-period-cohort modeling analysis

In this analysis, the age-period-cohort (APC) model was employed to investigate the impact of age, time period, and birth cohort on the burden of falls in China. For this purpose, data on mortality and DALYs from falls were organized across continuous five-year intervals from 1992 to 2021. The APC model utilized a log-linear approach to model the rates, incorporating additive effects from birth cohorts, calendar periods, and age. In the model, age effects illustrate variance in risk across age groups; period effects capture uniform temporal shifts affecting all groups; and cohort effects reflect risk variations among peers born during the same timeframe (17–19). We designated the median birth cohort, period group, and age group as reference categories, choosing the lower median when categories were even in number (20). The R package from the Biostatistics Branch of the NIH, USA, was used for modeling and deriving estimable functions (20).

2.5 BAPC model projection

This study utilized the Bayesian age-period-cohort (BAPC) model, an extension of the conventional generalized linear model that integrates Bayesian principles for dynamic age, period, and cohort analysis (21). We performed the BAPC model using the BAPC package (version 0.0.36) in R (version 4.4.2, available at http://www.r-project.org). The widespread verification and use of the BAPC model in epidemiological studies, particularly those examining age-structured populations with complex cohort dynamics underscore its efficacy (22).

2.6 Nordpred model projection

The Nordpred model, which builds on the APC framework, accurately projects future burdens for diseases or injuries by analyzing trends and demographic shifts, including population structure changes and generational impacts (23). For this analysis, we used the Nordpred APC model, implemented through the nordpred package (version 1.1), to estimate DALYs associated with falls from 2022 to 2030.

3 Results

3.1 Trends in the burden of falls in China from 1992 to 2021

In 2021, China experienced a substantial burden of falls, with a total prevalence of 111,705,688 cases, marking a 104.24% increase since 1992. The prevalence was more pronounced in men, accounting for 62,270,730 cases, compared to 49,434,958 cases in women. The incidence of falls stood at 39,776,772 cases for the year, a 59.25% rise from 1992, with women reporting 17,546,171 cases versus 22,230,601 cases in men. Regarding deaths, there were 141,657 fatalities due to falls, an 88.07% increase from 1992. Men accounted for 85,053 deaths and women for 56,604. DALYs for falls totaled 8,301,289, an increase of 39.7% over the past three decades, split between 5,106,057 for men and 3,195,232 for women. YLDs due to falls were reported at 4,821,165 person-years, up by 89.63% since 1992, with women contributing 2,202,854 person-years and men 2,618,310 person-years. YLLs from falls reached 3,480,124, showing a modest increase of 2.36%, where men had 2,487,747 and women accounted for 992,377 person-years.

The prevalence rate of falls per 100,000 population was 7,851.41, an increase of 73.16% since 1992. Men had a higher prevalence rate of 8552.46 per 100,000, while women registered a rate of 7116.6 per 100,000. The incidence rate stood at 2795.77 per 100,000 population, up by 35.02% from 1992, with women showing a rate of 2525.93 per 100,000 compared to men's 3053.22 per 100,000. The mortality rate was 9.96 per 100,000 in 2021, a 59.45% rise since 1992, with men displaying a higher rate of 11.68 per 100,000 than women's 8.15 per 100,000. The DALYs rate stood at 583.47 per 100,000, up by 18.44% from 1992, with rates for women and men at 459.98 and 701.28 per 100,000, respectively. The YLDs rate was 338.86 per 100,000 in 2021, a 60.77% rise since 1992, with men displaying a higher rate of 359.61 per 100,000 than women's 317.12 per 100,000. The YLLs rate was 244.61 per 100,000, decreasing by 13.21% over the years, with women and men showing rates of 142.86 and 341.67 per 100,000, respectively. Between 1992 and 2021, falls in China showed a declining trend in the ASRs for DALYs, YLLs and deaths. In contrast, the ASRs for prevalence, incidence, and YLDs exhibited an increasing trend during the same period. The gender-specific data summarized in Table 1 reveal a higher disease burden in males compared to females.

Figure 1 displays sex-specific, all-age numbers and age-standardized rates for falls in terms of prevalence, incidence, and mortality throughout China from 1992 to 2021. The data indicate an upward trend in the numbers of cases, incidences, and deaths due to falls, although these figures have fluctuated over the years. While there has been a general increase in prevalence and incidence rates across sexes, mortality rates have shown a declining trend during this period. Males consistently demonstrated higher age-standardized rates across all metrics compared to females. Further details on falls-related DALYs, YLDs, and YLLs are provided in Supplementary Figures 1A–C.

3.2 Disease burden of falls in China in 2021 by age and gender

Figure 2 illustrates the numbers of prevalence, incidence, and mortality (panels A, C, E) along with their respective rates (panels B, D, F) for falls across various age groups in 2021. In China, the total number of falls across different age groups initially increased and then decreased, with the highest number observed in the 50 to 74 years age group for both males and females. Regarding the total number of fall incidents, the figures remained relatively consistent across age groups, with most showing fewer than one million cases, particularly for females. For males, the number of incidents initially increased and then decreased, with the highest number seen in the 25 to 39 years age group. When it comes to falls-related mortality, there was a clear increasing trend, with the highest number of fatalities observed in the 80 to 89 years age group for both males and females. Notably, the rates of prevalence, incidence, and mortality exhibit a sharp increase beyond the age of 75.

The rates and numbers of DALYs, YLDs, and YLLs, segmented by sex and age group, are detailed in Supplementary Figure 2. In terms of DALYs due to falls, the total count showed an increasing trend, peaking in the 65 to 89 years age group, particularly among females. For males, the DALYs count initially increased and then decreased, with the highest number observed in the 45 to 59 years age group. The total YLLs due to falls followed a U-shaped curve, with a small peak in the under-9 years age group and the highest number of YLLs in the 75 to 94 years age group for females. In males, the YLLs count also followed a U-shaped pattern, with a small peak in the under-9 years age group and the highest YLLs count in the 30 to 59 years age group. The YLDs due to falls showed an initial increase followed by a decrease, with the highest number of YLDs observed in the 50 to 74 years age group for both males and females. Notably, the rates of DALYs, YLDs, and YLLs exhibit a sharp increase beyond the age of 75.

3.3 Trajectories in disease burden of falls in China based on joinpoint regression analysis

Figure 3 presents the joinpoint regression analyses of the ASRs for prevalence, incidence, and mortality of falls in China from 1992 to

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TABLE 1 Description analysis of burden of falls from 1992 to 2021.

Measure	Sex	All-ages number in thousands, 2021, n (95% UI)	All-ages cases changes, 1992–2021, (%)	All-ages rates per 100,000 people, 2021 (95% UI)	All-ages rates changes, 1992–2021 (%)	Age-standardized rates per 100,000 people, 2021 (95% UI)	Age-standardized rates changes, 1992–2021 (%)
Incidence	Male	22230.60 (20003.94, 24750.45)	48.08	3053.22 (2747.4, 3399.3)	26.75	3072.97 (2746.55, 3449.05)	28.69
	Female	17546.17 (15756.64, 19615.75)	76.08	2525.93 (2268.31, 2823.86)	47.78	2361.39 (2097.99, 2683.72)	32.99
	Both	39776.77 (35757.32, 44260.73)	59.25	2795.77 (2513.26, 3110.94)	35.02	2748.04 (2453.03, 3101.97)	30.52
Prevalence	Male	62270.73 (53807.96, 71043.15)	91.91	8552.46 (7390.15, 9757.29)	64.27	6873.49 (5967.58, 7846.62)	19.36
	Female	49434.96 (43200.79, 56518.55)	122.23	7116.6 (6219.14, 8136.35)	86.52	5282.18 (4612.16, 6036.15)	23.11
	Both	111705.69 (97251.67, 127663.20)	104.24	7851.41 (6835.49, 8973.01)	73.16	6116.41 (5325.81, 6972.99)	20.67
Deaths	Male	85.05 (53.14, 114.96)	68.91	11.68 (7.3, 15.79)	44.58	11.52 (7.25, 15.32)	−8.73
	Female	56.60 (31.91, 77.66)	126.7	8.15 (4.59, 11.18)	90.27	6.06 (3.45, 8.3)	−16.81
	Both	141.66 (91.10, 183.32)	88.07	9.96 (6.4, 12.89)	59.45	8.64 (5.54, 11.09)	−12.74
YLLs	Male	2487.75 (1648.55, 3307.33)	2.5	341.67 (226.42, 454.24)	−12.27	319.93 (216.49, 419.19)	−26.61
	Female	992.38 (574.99, 1350.11)	2.03	142.86 (82.78, 194.36)	−14.37	118.77 (70.3, 159.44)	−42.39
	Both	3480.12 (2344.16, 4493.21)	2.36	244.61 (164.76, 315.81)	−13.21	220.29 (149.56, 281)	−31.99
YLDs	Male	2618.31 (1814.22, 3584.31)	79.09	359.61 (249.17, 492.28)	53.3	286.63 (197.21, 394.46)	9.28
	Female	2202.85 (1493.64, 3017.62)	103.88	317.12 (215.02, 434.41)	71.12	231.86 (156.9, 318.91)	8.58
	Both	4821.16 (3291.15, 6625.63)	89.63	338.86 (231.32, 465.69)	60.77	261.52 (178.01, 360.3)	8.57
DALYs	Male	5106.06 (3981.54, 6439.55)	31.29	701.28 (546.84, 884.43)	12.38	606.56 (476, 759.7)	−13.13
	Female	3195.23 (2431.12, 4129.62)	55.63	459.98 (349.98, 594.5)	30.62	350.63 (267.7, 446.33)	−16.45
	Both	8301.29 (6363.99, 10467.99)	39.7	583.47 (447.3, 735.76)	18.44	481.81 (374.1, 600.84)	−14.69

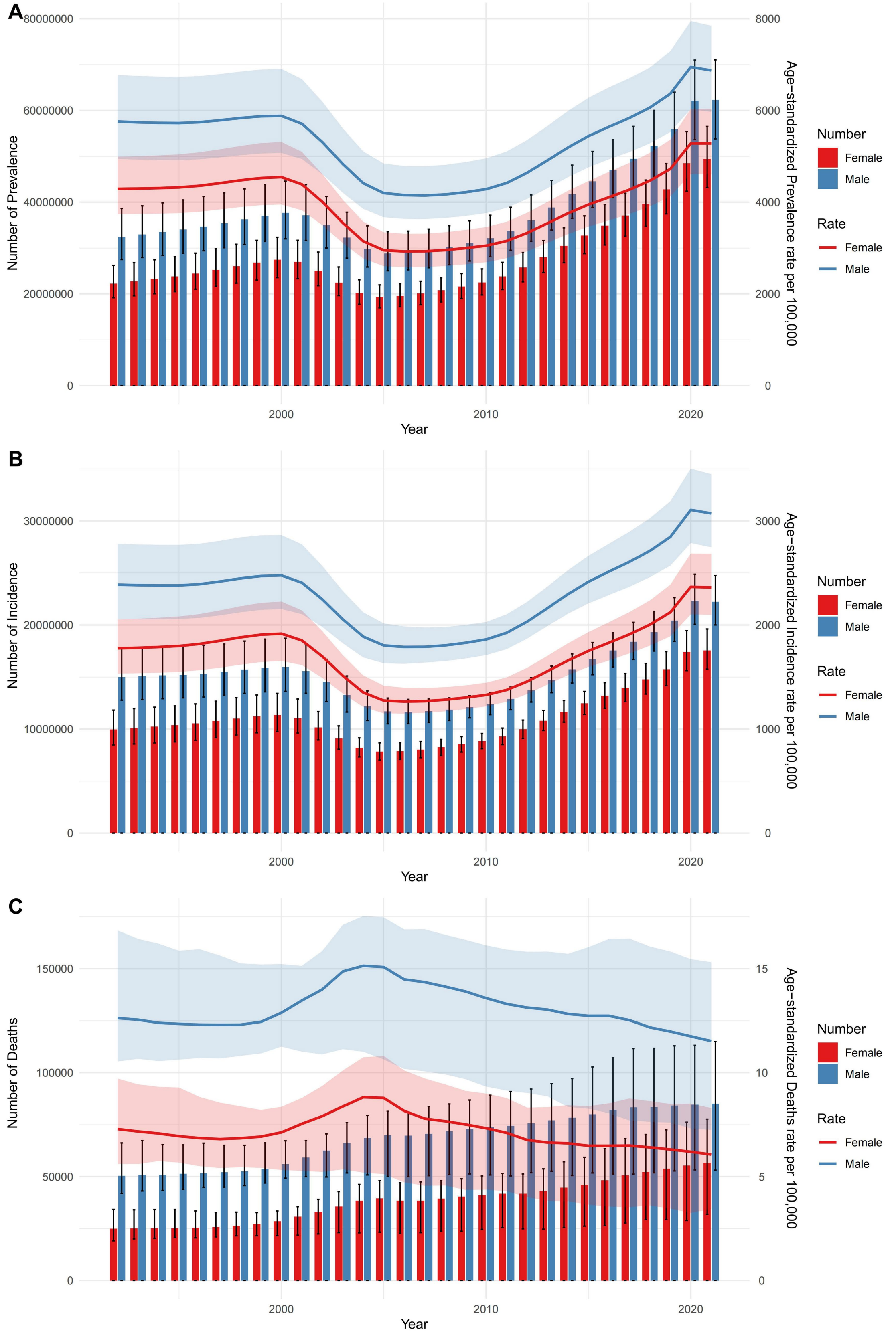

FIGURE 1
Trajectories of the age-standardized rates and all-age numbers of prevalence, incidence, and mortality due to falls by sex from 1992 to 2021. **(A)** Prevalence. **(B)** Incidence. **(C)** Deaths.

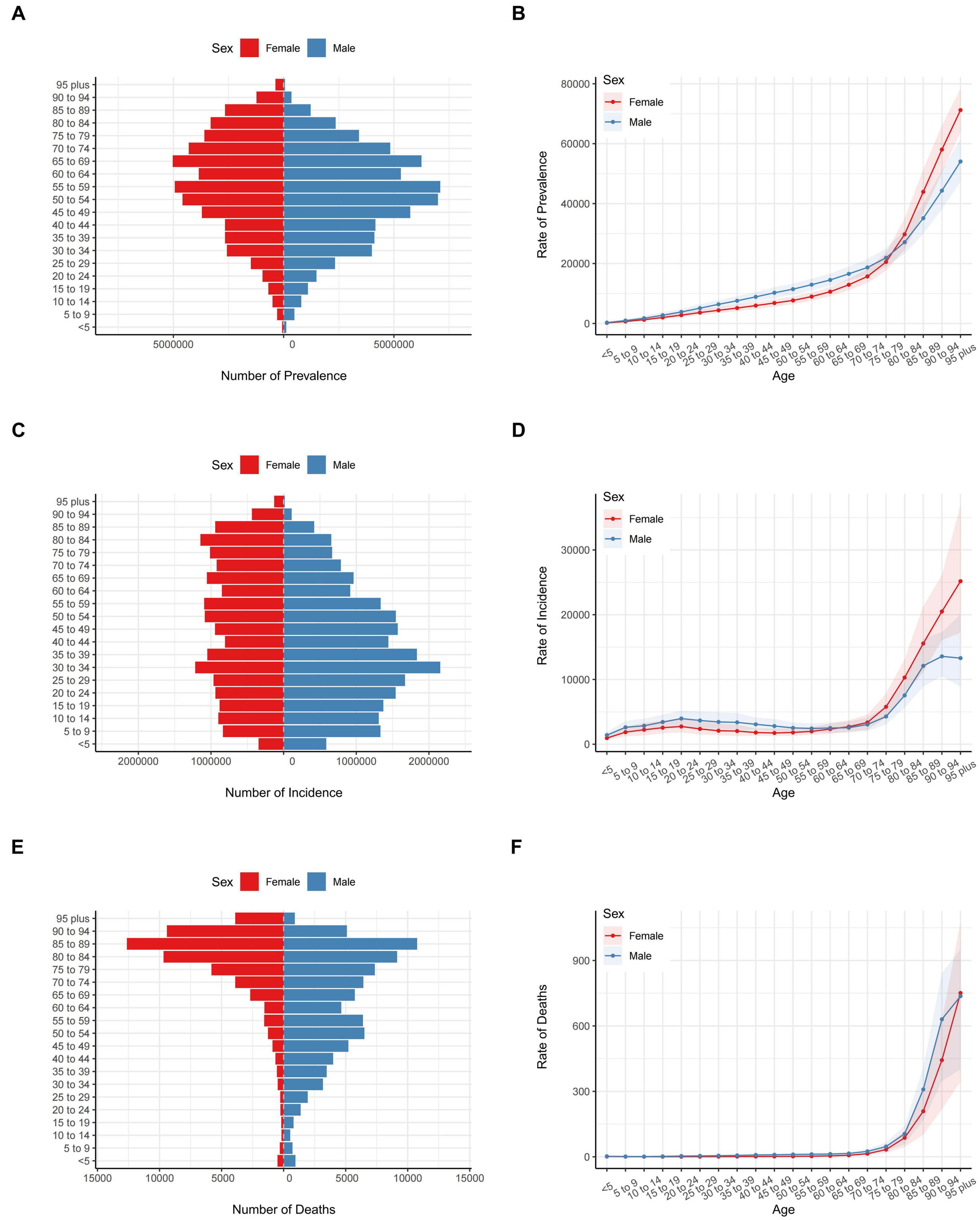

FIGURE 2
Numbers and rates of prevalence, incidence, and mortality due to falls among different age groups in China in 2021. **(A)** Number of prevalence. **(B)** Rate of prevalence. **(C)** Number of incidence. **(D)** Rate of incidence. **(E)** Number of deaths. **(F)** Rate of deaths.

2021. We observed that from 1992 to 2001, the prevalence exhibited a slight increasing trend (APC = +0.27). From 2001 to 2005, there was a significant decline in prevalence (APC = −9.18). The prevalence then showed a slight increase from 2005 to 2010 (APC = +0.8), followed by a significant rise from 2010 to 2021 (APC = +4.92). The trends in incidence rates were similar to those in prevalence. Regarding mortality rates, there was a decreasing trend from 1992 to 1996 (APC = −1.15), a slight increase from 1996 to 1999 (APC = +0.12), and a significant increase from 1999 to 2004 (APC = +4.55). From 2004 to 2021, the mortality rates continuously

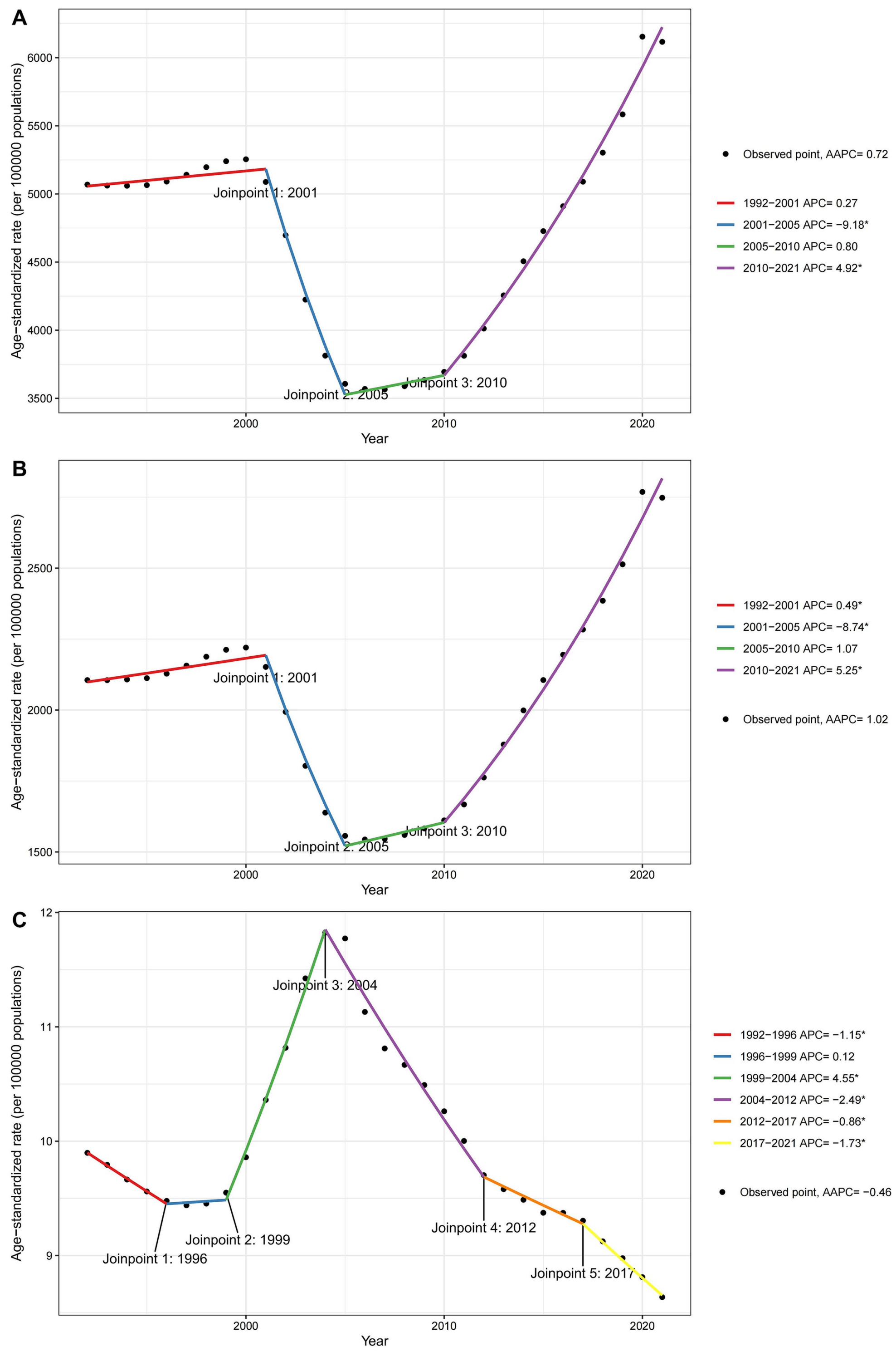

FIGURE 3
Joinpoint regression analysis of ASRs for falls in China over the period 1992 to 2021. **(A)** Prevalence, **(B)** Incidence, and **(C)** Mortality.

declined (APC = −2.49 from 2004 to 2012, APC = −0.86 from 2012 to 2017, and APC = −1.73 from 2017 to 2021). Supplementary Figure 3 presents joinpoint regression analyses of ASRs for incidence, prevalence, and mortality across both sexes from 1992 to 2021. The analysis reveals consistent trends in these rates across both genders over the observed period.

Joinpoint regression analyses of the ASRs for DALYs, YLLs, and YLDs of falls in China from 1992 to 2021 are depicted in Figure 4. For DALYs, a steady decrease is observed from 1992 to 1996 (APC = −0.80), followed by a stable phase from 1996 to 2001 (APC = +0.11). From 2001 to 2007, DALYs declined significantly (APC = −3.27), stabilizing slightly from 2007 to 2012 (APC = −0.83), before increasing again significantly

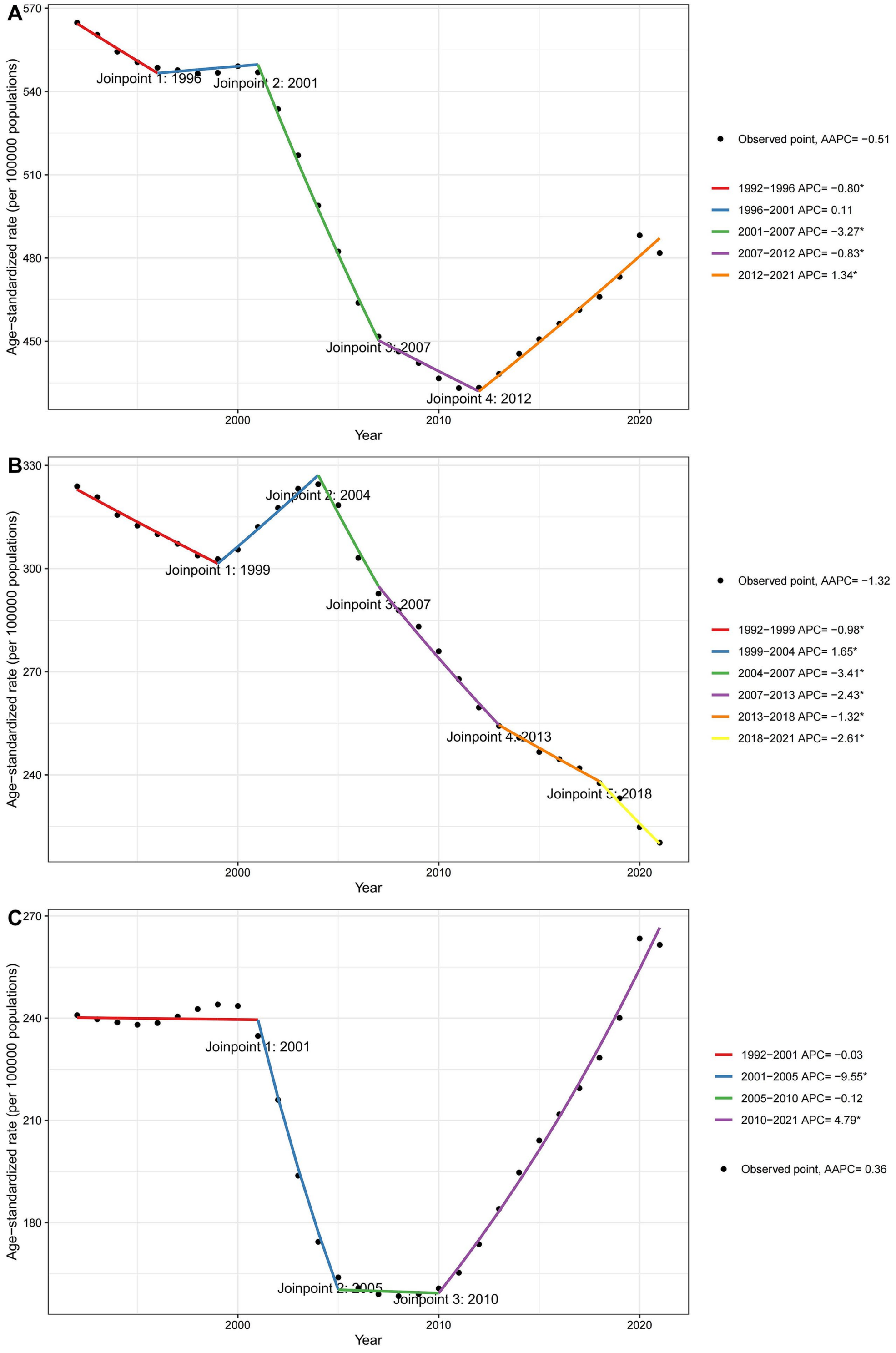

FIGURE 4
Joinpoint regression analysis of ASRs for falls in China over the period 1992 to 2021. **(A)** DALYs, **(B)** YLLs, and **(C)** YLDs.

from 2012 to 2021 (APC = +1.34). In Figure 4B for YLLs, the rate initially decreased from 1992 to 1999 (APC = −0.98), followed by a period of increase from 1999 to 2004 (APC = +1.65). From 2004 to 2021, the rates consistently decreased (APC = −3.41 from 2004 to 2007, APC = −2.43 from 2007 to 2013, and APC = −1.32 from 2013 to 2018). Subsequently, from 2018 to 2021, the rates experienced a significant decline (APC = −2.61). Figure 4C shows the trends for YLDs where the rates remained relatively stable from 1992 to 2001 (APC = −0.03). A significant decrease is noted from 2001 to 2005 (APC = −9.55), followed by a slight decrease from 2005 to 2010 (APC = −0.12). From 2010 to 2021, the YLDs exhibited a continuous increase (APC = +4.79). Supplementary Figure 4 presents joinpoint regression analyses of ASRs for DALYs, YLLs, and

YLDs in both sexes from 1992 to 2021. The analysis reveals consistent trends in these rates across both genders over the observed period.

3.4 Nature of injuries caused by falls

Figure 5 presents the age-specific distribution of injury types resulting from falls in China. The figure indicates that fractures of the patella, tibia, fibula, or ankle are the predominant reasons for disability due to falls across all age groups. Nevertheless, fractures of the hip increasingly contribute to disability among the older adult.

3.5 Decomposition analysis

Decomposition analysis of changes in fall prevalence over the past 30 years identified aging as the primary driver for the increase in cases, with a higher contribution observed in females (52.12%) compared to males (50.17%). Specifically, aging accounted for 52.12% (approximately 14,172,749 cases) of the total changes in prevalent cases among women and 50.17% (approximately 14,960,912 cases) among men. Epidemiological changes were the second largest contributing factor, with males (26.09%) showing a higher contribution than females (25.90%). Additionally, population growth contributed positively, accounting for 23.75% (approximately 7,082,161 cases) in men and 21.98% (approximately 5,975,713 cases) in women (Figure 6).

As per the decomposition analysis, aging was the primary positive driver for the increase in mortality numbers, contributing more significantly in females than in males (101.22% vs. 96.36%). Specifically, 101.22% (approximately 32,023.37 cases) of the total change in mortality among women and 96.36% (approximately 33,438.36 cases) among men were attributed to aging. Another important positive driver was population growth, which had a higher contribution in males compared to females (29.62% vs. 21.89%). Regarding mortality rate changes (i.e., epidemiological changes), negative contributions were observed in both sexes: −25.98% (approximately −9,014.87 cases) in males and − 23.11% (approximately −7,312.49 cases) in females (Figure 6).

3.6 Age−period−cohort analysis for falls mortality and DALYs rates in China

Figure 7 and Supplementary Tables present the estimated age, period, and cohort effects for falls mortality and DALYs rates. The age effects demonstrate a linear increase, peaking in later years for both mortality and DALYs rates. From 1992 to 2021, the period effects for falls mortality—overall, and specifically for both males and females—are favorable. In contrast, the DALYs rates for falls exhibit an unfavorable period effect from 1990 to 2019. Notably, however, both male and female period effects displayed favorable trends during 2007–2016. The cohort effects for mortality and DALYs rates reveal overall fluctuating downward trends throughout the period from 1992 to 2021.

3.7 Projections of falls DALYs rates and number for the next 9 years

Figure 8 and Supplementary Tables depict the ASRs for DALYs of falls in China from 1992 to 2030, as predicted by the BAPC model. The overall age-standardized rate declines to its lowest point in 2012, followed by a steady increase, reaching an estimated 547.4 per 100,000 people by 2030. For females, the age-standardized DALYs rate follows

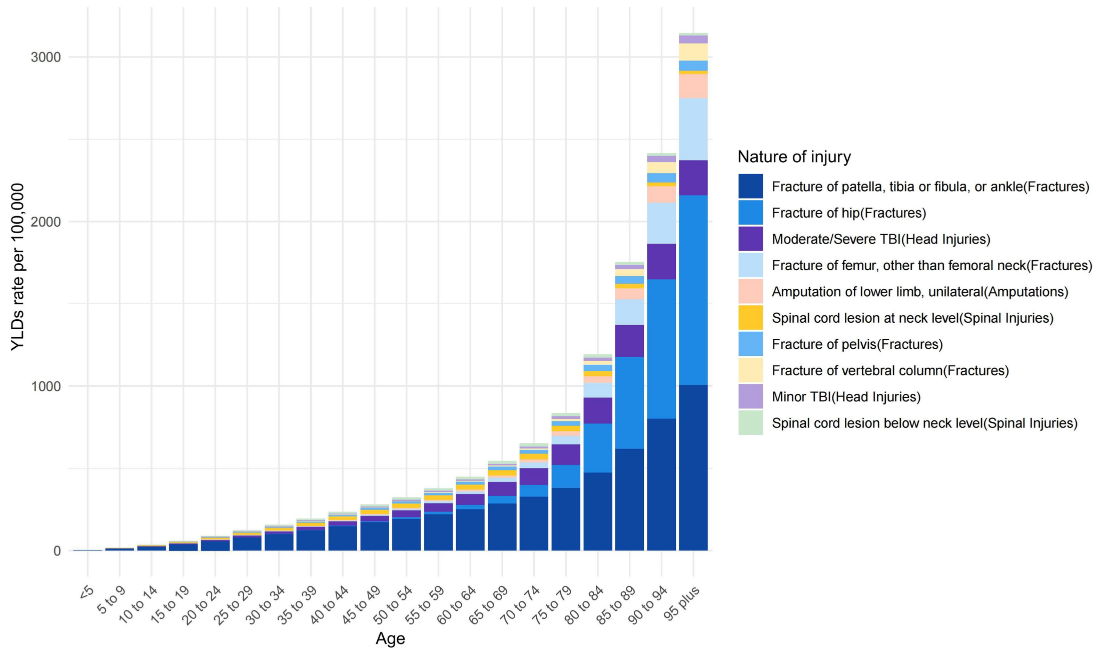

FIGURE 5
Age-specific nature-of-injury composition of falls in China.

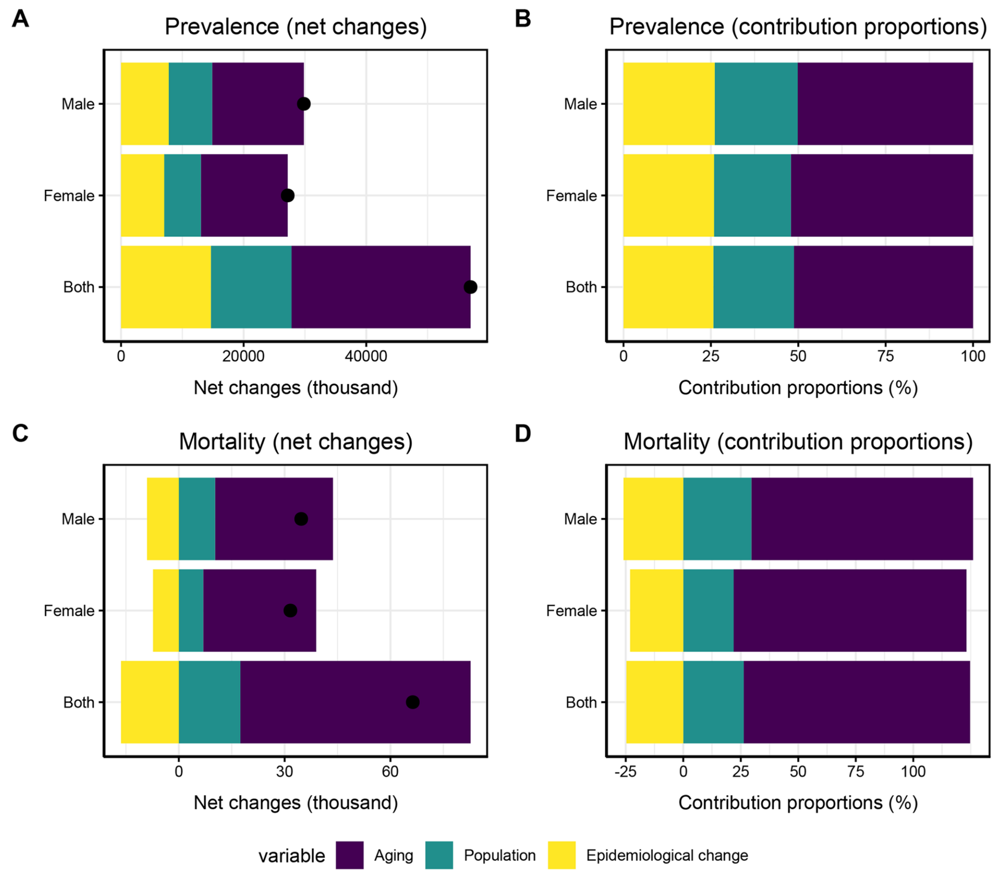

FIGURE 6
Decomposition analysis of Falls in China from 1992 to 2021. **(A)** Changes in Falls prevalence. **(B)** Proportion of the population-level determinants attributed to changes in Falls prevalence. **(C)** Changes in Falls mortality. **(D)** Proportion of the population-level determinants attributed to changes in Falls mortality.

a 'U-shaped' pattern, initially decreasing before rising again, with projections indicating a rate of approximately 447.1 per 100,000 people by 2030. In males, a similar trend is observed, with the rate expected to increase to about 617.0 per 100,000 by 2030. The total number of falls-related DALYs is projected to continue rising, peaking at approximately 11,872,183 by 2030. This upward trajectory is mirrored in the gender-specific analysis, with female and male DALYs expected to peak at about 5,602,737 and 6,269,447, respectively.

We used nordpred model to predict the future burden of falls-related DALYs in China as a sensitivity analysis. The results indicate a continuous increase in the ASRs for DALYs of falls from 2022 to 2030 (Figure 9 and Supplementary Tables). By 2030, the rate is projected to reach approximately 544.3 per 100,000 population, with the total number of falls-related DALYs rising to about 11,239,568. For females, the number of falls DALYs is expected to increase, potentially reaching 4,830,858 by 2030. Similarly, the male falls DALYs burden is also projected to rise, reaching approximately 6,408,710 by 2030.

3.8 Trends of associated risk factors of falls from 1992 to 2021

In China, the population attributable fraction (PAF) for low bone mineral density (LBMD) related to DALYs from falls increased steadily from 18.4% in 1992 to 23.2% by 2021 (Figure 10). Conversely, the PAF for occupational injuries exhibited a consistent decline over the same period, from 34.2 to 15.3%. The contributions of alcohol use and smoking to DALYs remained relatively stable and minor, each accounting for less than 5 % throughout the study period. Specifically, in 2021, the PAF for LBMD contributing to DALYs from falls was 33.3% among women, while for occupational injuries it was 18.0% among men.

3.9 Comparative analysis of the burden of falls globally, in the United States of America, India, and China from 1992 to 2021

Figure 11 shows the ASRs of fall burden globally, as well as in the United States of America, India, and China, from 1992 to 2021. During the study period, India consistently exhibited the highest DALYs rates due to falls, remaining above 900 per 100,000 in most years. The global DALYs rates gradually decreased from approximately 640 per 100,000 to 531 per 100,000. China's DALYs burden remained slightly below the global average, while the United States had the lowest DALYs burden, starting at around 425

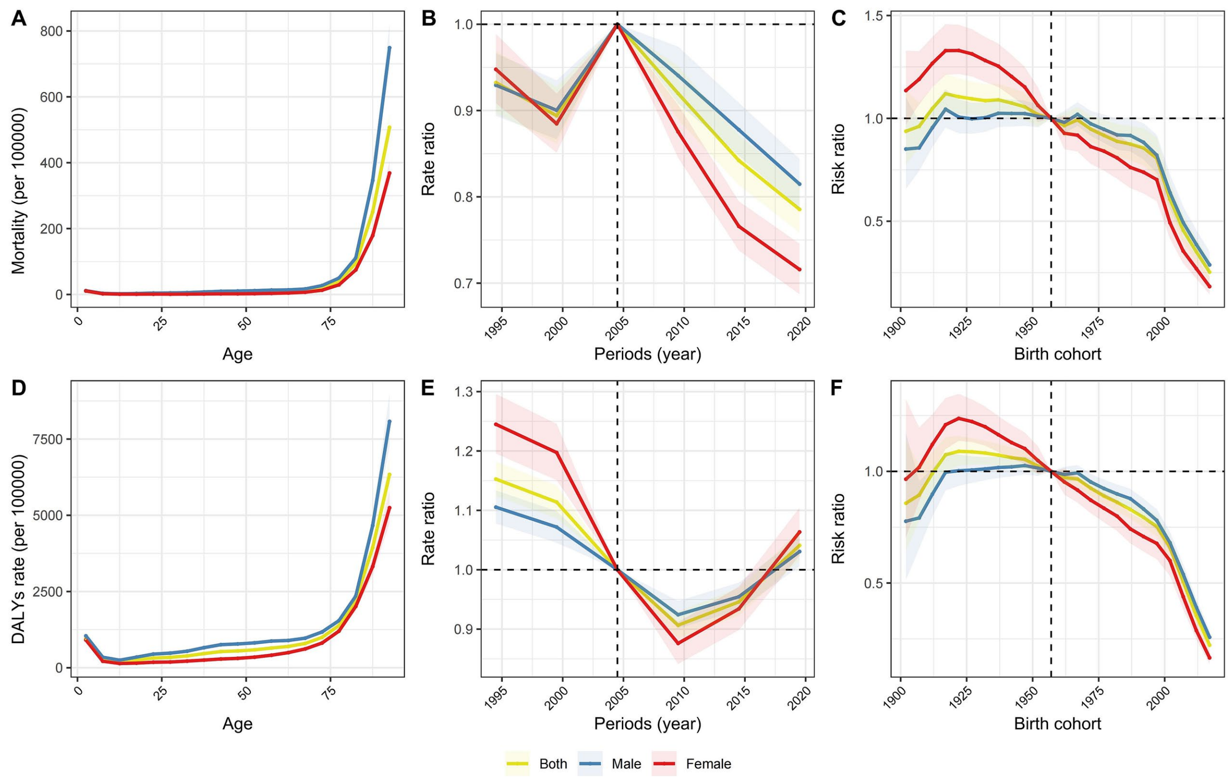

FIGURE 7
Age, period and cohort effects on falls mortality and DALY rates in China. **(A)** The age curves of falls mortality by gender. **(B)** The period RRs of falls mortality by gender. **(C)** The cohort RRs of falls mortality by gender. **(D)** The age curves of falls DALY by gender. **(E)** The period RRs of falls DALY by gender. **(F)** The cohort RRs of falls DALY by gender.

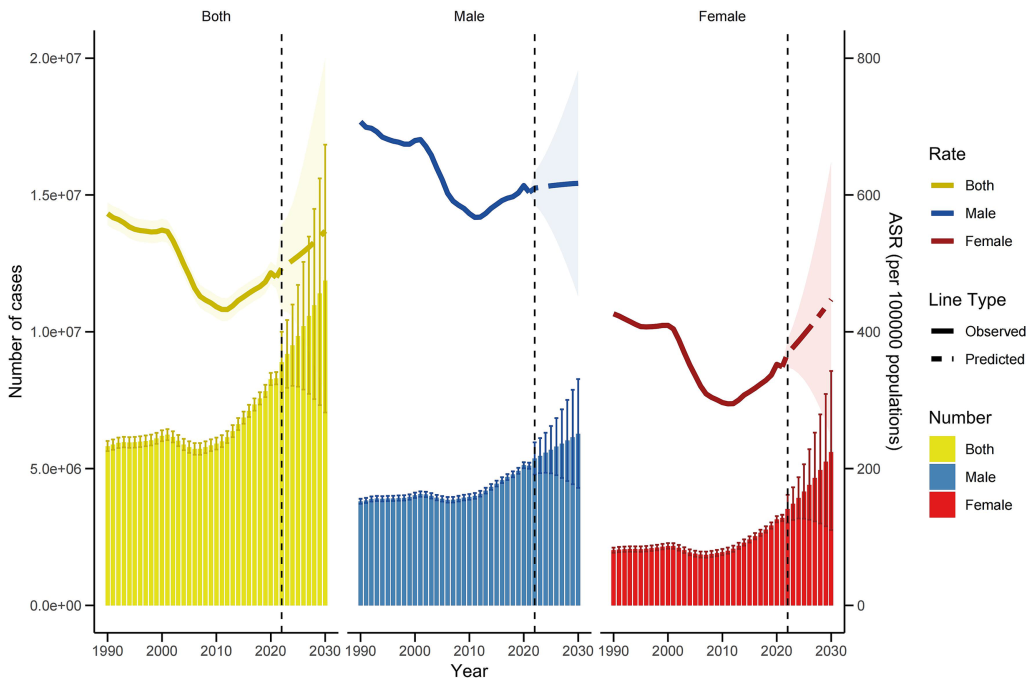

FIGURE 8
Trends in the ASRs for DALYs and numbers of DALYs by sex in China using BAPC.

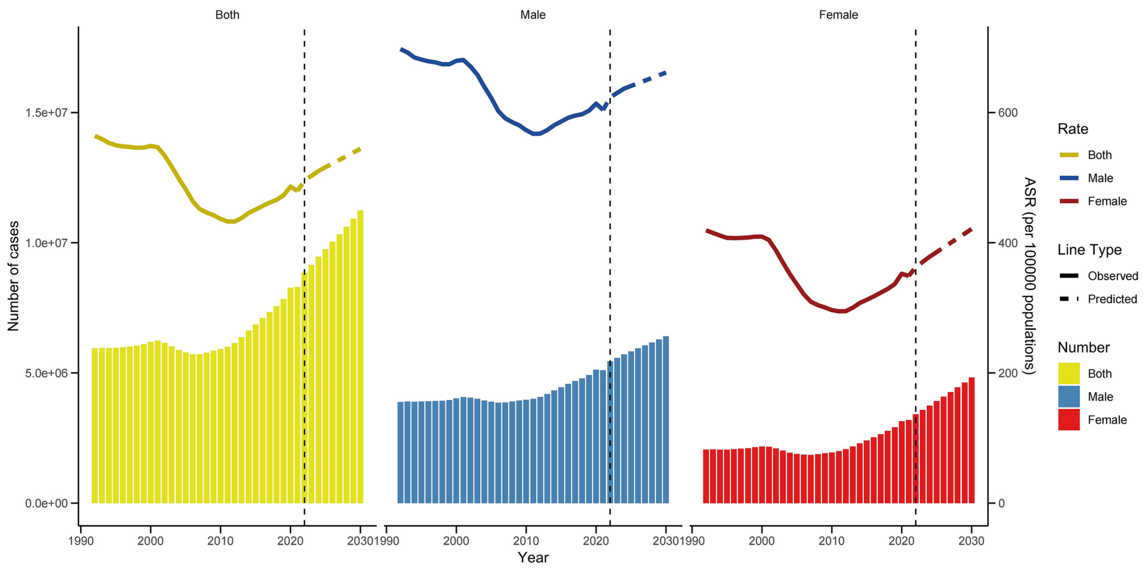

FIGURE 9
Trends in the ASRs for DALYs and numbers of DALYs by sex in China using Nordpred.

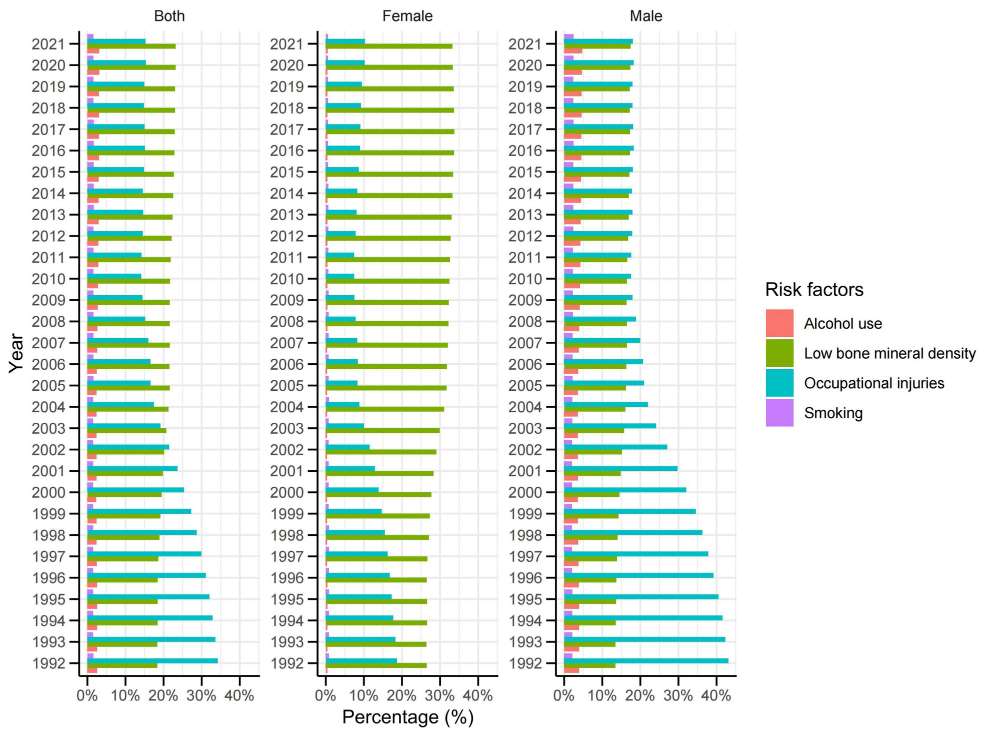

FIGURE 10
Population attributable fraction (PAF, %) of associated risk factors for falls DALYs from 1992 to 2021.

per 100,000 in the early 1990s and increasing to approximately 467 per 100,000 by 2021. India also had the highest mortality rate from falls, ranging from 24 to 29 deaths per 100,000, whereas the global mortality rate fluctuated between 10 and 11 deaths per 100,000. China's mortality rate remained at or slightly below the global average in recent years, and the United States had the lowest mortality rate, which increased from 4 deaths per 100,000 in 1992 to 8 deaths per 100,000 by 2021.

Regarding incidence, the United States initially had the highest rates, exceeding 3,836 cases per 100,000 in 1992. This rate declined to 3,116 cases per 100,000 by 2005, then rose to 3,436 cases per 100,000 by 2021. India's incidence rate slightly decreased over time, from 3,123

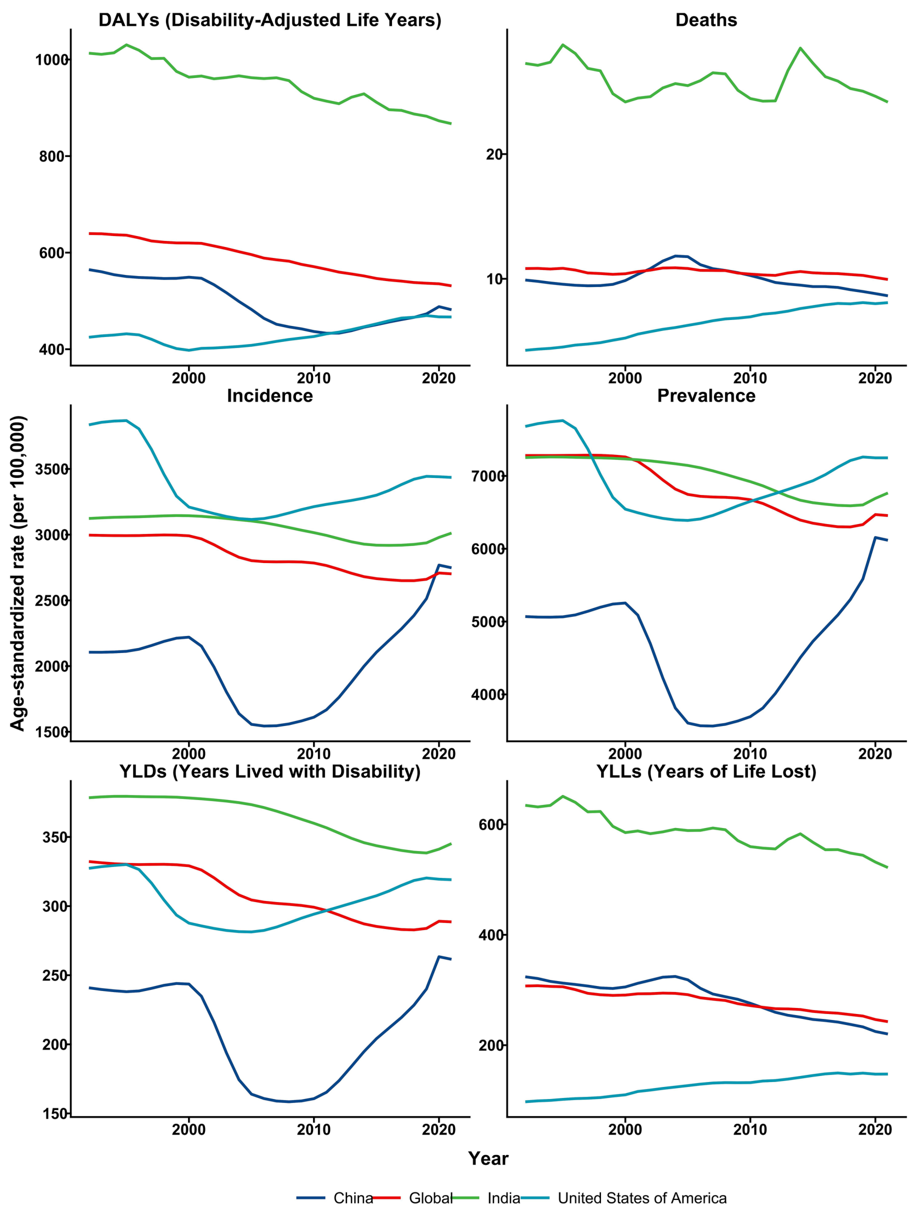

FIGURE 11
The trends in age-standardized rates of falls globally, as well as in the United States, India, and China, from 1992 to 2021.

cases per 100,000 to 3,012 cases per 100,000. In contrast, China consistently had the lowest incidence rate, dipping below 1,544 cases per 100,000 in 2006, then increasing to 2,748 cases per 100,000 by 2021.

The United States had the highest prevalence, starting at 7,680 cases per 100,000 in 1992, decreasing to 6,389 cases per 100,000 by 2005, and then rising to 7,248 cases per 100,000 by 2021. India and the global prevalence curves followed similar trends, both gradually decreasing from approximately 7,265 cases per 100,000 in 1992. Notably, China's prevalence initially declined but then increased, reaching its lowest point in 2007 (3,566 cases per 100,000) and rising to 6,116 cases per 100,000 by 2021.

In terms of YLDs, India had the highest value in 1992 (378 per 100,000), which decreased to 345 per 100,000 by 2021. The global YLDs rates gradually decreased from 332 per 100,000 in 1992 to 289 per 100,000 by 2021. The United States saw an initial decline in YLDs, reaching a minimum of 281 per 100,000 in 2005, before increasing to 319 per 100,000 by 2021. China's YLDs began at 241 per 100,000, decreased to 158 per 100,000 around 2008, and then gradually increased to 262 per 100,000 by 2021.

Regarding YLLs, India had the highest values, starting at 635 per 100,000 in 1992 and decreasing to 522 per 100,000 by 2021. China's YLLs started at 324 per 100,000 and declined to 220 per 100,000, while the global average decreased from 307 per 100,000 to 243 per 100,000. The United States had the lowest YLLs, starting at 97 per 100,000 and rising to over 148 per 100,000 by 2021.

4 Discussion

This longitudinal analysis of data from the GBD Study over the last three decades reveals key trends in the incidence, prevalence, mortality, and disability burden of falls in China. The study reveals significant increases in both new and existing fall rates, although mortality rates have declined. Additionally, disability burden rates exhibited gender-specific patterns, with males consistently experiencing higher rates than females. Aging is recognized as a major factor in the increasing prevalence and mortality from falls. Notably, the PAF for low bone mineral density, a major risk factor, has steadily increased from 1992 to 2021. The projected age-standardized DALYs rates of falls are expected to rise to approximately 547.4 per 100,000 individuals by 2030. This discussion seeks to interpret these findings, assess their implications for policy and practice, and recommend avenues for future research.

The increasing burden of falls among the Chinese population may be attributed to multiple factors, including an aging population (24–26), the prevalence of chronic diseases (27, 28), inappropriate environments (29), lifestyles, and a decline in physical function (30). The rise in the incidence of age-standardized rates of falls, coupled with a decline in the mortality of age-standardized rates of falls, may reflect increased awareness and reporting of falls, as well as advancements in China's primary healthcare system and emergency medical services during the study period (31, 32).

This study's findings align with prior research revealing the ASRs for prevalence, incidence, and mortality rates of falls have consistently been higher in males than in females over the past 30 years (33). The higher prevalence of falls in men can be linked to several risk factors. Men tend to engage in more outdoor activities, which increases their exposure to fall risks (34). Additionally, they often experience a more rapid decline in muscle strength and balance as they age, which can lead to more severe injuries when falls occur (35).

This study demonstrates that the incidence, prevalence, and mortality rates of falls increase markedly after the age of 75. Decomposition analysis reveals that aging is a primary factor contributing to the rise in fall prevalence and mortality over the past 30 years. The increased mortality from falls among individuals over 75 years of age can be attributed to several interrelated factors. One of the primary reasons is the higher prevalence of frailty and associated comorbidities in this age group. Frailty significantly increases the risk of adverse outcomes following a fall, including mortality. Studies have shown that frailty is the strongest predictor of mortality in older adults after a fall, with frail individuals experiencing notably higher mortality rates compared to their more robust peers (36). Additionally, the physiological changes associated with aging, such as decreased bone density, impaired balance, and reduced muscle strength, contribute to the severity of injuries sustained during falls. Moreover, the use of certain medications, particularly those that affect balance and cognition, can exacerbate the risk of falls and subsequent injuries. The interaction of multiple medications, known as polypharmacy, is common in older adults and can lead to side effects such as dizziness and confusion, increasing the likelihood of falls (37, 38).

The observed sex disparities in fall-related outcomes require comprehensive investigation through an age-strandified lens. The elevated incidence of falls among males in early adulthood (25–39 years) may reflect higher levels of physical activity combined with working at heights (39, 40). This pattern intensifies in middle age, as evidenced by the earlier DALYs peak in males (45–59 years) compared to females (65–89 years), potentially mirroring the cumulative exposure to occupational hazards in manual labor sectors versus the predominant influence of biological aging processes in postmenopausal females (41). The U-shaped YLLs distribution reveals critical vulnerabilities at life extremes - pediatric falls (<9 years) frequently involve high-energy mechanisms like falls from heights (42), while the secondary mortality peak in working-age males (30–59 years) suggests modifiable risk amplifiers including substance use patterns and safety protocol non-compliance in industrial settings (43, 44). The highest YLLs in females aged 75–94 years correlate with age-related physiological declines, including osteoporosis, sarcopenia, and impaired balance (45).

In our analysis, fractures of the patella, tibia or fibula, and ankle emerged as predominant causes of disability following injurious falls across all age groups. However, our study further delineates the age-related variance in fracture impact, highlighting an increased contribution to disability from hip and femur fractures in older populations. This age-related shift in fracture sites is likely attributable to changes in bone density and balance stability with advancing age (46, 47).

This study demonstrates that low bone mineral density showed a PAF that increased steadily from 1992 to 2021, in China. In 2021, the proportion of LBMD among women was 33.3%. LBMD presents a significant risk for early onset and severity in women (48), who have inherently smaller and thinner bone structures compared to men. Post-menopausal women are especially susceptible to calcium loss and osteoporosis due to decreased estrogen levels, which lack protective effects on the skeletal system. Consequently, fall prevention approaches for older adult individuals with LBMD should be gender-inclusive, considering the distinct needs and risks of both sexes.

The overall age-standardized DALYs rates of falls among the Chinese population is projected to escalate to an estimated 547.4 per 100,000 individuals by 2030. This significant increase underscores the need for comprehensive and tailored prevention and management strategies. Collaborative initiatives involving policymakers, healthcare providers, and community organizations are crucial. Effective strategies should encompass multifactorial risk assessments, home safety evaluations, medication reviews, and vision and hearing checks (49). To prevent falls in children under the age of nine, implementing safety measures such as the use of safety gates, furniture corner covers, and window locks can significantly reduce the risk (50, 51). It is essential to educate parents about potential fall hazards and effective prevention strategies, which include supervising children and modifying the home environment accordingly (52, 53). Encouraging behaviors like not leaving children unattended on high surfaces and minimizing the use of baby walkers are also important steps in fall prevention (50, 53). For the older adult, the model based on gait analysis can identify, prevent, and manage individuals at risk of falling (54). In addition, exercise programs that improve balance, strength, and mobility have been shown to effectively decrease the incidence of falls among community-dwelling older adult individuals (55–57). Gender-specific interventions are critical, with male-focused programs emphasizing risk reduction and behavioral safety, while female-focused initiatives should prioritize bone health and osteoporosis prevention, which is particularly relevant given its prevalence among older women (58, 59). Additionally, addressing environmental hazards—such as improving lighting and flooring in both private and public spaces—can significantly decrease fall risks (60, 61).

This study builds on previous research by conducting a decomposition analysis to distinguish the independent effects of aging, population growth, and epidemiological shifts on the burden of falls between 1992 and 2021. It utilized both the BAPC and Nordpred models to forecast future burdens, offering a methodological enhancement over prior studies. However, this research has several limitations that merit attention. It solely analyzes the GBD 2021 datasets within the context of China, neglecting potential variances across provinces and between urban and rural settings, which could affect the applicability of the findings across different regions. Additionally, as data collection ceased in 2021, the study may not capture recent trends that could influence the current and future burden of falls. The estimates were also derived using system dynamics and statistical modeling based on limited raw data, which might lead to potential distortions from significant assumptions required by these models. For future research, it would be advisable to extend the analysis to include more current data and explore regional differences within China. Additionally, addressing both inter-provincial differences and urban–rural disparities would yield a more holistic insight into the burden of falls across diverse demographic and geographical landscapes.

5 Conclusion

The burden of falls in China, both currently and in future projections, is substantial. Addressing this issue requires crucial enhancements in investment toward further research, the development of effective fall prevention initiatives, and improved healthcare accessibility.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://vizhub.healthdata.org/gbd-results/.

Author contributions

LS: Visualization, Writing – original draft, Writing – review & editing, Conceptualization, Investigation, Methodology. YL: Writing – review & editing, Methodology, Visualization, Writing – original draft, Conceptualization. KF: Writing – review & editing. FJ: Writing – review & editing, Project administration, Supervision.

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Conflict of interest

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Supplementary material

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EDITED BY
Nattawan Utoomprurkporn,
Chulalongkorn University, Thailand

REVIEWED BY
Wei-Chih Lien,
National Cheng Kung University, Taiwan
Geet Paul,
George Washington University, United States

*CORRESPONDENCE
Tengfei Niu
✉ niutengfei19860328@126.com

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Associated factors and gender differences of falls in older adults with hypertension: a national cross-sectional survey

Yazhu Wang[1], Yingying Zhang[2], Shiwei Cao[2], Xiyu Chen[3], Xiaobing Xian[4,5] and Tengfei Niu[6]*

[1]Department of Cardiology, The Shapingba Hospital, Chongqing University (People's Hospital of Shapingba District), Chongqing, China, [2]The Second Clinical College, Chongqing Medical University, Chongqing, China, [3]The First Clinical College, Chongqing Medical University, Chongqing, China, [4]The Thirteenth People's Hospital of Chongqing, Chongqing, China, [5]Chongqing Geriatrics Hospital, Chongqing, China, [6]Department of Basic Courses, Chongqing Medical and Pharmaceutical College, Chongqing, China

Background: Falls have become a crucial public health problem among older adults, especially those with hypertension. However, the current understanding of the risk of falls among them is still insufficient. The purpose of this study was to investigate the factors associated with falls and their gender differences among older adults with hypertension in China.

Methods: Based on the cross-sectional data of the Chinese Longitudinal Healthy Longevity Survey (CLHLS) 2018 database, this study defined 24 possible associated factors based on the five dimensions of the Health Ecology Model. Binary Logistic Regression Model was used to analyze the impact of each factor on falls among older adults with hypertension.

Results: The prevalence rate of falls in older adults with hypertension in China was 22.60%. Falls are associated with a variety of factors. Specifically, gender, self-rated health, hearing impairment, stroke, instrumental activities of daily living (IADL) disability, basic activities of daily living (BADL) disability, exercise, fresh fruit and taste preference are significant associated factors for falls among older adults with hypertension. Among them, the effects of self-rated health, stroke and exercise on falls are only significant in female with hypertension. The effect of fresh fruit on falls was significant only in men with hypertension.

Conclusion: The findings highlight that the current situation of falls among older adults with hypertension requires attention, necessitating comprehensive measures for prevention and control.

KEYWORDS

hypertension, falls, older adults, CLHLS, health ecology model

1 Introduction

As indicated by the latest data released by the World Health Organization (WHO) in 2023, around 1.28 billion adults worldwide suffer from hypertension. The number of patients with hypertension in China has reached 270 million, and its prevalence continues to rise (1). As a common chronic disease, hypertension causes mental illness and other chronic diseases that increase the burden on the body, so people with hypertension may have a higher risk of falling (2–4). In addition, antihypertensive drugs, as the most commonly prescribed drugs for older

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adults with hypertension, often cause orthostatic hypotension and then fall in older adults (5). A recent study suggested that high blood pressure medications enhanced the risk of harmful falls by 30 to 40 percent (4). Hence, older adults with hypertension have a higher chance of falling than the average people, and the consequences of falls can be more severe (6). This suggests that a more informed perspective on the epidemiological characteristics and associated factors of falls in hypertensive patients can help identify individuals at high risk of falls as early as possible, thereby improving their life quality. According to previous surveys, in excess of 25% of older adults worldwide encounter falls every year. About 35% of older adults who live in the community experience at least one fall every year, while this number rises to 50% among those in long-term care (7, 8). Falls in older people can also result in a drop in their life quality, loss of self-care, disability, and even death (9). These places a huge burden on social services and health care systems. In recent years, there has been heightened attention to early diagnosis and prevention of illness or injury. A multitude of previous studies have reported the factors associated with falls among older adults. For example, a study by Haibin Zhou et al. suggested that disease, living alone, and impaired vision are risk factors for falls among older adults in the community (10). Xingxing Xian et al. also emphasized that fall prevention programs might need to prioritize behavior-related risk factors based on WHO's Risk Factor Model for Falls (11). In addition, some studies have highlighted that there might be some gender differences in the incidence of falls among older adults (12), this may be because sex hormones can affect muscle atrophy, which can result in an unsteady gait (13). Undoubtedly, the findings of these previous studies have made outstanding contributions to the prevention and improvement of falls among older adults recently. However, these findings still might not be applied to older adults with hypertension in China.

Considering that the associated factors of falls among older adults with hypertension are numerous and complex, we introduced the Health Ecology Model (HEM) in this study, as it is often used by scholars to understand these complex effects (14, 15). HEM emphasizes the multiple levels of environmental and individual influences and the complexity of influencing factors. It studies the associated factors of diseases from five dimensions: personal characteristics, behavioral characteristics, interpersonal relationships, living and working conditions and policy environment. It is an important theoretical model to guide the field of public health and solve population health problems.

In summary, the purpose of this study was to use the cross-sectional data published in the Chinese Longitudinal Healthy Longevity Survey (CLHLS) in 2018, define possible associated factors based on the five dimensions of HEM, and analyze the associated factors and gender differences of falls among older adults with hypertension in China with Logistic Regression Model. These findings can help healthcare professionals better understand the needs of older adults with hypertension to provide accurate care and health management programs, and provide important references for policymakers to formulate relevant intervention strategies.

2 Method

2.1 Study population

The data for this study are derived from cross-sectional data published in 2018 by the CLHLS (16). The CLHLS baseline study began in 1998, and from 1998 to 2018, eight follow-up studies were conducted in 23 provinces, cities, and autonomous regions of China. The survey includes individual micro-data on family structure and living arrangements, marriage, health, and socioeconomic characteristics of older adults. All survey data for the project can be requested from the CLHLS website[1]. The CLHLS received ethical approval from the Bioethics Committee of Peking University (IRB00001052-13074), and each participant completed an informed consent form before data collection.

The screening of the study population was based on the question in the questionnaire: "Have you been diagnosed with high blood pressure by a doctor?" Respondents who answered "yes" to this question were included in our study. In 2018, CLHLS surveyed 15,874 participants aged 65 and above, of whom 6,261 were diagnosed with hypertension by doctors. Subsequent exclusion of missing data on falls and influencing factor variables resulted in the inclusion of 2,814 participants in this analysis. The sample screening process is shown in Figure 1.

2.2 Falls

CLHLS contains questions that are directly related to fall events. All information was obtained through face-to-face interviews conducted by trained investigators or local doctors/nurses. Falls among older adults with hypertension were defined based on the question "Have you fallen in the past year?." If the respondent answered "yes" to the question, it was defined as a fall. Previous studies have also shown the reliability of this measurement (17, 18).

2.3 Associated factors

Based on the five dimensions of the HEM (personal characteristics, behavioral characteristics, interpersonal relationships, living and working conditions and policy environment) (19), a total of 24 potential associated factors variables were defined from the CLHLS. The HEM emphasizes that health is influenced by both individual and environmental factors. Collecting and organizing variables based on the HEM allows us to include more comprehensive and structured variables. Specifically, in the personal characteristics dimension, variables include gender, age, body mass index (BMI), abdominal obesity, self-rated health, hearing impairment, visual impairment, heart disease, diabetes, stroke, basic activities of daily living (BADL) disability, and instrumental activities of daily living (IADL) disability. BMI is calculated by dividing your weight (in kilograms) by your height (in meters) squared. Abdominal obesity is defined as a waist circumference superior to 102 cm in men and 88 cm in women (20). The Basic Activities of Daily Living (BADL) Scale and the Instrumental Activities of Daily Living (IADL) Scale were used to measure the ability to perform daily activities among older adults, and participants were considered to be free of functional impairment (21) when they were all defined as "able to complete independently" on either the BADL or IADL Scales.

Behavioral characteristics dimension includes exercise, smoking, drinking, self-reported quality of life, fresh fruit, grease, and taste preference.

1 https://opendata.pku.edu.cn/dataverse/pku/

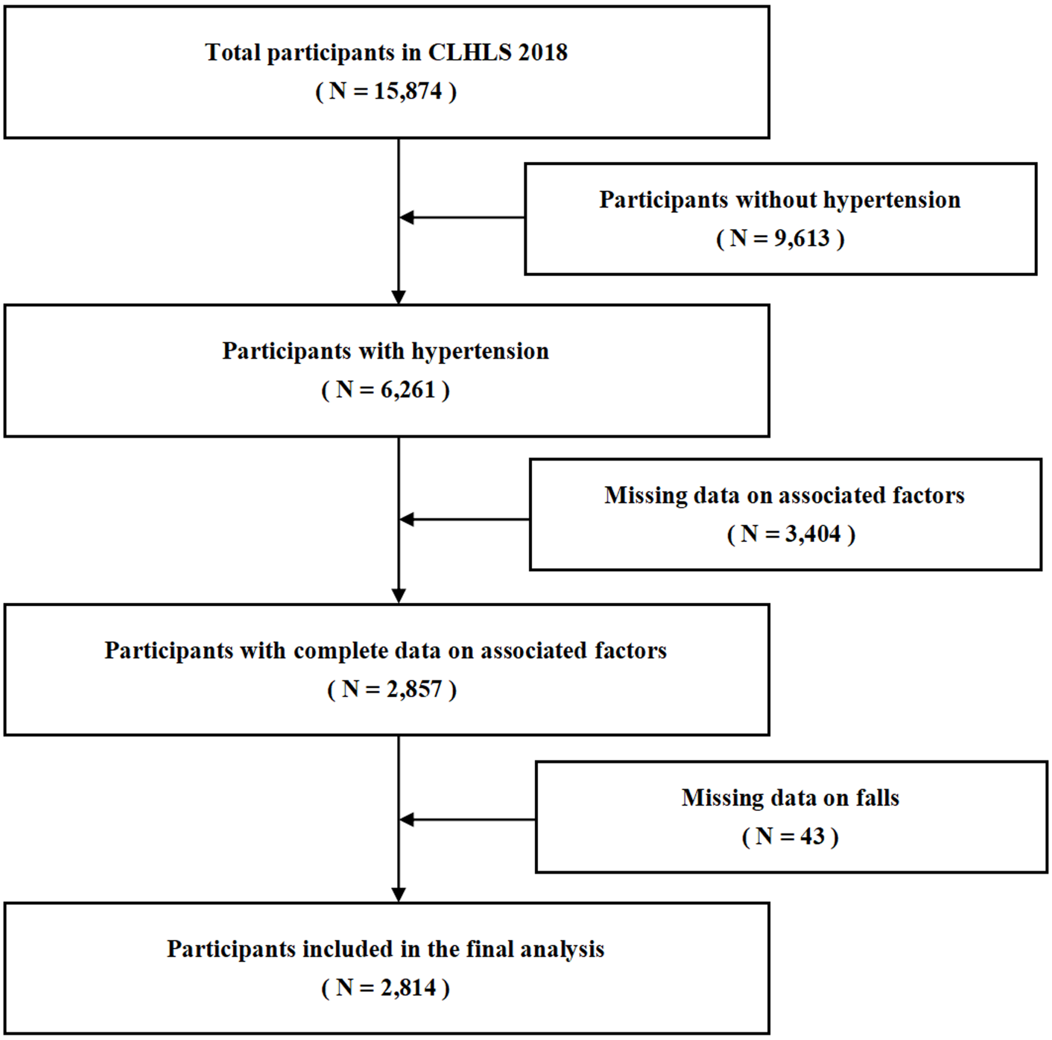

FIGURE 1
Study sample screening process.

The interpersonal relationships dimension includes co-residence, residence, and marital status.

The dimension of living and working conditions contains education level.

The policy environment dimension includes insurance.

Detailed variable measurements and assignments are shown in Appendix 1.

2.4 Statistical analysis

Categorical variables are described in frequency and percentage [*n* (%)]. The Chi-square test is used to compare the differences between different demographic characteristics in whether falls occur. Multifactor logistic regression was used to analyze the relationship between various associated factors and falls. In addition, we took falls as the dependent variable and gender and other associated factors as covariates, and conducted a product interaction analysis to explore whether there are gender differences in the associated factors of falls. We report odds ratios (OR) and 95% confidence intervals (CI) for all variables. All statistical analyses were performed using SPSS 25.0 software. The statistical test was a bilateral test, and a p value less than 0.05 indicated significant statistical significance.

3 Result

3.1 Results of descriptive analysis

According to the statistical results, 636 (22.60%) of the respondents experienced falls. Of all the respondents, 1,670 (59.35%) were female, 1,303 (46.30%) were married, and 1,371 (48.72%) were illiterate. 1,603 (56.97%) respondents were over 80 years old, 1,591 (56.54%) rated their health as poor, 1,760 (62.54%) had IADL disability, and 2,562 (91.04%) preferred vegetable grease. Among the respondents, 1,966 (69.86%) had a light taste. 1,873 (66.56%) did not exercise, 2,409 (85.61%) did not smoke, 2,436 (86.57%) did not drink alcohol, 1,671 (59.38%) were not insured, and 769 (27.33%) had abdominal obesity (Table 1).

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The frequency of falls in hypertensive patients was significantly different in age, gender, BMI, self-rated health, hearing impairment, visual impairment, heart disease, stroke, IADL disability, BADL disability, smoking, fresh fruit, taste preference, self-reported quality of life, marital status, and education level ($p < 0.05$). Detailed descriptive results are presented in Table 1.

3.2 Associated factors of falls among older adults with hypertension

The findings of multivariate logistic regression indicated that gender, self-rated health, hearing impairment, stroke, BADL disability, IADL disability, exercise, fresh fruit, and taste preference were

TABLE 1 Characteristics of participants.

Variables	Total (*n* = 2,814)	No falls (*n* = 2,178)	Falls (*n* = 636)	Statistic	*p*
Gender, *n* (%)				$\chi^2 = 16.72$	<0.001
Female	1,670 (59.35)	1,248 (57.30)	422 (66.35)		
Male	1,144 (40.65)	930 (42.70)	214 (33.65)		
Age, *n* (%)				$\chi^2 = 15.83$	<0.001
60–79	1,211 (43.03)	981 (45.04)	230 (36.16)		
≥ 80	1,603 (56.97)	1,197 (54.96)	406 (63.84)		
BMI, *n* (%)				$\chi^2 = 10.43$	0.015
< 18.5	306 (10.87)	231 (10.61)	75 (11.79)		
18.5–24	1,358 (48.26)	1,022 (46.92)	336 (52.83)		
24–28	816 (29.00)	659 (30.26)	157 (24.69)		
≥ 28	334 (11.87)	266 (12.21)	68 (10.69)		
Abdominal obesity, *n* (%)				$\chi^2 = 0.69$	0.407
No	2,045 (72.67)	1,591 (73.05)	454 (71.38)		
Yes	769 (27.33)	587 (26.95)	182 (28.62)		
Self-rated health, *n* (%)				$\chi^2 = 24.48$	<0.001
Good	1,223 (43.46)	1,001 (45.96)	222 (34.91)		
Bad	1,591 (56.54)	1,177 (54.04)	414 (65.09)		
Hearing impairment, *n* (%)				$\chi^2 = 27.81$	<0.001
No	1,860 (66.10)	1,495 (68.64)	365 (57.39)		
Yes	954 (33.90)	683 (31.36)	271 (42.61)		
Visual impairment, *n* (%)				$\chi^2 = 5.93$	0.015
No	1,938 (68.87)	1,525 (70.02)	413 (64.94)		
Yes	876 (31.13)	653 (29.98)	223 (35.06)		
Heart disease, *n* (%)				$\chi^2 = 4.81$	0.028
No	2,254 (80.10)	1,764 (80.99)	490 (77.04)		
Yes	560 (19.90)	414 (19.01)	146 (22.96)		
Diabetes, *n* (%)				$\chi^2 = 0.50$	0.481
No	2,435 (86.53)	1,890 (86.78)	545 (85.69)		
Yes	379 (13.47)	288 (13.22)	91 (14.31)		
Stroke, *n* (%)				$\chi^2 = 12.59$	<0.001
No	2,441 (86.74)	1,916 (87.97)	525 (82.55)		
Yes	373 (13.26)	262 (12.03)	111 (17.45)		
BADL disability, *n* (%)				$\chi^2 = 36.93$	<0.001
No	2,301 (81.77)	1,833 (84.16)	468 (73.58)		
Yes	513 (18.23)	345 (15.84)	168 (26.42)		
IADL disability, *n* (%)				$\chi^2 = 55.80$	<0.001

(Continued)

TABLE 1 (Continued)

Variables	Total (n = 2,814)	No falls (n = 2,178)	Falls (n = 636)	Statistic	p
No	1,054 (37.46)	896 (41.14)	158 (24.84)		
Yes	1,760 (62.54)	1,282 (58.86)	478 (75.16)		
Exercise, n (%)				χ^2 = 0.85	0.355
No	1,873 (66.56)	1,440 (66.12)	433 (68.08)		
Yes	941 (33.44)	738 (33.88)	203 (31.92)		
Smoking, n (%)				χ^2 = 6.29	0.012
No	2,409 (85.61)	1845 (84.71)	564 (88.68)		
Yes	405 (14.39)	333 (15.29)	72 (11.32)		
Drinking, n (%)				χ^2 = 2.70	0.100
No	2,436 (86.57)	1,873 (86.00)	563 (88.52)		
Yes	378 (13.43)	305 (14.00)	73 (11.48)		
Self-reported quality of life, n (%)				χ^2 = 5.30	0.021
Good	1,992 (70.79)	1,565 (71.85)	427 (67.14)		
Bad	822 (29.21)	613 (28.15)	209 (32.86)		
Fresh fruit, n (%)				χ^2 = 12.71	<0.001
No	719 (25.55)	522 (23.97)	197 (30.97)		
Yes	2,095 (74.45)	1,656 (76.03)	439 (69.03)		
Grease, n (%)				χ^2 = 0.91	0.340
Animal grease	252 (8.96)	189 (8.68)	63 (9.91)		
Vegetable grease	2,562 (91.04)	1,989 (91.32)	573 (90.09)		
Taste preference, n (%)				χ^2 = 5.72	0.017
Other	848 (30.14)	632 (29.02)	216 (33.96)		
Light taste	1,966 (69.86)	1,546 (70.98)	420 (66.04)		
Co-residence, n (%)				χ^2 = 0.87	0.351
Alone	495 (17.59)	391 (17.95)	104 (16.35)		
Other	2,319 (82.41)	1,787 (82.05)	532 (83.65)		
Residence, n (%)				χ^2 = 0.00	0.960
Urban	1,378 (48.97)	1,066 (48.94)	312 (49.06)		
Rural	1,436 (51.03)	1,112 (51.06)	324 (50.94)		
Marital status, n (%)				χ^2 = 12.11	<0.001
Other	1,511 (53.70)	1,131 (51.93)	380 (59.75)		
Married	1,303 (46.30)	1,047 (48.07)	256 (40.25)		
Education level, n (%)				χ^2 = 21.47	<0.001
Illiteracy	1,371 (48.72)	1,012 (46.46)	359 (56.45)		
Primary school or below	1,060 (37.67)	847 (38.89)	213 (33.49)		
Secondary school or above	383 (13.61)	319 (14.65)	64 (10.06)		
Insurance, n (%)				χ^2 = 0.24	0.625
No	1,671 (59.38)	1,288 (59.14)	383 (60.22)		
Yes	1,143 (40.62)	890 (40.86)	253 (39.78)		

χ^2, Chi-square test; BMI, body mass index; IADL, instrumental activity of daily living; BADL, basic activity of daily living.

significant risk factors for falls in older patients with hypertension ($p < 0.05$). Males (OR = 0.766; 95% CI: 0.602–0.975) were less likely to fall than females, and those who self-rated to be in poor health (OR = 1.376; 95% CI: 1.116–1.695) were more likely to fall than those who self-rated to be in good health. Those with hearing impairment (OR = 1.274; 95% CI: 1.034–1.570), those with stroke (OR = 1.404; 95% CI: 1.088–1.811), those with BADL disability (OR = 1.367; 95% CI: 1.072–1.743), and those with IADL disability (OR = 1.625; 95% CI:

1.266–2.086) had a higher risk of falling than normal people, and people who exercised regularly (OR = 1.269; 95% CI: 1.029–1.566) were more likely to fall than those who did not. People who ate fresh fruit (OR = 0.775; 95% CI: 0.632–0.950) were less likely to fall than those who did not, and those with light taste (OR = 0.748; 95% CI: 0.615–0.909) were less likely to fall than those with other tastes (Table 2).

3.3 Comparison of the associated factors of falls in older male and female patients with hypertension

Chi-square test results in Table 3 showed that the fall prevalence of older men with hypertension was significantly different in different BMI, self-rated health, hearing impairment, BADL disability, IADL disability, self-reported quality of life, fresh fruit, and education level ($p < 0.05$). The prevalence of falls in older women with hypertension was significantly different in different ages, BMI, self-rated health status, hearing impairment, stroke, BADL disability and IADL disability ($p < 0.05$).

The results of the binary logistic regression analysis shown in Table 4 indicated that in men, IADL disability, fresh fruit, and taste were important associated factors for falls among older adults with hypertension. Specifically, people with IADL disability (OR = 1.585; 95% CI: 1.063–2.362) were more likely to fall than normal people, those who ate fresh fruit (OR = 0.640; 95% CI: 0.457 to 0.895) were less likely to fall than those who did not, and those with a light taste (OR = 0.712; 95% CI: 0.513–0.989) had a lower risk of falling than people with other tastes. In women, self-rated health, stroke, IADL disability, exercise, and taste preference were important factors for falls among older adults with hypertension. Those with self-rated poor health (OR = 1.446; 95% CI: 1.115–1.876), those with stroke (OR = 1.423; 95% CI: 1.022–1.981), and those with IADL disability (OR = 1.617; 95% CI: 1.168–2.237) were more likely to fall than normal people. Also, people who exercised regularly (OR = 1.410; 95% CI: 1.077–1.847) were more likely to fall than those who did not. In contrast, people with a light taste (OR = 0.768; 95% CI: 0.5999–0.985) were more likely to have a lower risk of falls than those with other tastes.

The results of the interactive analysis in Table 4 showed that exercise (coefficient = −0.305, $p < 0.05$) and fresh fruit (coefficient = −0.356, $p < 0.05$) had statistically significant interaction with gender, suggesting that there were significant gender differences in the effects of these two variables on falls.

4 Discussion

Based on the nationally representative survey data, we observed that 22.60% of older adults with hypertension experienced falls. Logistic regression results suggested that people with poor self-rated health, hearing impairment, stroke, BADL disability, IADL disability, and regular exercise were more likely to fall, while men, people who ate fresh fruit, and people with a light taste were less likely to fall. In addition, our analysis results showed that there were significant gender differences in the effects of exercise and fresh fruit on falls.

Our study found that older women with hypertension had a higher prevalence of falls (25.27%) than men (18.71%). Multivariate

TABLE 2 Logistic regression results of falls.

Variables	OR	95% CI	*p*
Gender, *n* (%)			
Female	1.00 (Ref.)	1.00 (Ref.)	
Male	0.766	0.602–0.975	0.030
Age, *n* (%)			
60–79	1.00 (Ref.)	1.00 (Ref.)	
≥ 80	0.922	0.718–1.183	0.522
BMI, *n* (%)			
< 18.5	1.00 (Ref.)	1.00 (Ref.)	0.100
18.5–24	1.194	0.882–1.616	0.252
24–28	0.922	0.653–1.302	0.645
≥ 28	0.917	0.603–1.393	0.684
Abdominal obesity, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.019	0.803–1.293	0.878
Self-rated health, *n* (%)			
Good	1.00 (Ref.)	1.00 (Ref.)	
Bad	1.376	1.116–1.695	0.003
Hearing impairment, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.274	1.034–1.570	0.023
Visual impairment, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	0.953	0.773–1.174	0.650
Heart disease, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.139	0.907–1.430	0.264
Diabetes, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.059	0.809–1.388	0.676
Stroke, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.404	1.088–1.811	0.009
BADL disability, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.367	1.072–1.743	0.012
IADL disability, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.625	1.266–2.086	<0.001
Exercise, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.269	1.029–1.566	0.026
Smoking, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	0.798	0.587–1.084	0.148

(Continued)

TABLE 2 (Continued)

Variables	OR	95% CI	*p*
Drinking, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	1.195	0.883–1.617	0.248
Self-reported quality of life, *n* (%)			
Good	1.00 (Ref.)	1.00 (Ref.)	
Bad	1.084	0.877–1.341	0.455
Fresh fruit, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	0.775	0.632–0.950	0.014
Grease, *n* (%)			
Animal grease	1.00 (Ref.)	1.00 (Ref.)	
Vegetable grease	0.825	0.603–1.128	0.227
Taste preference, *n* (%)			
Other	1.00 (Ref.)	1.00 (Ref.)	
Light taste	0.748	0.615–0.909	0.004
Co-residence, *n* (%)			
Alone	1.00 (Ref.)	1.00 (Ref.)	
Other	1.140	0.875–1.485	0.333
Residence, *n* (%)			
Urban	1.00 (Ref.)	1.00 (Ref.)	
Rural	0.971	0.807–1.169	0.758
Marital status, *n* (%)			
Other	1.00 (Ref.)	1.00 (Ref.)	
Married	0.942	0.746–1.190	0.618
Education level, *n* (%)			
Illiteracy	1.00 (Ref.)	1.00 (Ref.)	0.556
Primary school or below	0.925	0.739–1.158	0.497
Secondary school or above	0.831	0.588–1.174	0.293
Insurance, *n* (%)			
No	1.00 (Ref.)	1.00 (Ref.)	
Yes	0.979	0.811–1.182	0.823

χ^2, Chi-square test; BMI, body mass index; IADL, instrumental activity of daily living; BADL, basic activity of daily living; Ref., reference.

logistic regression analysis revealed that the fall risk of older men with hypertension was 0.766 times that of the women. These results are consistent with some previous studies showing that there were gender differences in the risk of falls among older adults (12, 22). One possible explanation is that older Chinese women are more likely to suffer from osteoporosis, which affects their bone and muscle function, making their knee muscles weaker (23), and thus increasing the risk of falls. A lack of estrogen in women's bodies after menopause may cause bone loss in women at a faster rate than in men, reducing their physical function (24, 25).

This study found that people with poor self-rated health were more likely to fall than those with good self-rated health. Previous studies have shown that falls are associated with poorer self-rated health among older Chinese adults (26, 27). Physically, people with poorer self-rated health are more likely to have chronic diseases, such as diabetes (28). Chronic diseases can lead to sarcopenia, which increases the risk of falls in older people (29). Psychologically, poor self-rated health is an important predictor of depression (30). Studies have shown that depressive symptoms can lead to psychomotor disorders, which can impair an individual's balance and ability to effectively respond to environmental challenges and increase the risk of falls (31). People with depression often have abnormal standing posture, which can result in falls (31). There are also some studies suggesting that side effects of medications used to treat depressive symptoms can also increase the risk of falls (31). It is worth mentioning that our findings found that self-rated health only had a significant impact on older women with hypertension, which may be because women tend to be more sensitive to their own health status, and when the self-rated health status is poor, they may have greater psychological stress and anxiety, which will interfere with the nervous system's control of muscles and affect body coordination and reaction speed, thereby increasing the risk of falls.

Consistent with previous findings, older adults with hearing impairment were 2.4 times more likely to have a fall than those with normal hearing of the same age and were more likely to have a fatal injury (32, 33). This may be because the hearing system is closely related to maintaining balance in the body. Studies have shown that the auditory system is responsible for integrating head and body movement and position information into the brainstem, cerebellum, and somatosensory cortex to maintain balance (34). Damage to the hearing system affects the vestibular system, causing many people with age-related hearing loss to experience dizziness, resulting in an imbalance in the body (35, 36). At the same time, hearing impairment reduces perception, resulting in an increased burden on cognitive and attention resources that are also necessary for maintaining bodily functions such as postural control and balance (36, 37). Part of the explanation for the association between hearing impairment and fall risk could also be that older adults with hearing impairment are unable to hear their own footfall (38). In our findings, hearing impairment had a significant effect on falls across the population, but no significant associations were identified in subgroup analyses of men and women. This may be due to the small sample size of males and females in the subgroup analysis, resulting in insufficient statistical power. Therefore, the sample size should be further expanded in future studies to determine the causes of this difference.

Our results also demonstrated that people who had stroke were more likely to have falls than those who did not. Falls are a common complication after stroke, and both the physical and psychological impairments associated with stroke can lead to frequent falls later in life (39). Physically, residual sensorimotor deficits after stroke can cause impaired balance and increase the risk of falls among older adults (40). At the same time, stroke survivors are prone to osteoporosis (41). Accelerated bone loss often leads to an increased risk of fracture in stroke patients, and further increases the risk of falls (42), and fractures resulting from falls can affect the patient's mobility, creating a vicious cycle (39). In terms of psychology, studies have revealed that the reason for the increased risk of falls in older stroke patients may be a maladaptive fear of falls caused by factors such as depression, anxiety, past fall experiences, poor balance, and limited mobility, and this maladaptive fear of falls can cause older adults to

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TABLE 3 Chi-square test results of falls in male and female.

Variables	Male					Female				
	Total (n = 1,144)	No falls (n = 930)	Falls (n = 214)	Statistic	p	Total (n = 1,670)	No falls (n = 1,248)	Falls (n = 422)	Statistic	p
Age, n (%)				χ^2 = 4.20	0.04				χ^2 = 9.33	0.002
≥ 80	548 (47.90)	459 (49.35)	89 (41.59)			663 (39.70)	522 (41.83)	141 (33.41)		
≥ 80	596 (52.10)	471 (50.65)	125 (58.41)			1,007 (60.30)	726 (58.17)	281 (66.59)		
BMI, n (%)				χ^2 = 6.11	0.107				χ^2 = 6.01	0.111
< 18.5	106 (9.27)	88 (9.46)	18 (8.41)			200 (11.98)	143 (11.46)	57 (13.51)		
18.5–24	577 (50.44)	453 (48.71)	124 (57.94)			781 (46.77)	569 (45.59)	212 (50.24)		
24–28	339 (29.63)	287 (30.86)	52 (24.30)			477 (28.56)	372 (29.81)	105 (24.88)		
≥ 28	122 (10.66)	102 (10.97)	20 (9.35)			212 (12.69)	164 (13.14)	48 (11.37)		
Abdominal obesity, n (%)				χ^2 = 0.11	0.736				χ^2 = 0.71	0.401
No	1,049 (91.70)	854 (91.83)	195 (91.12)			996 (59.64)	737 (59.05)	259 (61.37)		
Yes	95 (8.30)	76 (8.17)	19 (8.88)			674 (40.36)	511 (40.95)	163 (38.63)		
Self-rated health, n (%)				χ^2 = 10.78	0.001				χ^2 = 12.44	<0.001
Good	527 (46.07)	450 (48.39)	77 (35.98)			696 (41.68)	551 (44.15)	145 (34.36)		
Bad	617 (53.93)	480 (51.61)	137 (64.02)			974 (58.32)	697 (55.85)	277 (65.64)		
Hearing impairment, n (%)				χ^2 = 12.91	<0.001				χ^2 = 14.78	<0.001
No	766 (66.96)	645 (69.35)	121 (56.54)			1,094 (65.51)	850 (68.11)	244 (57.82)		
Yes	378 (33.04)	285 (30.65)	93 (43.46)			576 (34.49)	398 (31.89)	178 (42.18)		
Visual impairment, n (%)				χ^2 = 3.66	0.056				χ^2 = 1.71	0.19
No	830 (72.55)	686 (73.76)	144 (67.29)			1,108 (66.35)	839 (67.23)	269 (63.74)		
Yes	314 (27.45)	244 (26.24)	70 (32.71)			562 (33.65)	409 (32.77)	153 (36.26)		
Heart disease, n (%)				χ^2 = 2.68	0.102				χ^2 = 1.60	0.206
No	947 (82.78)	778 (83.66)	169 (78.97)			1,307 (78.26)	986 (79.01)	321 (76.07)		
Yes	197 (17.22)	152 (16.34)	45 (21.03)			363 (21.74)	262 (20.99)	101 (23.93)		
Diabetes, n (%)				χ^2 = 2.03	0.154				χ^2 = 0.05	0.823
No	996 (87.06)	816 (87.74)	180 (84.11)			1,439 (86.17)	1,074 (86.06)	365 (86.49)		
Yes	148 (12.94)	114 (12.26)	34 (15.89)			231 (13.83)	174 (13.94)	57 (13.51)		
Stroke n (%)				χ^2 = 5.92	0.015				χ^2 = 8.00	0.005

(Continued)

TABLE 3 (Continued)

Variables	Male					Female				
	Total (n = 1,144)	No falls (n = 930)	Falls (n = 214)	Statistic	p	Total (n = 1,670)	No falls (n = 1,248)	Falls (n = 422)	Statistic	p
No	975 (85.23)	804 (86.45)	171 (79.91)			1,466 (87.78)	1,112 (89.10)	354 (83.89)		
Yes	169 (14.77)	126 (13.55)	43 (20.09)			204 (12.22)	136 (10.90)	68 (16.11)		
BADL disability, n (%)				χ^2 = 16.33	<0.001				χ^2 = 17.23	<0.001
No	990 (86.54)	823 (88.49)	167 (78.04)			1,311 (78.50)	1,010 (80.93)	301 (71.33)		
Yes	154 (13.46)	107 (11.51)	47 (21.96)			359 (21.50)	238 (19.07)	121 (28.67)		
IADL disability, n (%)				χ^2 = 23.76	<0.001				χ^2 = 25.07	<0.001
No	535 (46.77)	467 (50.22)	68 (31.78)			519 (31.08)	429 (34.38)	90 (21.33)		
Yes	609 (53.23)	463 (49.78)	146 (68.22)			1,151 (68.92)	819 (65.62)	332 (78.67)		
Exercise, n (%)				χ^2 = 2.59	0.108				χ^2 = 0.41	0.522
No	693 (60.58)	553 (59.46)	140 (65.42)			1,180 (70.66)	887 (71.07)	293 (69.43)		
Yes	451 (39.42)	377 (40.54)	74 (34.58)			490 (29.34)	361 (28.93)	129 (30.57)		
Smoking, n (%)				χ^2 = 0.51	0.474				χ^2 = 1.35	0.245
No	811 (70.89)	655 (70.43)	156 (72.90)			1,598 (95.69)	1,190 (95.35)	408 (96.68)		
Yes	333 (29.11)	275 (29.57)	58 (27.10)			72 (4.31)	58 (4.65)	14 (3.32)		
Drinking, n (%)				χ^2 = 0.21	0.648				χ^2 = 0.03	0.852
No	852 (74.48)	690 (74.19)	162 (75.70)			1,584 (94.85)	1,183 (94.79)	401 (95.02)		
Yes	292 (25.52)	240 (25.81)	52 (24.30)			86 (5.15)	65 (5.21)	21 (4.98)		
Self-reported quality of life, n (%)				χ^2 = 9.30	0.002				χ^2 = 0.46	0.496
Good	799 (69.84)	668 (71.83)	131 (61.21)			1,193 (71.44)	897 (71.88)	296 (70.14)		
Bad	345 (30.16)	262 (28.17)	83 (38.79)			477 (28.56)	351 (28.12)	126 (29.86)		
Fresh fruit, n (%)				χ^2 = 13.68	<0.001				χ^2 = 3.14	0.076
No	302 (26.40)	224 (24.09)	78 (36.45)			417 (24.97)	298 (23.88)	119 (28.20)		
Yes	842 (73.60)	706 (75.91)	136 (63.55)			1,253 (75.03)	950 (76.12)	303 (71.80)		
Grease, n (%)				χ^2 = 0.20	0.651				χ^2 = 0.63	0.427
Animal grease	98 (8.57)	78 (8.39)	20 (9.35)			154 (9.22)	111 (8.89)	43 (10.19)		
Vegetable grease	1,046 (91.43)	852 (91.61)	194 (90.65)			1,516 (90.78)	1,137 (91.11)	379 (89.81)		
Taste preference, n (%)				χ^2 = 3.23	0.072				χ^2 = 4.08	0.043
Other	389 (34.00)	305 (32.80)	84 (39.25)			459 (27.49)	327 (26.20)	132 (31.28)		
Light taste	755 (66.00)	625 (67.20)	130 (60.75)			1,211 (72.51)	921 (73.80)	290 (68.72)		

(Continued)

TABLE 3 (Continued)

Variables	Male					Female				
	Total (n = 1,144)	No falls (n = 930)	Falls (n = 214)	Statistic	p	Total (n = 1,670)	No falls (n = 1,248)	Falls (n = 422)	Statistic	p
Co-residence, n (%)				χ^2 = 0.48	0.487				χ^2 = 0.95	0.329
Alone	167 (14.60)	139 (14.95)	28 (13.08)			328 (19.64)	252 (20.19)	76 (18.01)		
Other	977 (85.40)	791 (85.05)	186 (86.92)			1,342 (80.36)	996 (79.81)	346 (81.99)		
Residence, n (%)				χ^2 = 0.83	0.363				χ^2 = 0.41	0.52
Urban	556 (48.60)	446 (47.96)	110 (51.40)			822 (49.22)	620 (49.68)	202 (47.87)		
Town	588 (51.40)	484 (52.04)	104 (48.60)			848 (50.78)	628 (50.32)	220 (52.13)		
Marital status, n (%)				χ^2 = 2.09	0.148				χ^2 = 3.73	0.053
Other	416 (36.36)	329 (35.38)	87 (40.65)			1,095 (65.57)	802 (64.26)	293 (69.43)		
Married	728 (63.64)	601 (64.62)	127 (59.35)			575 (34.43)	446 (35.74)	129 (30.57)		
Education level, n (%)				χ^2 = 6.42	0.04				χ^2 = 5.34	0.069
Illiteracy	288 (25.17)	220 (23.66)	68 (31.78)			1,083 (64.85)	792 (63.46)	291 (68.96)		
Primary school or below	592 (51.75)	488 (52.47)	104 (48.60)			468 (28.02)	359 (28.77)	109 (25.83)		
Secondary school or above	264 (23.08)	222 (23.87)	42 (19.63)			119 (7.13)	97 (7.77)	22 (5.21)		
Insurance, n (%)				χ^2 = 0.01	0.943				χ^2 = 0.07	0.797
No	639 (55.86)	519 (55.81)	120 (56.07)			1,032 (61.80)	769 (61.62)	263 (62.32)		
Yes	505 (44.14)	411 (44.19)	94 (43.93)			638 (38.20)	479 (38.38)	159 (37.68)		

χ^2, Chi-square test; BMI, body mass index; IADL, instrumental activity of daily living; BADL, basic activity of daily living.

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TABLE 4 Logistic regression results of the falls in male and female.

Variables	Male			Female			Coefficient(B)
	OR	95% CI	*p*	OR	95% CI	*p*	
Age, *n* (%)							
60–79	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
≥ 80	0.894	0.601–1.330	0.580	0.949	0.684–1.317	0.754	0.030
BMI, *n* (%)							
< 18.5	1.00 (Ref.)	1.00 (Ref.)	0.091	1.00 (Ref.)	1.00 (Ref.)		
18.5–24	1.564	0.883–2.767	0.125	1.071	0.743–1.543	0.714	0.345
24–28	1.117	0.599–2.082	0.728	0.879	0.575–1.344	0.551	0.201
≥ 28	0.894	0.414–1.929	0.775	0.912	0.548–1.517	0.722	0.034
Abdominal obesity, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.220	0.667–2.231	0.520	0.987	0.757–1.285	0.921	0.089
Self-rated health, *n* (%)							
Good	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Bad	1.235	0.865–1.762	0.245	1.446	1.115–1.876	0.005	0.062
Hearing impairment, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.342	0.949–1.896	0.096	1.255	0.962–1.638	0.094	0.112
Visual impairment, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	0.996	0.695–1.427	0.982	0.930	0.718–1.205	0.585	0.149
Heart disease, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.304	0.875–1.944	0.193	1.070	0.809–1.414	0.637	0.188
Diabetes, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.328	0.851–2.070	0.211	0.958	0.680–1.350	0.808	0.306
Stroke, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.367	0.910–2.053	0.132	1.423	1.022–1.981	0.037	−0.003
BADL disability, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.516	0.980–2.346	0.061	1.324	0.983–1.783	0.065	0.200
IADL disability, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.585	1.063–2.362	0.024	1.617	1.168–2.237	0.004	0.105
Exercise, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.111	0.788–1.566	0.548	1.410	1.077–1.847	0.013	−0.305*
Smoking, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	0.841	0.581–1.218	0.360	0.690	0.372–1.279	0.239	0.254

(Continued)

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TABLE 4 (Continued)

Variables	Male			Female			Coefficient(B)
	OR	95% CI	*p*	OR	95% CI	*p*	
Drinking, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	1.263	0.863–1.848	0.230	1.069	0.628–1.820	0.805	0.163
Self-reported quality of life, *n* (%)							
Good	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Bad	1.407	0.990–2.001	0.057	0.942	0.720–1.233	0.666	0.359
Fresh fruit, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	0.640	0.457–0.895	0.009	0.867	0.669–1.123	0.279	−0.356*
Grease, *n* (%)							
Animal grease	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Vegetable grease	0.857	0.496–1.480	0.580	0.795	0.540–1.170	0.244	0.081
Taste preference, *n* (%)							
Other	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Light taste	0.712	0.513–0.989	0.043	0.768	0.599–0.985	0.038	−0.092
Co-residence, *n* (%)							
Alone	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Other	1.349	0.813–2.237	0.246	1.075	0.786–1.470	0.652	0.156
Residence, *n* (%)							
Urban	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Rural	0.853	0.622–1.169	0.323	1.039	0.824–1.309	0.746	−0.210
Marital status, *n* (%)							
Other	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Married	0.873	0.595–1.281	0.489	0.959	0.711–1.293	0.782	−0.031
Education level, *n* (%)							
Illiteracy	1.00 (Ref.)	1.00 (Ref.)	0.636	1.00 (Ref.)	1.00 (Ref.)		
Primary school or below	0.837	0.576–1.217	0.352	0.976	0.734–1.300	0.870	−0.245
Secondary school or above	0.845	0.518–1.377	0.499	0.716	0.419–1.222	0.220	0.064
Insurance, *n* (%)							
No	1.00 (Ref.)	1.00 (Ref.)		1.00 (Ref.)	1.00 (Ref.)		
Yes	0.988	0.720–1.357	0.941	0.968	0.764–1.227	0.790	−0.003

BMI, body mass index; IADL, instrumental activity of daily living; BADL, basic activity of daily living; Ref., reference.

limit their social activities, resulting in muscle atrophy and decreased athletic ability (43). Of concern, stroke only had a significant effect on falls in older women with hypertension, possibly because women are more likely than men to have osteoporosis, have less muscle strength and are therefore more likely to have falls during stroke recovery (23).

People with BADL and IADL disability were more likely to fall than normal people. Studies have shown that people with BADL and IADL disability are more likely to have limited mobility and slow gait, which affects body balance (23, 25, 44). People with BADL and IADL disability have worse self-care ability (21), and being less involved or not participating in social activities for a long time not only leads to muscle atrophy and continuous decline in exercise ability (43) but also increases their loneliness and thus increases the risk of depression (45). At the same time, poor social relationships can give rise to reduced access to health care and reduced adherence to medication (25). We found that BADL disability had no significant effect on falls in subgroup analyses of both older male and female patients, with possible causes consistent with the 'hearing impairment' explanation.

Taste preference had a significant effect on falls among older adults with hypertension, both in the population as a whole and in men and women, respectively. That is, people with a light taste were less likely to fall than people with other tastes. The light taste helps patients control the occurrence and progression of chronic diseases such as high blood pressure and reduces patients' dependence on medication (46). For example, a light diet is low in sodium, and there is a broad linear association between sodium intake and the risk of complex cardiovascular outcomes (stroke, myocardial infarction, coronary revascularization) (47, 48). At the same time, a light diet helps to maintain a healthy weight and reduce the burden on the body, thereby improving the flexibility and balance of the body.

Fresh fruit was also a significant risk factor in our study. In addition to containing micronutrients and macronutrients, fresh fruit also contains a large amount of bioactive compounds (49). Bioactive compounds are compounds present in foods that produce reproducible biological effects at the dietary level, with polyphenols as a representative (50). Polyphenols contain flavonoids, which have a variety of biological activities such as anti-inflammatory, antioxidant, anti-free radical and neuroprotective effects (51). Long-term intake of polyphenols can not only reduce oxidative stress in muscles and have a positive impact on mitochondria, but also can beneficially act on blood vessels, ensure the supply of nutrients to muscles, and prevent loss of muscle mass (52). Therefore, eating fresh fruit can improve muscle strength and balance, and reduce the risk of falls (50). At the same time, eating fresh fruit can also prevent and control high blood pressure and other chronic diseases (49, 53).

Interestingly, our results suggested that people who exercised regularly were more likely to fall than those who did not, contrary to most previous research. Previous studies have shown that exercise can reduce the risk of falls by improving balance and leg strength among older adults (54–56). At the same time, a small number of studies have shown that exercise has no effect on preventing falls (57, 58). The differences in these findings may be due to differences in exercise styles. Studies have shown that long-term exercises, especially those that promote balance, can reduce the risk of falls, but short-term exercises, more complex exercises, or exercises that do not include balance and function training do not reduce the risk of falls (59, 60). In fact, this difference is still not fully explained by research, and future studies could employ more refined experimental designs to reveal the complex dynamics behind it.

In addition, the results of the interaction analysis showed that there was a significant interaction between exercise and fresh fruit on the impact of falls in hypertensive patients. Our findings suggest that exercise is a significant risk factor for falls only in older women with hypertension. Influenced by exercise habits and roles, women may be less willing to participate in physical exercise than men. At the same time, there are differences in the ways of exercise among older adults of different genders, which may contribute to gender differences affecting falls. In addition, the body structures of men and women are different, men's fat is mainly stored in the abdomen, and women's fat is mainly stored in the buttocks and hips (61), which may have an impact on the effect of exercise.

The effect of fresh fruit on falls among older adults with hypertension was significant only in men. Women's diets are typically characterized by higher carbohydrate intake, including fruit and vegetables. In contrast, men consume more of an animal protein-rich diet and less fruit than women (62). Research results show that women consume more fruit than men (2.6 servings/day vs. 2.2 servings/day) (63). Therefore, the potential changes in the body caused by eating fresh fruit may be more significant in men than in women.

5 Conclusion

Overall, falls are common among older adults with hypertension, with a prevalence of 22.60%. Based on the five dimensions of the Health Ecology Model, the Logistic Regression Model identified gender, self-rated health, hearing impairment, stroke, BADL disability, IADL disability, exercise, fresh fruit and taste preference as significant associated factors for falls among older adults with hypertension. Among them, the effects of self-rated health, stroke and exercise on falls were only significant in female hypertensive patients. The effect of fresh fruit on falls was significant only in men with hypertension. The results of further interaction analysis showed that there were significant gender differences in the effects of exercise and fresh fruit on falls. These results suggest that in the clinical practice of focusing on falls in hypertensive patients, it may be effective to target these significant influencing factors and carry out appropriate interventions.

6 Limitations

Admittedly, there are still some limitations to our study. First, this study used cross-sectional data published by the CLHLS database in 2018, unable to establish a causal relationship between the fall risk of older adults with hypertension and their associated factors, which is worthy of further proof in future cohort studies. Second, the measurement of all indicators mainly relied on the self-reported data of the participants, and although the investigators were professionally trained, there were still some inevitable subjective biases. Third, although we applied the HEM to conduct a relatively comprehensive examination of associated factors, due to the limitation of investigation resources in the database, fewer factors were included in the living and working conditions and policy environment dimensions, and other potentially significant important variables (such as pre-retirement occupation and public health policy) were not included in the study. Finally, although the data in our study came from a high-quality nationwide survey, the sample size obtained is still limited due to the limitations of special populations and the absence of some data. It is suggested that further studies with larger sample sizes should be conducted to verify these conclusions.

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

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 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

YW: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. YZ: Data curation, Writing – original draft, Writing – review & editing. SC: Writing – original draft, Writing – review & editing. XC: Conceptualization, Data curation, Writing – original draft. XX: Formal analysis, Methodology, Writing – original draft. TN: Funding acquisition, 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.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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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.2025.1537587/full#supplementary-material

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Predictive model for the therapeutic effect of bilateral subthalamic nucleus deep brain stimulation on the freezing of gait in Parkinson's disease

Qi Limuge[1], Yuqing Zhang[2], Xiaofei Jia[2], Fang Wang[3], Dongsheng Yu[4], Lixia Chen[4], Li Zhang[4] and Yongqiang Jiang[1,4]*

[1]Department of Neurosurgery, Baotou Central Hospital, Affiliated Baotou Clinical College of Inner Mongolia Medical University, Baotou, China, [2]Department of Functional Neurosurgery, Xuanwu Hospital, Capital Medical University, Beijing, China, [3]Inner Mongolia People's Hospital, Hohhot, China, [4]Department of Neurosurgery, Inner Mongolia Third Hospital, Hohhot, China

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EDITED BY
Robert Petersen,
Central Michigan University, United States

REVIEWED BY
Matteo Costanzo,
Sapienza University of Rome, Italy
Hougelle Simplicio,
Santos Dumont Institute (ISD), Brazil

*CORRESPONDENCE
Yongqiang Jiang
✉ 13347083336@163.com

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Background: Freezing of gait (FOG) is a major disabling symptom that affects the quality of life of patients with Parkinson's disease (PD). To date, notions regarding the effects of deep brain stimulation of the subthalamic neucleus (STN-DBS) on FOG remain controversial. Therefore, we developed a prediction model based on the influence of bilateral deep brain stimulation (DBS) of the subthalamic nucleus (STN) on FOG in patients with PD.

Methods: We collected data from 104 PD participants with FOG who underwent STN-DBS at Xuanwu Hospital between September 2017 and June 2022. The patients were divided into a training set (70%; $n = 68$) and a validation set (30%; $n = 36$). The selected characteristics in the LASSO regression were used in multivariate logistic regression to build the prediction model. The receiver operating characteristic (ROC) curves were constructed for the training and validation sets to verify the model's efficiency.

Results: Independent variables in the prediction model included Unified Parkinson's Disease Rating Scale II (UPDRS II), UPDRS IV, leg rigidity, Montreal Cognitive Assessment (MoCA) score, and Mini-Mental State Examination (MMSE) score. The prediction model formula is as follows: Logit(y) = −1.0043 + 0.159 × UPDRS II + 0.030 × UPDRS IV - 1.726 × leg rigidity + 0.121 × MoCA + 0.036 × MMSE. To validate the model, we analyzed the ROC curves of the training and validation sets. The area under the ROC curve (AUC) of internal validation was 0.869 (95% confidence interval [CI]: 0.771–0.967) and the AUC of external validation was 0.845 (95% CI: 0.6526–1). The calibration plots showed good calibration.

Conclusion: The model we developed can effectively assist clinicians in assessing the efficacy of deep brain stimulation of the bilateral subthalamic nucleus for freezing of gait in Parkinson's disease patients. This approach can support the formulation of personalized treatment plans and has the potential to improve patient outcomes.

KEYWORDS
Parkinson's disease, freezing of gait, prediction model, deep brain stimulation, subthalamic nucleus

Introduction

Parkinson's disease (PD) is a complex, chronic, and progressive neurodegenerative disease (Bloem et al., 2021). Freezing of gait (FOG) is a major motor disability that affects the daily quality of life of patients with PD. It usually occurs when starting, turning, or approaching a target. FOG can be induced or aggravated by narrow aisles or thresholds, crowded and noisy places, dual-task interference, time pressure, and psychological stress (Rahimpour et al., 2021). Statistics reveal that the incidence of FOG in the early stage of PD is 27%, while the incidence of FOG in the late stages of PD can reach 80% (Tan et al., 2011). From a neurophysiological viewpoint, the motor symptoms of PD appear to result largely from abnormalities in one of the several parallel and largely segregated basal ganglia thalamocortical circuits in the human brain (Bostan et al., 2013; Hallett, 2014). Dysfunction of one or more of these circuits—either individually or in combination—results in the disruption of downstream network activity in the thalamus, cortex, and brainstem (DeLong and Wichmann, 2015). Deep brain stimulation (DBS) involves implanting a stimulation electrode into a target nucleus deep within the brain tissue of the patient, followed by the delivery of weak electric pulses at specific frequencies via a pulse generator, allowing downstream network activity to function more normally (Fejeran et al., 2022). DBS in the subthalamic nucleus (STN) can alleviate tremors, rigidity, and dyskinesias and reduce the doses of medications, even among patients with advanced stages of the disease, which makes the STN a preferred target for DBS (Hariz and Blomstedt, 2022). At present, several studies have focused on the effect of bilateral STN-DBS on FOG, while others have revealed improved gait in the first few years following surgery, which gradually deteriorates with disease progression (Kim et al., 2019; Krack et al., 2003). This deteroitation is reminiscent of the reduced responsiveness of axial symptoms to L-dopa in the long term (Ferraye et al., 2008). Phibbs et al. (2014) propose that the improvement of axial symptoms, such as FOG, in DBS therapy is closely associated with maintaining a constant range of total electrical energy delivered (TEED). In the early postoperative period, the stimulation voltage is relatively low, enabling TEED to remain within a stable range, which effectively alleviates FOG and other axial symptoms. However, as Parkinson's disease (PD) progresses, clinicians often gradually increase the stimulation voltage to address worsening symptoms. While this adjustment aims to improve motor symptoms, it may lead to an imbalance in TEED, thereby disrupting the stability of neural network regulation. This imbalance could further exacerbate the deterioration of FOG symptoms (Phibbs et al., 2014; Koss et al., 2005). Thus, the efficacy and effects of STN-DBS on FOG levels remain controversial.

This study investigated the clinical preoperative evaluation of patients with PD to further assess and discuss the effect of bilateral STN-DBS on FOG. Furthermore, for the first time, we developed a prediction model based on the influence of STN-DBS on FOG in patients with PD.

Materials and methods

Study population

This study investigated 104 patients with PD with FOG who underwent bilateral STN-DBS at the Xuanwu Hospital from September 2017 to June 2022.

The data used in this study were obtained from the Xuanwu Hospital and were completely anonymized prior to analysis. As no identifiable patient information was used, our institutional review board (IRB) granted a waiver of informed consent. The IRB reviewed and approved the study protocol, confirming that it met ethical standards for retrospective research.

Inclusion and exclusion criteria

The inclusion criteria were as follows: (1) a definite diagnosis of primary PD, (2) a preoperative state without medicine (Med-off state) with a Movement Disorder Society (MDS)-Unified Parkinson's Disease Rating Scale III (UPDRS III) item 11 freezing score ≥1, (3) bilateral STN-DBS performed, and (4) postoperative follow-up for 1 year. The exclusion criteria were as follows: (1) patients with secondary PD caused by cerebral infarction, cerebral hemorrhage, and drugs, among others, (2) patients with PD who could not complete the MDS-UPDRS III, and (3) patients with other brain tissue diseases or who had undergone other brain surgeries.

Groups

A total of 104 participants were divided into training (70%; $n = 68$) and validation sets (30%; $n = 36$).

Participants in the training set were further divided into the improved ($n = 58$) and non-improved ($n = 10$) groups, while the validation set was also divided into the improved ($n = 31$) and non-improved ($n = 5$) groups. Grouping was based on the difference in the MDS-UPDRS III (Regnault et al., 2019) item 11 freezing score between the preoperative med-off status and the postoperative status at 1 year (Stim-on/Med off). Scores with differences of ≥1 and <1 were categorized as the improved and non-improved groups, respectively.

Data collection

We collected 30 influencing factors, including general characteristics as well as motor and non-motor symptom scores.

1 The general information included sex, age, age at onset, disease duration, and preoperative levodopa-equivalent daily dose (LEDD).
2 The motor symptom assessment included the MDS-UPDRS II and III (including leg activity, leg rigidity, leg tremor, and

postural stability), MDS-UPDRS IV, New Freezing of Gait Questionnaire (NFOGQ) (Mezzarobba et al., 2023), the improvement rate of the levodopa stress test, the Berg Balance Scale (BBS), the Hoehn and Yahr stage scale (HY-stage scale), and the Unified Dyskinesia Rating Scale (UDysRS).

3 The non-motor symptoms assessments included the Montreal Cognitive Assessment (MoCA) and Mini-Mental State Examination (MMSE) to assess cognitive status. The Hamilton Anxiety Scale (HAMA) and Hamilton Depression Scale (HAMD) were use to assess the patients' moods, and the Epworth Sleepiness Scale (ESS), Pittsburgh Sleep Quality Index (PSQI), Rapid Eye Movement Sleep Disorder Questionnaire - Hong Kong edition (RBD-HK), and Non-motor Symptoms Scale (NMSS) and MDS-UPDRS I were used to assess other non-motor symptoms.

Statistical analysis

The Statistical Package for the Social Sciences version 25.0 was used for descriptive data analysis. Measurement data conforming to normal distribution are expressed as mean ± standard deviation ($\bar{x} \pm s$), and an independent sample *t*-test was used for comparison between the groups. The median and quartile [M (P25–P75)] represent the non-normally distributed measurement data, and the Mann–Whitney U-test was used for between-group comparisons. Counting data are expressed as a percentage (%), and the X^2 test was used for between-group comparison. The R4.3.2 "glmnet" package was used for the least absolute shrinkage and selection operator (LASSO) analysis to select variables before developing the predictive model to select the optimal variables and eliminate redundant ones. A multivariate logistic regression analysis was performed, and a visual nomogram was constructed as a predictive model based on the variables selected from the LASSO regression model. Receiver operating characteristic (ROC) (Nahm, 2022) curve analysis, calibration curve, and decision curve analysis (DCA) (Vickers and Holland, 2021) were used to assess the differentiation and calibration degree of the model. The ROC curve was generated for the validation set data, and the area under the ROC curve (AUC) values of the training and validation sets were compared to complete the external validation of the model.

Results

Comparison of clinical data between groups in the training set

Participants in the training set (68 participants in total) were categorized into the improved (58 participants) and non-improved (10 participants) groups. A comparison of clinical data between the improved and non-improved groups revealed that the median age (non-improved: 65.7 ± 7.96 vs. improved: 63.88 ± 7.56), MDS-UPDRS I (non-improved: 14.6 ± 5.97 vs. improved: 13.62 ± 5.72), and MDS-UPDRS III (non-improved: 62 ± 10.76 vs. improved: 61 ± 16.3) were significantly higher in the non-improved group than the improved group. Additionally, the median disease duration [non-improved: 9.5 (5.75–13.25) vs. improved: 9 (7–12.25)], NFOGQ score [non-improved: 25 (15.75–26.25) vs. improved: 24 (20–27)], leg rigidity [non-improved: 2.5 (2.375–3) vs. improved: 2 (1.5–2.5)], and HAMD [non-improved: 9.5 (6.5–11.75) vs. improved: 9 (5–13.25)] were also higher in the non-improved group compared to the improved group. A statistically significant difference in leg rigidity was observed between the two groups ($p = 0.025 < 0.05$). It should be noted that the non-improved group consisted of only 10 patients, which may limit the generalizability of our findings. Further studies with larger sample sizes are needed to confirm these results. (Table 1).

LASSO-logistic regression analysis screened the Most valuable variables

Variables were selected using the LASSO binary logistic regression model in the training set. Optimal parameter selection (λ. min = 0.05438572) in the LASSO model was performed using 5-fold cross-validation with the minimum criteria. The binomial deviance curve was plotted against log(λ). The analysis revealed five characteristics, which included MDS-UPDRS II, MDS-UPDRS IV, leg rigidity, MoCA, and MMSE, with non-zero coefficients in the LASSO regression, which were selected as independent predictors (Figure 1).

Through intergroup comparisons between the improvement and non-improvement groups, a significant difference was found in leg rigidity ($p = 0.025 < 0.05$), suggesting that the severity of preoperative leg rigidity may be an important predictor of freezing of gait (FOG) improvement following STN-DBS. The multivariate logistic regression analysis further confirmed that leg rigidity is an independent predictor of postoperative FOG improvement ($p = 0.028 < 0.05$). Nonetheless, there was no significant difference in MDS-UPDRS II between the groups in the intergroup comparison ($p = 0.056$), but the multivariate logistic regression analysis revealed that the MDS-UPDRS II score was the strongest influencing factor ($p = 0.026 < 0.05$). (Table 2).

Construction of the predictive nomogram

LASSO-logistic regression analysis identified the factors related to FOG symptom improvement in patients with PD after STN-DBS, which were then used to construct a prediction model. The prediction model formula is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5$$

Where Y is the dependent variable, X_1, X_2, X_3, X_4 and X_5 are independent variables, β_0 is the intercept, and β_1, β_2, β_3, β_4 and β_5 are coefficients.

FOG symptoms in patients with PD after STN-DBS could be easily and visually predicted using the nomogram drawn from this model. Figure 2A One patient was randomly selected, and the probability of postoperative FOG symptom improvement was 97.7% (Figure 2B).

TABLE 1 Comparison of clinical data between the improved and non-improved groups in the training set.

Factor	Non-improved group	Improved group	*p*-value
Sex			0.701
Female	4 (40%)	27 (46.6%)	
Male	6 (60%)	31 (53.4%)	
Age (years)	65.7 ± 7.96	63.88 ± 7.56	0.984
Age of onset (years)	55.5 (47–63.25)	57 (49–61)	0.671
Disease duration (years)	9.5 (5.75–13.25)	9 (7–12.25)	0.794
LEDD	0.375 (0.297–0.453)	0.375 (0.312–0.375)	0.506
MDS-UPDRS III-11	2 (1–4)	2 (1.75–3.25)	0.724
NFOGQ	25 (15.75–26.25)	24 (20–27)	0.855
FOG type			0.974
Levodopa-responsive FOG	9 (90%)	52 (89.7%)	
Levodopa-resistant FOG.	1 (10%)	6 (10.3)	
Improvement rate	0.52 ± 0.17	0.53 ± 0.17	0.754
MDS-UPDRS I	14.6 ± 5.97	13.62 ± 5.72	0.656
MDS-UPDRS II	17 ± 4.72	22 ± 8.51	0.056
MDS-UPDRS III	62 ± 10.76	61 ± 16.30	0.263
MDS-UPDRS IV	6.4 ± 3.66	8.6 ± 3.82	0.881
BBS	40.5 (32–47.5)	41 (29–47)	0.768
Leg rigidity	2.5 (2.375–3)	2 (1.5–2.5)	0.025
Leg activity	2.52 ± 0.85	2.38 ± 0.90	0.580
Leg tremor	0.75 (0–2.125)	1 (0–1.625)	0.766
Balance	3 (1.75–3)	3 (2–3)	0.862
H-Y score	3 (2.5–3)	3 (2.5–3)	0.744
MOCA	20.4 ± 2.99	22.4 ± 4.16	0.208
MMSE	27.5 (24–29)	28 (25.75–29)	0.420
HAMA	7 (3.75–12.25)	7 (4–11)	0.931
HAMD	9.5 (6.5–11.75)	9 (5–13.25)	0.645
ESS	2 (1–4.5)	3 (0.75–6.25)	0.524
PSQI	96.4 ± 34.76	106.78 ± 27.32	0.284
RBD-HK	13.5 (5.5–29)	24 (10–38.75)	0.203
NMSS	41 (22.25–78)	51.5 (34.25–66.75)	0.368
UDysRS	8.5 (0–19.25)	16.5 (0–26.25)	0.433
On UDysRS			0.539
No	5 (50%)	23 (39.7%)	
Yes	5 (50%)	35 (60.3%)	
Off UDysRS			0.601
No	7 (70%)	45 (77.6%)	
Yes	3 (30%)	13 (22.4%)	

LEDD, Levodopa-equivalent daily dose; MDS, Movement Disorder Society; UPDRS, Unified Parkinson's Disease Rating Scale; NFOGO, New Freezing of Gait Questionnaire; BBS, Berg Balance Scale; HY-stage scale, Hoehn and Yahr stage scale; UDysRS, Unified Dyskinesia Rating Scale; MoCA, Montreal Cognitive Assessment; MMMSE, Mini-Mental State Examination; HAMA, Hamilton Anxiety Scale; HAMD, Hamilton Depression Scale; ESS, Epworth Sleepiness Scale; PSQI, Pittsburgh Sleep Quality Index; RBD-HK, Rapid Eye Movement Sleep Disorder Questionnaire - Hong Kong edition; NMSS, Non-Motor Symptoms Scale.

Predictive model evaluation and comparison

To assess the stability and reliability of the predictive model, we performed bootstrap resampling with 1,000 iterations. The bootstrap results demonstrated that the model's performance was robust, with narrow confidence intervals, indicating high reliability in predicting the efficacy of bilateral STN-DBS for freezing of gait in Parkinson's disease. Additionally, decision curve analysis (DCA) was performed to assess the clinical utility of the model (Figure 3A). The

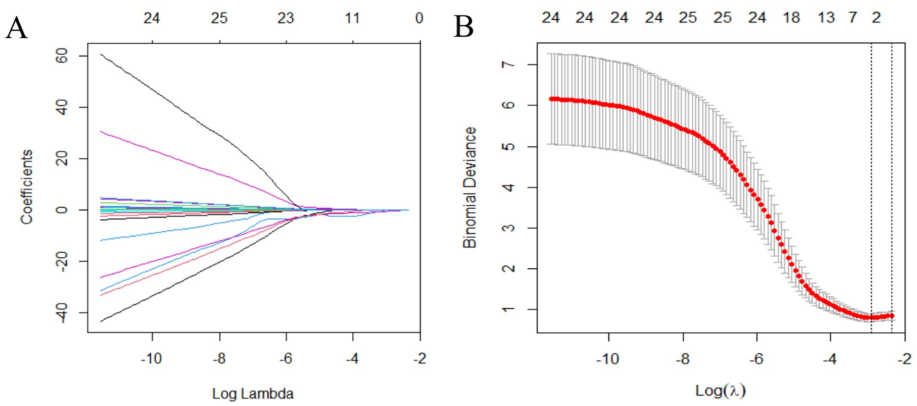

FIGURE 1
Variable selection using the LASSO binary logistic regression model. **(A)** LASSO coefficients of 30 variables. The optimal penalization coefficient (lambda) is identified in the LASSO model where optimal λ results in five features with non-zero coefficients. **(B)** The partial likelihood deviance (binomial deviance) curve is plotted against log(lambda). The left vertical line is dotted at the minimum criteria of λ, and the right vertical line is dotted at one standard error of the minimum λ. LASSO, least absolute shrinkage and selection operator.

TABLE 2 Multivariate logistic regression analysis of STN-DBS effects on FOG in PD.

	Coefficient (β)	*Z*-value	*P*-value	OR	95% CI
Intercept	−1.0043	−0.26	0.7930	0.366	
MDS-UPDRS II	0.159	2.23	0.026	1.172	1.019–1.349
MDS-UPDRS IV	0.030	0.25	0.806	1.031	0.81–1.311
Leg rigidity	−1.726	−2.20	0.028	0.178	0.038–0.827
MoCA	0.121	0.98	0.329	1.128	0.886–1.438
MMSE	0.036	0.25	0.801	1.037	0.782–1.376

STN-DBS, Subthalamic nucleus deep brain stimulation; FOG, freezing of gait; MDS, Movement Disorder Society; UPDRS, Unified Parkinson's Disease Rating Scale; MoCA, Montreal Cognitive Assessment; MMSE, Mini-Mental State Examination; OR, odds ratio; CI, confidence interval.

DCA curves demonstrated that the model provided a higher net benefit than the "improve all" or "improve none" strategies across a range of clinically relevant threshold probabilities, highlighting its potential value in guiding clinical decisions for bilateral STN-DBS in patients with freezing of gait (Figure 3B).

We plotted ROC curves for the LASSO model in the training set and validated this predictive model using the validation set. The area under the ROC curve is used to determine the predictive ability of the prediction model to distinguish outcomes. The AUC of the nomogram in the training set was 0.869 (95% confidence interval [CI]: 0.771–0.967). Furthermore, we revealed an AUC of 0.845 (95% CI: 0.6526–1) in the validation set. The AUC of both the training and validation sets highlighted the good predictive ability of the model. Therefore, the current model can accurately predict FOG symptom improvement in participants with PD receiving STN-DBS postoperatively (Figure 4).

Discussion

FOG is a major disabling symptom that significantly affects the daily lives of patients with PD. The currently available treatment options for FOG include pharmacological treatments (Gao et al., 2020), surgical treatments, and physiotherapy (Gao et al., 2020). FOG tends to show a poor response to pharmacological treatments. Therefore, surgical treatments have become an indispensable approach to managing FOG. Surgical treatments, including DBS and spinal cord stimulation (SCS), have been reported to alleviate the symptoms of FOG (Opova et al., 2023). Among these symptoms, STN-DBS is one of the primary surgical treatments for FOG (Xie et al., 2015).

Based on the prediction model, we established that MDS-UPDRS II, MDS-UPDRS IV, leg rigidity, MoCA, and MMSE scores were the influencing factors for the improvement of FOG postoperatively. This is the most comprehensive study for developing and validating a prediction model based on the influence of STN-DBS on FOG in patients with PD. We analyzed the general characteristics and the scores of all preoperative assessment items in patients with PD when investigating the effect of STN-DBS on FOG, in addition to the individual scores on the UPDRS III, which may influence FOG, such as leg rigidity, leg tremor, and balance (Bloem et al., 2004; Nieuwboer and Giladi, 2008; Plotnik et al., 2009). The preoperative evaluation of the participants revealed that those with poor individual scores were more likely to have FOG symptoms or have worse FOG improvement. Previous studies on the effect of STN-DBS on FOG have only analyzed the general characteristics and common influencing scores preoperatively in patients with PD (Vercruysse et al., 2014; Schlenstedt et al., 2017; Barbe et al., 2020).

The MDS-UPDRS II score indicates the activities of daily living in PD patients. This study revealed that higher pre-operative UPDRS II

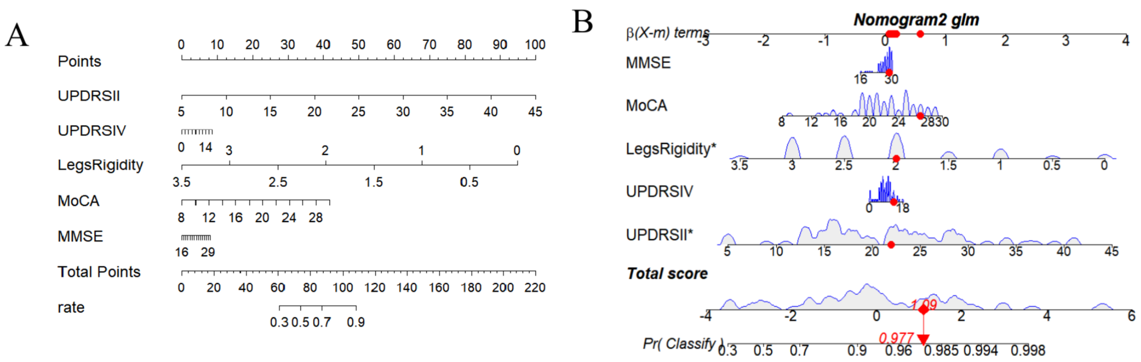

FIGURE 2
(A) Nomogram including MDS-UPDRS II, MDS-UPDRS IV, Legs rigidity, MoCA, and MMSE. **(B)** One patient is randomly selected, and the probability of postoperative FOG symptom improvement in this patient is predicted based on the five characteristic indicators of the nomogram.

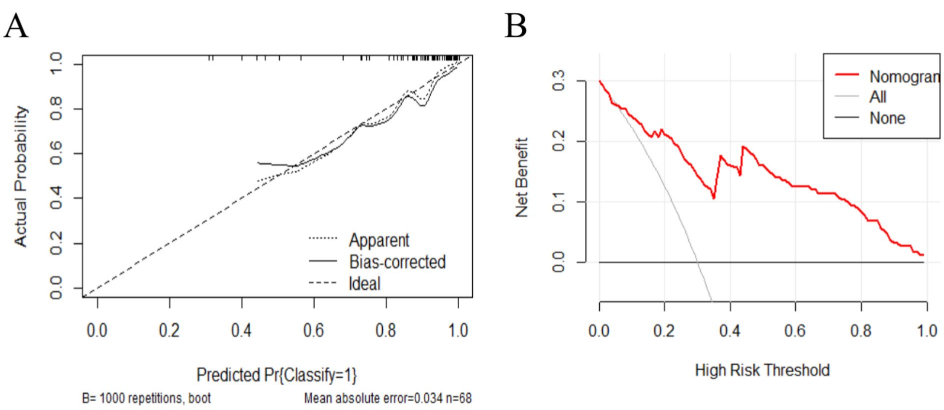

FIGURE 3
(A) The x-axis represents the predicted probability of FOG symptom improvement 1 year postoperatively, while the y-axis represents the actual probability. The diagonal line represents perfect prediction by an ideal model. The higher the ideal curve, the actual curve, and the calibration curve overlap, the better the model accuracy. **(B)** The x-axis represents the threshold probability, and the y-axis represents the net benefit. The solid line parallel to the x-axis represents patients who showed no postoperative improvement, the gray oblique solid line represents those who showed all improvement postoperatively, and the red curve represents the prediction model (nomogram) developed in the present study.

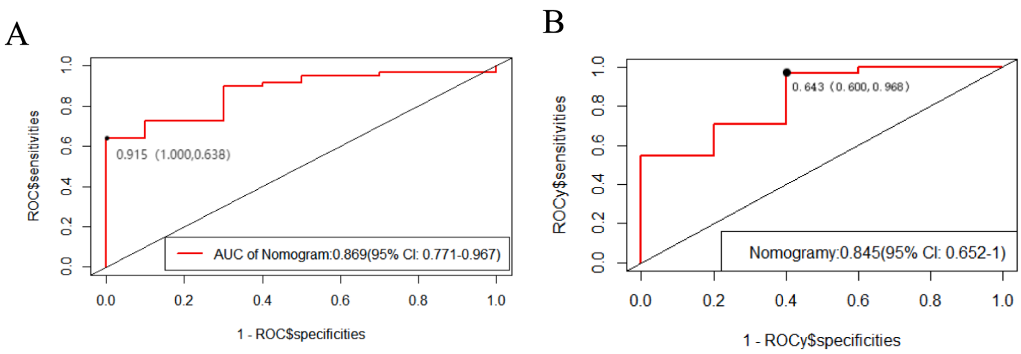

FIGURE 4
The area under the ROC curve is used to determine the predictive ability of the prediction model. The x-axis represents the false positive rate predicted by the model; while the y-axis represents the true positive rate predicted by the model. The red curve represents the performance of the nomogram. **(A)** The performance of the model in the training set. **(B)** The performance of the model in the validation set.

scores were associated with more severe FOG symptoms in the Med-off/Stim-on state 1 year postoperatively. This finding indicates that poorer daily living ability before surgery is associated with greater postoperative improvement in FOG. Studies by Vercruysse et al. (2014), Schlenstedt et al. (2017), Zhang et al. (2021), Akturk et al. (2021), and Barbe et al. (2020) that investigated clinical factors related to FOG in PD also found that UPDRS II significantly influences the occurrence of FOG. They proposed that patients with poor daily living abilities were more likely to develop FOG, possibly due to the cumulative impact of motor and non-motor symptoms on their functional capacity. Combined with the results of our study, patients with poor daily living abilities may have more frequent or severe FOG symptoms at baseline. This phenomenon may be attributed to the greater improvement in patients with more severe symptoms, as well as the potential for STN-DBS to address both motor and non-motor aspects of PD that contribute to FOG. Our study, combined with existing literature, highlights the need for personalized treatment approaches that consider the mutual influence between activities of daily living, FOG severity, and other clinical factors in PD patients undergoing STN-DBS. Therefore, it is essential to optimize patient selection and postoperative management for maximal therapeutic benefit.

Our study revealed that the higher the preoperative leg rigidity score, the worse the postoperative FOG symptom improvement; this finding is consistent with several previous studies. For example, Fasano et al. (2012) found that patients with more severe preoperative motor symptoms, including rigidity, had a poorer response to STN-DBS, particularly in terms of axial symptoms such as FOG (Fasano et al., 2012). Additionally, Zibetti et al. (2011) demonstrated that the severity of preoperative leg rigidity was negatively correlated with gait improvement after STN-DBS. Wichmann and DeLong (2016) proposed that leg rigidity is primarily associated with abnormal activity within the basal ganglia-thalamocortical loop. Specifically, leg rigidity may arise from hyperactivity of the indirect pathway, leading to enhanced inhibitory motor signals that restrict the range and coordination of lower limb movements. STN-DBS modulates the activity of the subthalamic nucleus (STN), partially restoring the balance of the basal ganglia circuitry and thereby improving motor symptoms. However, in patients with more severe preoperative leg rigidity, the dysfunction of the basal ganglia-thalamocortical circuitry may have progressed to a degree that is less amenable to complete reversal through STN-DBS (Wichmann and DeLong, 2016). In combination with our study, for PD-FOG patients with more severe rigidity, STN-DBS is difficult to improve their FOG symptoms. This finding suggests that future STN-DBS treatment plans for FOG should consider patients' leg rigidity symptoms to achieve personalized therapeutic strategies.

MMSE and MoCA are used to evaluate cognition in patients with PD. Our study revealed that the higher the preoperative cognitive score, the greater the postoperative FOG improvement. Previous studies (Scholl et al., 2021; Gan et al., 2023) have indicated that FOG severity is closely associated with impairments in executive function, attention, and visuospatial abilities, which are commonly affected in PD patients with cognitive decline. In addition, another study (Aybek et al., 2007) revealed that DBS surgery resulted in cognitive decline. Combined with the results of our study, these findings highlight the importance of carefully evaluating cognitive function before considering STN-DBS for the treatment of FOG in PD patients. Patients with poor preoperative cognitive function may not only experience limited improvement in FOG but also face a higher risk of postoperative cognitive decline. Therefore, STN-DBS surgery to improve FOG symptoms may not be advisable for patients with significant cognitive impairment.

MDS-UPDRS IV includes levodopa-induced dyskinesia, fluctuations in the on/off phenomenon, and other complications of levodopa therapy. This study revealed that a higher preoperative UPDRS IV score was associated with greater improvement in postoperative FOG symptoms. This finding was consistent with the results of a study by Vercruysse et al. (2014), which identified UPDRS IV as a clinical predictor of postoperative FOG symptom improvement. Additionally, Vercruysse et al. (2014) believed that FOG with more pronounced on/off fluctuations after consuming levodopa had a higher likelihood of having no-FOG postoperatively. Therefore, patients with a greater response to levodopa have better postoperative FOG symptom improvement.

The majority of studies (Vercruysse et al., 2014; Ferraye et al., 2008; Kleiner-Fisman et al., 2003; Schlenstedt et al., 2017) support the finding that the levodopa-responsive preoperative type is a predictor of postoperative motor symptom improvement, whereas the LEDD dose as a predictor remains controversial. Several studies (Ferraye et al., 2008; Niu et al., 2012) have revealed that LEDD dose is a predictor of postoperative FOG symptom improvement. However, in 2016, Schlenstedt et al. (2017) investigated the effect of STN-DBS on FOG among patients with PD through a meta-analysis and proposed the lack of correlation between the LEDD dose and postoperative FOG symptom improvement. Additionally, age, disease duration (Vercruysse et al., 2014), and neuropsychological function (Niu et al., 2012) were considered predictors of postoperative FOG symptom improvement. In contrast to the above results, our study revealed that MDS-UPDRS II and leg rigidity were the strongest influencing factors for postoperative FOG symptom improvement.

This study has some potential limitations. First, this was a retrospective study, and some clinical indicators with more vacancy values were eliminated, which may lead to unavoidable selection deviation. Second, the construction and verification of the prediction model were limited to PD patients with FOG who underwent STN-DBS surgery at Xuanwu Hospital of Capital Medical University, resulting in a small sample size. Data from patients with PD with FOG symptoms can be further collected in a multicenter and large-scale manner for model construction and verification. Third, the majority of studies confirmed that bilateral STN-DBS surgery improved FOG after 6 months or 1 year of follow-up (Kim et al., 2019); however, the long-term viability of these effects remains unclear. The follow-up period in this study was short, making the prediction of long-term efficacy uncertain. However, the prediction of short-term efficacy was relatively reliable. Fourth, the cohort included a large proportion of patients with levodopa-responsive freezing, thus caution should be exercised when extrapolating the data.

Conclusion

This study developed a simple and effective model to predict the postoperative efficacy of bilateral STN-DBS surgery on FOG symptoms among PD patients. The obtained model can effectively assist clinicians in preoperatively assessing the therapeutic effects of STN-DBS on freezing of gait in Parkinson's disease patients. Through personalized treatment planning, it aims to improve long-term quality of life and clinical outcomes. Based on the findings of this study, during preoperative evaluation, clinicians can focus on patients' MDS-UPDRS II, MDS-UPDRS IV, leg rigidity, MoCA, and MMSE to predict the potential improvement of STN-DBS surgery on freezing of gait symptoms in Parkinson's disease patients.

Data availability statement

Due to patient confidentiality agreements, the raw data containing substantial information beyond the scope of the results presented in this manuscript cannot be made publicly available.

Ethics statement

The data used in this study were obtained from Xuanwu Hospital and were completely anonymized prior to analysis. As no identifiable patient information was used, our institutional review board (IRB) granted a waiver for informed consent. The IRB reviewed and approved the study protocol, confirming that it met ethical standards for retrospective research.

Author contributions

QL: Conceptualization, Data curation, Formal analysis, Writing – original draft. YZ: Writing – review & editing, Supervision. XJ: Investigation, Data curation, Formal analysis, Writing – original draft. FW: Writing – original draft, Project administration. DY: Data curation, Investigation, Methodology, Writing – original draft. LC: Data curation, Resources, Validation, Writing – original draft. LZ: Data curation, Software, Visualization, Writing – original draft. YJ: Writing – review & editing. Conceptualization, Supervision.

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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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EDITED BY
Nattawan Utoomprurkporn,
Chulalongkorn University, Thailand

REVIEWED BY
Semra Bulbuloglu,
Istanbul Aydın University, Türkiye
Margot Buyle,
Sciensano, Belgium

*CORRESPONDENCE
Sung Min Kim
✉ minarthur@hanyang.ac.kr

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The Otago Exercise Program's effect on fall prevention: a systematic review and meta-analysis

Chenyu Wang [1] and Sung Min Kim [1,2,3*]

[1]Department of Sport Science, Hanyang University, Seoul, Republic of Korea, [2]Department of Physical Education, Human-Tech Convergence Program, Hanyang University, Seoul, Republic of Korea, [3]Center for Artificial Intelligence Muscle, Hanyang University, Seoul, Republic of Korea

Objectives: This study aims to compare the effectiveness of the Otago Exercise Program (OEP) in fall prevention between generally healthy older adults and those with compromised health conditions, assessing which group benefits more from the intervention.

Design: This meta-analysis evaluated the effectiveness of the OEP in fall prevention among general older adults and older adults with compromised health, including individuals at high risk of falls, cognitive impairment, musculoskeletal disorders, or frailty syndrome.

Methods: A comprehensive search was conducted in Web of Science, PubMed, Scopus, Cochrane Library, and Embase, following strict eligibility criteria. Data extraction, risk of bias assessment, and meta-analysis were conducted to evaluate the effectiveness of the intervention.

Results: Fifteen studies with 1,278 participants were included. The OEP significantly improved balance (WMD = 0.15, 95% CI [−0.05, 0.35]), gait (WMD = 0.49, 95% CI [0.18, 0.80]), and lower limb strength (WMD = 0.84, 95% CI [0.61, 1.07]) in general older adults. The effects were more pronounced in older adults with compromised health, particularly in gait, particularly in gait (WMD = 0.92, 95% CI [0.13, 1.72]) and lower limb strength (WMD = 2.24, 95% CI [1.04, 3.45]). However, the OEP did not significantly improve physical function or upper limb strength in either group.

Conclusion: The OEP effectively improves balance, gait, and lower limb strength, especially in older adults with compromised health. However, it does not significantly impact physical function or upper limb strength. This study has limitations, including potential bias, study heterogeneity, and variations in interventions, which may affect result reliability. A cautious interpretation is needed, and future research should focus on analyzing diverse populations and ensuring adequately sized samples to enhance the reliability of the findings.

Systematic review registration: PROSPERO (CRD42024549302), https://www.crd.york.ac.uk/PROSPERO/view/CRD42024549302.

KEYWORDS

Otago exercise, older adult, meta-analysis, fall, prevention

1 Introduction

As of 2023, the global population of individuals aged 60 years or older has reached approximately 1.1 billion, with projections indicating an increase to 1.4 billion by 2030 and 2.1 billion by 2050 (1). Falls are the second leading cause of accidental injury deaths globally (2), resulting in approximately 684,000 deaths annually, the majority of which occur among adults aged 60 years or older. Repeated falls can cause serious medical issues in older adults, Mgbeojedo et al. (3) including fractures and physical frailty, Kannus et al. (4) and Liston et al. (5) which may result in increased dependence on family members or assistive devices, fall-related anxiety, high economic costs, extended limitations on activity, and related issues (6, 7). Consequently, falls represent a significant risk to the wellbeing of older adults, highlighting the urgent need for effective interventions to mitigate this risk.

To mitigate the effect of falls among older adults, preventive interventions and education aimed at reducing fall risk are commonly implemented. Diverse exercise programs targeting flexibility, strength, balance, and endurance can improve mobility and physical function in older adults while reducing fall risk and related injuries (8, 9). OEP is a progressive training regimen specifically designed for older adults (10), emphasizing exercises that target balance and strength to reduce fall risk by improving physical stability (11). The OEP is a structured exercise program designed to enhance balance, strength, and mobility in older adults (12). It integrates lower limb exercises, such as single-leg stands and walking, with upper limb strength training, including arm curls, to promote overall functional stability and physical wellbeing (13). These exercises aim to strengthen core and lower limb muscles, improve coordination and reaction time, while enhancing stability during standing and walking (14, 15) By gradually increasing the difficulty and complexity of the exercises, the OEP effectively enhances the physical fitness and daily living abilities of older adults (16). The structured nature of this exercise program not only helps reduce the occurrence of falls but also significantly improves physical function in older adults, effectively lowering the risk of fall-related injuries (17).

However, the effectiveness of the OEP might vary between general older adults and those with compromised health, with existing research yielding inconsistent findings. In general older adults, studies have demonstrated significant benefits of OEP in improving mobility, physical function, and balance (18). Nonetheless, the OEP shows low to moderate certainty regarding its effectiveness in improving balance, mobility, and grip strength in frail or pre-frail older adults (19). The Otago Exercise Program enhances fall efficacy in older stroke survivors and has a positive impact on daily activities and quality of life. However, these effects do not reach statistical significance (20). When the OEP was implemented in individuals with dementia, four out of five participants improved from a higher to a lower fall risk category in at least one functional assessment measure (TUG, 30s-CST, 4-SBT, or BBS) (21). The OEP intervention for osteoarthritis (OA) led to significant improvements in balance, stability, and fall efficacy over six months. However, it did not effectively reduce the incidence of falls or prolong fall-free survival time (22). Other research suggests that the OEP has no significant effect on upper limb strength in older adults (23). These results suggest that the effectiveness of the OEP may vary based on health status, particularly in older adults with poorer health conditions, where the impact of the OEP may be limited. Therefore, this study aims to evaluate the effectiveness of the OEP in preventing falls among general older adults and those with compromised health, providing scientific evidence to optimize targeted intervention strategies.

Most existing research has primarily focused on the general older adult population, with limited comparative analysis of its effects across these two groups. It remains uncertain whether the OEP is more effective in preserving mobility and preventing falls among healthier older adults or in improving physical function and reducing fall risk in those with compromised health. Clarifying these distinctions is essential for refining fall prevention strategies tailored to diverse aging populations. Further research is needed to compare the effects of the OEP between general older adults and older adults with compromised health.

To address this, the present study systematically evaluates the effectiveness of the Otago Exercise Program (OEP) in improving fall-related outcomes and physical function through a meta-analysis, comparing its effects between two distinct groups: (1) generally healthy older adults and (2) older adults with compromised health conditions. Specifically, we examine whether OEP is more effective in preventing falls and enhancing physical function in generally healthy older adults or in reducing fall risk and improving physical function in older adults with compromised health conditions.

2 Methodology

This study is based on the PICOS framework and follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) standards and has been retrospectively registered on the PROSPERO platform (CRD42024549302).

Meta-analysis was conducted using Review Manager (RevMan 5.4) and Stata 18.0. Effect sizes were reported as weighted mean differences (WMD) with 95% confidence intervals (CI), as all included studies measured the same continuous outcomes using a consistent unit of measurement. This approach enables direct comparison of effect sizes without standardization, preserving clinical interpretability and providing a clearer understanding of the intervention's impact. A random-effects model was employed to account for potential heterogeneity, which was assessed using I^2 statistic, with $I^2 > 50\%$ indicating moderate-to-high heterogeneity.

Potential publication bias was assessed through funnel plots and Egger's regression test (24). To further adjust for potential publication bias, the Trim-and-Fill method was applied (25). This non-parametric statistical method estimates the number of missing studies due to publication bias and imputes them to produce an adjusted overall effect size. The method helps determine whether the observed results are robust even after accounting for potentially missing studies. Data visualization incorporated forest plots to illustrate effect estimates with corresponding 95% CIs for each study, while sensitivity analyses were conducted to evaluate the robustness of the findings.

We conducted subgroup analyses of the Otago Exercise Program (OEP) intervention to examine the effects of session duration and total intervention duration on its effectiveness. This analysis aimed to assess whether variations in intervention length influenced fall prevention outcomes. Due to the limited number of available studies, subgroup analyses based on health conditions (e.g., cognitive impairment, musculoskeletal disorders, and frailty syndrome) were not performed. Future research should consider stratified analyses to further investigate potential differences in OEP effectiveness across these specific health conditions.

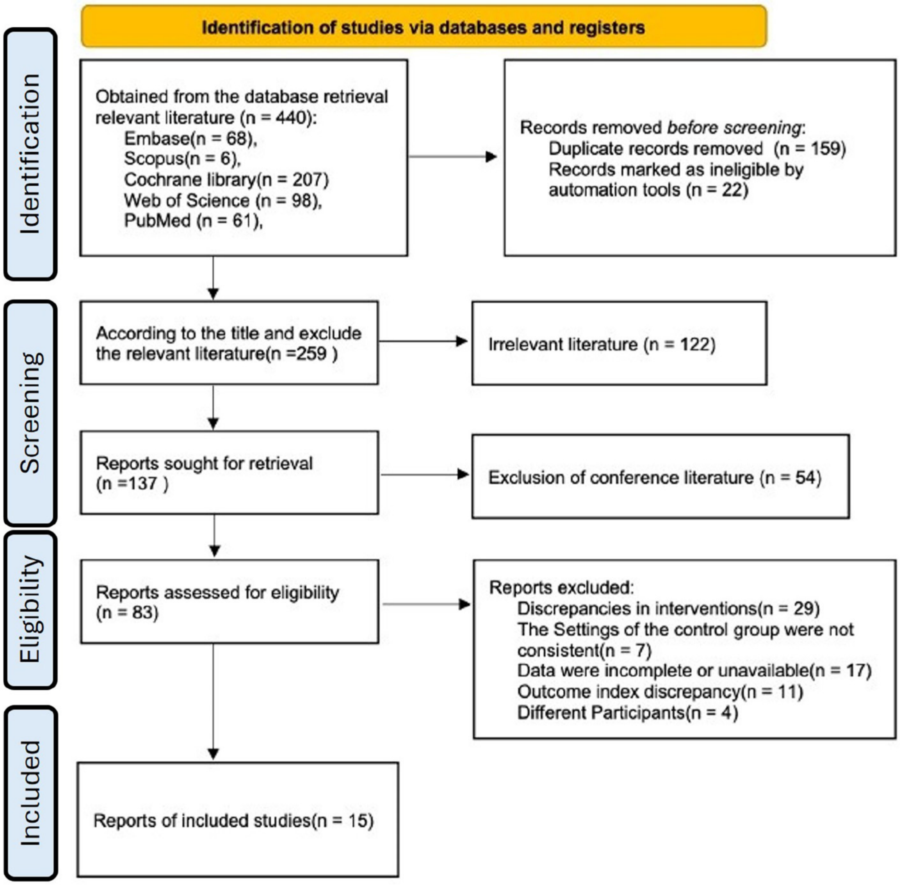

FIGURE 1
Screening flowchart.

2.1 Literature inclusion and exclusion criteria

2.1.1 Inclusion criteria

(1) This study included older adults aged ≥ 60 years, categorized into two groups: General older adults: Individuals without chronic diseases, mobility impairments, and with no cognitive impairment (MMSE ≥ 24). (2) Older adults with compromised health: Individuals with at least one of the following conditions-history of falls, cognitive impairment (defined as MMSE < 24, or where MMSE was not specified in the original study), musculoskeletal disorders, or frailty syndrome. Studies were included only if they reported fall-related outcome measures and met predefined selection criteria.

2.1.2 Exclusion criteria

(1) Duplicate publications or redundant studies reporting the same data. (2) Review articles, meta-analyses, or conference abstracts that did not contain original data. (3) Studies lacking extractable data or failing to report relevant fall-related outcomes. (4) Studies with poor methodological quality, as determined by a risk of bias assessment. (5) Studies on the OEP that did not assess fall prevention or fall-related parameters. (6) Studies without a control group, including single-arm intervention studies and observational studies without a comparator. (7) Studies involving hospitalized older adults or those in long-term care facilities, as their rehabilitation settings differ from those of community-dwelling older adults. (8) Studies including older adults with severe health conditions that could significantly limit their ability to participate in exercise interventions, such as advanced neurodegenerative diseases (e.g., late-stage Alzheimer's or Parkinson's disease), terminal illnesses, or severe cardiovascular conditions. The search strategy, inclusion criteria, screening process, and exclusion criteria were established in accordance with PRISMA guidelines.

2.2 Literature search strategy

Searches were conducted in the Web of Science, PubMed, Scopus, Cochrane Library, and Embase databases using the Boolean search terms ("old people" OR "older adult" OR "senior" OR "senior citizen" OR "aged" OR "senior adult" OR "old-age person" OR "older adult") AND ("Otago exercise" OR "Otago"). The search was conducted up to July 1, 2024. Moreover, the reference lists of included studies were hand-searched to detect any possibly missed studies, and the references of pertinent studies were also traced.

TABLE 1 Basic information of literature.

Study	Participants	Intervention characterization	Outcomes of interest/results
García-Gollarte et al. (41)	Frail older adults, EG/CG: 39/34	EG: Otago exercise, CG: Regular care	BBS, TUG, SPPB, 6MWT
Jahanpeyma et al. (42)	Older adults at high risk of falling, EG/CG: 35/36	EG: Otago exercise, CG: Walking training	BBS, 6MWT, 30CST
Liew et al. (43)	Older adults with a history of falls in the past year, EG/CG: 34/33	EG: Otago exercise, CG: Regular care	TUG, HGS-R, HGS-L
Liu-Ambrose et al. (11)	Older adults at high risk of falling, EG/CG: 31/28	EG: Otago exercise, CG: Regular care	TUG
Xiao et al. (44)	Older Adults Undergoing Hip Fracture Replacement (HFR) Patients, EG/CG: 38/39	EG: Otago exercise, CG: Regular care	TUG
Chen et al. (40)	Older adults with cognitive impairment, EG/CG: 31/31	EG: Otago exercise, CG: Regular care	BBS, TUG
Bjerk et al. (39)	Older adults with a history of falls in the past year, EG/CG: 77/78	EG: Otago exercise, CG: Regular care	BBS, 30CST
Johnson et al. (34)	Older, EG/CG: 61/56	EG: Otago exercise + Motivational interviewing, CG: Regular care	SPPB
Lytras et al. (36)	Older, EG/CG: 75/75	EG: Otago exercise, CG: Regular care	BBS, TUG, 30CST
Arkkukangas et al. (32)	Older, EG/CG: 61/56	EG: Otago exercise, CG: Regular care	SPPB, HGS-R, HGS-L
Benavent-Caballer et al. (38)	Older, EG/CG: 28/23	EG: Otago exercise, CG: No intervention	BBS, TUG, SPPB, 6MWT
Son et al. (37)	Older, EG/CG: 24/26	EG: Otago exercise, CG: Tai Chi	TUG, 30CST
Kp et al. (6)	Older, EG/CG: 15/15	EG1: Otago exercise, EG2: Gaze stability exercise	BBS
Genç and Bilgili (33)	Older, EG/CG: 28/28	EG: Otago exercise, CG: Regular care	BBS, HGS-R, HGS-L, 6MWT, 30CST
Kocic et al. (35)	Older, EG/CG: 38/39	EG: Otago exercise, CG: Regular care	TUG

2.3 Literature screening and data extraction

Two researchers performed the literature screening and data extraction. Data extracted from all selected RCTs included: detailed participant information (characteristics, sample size, age, and gender), intervention characteristics (type and frequency), and outcome measures. Balance was measured using the Berg Balance Scale (BBS) (26); physical function was evaluated with the Short Physical Performance Battery (SPPB) (27); gait was evaluated by the 6-Min Walk Test (6MWT) (28); lower limb strength was assessed using the 30-Second Chair Stand Test (30s CST) (29); mobility was evaluated with the Timed Up and Go Test (TUG) (30); and upper limb strength was measured by grip strength tests (HGR, HGL) (31).

2.4 Bias risk assessment of included studies

Two researchers used the Cochrane Handbook for Systematic Reviews of Interventions to evaluate the standard of the selected studies. For each study, judgments were made on the following seven factors: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, missing outcome data, selective reporting, and other bias sources. Each aspect was rated as "Yes" (low risk), "No" (high risk), or "Unclear." The greater the number of "low risk" ratings, the lower the potential for publication bias and the higher the study quality.

2.5 Statistical analysis

Data were analyzed using Stata 17.0 software, and a meta-analysis was conducted. Heterogeneity of the included studies was tested; if $I^2 < 50\%$, the studies were deemed homogeneous, and a fixed-effects model was applied for meta-analysis. If $I^2 \geq 50\%$, the studies were considered heterogeneous, and a random-effects model was applied for meta-analysis, along with an analysis of the sources of heterogeneity. Sensitivity analysis and Egger's regression intercept test were used to evaluate the robustness of the results and assess publication bias.

3 Research results

3.1 Basic characteristics of included studies

A total of 440 articles were collected from database searches and other sources, including 159 duplicates and 22 records marked as non-eligible (review articles) by the automation tool (EndNote20). This left 259 studies for further examination. After reviewing titles and abstracts, 176 studies were excluded for not meeting the

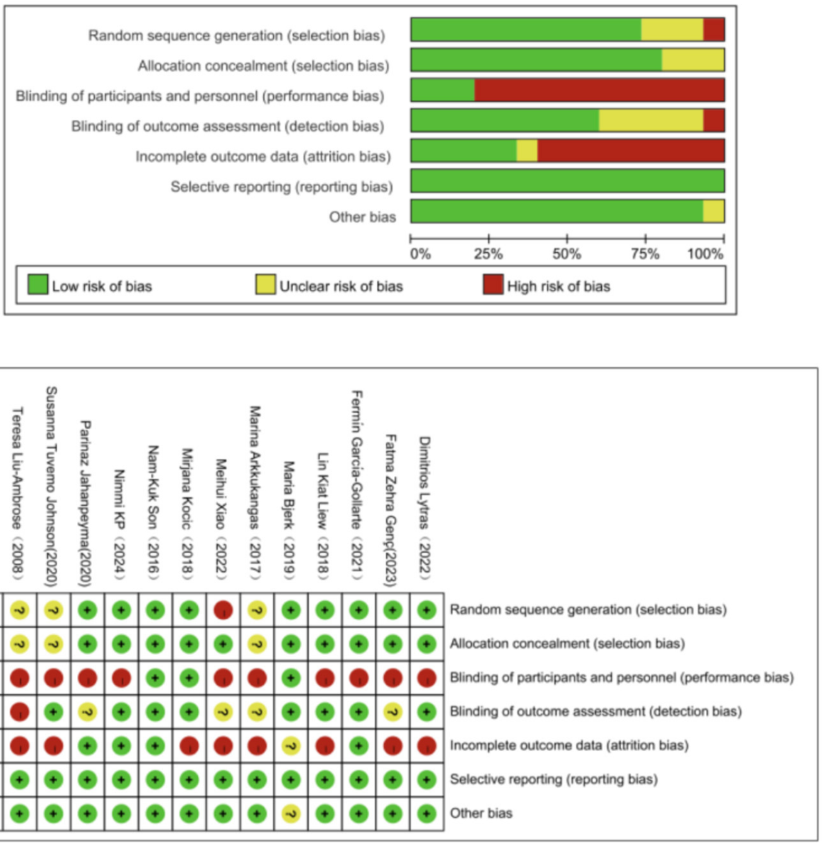

FIGURE 2
Risk of bias assessment.

criteria, leaving 83 studies for full-text review. After reviewing the full text, 15 studies were included in the meta-analysis (Figure 1).

A total of 15 RCTs included 696 participants in the intervention group and 582 participants in the control group, with a combined sample size of 1,278 participants, ranging from 15 to 160 per study. The participants were older adults aged between 60 and 92 years. Eight studies applied OEP to the general older adult population (14, 32–38), while seven studies applied OEP to older adults with high fall risk, previous fall experiences, cognitive impairment, or certain diseases (11, 39–44). Control group participants engaged in other exercise programs, such as walking (42), gaze stability exercises (GSE) combined with core muscle strengthening (6), or Tai Chi (37), Some control groups received usual care (11, 32–36, 39–41, 43, 44), while others maintained regular activities without any intervention (38). In the intervention group, three studies used a combination of OEP with other interventions: OEP plus core muscle strengthening (6), OEP plus oral nutritional supplements (41), and OEP plus motivational interviewing (32). All other studies used OEP alone, details can be seen in Table 1.

3.2 Quality assessment of included studies

The assessment was performed using the Cochrane Risk of Bias Tool, evaluating seven domains: random sequence generation (selection bias), allocation concealment (selection bias), blinding of participants and personnel (performance bias), blinding of outcome assessment (detection bias), incomplete outcome data (attrition bias), selective reporting (reporting bias), and other biases (45).

The evaluation of quality of the included studies revealed that, although most studies employed sound methods for randomization and concealment of allocation, three studies stated random allocation but failed to provide detailed information on the randomization process (11, 32, 34), and were therefore rated as having a moderate bias risk. One study used hospital admission order as the randomization method (44), and was therefore rated as having a high bias risk. Within the included studies, one was not an RCT (35). There were deficiencies in the implementation of blinding and handling of missing data. Several studies did not implement blinding (11, 14, 32–34, 36–38, 40–43), and were therefore assessed as having a high risk of bias. Two studies implemented single-blinding (39) and double-blinding (35), and were therefore rated as having a low bias risk (Figure 2).

Studies were classified as high, moderate, or low quality using the Cochrane Risk of Bias Tool. Low-quality studies were defined as those exhibiting a high risk of bias in three or more key domains, severe methodological flaws (e.g., non-randomized design, inadequate control groups), or

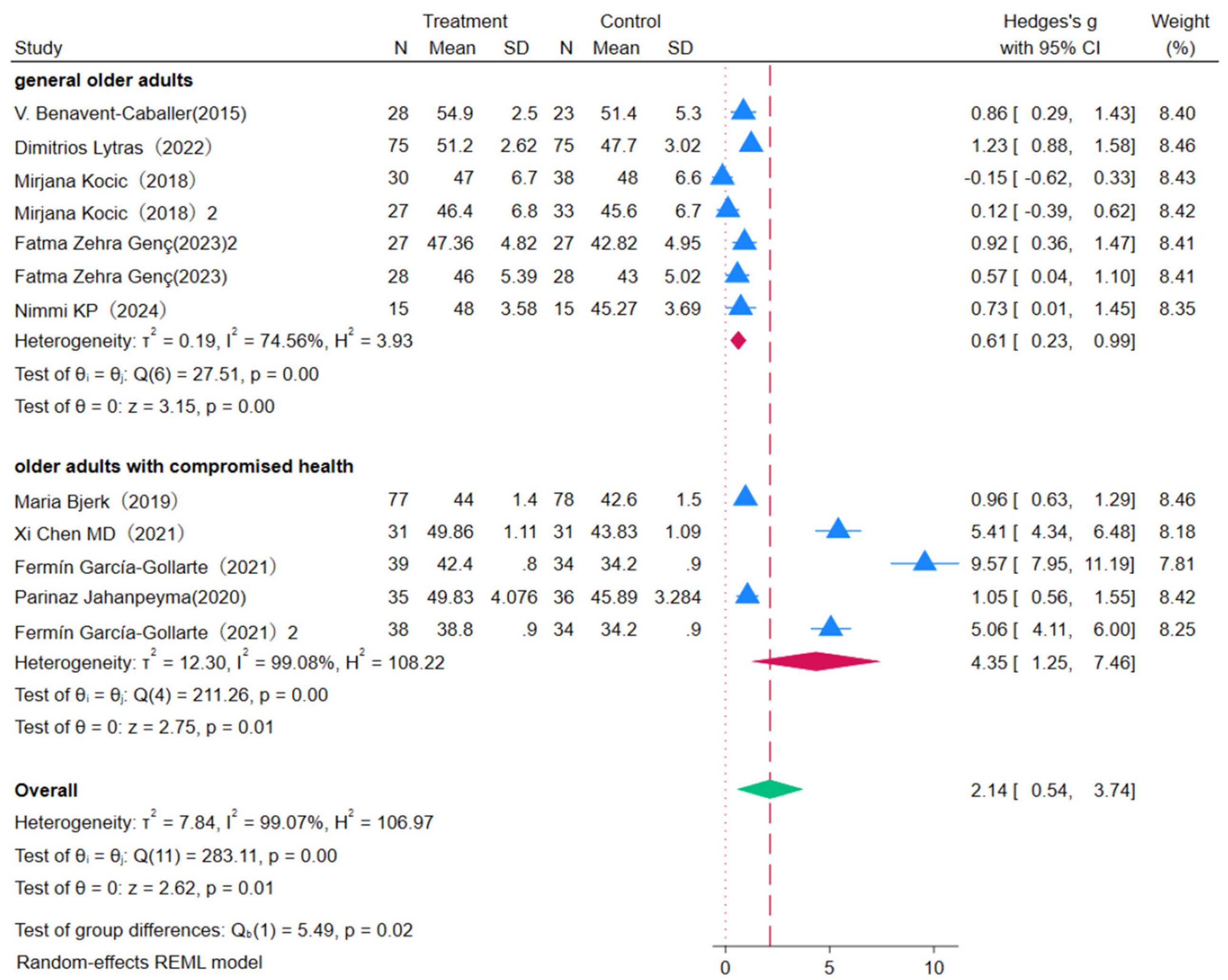

FIGURE 3
The impact of the OEP on improving balance in older adults.

small sample sizes that compromised statistical power. Such studies were excluded to ensure the reliability and validity of the results.

The quality assessment of the included studies confirmed that none met the exclusion criteria for low quality. While some exhibited moderate risk of bias (e.g., unclear randomization, lack of blinding), all adhered to essential methodological standards and were deemed appropriate for inclusion in the meta-analysis.

3.3 Effect of OEP on balance in older adults

Eight studies were included to evaluate the impact of OEP intervention on balance in older adults, using the Berg Balance Scale (BBS) as the assessment metric (Figure 3). Due to high heterogeneity among studies ($P = 0.00$, $I^2 = 99.07\%$), a random-effects model was used for the meta-analysis. The results showed that the OEP program significantly improves balance in older adults [WMD = 2.14, 95% CI $(0.54, 3.74)$, $p = 0.00$], though the effects varied among different populations. Specifically, the effect was more pronounced in older adults with compromised health [WMD = 0.61, 95% CI $(0.23, 0.99)$] and in the general older adult population [WMD = 4.35, 95% CI $(1.25, 7.46)$]. This indicates that populations with poorer baseline balance have greater potential for improvement. The p-value of 0.02 and $p < 0.05$ indicate a statistically significant difference between the two groups, suggesting that older adults with compromised health showed more significant improvements in balance following OEP intervention relative to the general older adult population. Given the high heterogeneity in the meta-analysis, sensitivity analysis showed that excluding the majority of studies did not notably change the effect size estimates or confidence intervals, indicating the robustness of the meta-analysis results. Egger's regression intercept test showed notable reporting bias ($p = 0.002$). To further assess the reliability of the findings, the Trim-and-Fill method was applied to identify and adjust for potential publication bias. After imputing

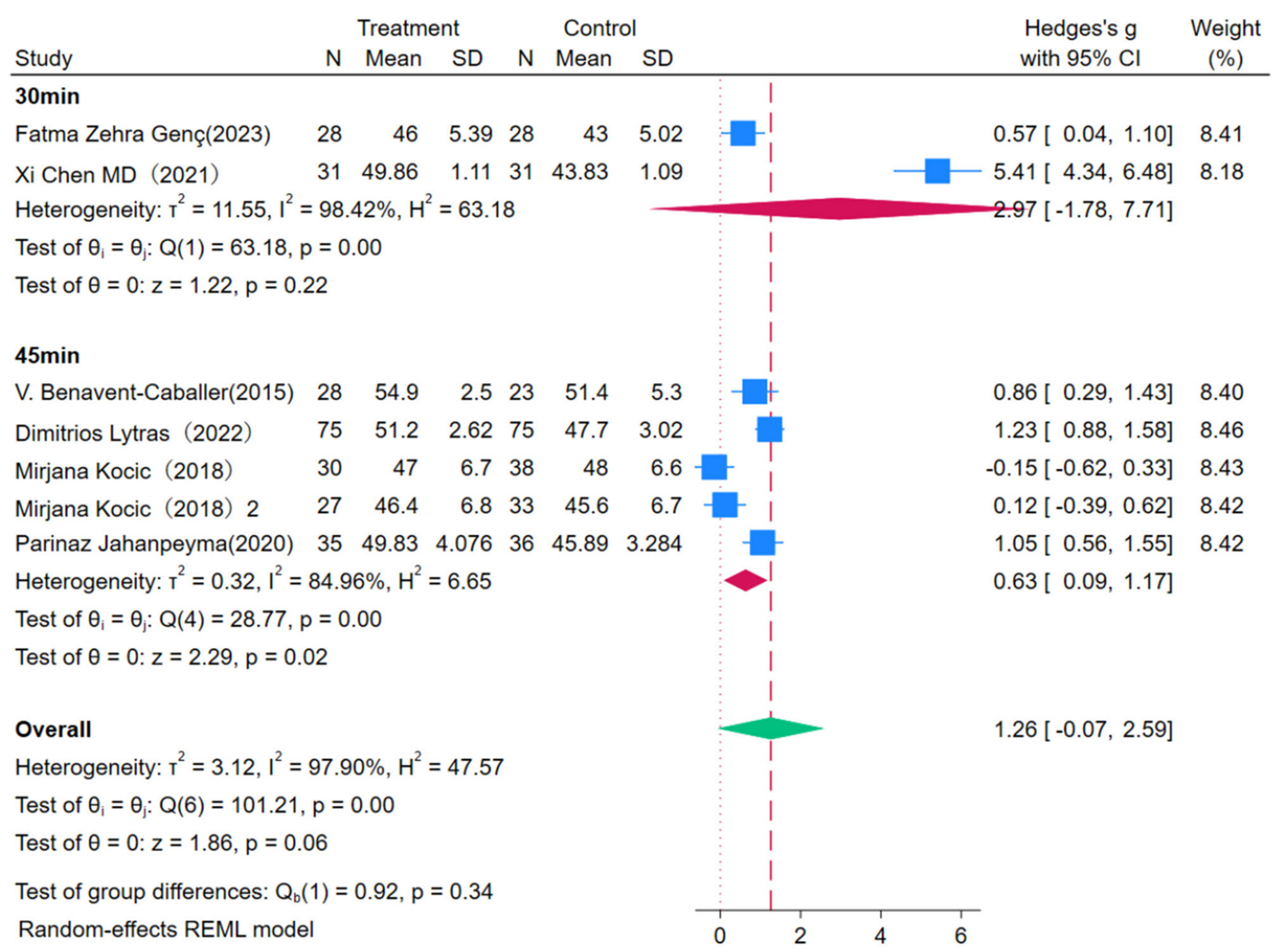

FIGURE 4
Subgroup analysis results for balance.

the missing studies, the combined effect size was slightly reduced but remained statistically significant, indicating the robustness of the results.

This study conducted a subgroup analysis on the effect of OEP intervention duration on balance improvement in older adults (Figures 4, 5). The overall effect size [WMD = 2.14, 95% CI (0.54, 3.74)], indicating a positive impact of OEP on balance ability. Among different intervention durations, the 4 month intervention showed the most stable effect [WMD = 0.86, 95% CI (0.29, 1.43)], whereas the 2–3 month [WMD = 1.32, 95% CI (0.02, 2.61)] and 6 month [WMD = 3.94, 95% CI (–0.21, 8.10)] groups exhibited high heterogeneity, making the results less robust. Interventions with 45 minutes of exercise per session were more effective in improving balance in older adults [WMD = 0.63, 95% CI (0.09, 1.17)], whereas 30-min sessions, although statistically significant [WMD = 2.97, 95% CI (–1.78, 7.71)], had a wider confidence interval including zero, making the effect statistically non-significant. Therefore, it is recommended to consider extending exercise duration in clinical practice to enhance effectiveness.

3.4 Impact of Otago Exercise Program on older adults' physical function

Four studies evaluating the impact of OEP intervention on older adults' physical function used SPPB as the assessment measure. Due to substantial heterogeneity among studies (P = 0.00, I^2 = 82.10%), a random-effects model was used for the meta-analysis (Figure 6). The results indicate that OEP has a marginal impact on the overall physical function of older adults [WMD = 0.11, 95% CI $(-0.05, 0.35)$], with a wide confidence interval that includes zero, making the effect statistically non-significant. The effect on older adults with compromised health [WMD = 0.00, 95% CI $(-1.54, 1.54)$] and on the general older adult population [WMD = 0.15, 95% CI $(-0.05, 0.35)$] was also non-significant. This lack of significance may be due to insufficient sample sizes. Future research should increase sample size and diversity to further validate and expand these findings. Given the high heterogeneity, sensitivity analysis was conducted to assess the impact of each study on the overall results. The results indicated that the exclusion of most studies did not significantly alter the effect size

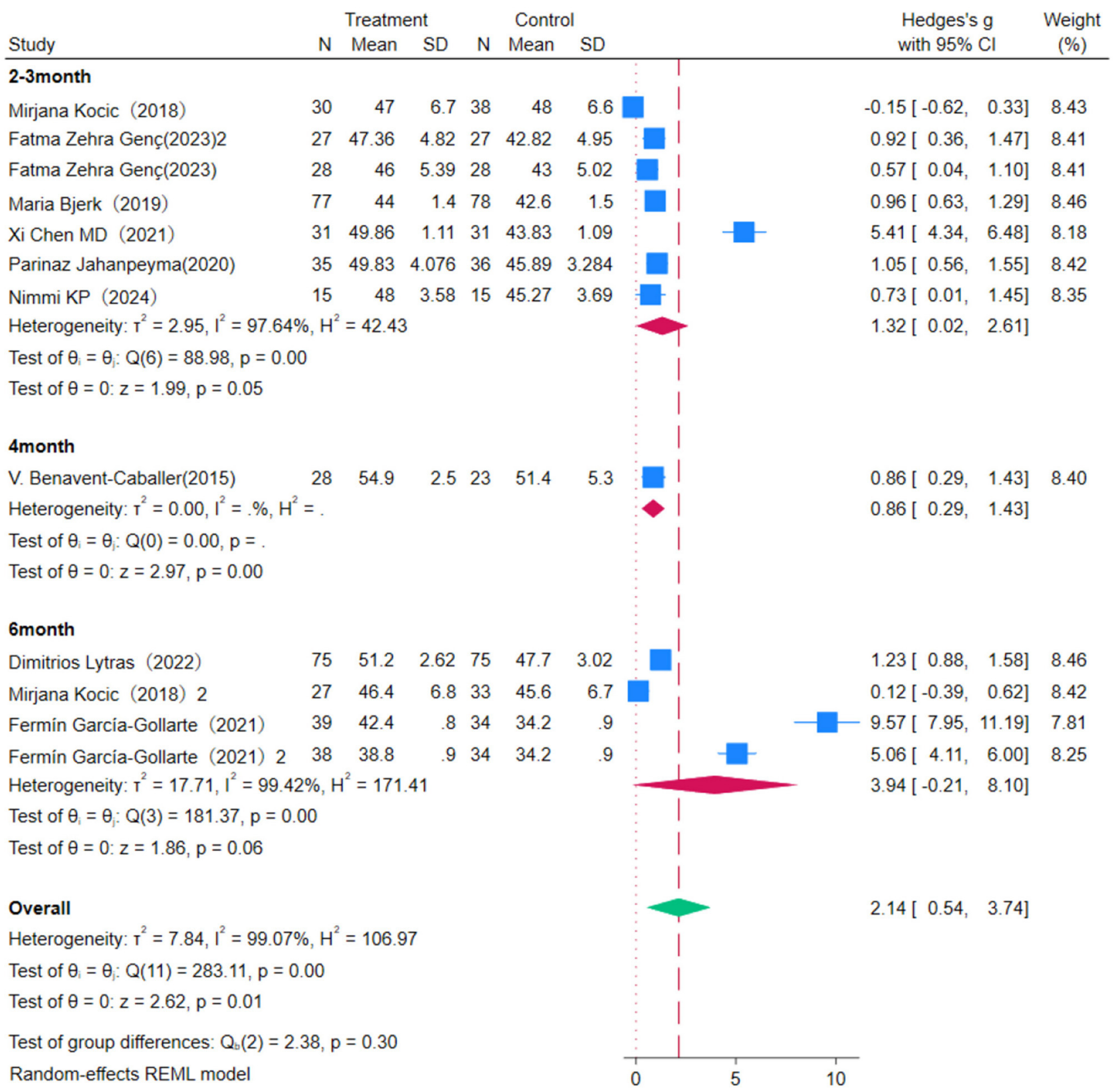

FIGURE 5
Subgroup analysis results for balance.

estimates or confidence intervals, demonstrating the robustness of the meta-analysis findings. The meta-analysis results were not significantly affected by individual study biases. The Egger's regression intercept test indicated no significant publication bias ($p = 0.957$). However, the Trim-and-Fill method identified and imputed two potentially missing studies, indicating a certain degree of publication bias. However, after adjusting for these missing studies, the effect size remained statistically non-significant. This suggests that while some publication bias may be present, it is unlikely to have a substantial impact on the overall conclusion.

Subgroup analysis indicated that OEP did not significantly affect the Physical Function of older adults across different intervention durations and session lengths. To better understand the true impact of varying intervention durations, further high-quality, standardized studies are recommended.

3.5 Impact of OEP on older adults' gait

Four studies evaluated the impact of OEP intervention on older adults' gait, using the 6MWT as the assessment measure.

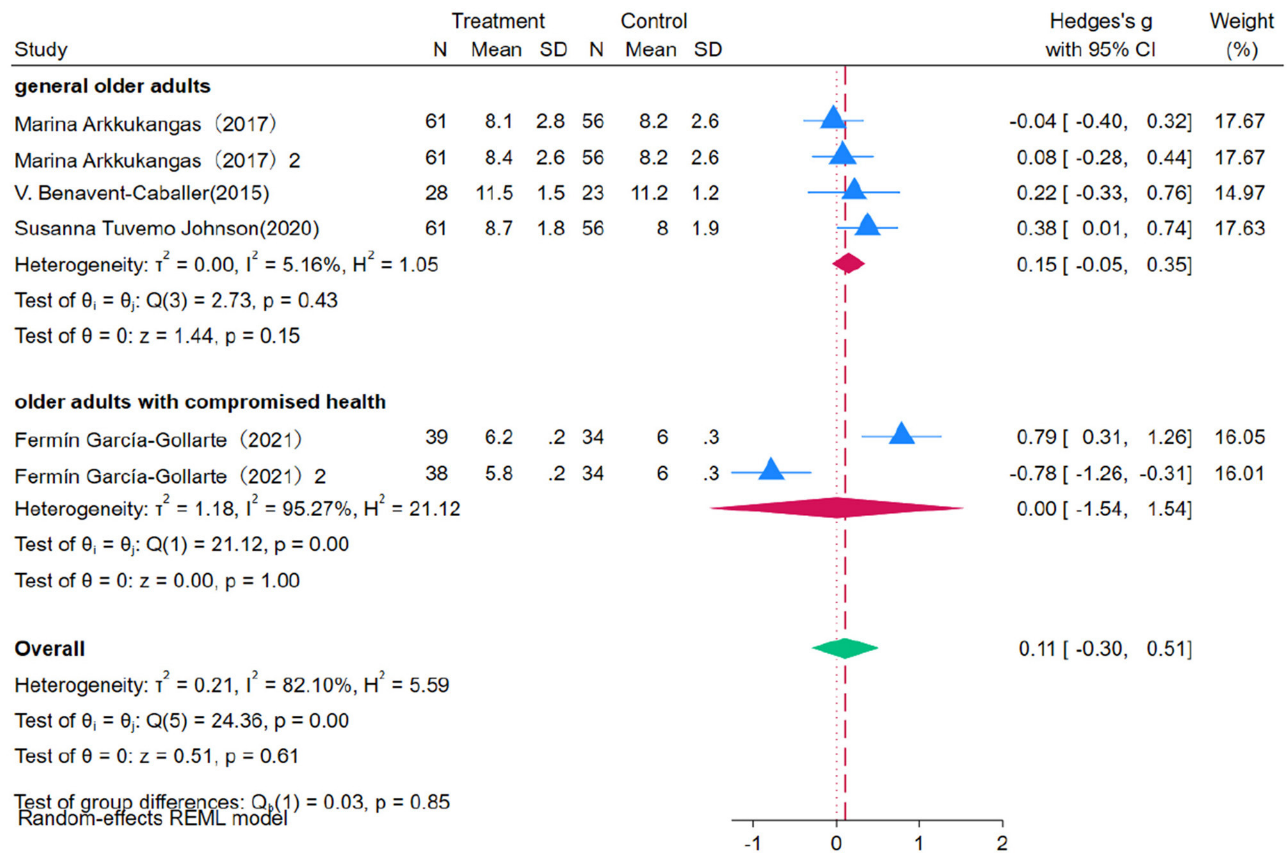

FIGURE 6
The impact of the OEP on improving physical function in older adults.

Due to substantial heterogeneity among studies ($P = 0.00$, $I^2 = 73.72\%$), a random-effects model was employed for the meta-analysis (Figure 7). The results showed that OEP significantly improved older adults' gait [WMD = 0.71, 95% CI (0.30, 1.11)]. The improvement in gait for general older adults [WMD = 0.49, 95% CI (0.18, 0.80)] was less pronounced compared to the improvement for older adults with compromised health [WMD = 0.92, 95% CI (0.13, 1.72)]. Given the high heterogeneity observed in the meta-analysis, sensitivity analysis revealed that excluding the majority of studies did not substantially alter the effect size estimates or confidence intervals, confirming the robustness of the findings. The Egger's regression intercept test indicated that publication bias was not significant ($p = 0.573$), suggesting that the results are reliable and representative. The Trim-and-Fill method identified and imputed two potentially missing studies, suggesting the presence of some publication bias. The adjusted effect size remained statistically significant, indicating that while some publication bias may exist, it does not substantially affect the overall conclusions, and the findings remain robust.

Through subgroup analysis, it was found that OEP is more effective for older adults who engage in long-term participation (Figures 8, 9). The effect of a six-month intervention [WMD = 0.89, 95% CI (0.05, 1.74), $p = 0.00$] is superior to that of a 2–3-month intervention [WMD = 0.52, 95% CI (0.22, 0.81), $p = 0.86$]. These findings suggest that a longer duration of OEP intervention may be more effective in improving gait among older adults, particularly those with compromised health. Clinical practice should consider extending the intervention duration to maximize its benefits and enhance overall effectiveness. For exercise duration per session, 30 min [WMD = 0.49, 95% CI (−0.04, 1.01)] has a broad confidence interval including zero, indicating statistical insignificance; while 45 minutes of exercise per session [WMD = 0.40, 95% CI (0.04, 0.75)] demonstrates a significant positive impact, suggesting that longer exercise duration may be more effective in improving gait in older adults. Although OEP significantly improves gait in older adults, the limited number of included studies necessitates cautious interpretation of the generalizability of these findings. Future research should aim for larger sample sizes and longer intervention durations to provide more robust evidence.

3.6 The impact of the OEP on improving lower limb strength in older adults

Four studies were included to evaluate the effect of OEP intervention on lower limb strength in the older adult, using the 30s CST as the assessment metric. Due to substantial

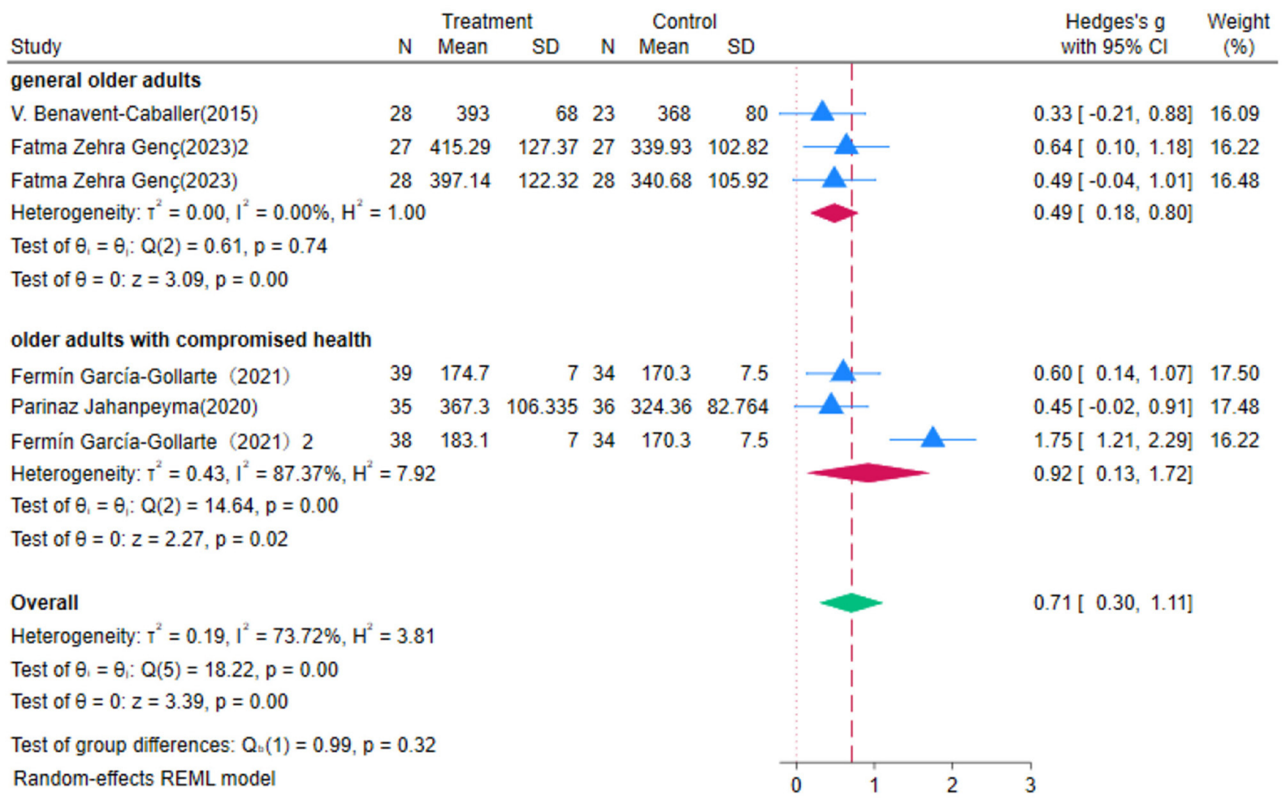

FIGURE 7
The impact of the OEP on improving gait in older adults.

heterogeneity among the studies ($P = 0.00$, $I^2 = 91.67\%$), a random-effects model was employed for the meta-analysis (Figure 10). The results indicate that OEP significantly improves lower limb strength in older adults [WMD = 1.30, 95% CI (0.63, 1.98)]. OEP intervention demonstrates a more pronounced effect on improving lower limb strength in older adults with compromised health [WMD = 2.24, 95% CI (1.04, 3.45)] compared to the general older adult population [WMD = 0.84, 95% CI (0.61, 1.07)]. The statistical significance ($P = 0.03$, $p < 0.05$) indicates that the difference in effect size between the two groups is significant, suggesting that older adults with compromised health experience greater improvements in lower limb strength following OEP intervention compared to the general older adult population. Funnel plot analysis indicated potential publication bias in the 30s CST, as evidenced by asymmetry and the presence of imputed studies identified through the Trim-and-Fill method. However, after adjusting for these missing studies, the overall effect size remained statistically significant, suggesting that while some degree of publication bias may exist, it does not substantially affect the robustness of the findings. Egger's regression intercept test indicated that publication bias was not significant ($p = 0.545$), suggesting that the results are reliable and representative.

Subgroup analysis reveals that OEP significantly improves lower limb strength in older adults (Figures 11, 12), with a more pronounced effect observed in interventions lasting 2–3 months [WMD = 1.66, 95% CI (0.84, 2.47)] compared to those lasting six months [WMD = 0.84, 95% CI (0.50, 1.17)]. These differences suggest that short-term interventions may yield quicker results, while longer interventions might help in consolidating these gains. Regarding the duration of each exercise session, 30-min sessions [WMD = 0.95, 95% CI (0.40, 1.49)] were effective in improving lower limb strength. In contrast, 45-minute [WMD = 1.84, 95% CI (−1.84, 3.85)] and 60-min sessions [WMD = 0.37, 95% CI (−0.21, 0.95)] had wide confidence intervals that included zero, indicating statistically non-significant effects. The significant improvement with 30-min sessions could be attributed to the duration being short enough to avoid fatigue, thereby maximizing the exercise's benefits. This indicates that OEP is particularly effective under specific conditions, such as 30-min sessions, but the optimal exercise duration may vary depending on participant characteristics and specific study conditions. To achieve the best outcomes, it is recommended that exercise duration be adjusted in clinical practice according to individual needs and capabilities.

3.7 The impact of the OEP on improving mobility in older adults

Nine studies were included to evaluate the effect of OEP on the mobility of older adults, using the Timed Up and Go

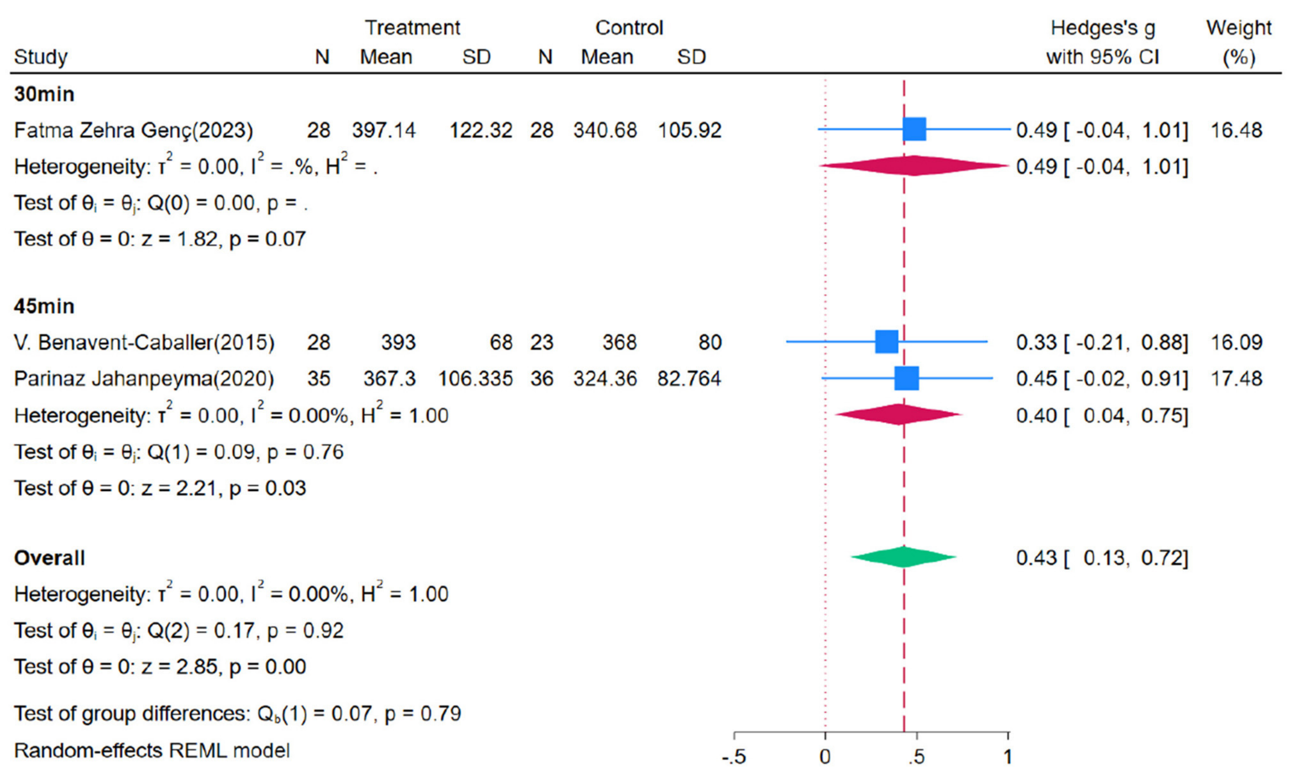

FIGURE 8
Subgroup analysis results for gait.

(TUG) test as the assessment metric. Given the low heterogeneity observed ($P = 0.00$, $I^2 = 97.97\%$), a fixed-effects model was used in the meta-analysis (Figure 13). According to the findings, OEP significantly improved mobility in older individuals [WMD $= -1.32$, 95% CI $(-2.45, -0.20)$]. Compared to general older adults [WMD $= -0.43$, 95% CI $(-0.99, 0.13)$], the improvement in mobility was more pronounced in older adults with compromised health [WMD $= -2.10$, 95% CI $(-4.00, -0.20)$]. However, the wide confidence intervals that included zero for the general older adults group indicate that the effect was not statistically significant. Thus, OEP may be particularly beneficial for older adults with compromised health, as it can significantly improve their mobility. For general older adults, further adjustments or enhancements to interventions may be necessary to achieve significant effects. Despite the high heterogeneity in the meta-analysis, sensitivity analysis showed that the exclusion of most studies did not significantly alter the effect size estimates or confidence intervals, indicating robust results in this meta-analysis. Egger's regression intercept test indicated significant publication bias ($p = 0.001$). To further assess the stability of the results, the Trim-and-Fill method was applied, identifying and imputing two potentially missing studies. The adjusted effect size remained statistically significant, suggesting that while some degree of publication bias may be present, the core findings remain robust.

Subgroup analysis revealed that OEP did not significantly impact the mobility of older adults across varied intervention durations and session lengths. It is recommended that more standardized, high-quality studies be conducted to clarify the actual impact of different intervention durations.

3.8 The impact of the OEP on improving upper limb strength in older adults

Nine studies were included to evaluate the impact of OEP on upper limb strength in older adults, using grip strength as the primary outcome measure. Due to minimal heterogeneity ($P = 0.00$, $I^2 = 0.00\%$), a fixed-effects model was applied for the meta-analysis (Figures 14, 15). The results indicated that the improvement in right-hand grip strength [WMD $= 0.17$, 95% CI $(-0.06, 0.41)$] and left-hand grip strength [WMD $= 0.11$, 95% CI $(-0.12, 0.35)$] was not statistically significant, as the confidence intervals included zero. Similarly, for general older adults, the improvement in right-hand grip strength [WMD $= 0.24$, 95% CI $(-0.22, 0.50)$] and left-hand grip strength [WMD $= 0.19$, 95% CI $(-0.07, 0.44)$] was not significant, nor was the improvement in right-hand [WMD $= -0.14$, 95% CI $(-0.70, 0.42)$] and left-hand grip strength [WMD $= -0.22$, 95% CI $(-0.77, 0.34)$] among older adults with compromised health. Therefore, the OEP does not appear to significantly improve upper limb strength in older adults. Egger's regression intercept test revealed no significant publication bias (right-hand grip strength $p = 0.863$, left-hand grip strength

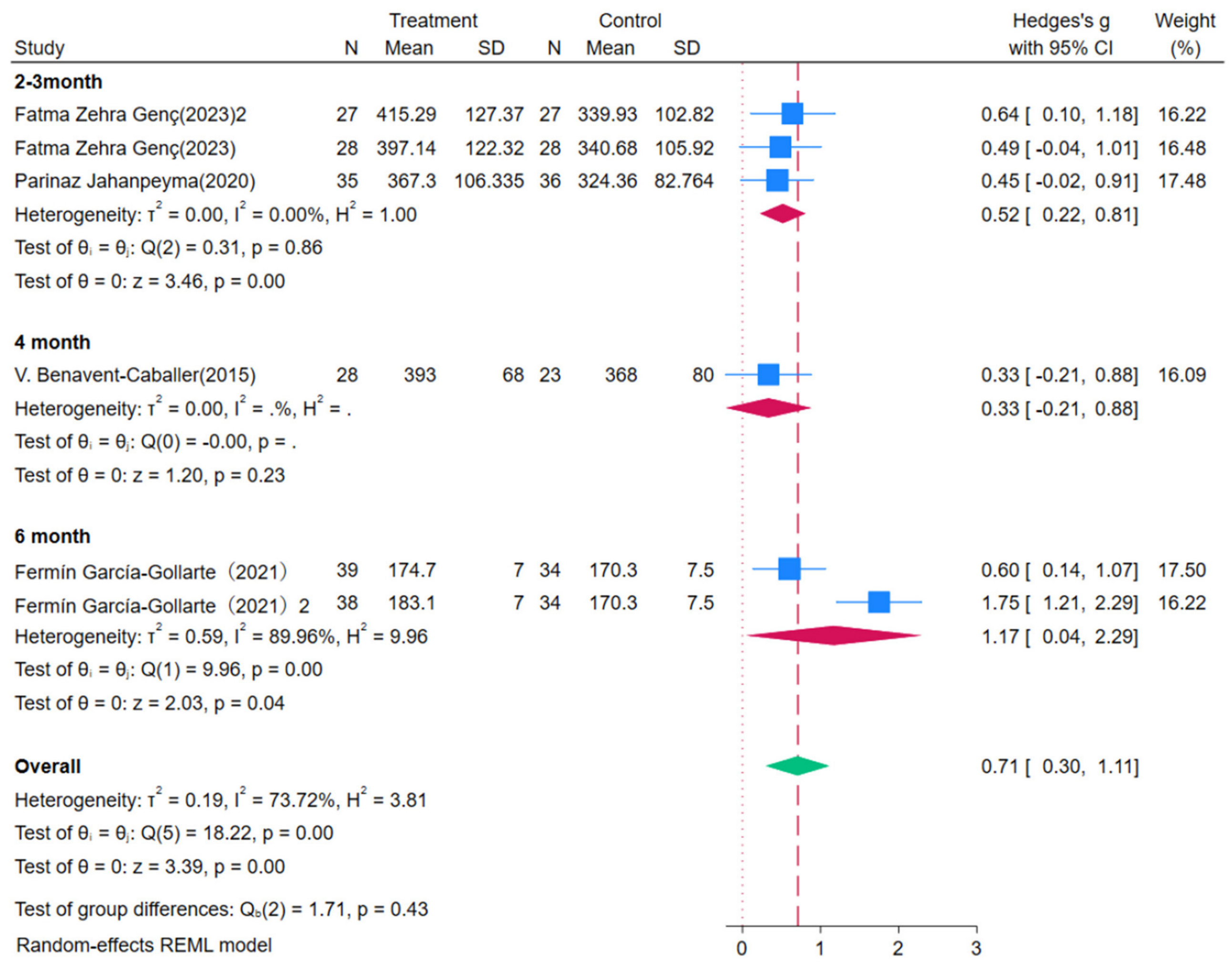

FIGURE 9
Subgroup analysis results for gait.

$p = 0.981$), indicating the reliability and representativeness of the results.

Due to the extremely low heterogeneity ($I^2 = 0.00\%$) observed in the meta-analysis, a sensitivity analysis was not performed, as excluding individual studies is unlikely to impact the effect size estimates. The use of a fixed effects model further reinforces the robustness of the results. Additionally, Egger's regression intercept test indicated no significant publication bias (right-hand grip strength: $p = 0.863$; left-hand grip strength: $p = 0.981$), confirming the reliability and representativeness of the findings.

4 Discussion

This study conducted a meta-analysis to evaluate the impact of OEP on fall-related outcomes in both general older adults and older adults with compromised health. While OEP is designed to target fall susceptibility—a common risk factor among the older adults with compromised health—we acknowledge that variations in underlying health conditions may lead to subtle differences in intervention effectiveness. This study includes older adults with various conditions; however, the number of available studies was insufficient to conduct a meaningful subgroup analysis. Nonetheless, previous research has consistently demonstrated the effectiveness of OEP in reducing fall risk among individuals with cognitive impairment, musculoskeletal disorders, and frailty syndrome (19, 46, 47). Therefore, we analyzed these conditions collectively while acknowledging the potential for variations in intervention effects.

Although 17 included studies had a moderate to high risk of bias, their inclusion in the meta-analysis was essential to ensure a comprehensive synthesis of the available evidence. Excluding these studies would have significantly reduced the sample size, potentially introduced selection bias and limited the generalizability of the findings. To assess the impact of these methodological limitations, we conducted sensitivity analyses

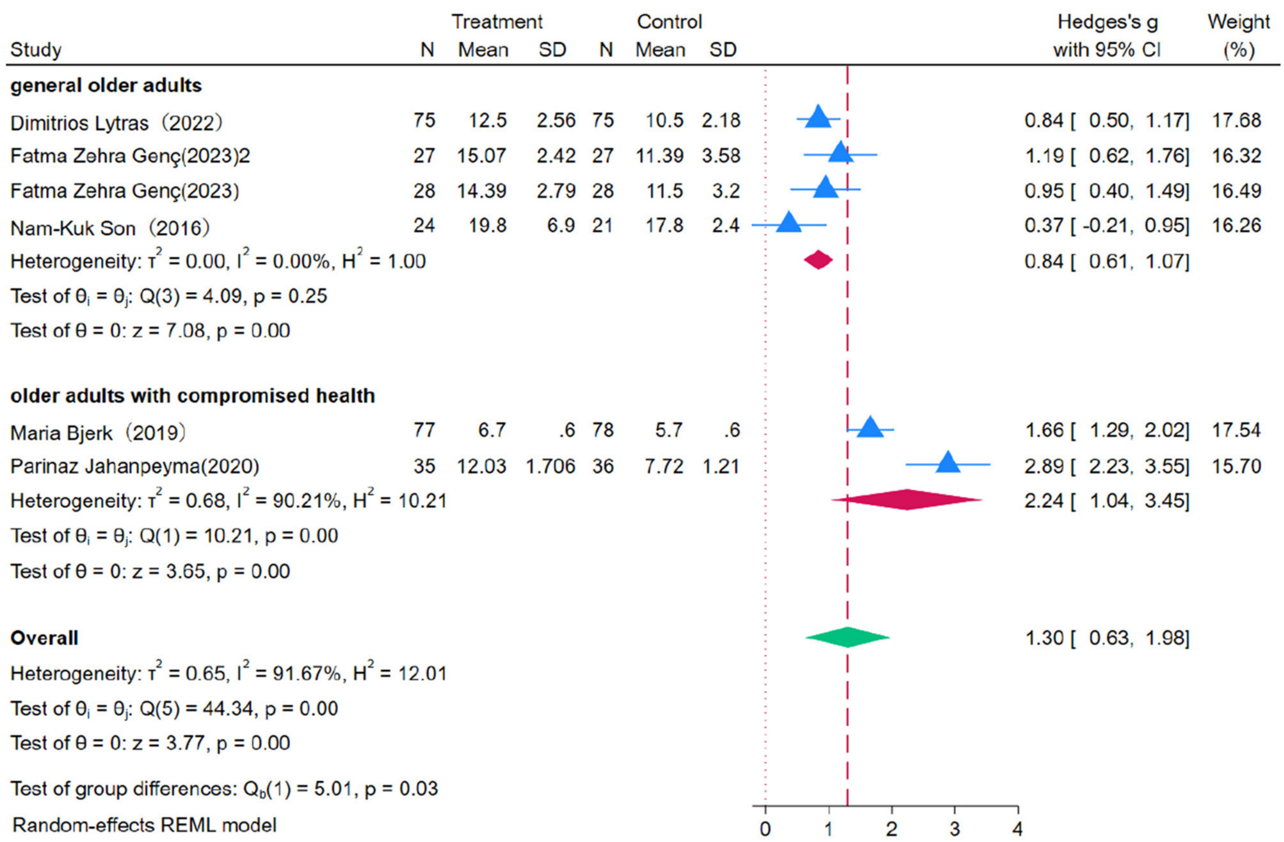

FIGURE 10
The impact of the OEP on improving lower limb strength in older adults.

by systematically excluding these studies. The results remained consistent, confirming that their inclusion did not substantially alter the overall effect size estimates or confidence intervals. Additionally, Egger's regression test indicated significant reporting bias ($p = 0.002$), prompting the application of the Trim-and-Fill analysis to adjust for potential publication bias. The adjusted results remained statistically significant, further supporting the robustness of our conclusions. While certain studies exhibited biases in allocation concealment and blinding, their outcome assessments remained reliable, and these limitations were carefully considered in the interpretation of results. Therefore, despite inherent methodological concerns, the inclusion of these studies strengthens the overall analysis by maximizing available data, and sensitivity analyses affirm the stability and validity of our findings.

The results indicate that the OEP has a significant effect on improving balance, gait, and lower limb strength in older adults, although the extent of improvement varies among different populations. Consistent with previous studies, OEP has been shown to effectively enhance lower limb strength, balance, and gait in general older adults (13, 17, 48, 49). However, it does not significantly improve physical function, mobility, or upper limb strength in this population. Conversely, some studies have reported positive effects of OEP on physical function (43), mobility (23), and upper limb strength (50), highlighting the variability in outcomes across different study populations and intervention protocols. These discrepancies may be attributed to differences in participant characteristics, baseline functional levels, and variations in OEP implementation, including exercise intensity, frequency, and adherence rates.

As a fall prevention intervention, the OEP provides significant health benefits for general older adults, particularly in enhancing lower limb strength and balance. This effect may be attributed to specific exercises in the program, such as knee flexion, knee extension, and hip abduction, which are designed to strengthen leg muscles in older adults. Through cyclical contraction and relaxation, these exercises promote muscle and joint flexibility, balance, and motor control. Research has shown that the OEP is beneficial for older adults with osteoarthritis and gait balance disorders, significantly improving postural control (10).

Repeated exercises involving sitting, standing, and walking have been shown to improve lower limb strength in older adults (10). However, the results of this study indicate that its impact on physical function, mobility, and upper limb strength is not significant. Studies have shown that the OEP can improve physical function in older adults, including balance, lower limb strength, and mobility (23). This is inconsistent with the findings of the

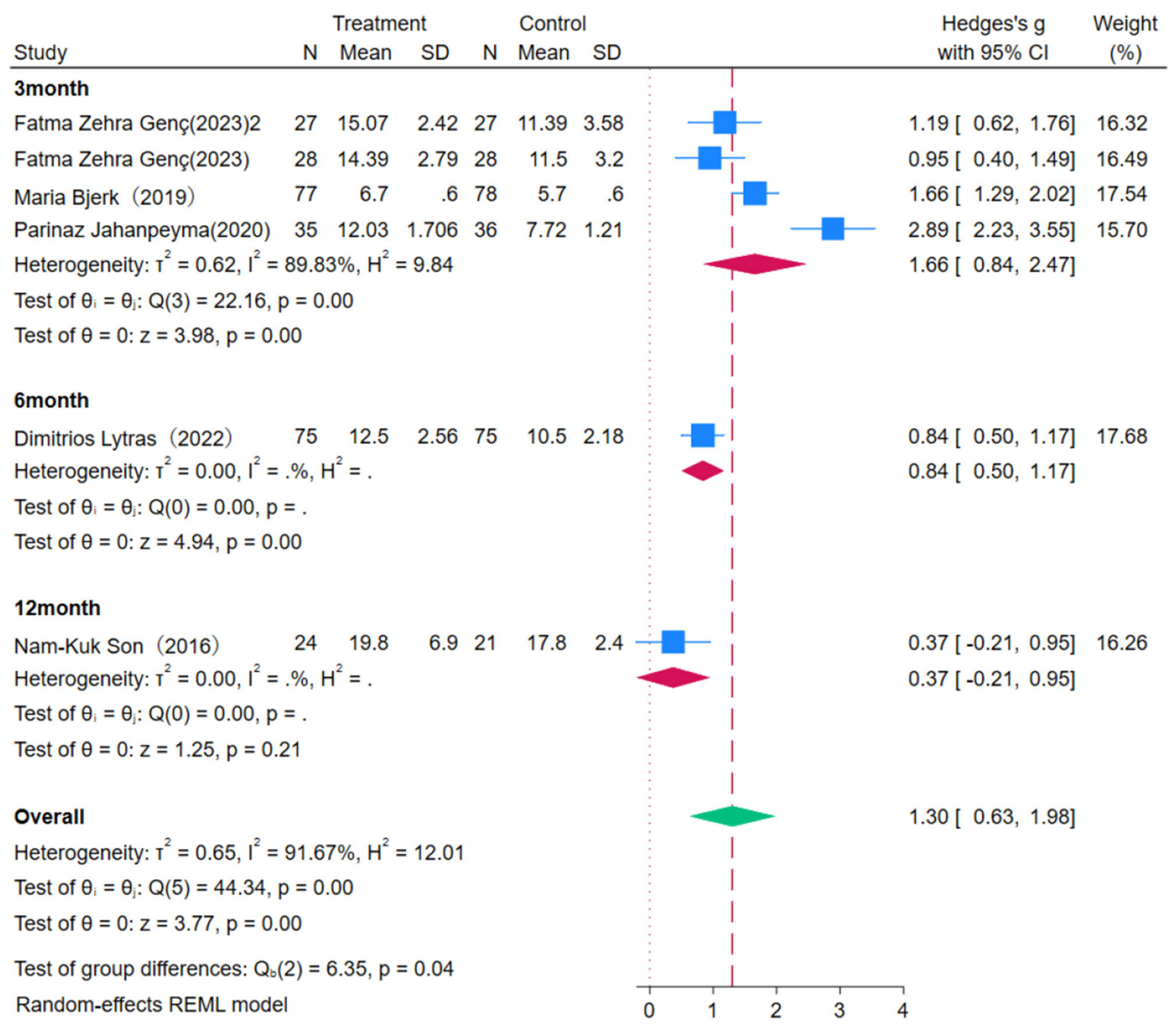

FIGURE 11
Subgroup analysis results for lower limb strength.

present study. This may be due to the OEP's primary focus on lower limb strength and balance training, which incorporates resistance and aerobic exercises through warm-up activities, strength training, balance exercises, and walking training (17). The program is heavily focused on lower limb strength and balance training, incorporating both resistance and aerobic exercises (28), which leads to higher intensity and frequency for lower limb and balance training. However, the upper limb strength training may not be sufficiently systematic or intense, thus failing to produce significant improvements.

This study demonstrates that OEP exhibits more significant positive effects on balance, gait, lower limb strength, and mobility in older adults with compromised health. This study demonstrates that the OEP has significant positive effects on balance, gait, lower limb strength, and mobility in older adults with compromised health.

High-quality evidence supports the effectiveness of the Otago Exercise Program in reducing fall risk among individuals with osteoarthritis (OA) (46). Additionally, OEP has been shown to benefit individuals with cognitive impairment, enhancing balance and functional mobility (51). These findings highlight OEP as a valuable intervention for older adults with varying health conditions, particularly those at higher risk of falls. The observed outcomes may be attributed to the lower baseline functional levels of older adults with compromised health, including reduced muscle strength, balance, and mobility. Additionally, these individuals often have stronger expectations for recovery, which may lead to higher engagement and adherence to rehabilitation training, thereby maximizing the benefits of OEP. Research has shown that OEP positively impacts balance, physical activity, and upper limb strength in older adults with reduced health status (19).

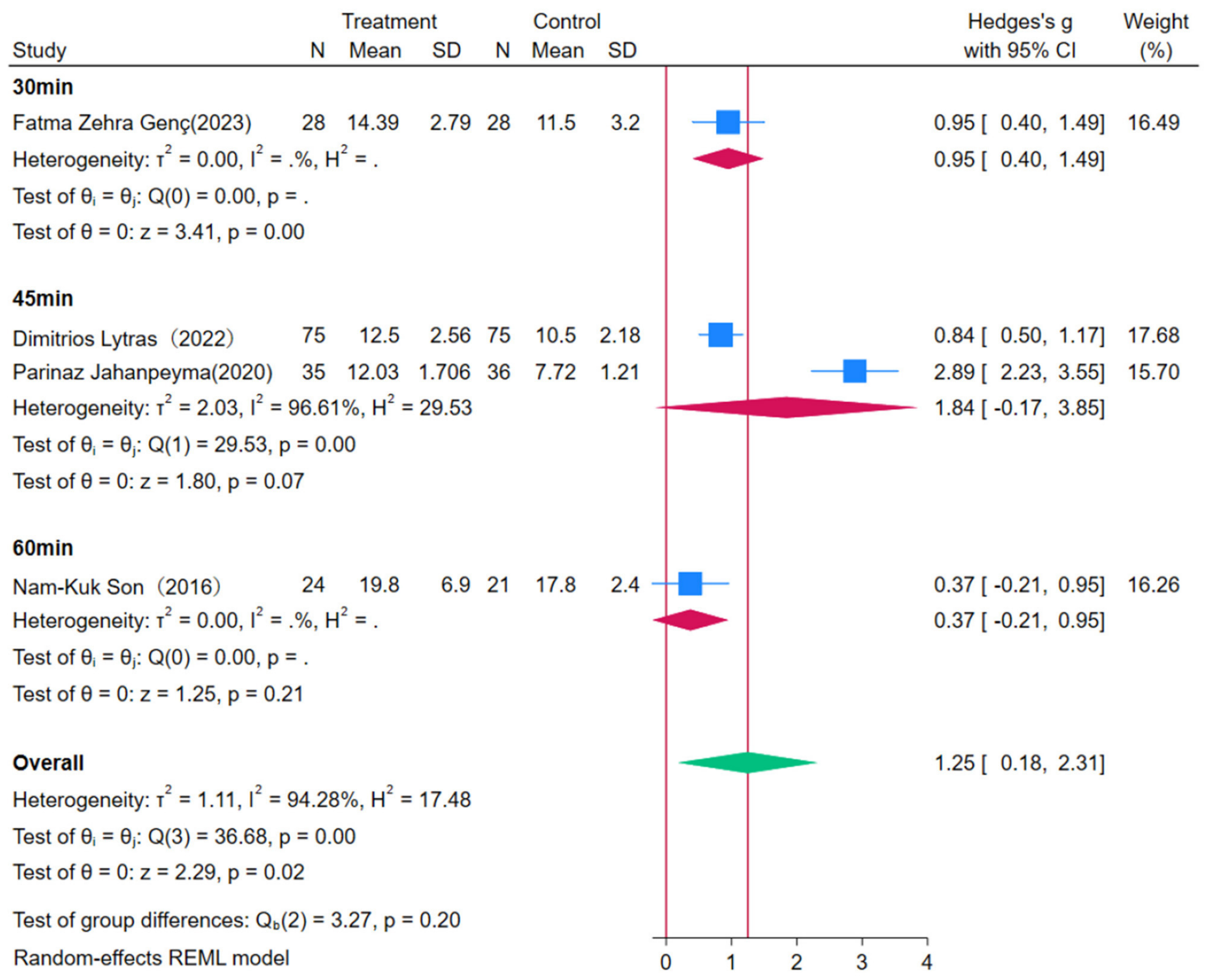

FIGURE 12
Subgroup analysis results for lower limb strength.

Our findings align with previous studies indicating that OEP can effectively mitigate the decline in lower limb muscle strength in older adults (22). The walking exercises included in the OEP—such as backward walking, zigzag walking, side walking, straight walking, and stair climbing—likely contribute to muscle strengthening and improved coordination through continuous isometric flexion of the hip flexors and ankle joints (22). The primary goal of the Otago Exercise Program is to reduce fall risk through targeted limb strength training and balance exercises (46). These diverse gait training exercises not only enhance lower limb muscle strength but also improve balance and gait control, thereby reducing fall risk and improving mobility in daily life. However, the results regarding upper limb strength contrast with those of other studies (43). In this study, OEP did not significantly improve upper limb strength in older adults with compromised health.

The primary goal of the OEP is fall prevention, with a focus on lower limb strength, balance, and gait training, rather than systematic upper limb strength exercises. This suggests that upper limb training is not a central component of the OEP. Additionally, older adults generally have lower baseline upper limb muscle strength, indicating that more targeted and intensive training may be required to achieve significant improvements. The OEP alone may not provide sufficient stimulus for upper limb muscle adaptation and strengthening, resulting in non-significant improvements in upper limb strength. Future research should explore incorporating dedicated upper limb strength training into the OEP to enhance overall physical function in older adults. Research indicates that lower upper limb strength is directly related to impaired activities of daily living (52) and slower walking speed (53). Thus, the lack of significant improvements in physical function and the limited effects on mobility observed in this study can be attributed to this.

Additionally, the results of the subgroup analysis indicate that differences exist in study design, sample selection, data

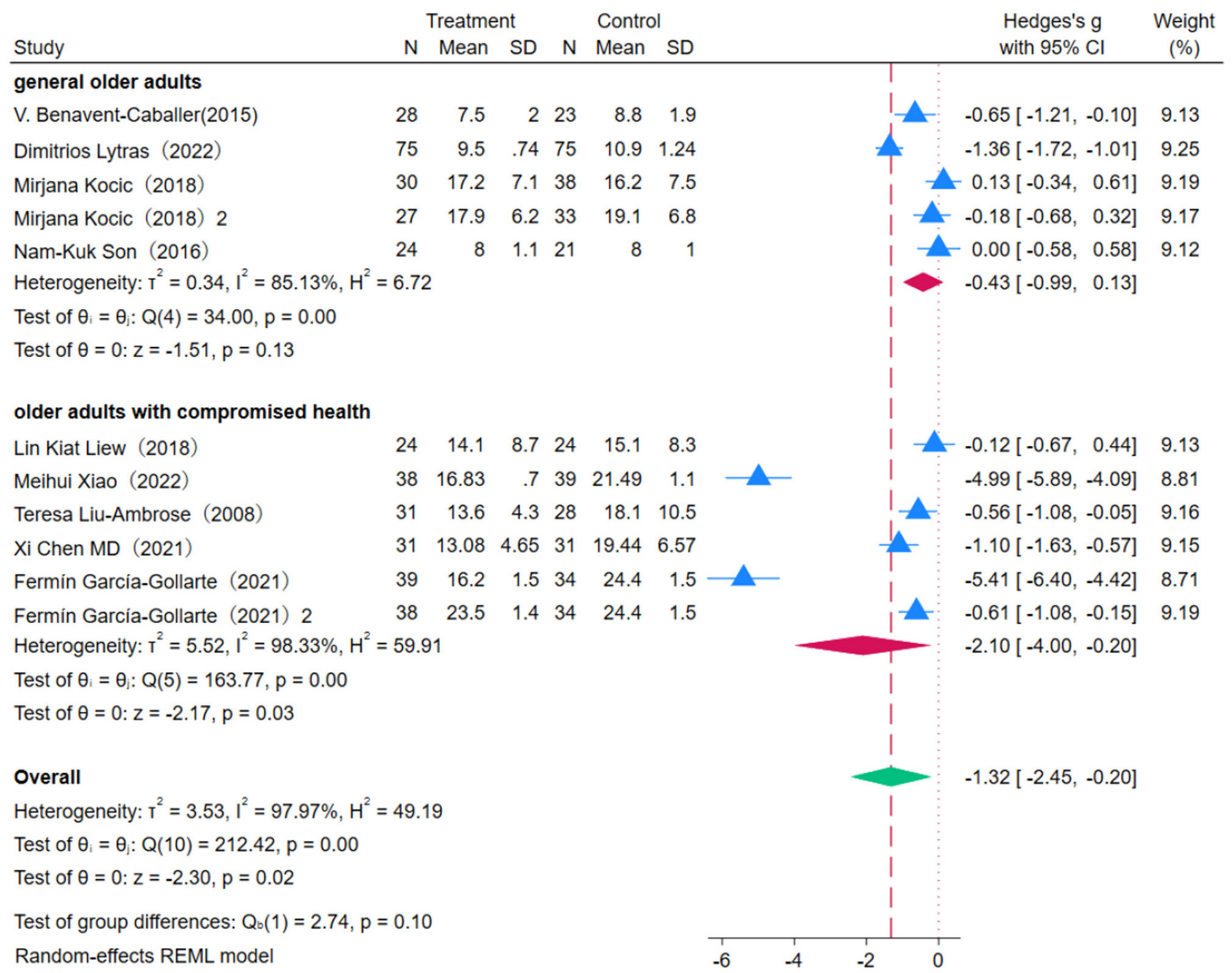

FIGURE 13
The impact of the OEP on mobility in older adults.

collection, and analytical methods across studies (54). The duration of the intervention has varying effects on different outcomes. Specifically, a 4-month intervention demonstrated the most stable effects on balance improvement, while the effectiveness of 3-month and 6-month interventions showed high heterogeneity. Our findings align with previous research suggesting that a training program lasting at least 12 weeks, conducted three or more times per week, with each session lasting 30 to 45 minutes, can significantly reduce fall risk and enhance postural stability (45). However, no significant differences were found between different intervention durations ($p = 0.30$), indicating that the effectiveness of OEP may not be solely dependent on the intervention length. This is consistent with the findings of the present study.

As research suggests, sessions lasting more than 30 min are most effective in enhancing balance among older adults (55). Based on these findings, a 45-min session duration sustained for at least six months is recommended. Conversely, shorter intervention periods (2–3 months) and 30-min sessions appear to be more effective for improving lower limb strength. This may be because balance and gait primarily rely on neuromuscular coordination (56), which typically requires long-term practice and repetition for significant improvements. In contrast, lower limb strength training primarily targets large muscle groups, which require adequate recovery time post-exercise. Therefore, shorter intervention durations and 30-minute training sessions may be more suitable for lower limb strengthening, as they help prevent overtraining and muscle fatigue.

From a clinical perspective, these findings reinforce the importance of OEP as an effective intervention for maintaining lower limb strength and mobility in aging populations. The progressive nature of OEP exercises, such as knee flexion, knee extension, and hip abduction, may contribute to improved walking ability, reduced fall risk, and enhanced functional independence in older adults. Given that longer intervention durations (≥6 months) were associated with greater improvements in lower limb strength and gait, clinical practice should

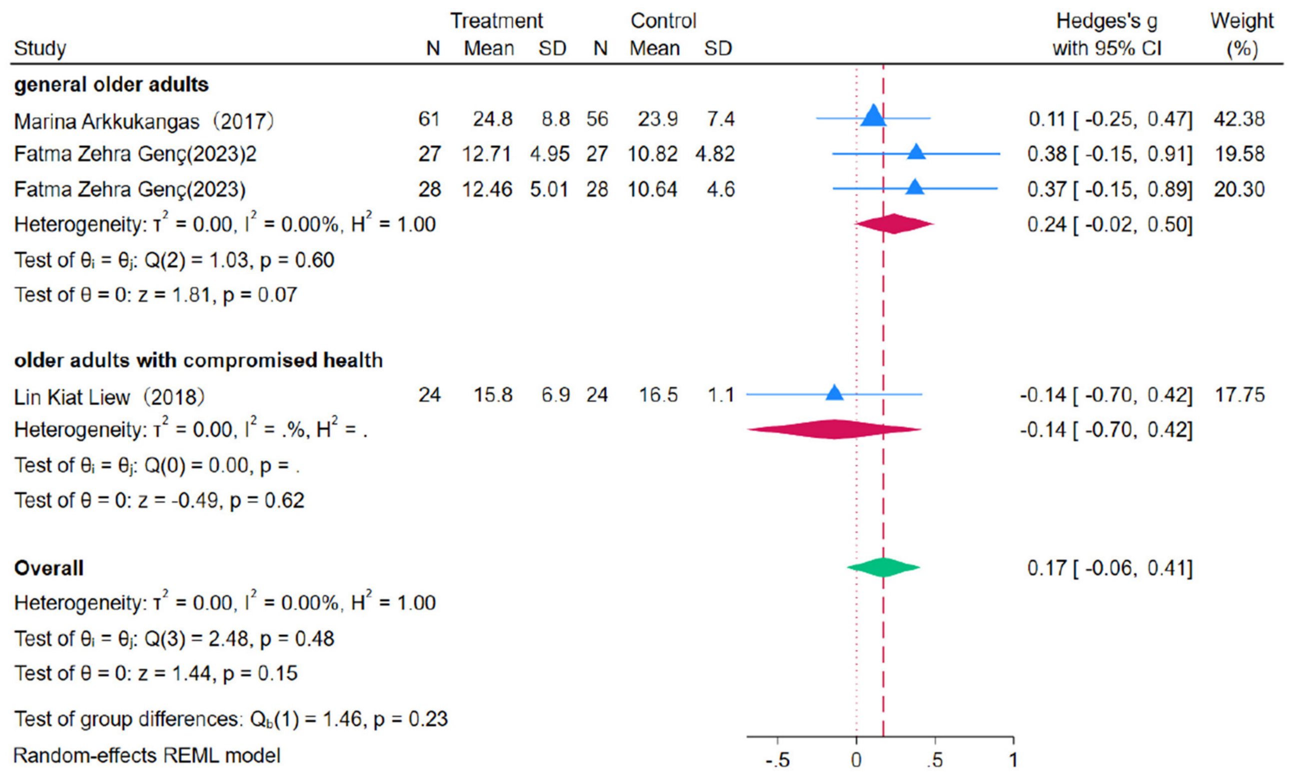

FIGURE 14
The impact of the OEP on right hand grip strength in older adults.

consider extending the program duration to maximize benefits. Additionally, incorporating upper limb resistance training into OEP may enhance its overall effectiveness, particularly for older adults with functional limitations. Future research should explore the integration of combined training approaches and assess their impact on overall musculoskeletal health in aging populations.

Although this study provides valuable insights into the effects of OEP intervention, it has certain limitations. The relatively small sample size may reduce statistical power, potentially limiting the generalizability and reliability of the findings. Moreover, the effectiveness of OEP may be influenced by various factors, including participants' health status, age, and baseline functional levels. Some included studies did not specify the MMSE criteria used to define cognitive impairment, which may have introduced variability in participant classification and contributed to heterogeneity across studies. Given that different older adult populations may respond differently to OEP, there is a need for more personalized training approaches. In this study, older adults with varying health conditions (e.g., cognitive impairment, musculoskeletal disorders, and frailty syndrome) were categorized into a single compromised health group. Previous research (19, 46, 47) has consistently demonstrated the effectiveness of OEP in reducing fall risk across these populations, supporting its broad applicability. While these individuals share a common risk factor—fall susceptibility, which OEP is specifically designed to address—differences in underlying health conditions may contribute to subtle variations in intervention effectiveness.

However, due to the limited number of available studies, subgroup analyses were not feasible. Future research should consider conducting stratified analyses to further explore whether OEP's effectiveness varies across specific health conditions. Furthermore, future studies should aim to optimize OEP protocols by tailoring them to individuals' health profiles, baseline fitness levels, and personal preferences to maximize intervention effectiveness.

5 Conclusion

OEP has been associated with improvements in balance, gait, and lower limb strength in older adults, particularly among those with compromised health, where the effects appeared more pronounced. These findings suggest that OEP may be particularly beneficial for enhancing lower limb strength and improving balance and gait. However, its impact on upper limb strength remains limited. Future research with larger, well-controlled trials is essential to validate these findings and refine intervention protocols to maximize their effectiveness in diverse aging populations.

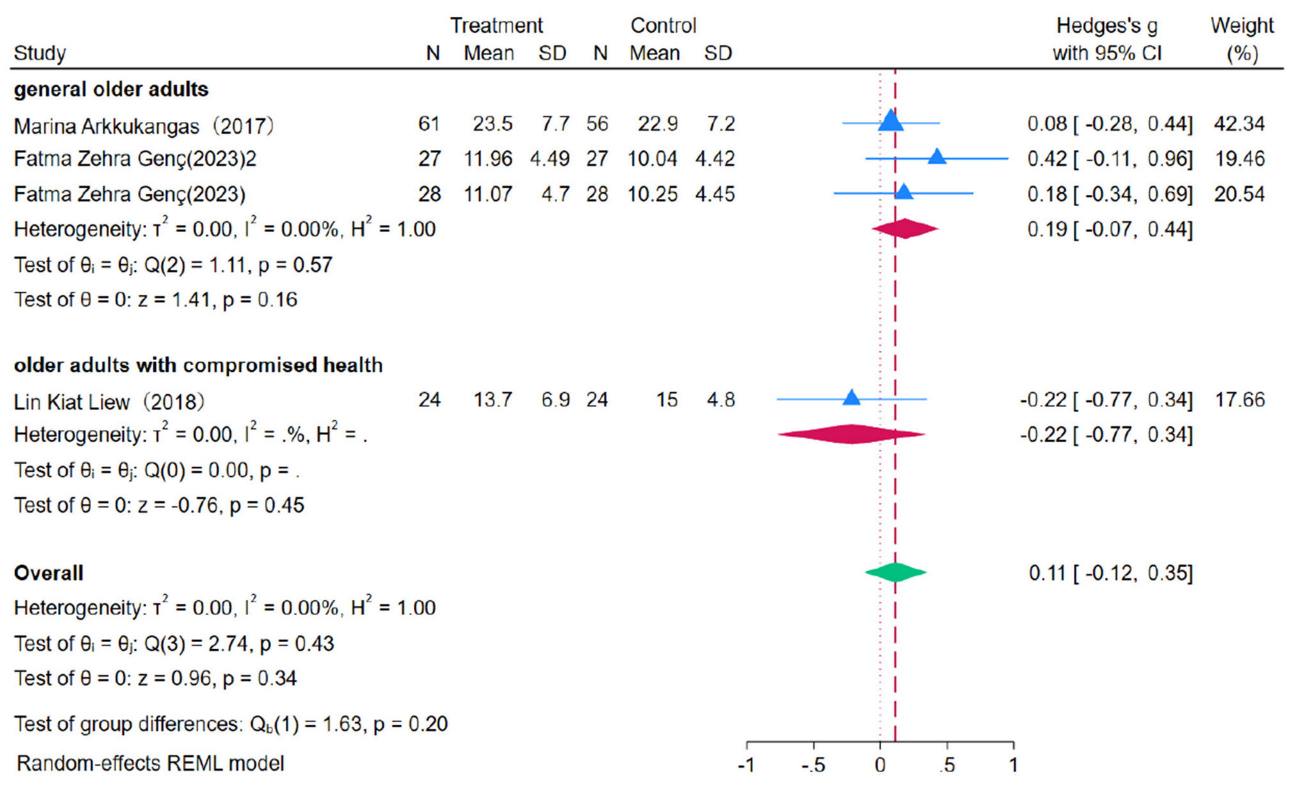

FIGURE 15
The impact of the OEP on left hand grip strength in older adults.

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/s.

Author contributions

CW: Writing – original draft, Writing – review & editing. SK: Writing – review & editing.

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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.2025.1522952/full#supplementary-material

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EDITED BY
Tadayoshi Asaka,
Hokkaido University, Japan

REVIEWED BY
Michael B. Steinborn,
Julius Maximilian University of Würzburg, Germany
Hiroki Mani,
Oita University, Japan

*CORRESPONDENCE
Manuel E. Hernandez
✉ mhernand@illinois.edu

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Exploration of the effects of Tai Chi practice on lower limb corticomuscular coherence during balance-demanding virtual reality conditions in older adults

Yang Hu[1], Elizabeth T. Hsiao-Wecksler[2] and Manuel E. Hernandez[3]*

[1]Department of Kinesiology, San Jose State University, San Jose, CA, United States, [2]Department of Mechanical Science and Engineering, Grainger College of Engineering, University of Illinois Urbana Champaign, Urbana, IL, United States, [3]Department of Biomedical and Translational Sciences, Carle Illinois College of Medicine, University of Illinois Urbana Champaign, Urbana, IL, United States

Tai Chi practice has been widely adopted to improve balance and prevent falls in older adults. However, the neural mechanisms underlying the benefits of Tai Chi are difficult to evaluate during traditional balance assessments. The goal of this study was to evaluate the effects of Tai Chi and healthy aging on corticomuscular coherence (CMC) while standing in virtual balance-demanding environments. We recorded neural, muscular, and behavioral data in an immersive virtual reality environment while implementing sensory and mechanical perturbations to introduce high postural threats. Through the acquisition of electroencephalography and electromyography signals, we examined β and γ CMC changes in frontal, central, parietal, and occipital cortical areas and ankle plantar- and dorsi-flexors in older adults (n = 10), older adults with Tai Chi practice (n = 10), and young adults (n = 10). The results showed that older adults have higher γ CMC in comparison with Tai Chi practitioners and young adults as evaluated by the magnitude square coherence. Increased β and γ CMC correlated with decreased mediolateral postural sway in older adults, while young adults demonstrated the opposite relationship. Furthermore, lower tibialis anterior and soleus β CMC were found in older adults during ground conditions compared to Tai Chi practitioners and young adults. The results demonstrate the effects of aging and Tai Chi on CMC during balance-demanding standing tasks, and the potential application of the novel system to quantify cortical and muscular adaptation after rehabilitation.

KEYWORDS
EEG, EMG, virtual reality, Tai Chi, corticomuscular coherence

1 Introduction

With a rapidly increasing number of individuals over 65 years of age globally, more people face functional impairment associated with the aging process, such as reductions in balance and increasing falls (Sturnieks et al., 2008). Balance control is defined as the act of maintaining, achieving or restoring a state of balance that may involve either a fixed support or a change in support response (Pollock et al., 2000). Balance control requires a complex interplay with and between the cortical, sensory, and motor systems (Dieën and Pijnappels, 2017). At the same time, Tai Chi practice has been widely used as a non-pharmacological approach to improve postural control and prevent falls in older adults (Li et al., 2019). However, the neural mechanisms underlying Tai Chi practice benefits remain to be explored (Zhu et al., 2010).

Tai Chi practice has been well documented in changing neuromuscular functions in older adults, as measured by electromyography (EMG), and provides a potential mechanism for the improvement of postural control abilities (Hu et al., 2021). These neuromuscular changes include decreased reaction time, earlier muscle onset time, H-reflex modulation, increased muscle strength, and improved muscle coordination pattern (Hu et al., 2021). Meanwhile, previous studies also suggest alterations in cortical structure and functional neural activity after Tai Chi practice, which give rise to beneficial neurological changes in the human brain (Pan et al., 2018). Significant changes were reported on subjects' cortical thickness, functional connectivity, homogeneity of the brain, and executive network functions after Tai Chi intervention (Pan et al., 2018). Specifically, in a study that compared Tai Chi experts and novices, they found significantly higher β-wave amplitude in Tai Chi experts than Tai Chi novices (Liu et al., 2003). In task-switch tests under homogenous and heterogeneous conditions, long-term Tai Chi practitioners demonstrated significantly larger P3 event-related potential than sedentary older adults, which were more like young adults' P3 (Fong et al., 2014). Tai Chi practice may influence cortical control processes under energetic constraints, as seen in older adults (Schumann et al., 2022; Tomporowski, 2008) and allow for task-specific increases in cortical resources to meet increased balance demands. Furthermore, while hand beta corticomuscular coherence (CMC) has been found to be altered with increased Tai Chi practice (Kerr et al., 2016), examining CMC while standing in complex virtual reality environments might provide additional insight into the mechanism of the Tai Chi practice's benefits on improving postural control performance.

Virtual reality allows for precise and synchronized multimodal stimuli, such as visual and auditory cuing of elevated heights, that has been demonstrated to elicit physical and physiological responses comparable to real-world exposure (Cleworth et al., 2012). Virtual height exposure can be combined with mechanical perturbations, to create immersive balance-demanding tasks that may be more generalizable to real-world conditions and detection of psychological contributions (Bzdúšková et al., 2022) , than traditional clinical evaluations of postural control, such as a Romberg test (Black et al., 1982) or computerized dynamic posturography (Baloh et al., 1994).

Coherence between electroencephalography (EEG) and EMG, defined as cross spectra normalized by auto spectra (Mima and Hallett, 1999), calculated using is thought to reflect corticospinal coupling between cortical areas and muscle motor units (Mima and Hallett, 1999; Negro and Farina, 2011). The coherence between EEG and EMG, which are consistent with the conduction time between the motor cortex and the respective muscle (Gwin and Ferris, 2012), can be evaluated by CMC phase lags. Meanwhile, the frequency band where CMC is most prominent is affected by the type of motor task. Specifically, β range (13–30 Hz) CMC between cortical area and lower limb muscles has been documented during static force output and isometric contractions, and γ range (31–45 Hz) CMC has been documented during isokinetic contractions (Gwin and Ferris, 2012).

Aging is associated with neuromuscular changes that impair corticomuscular communication (Yoshida et al., 2017), including decreased white matter volume (Salat et al., 2005) and motor neuron recruitment (Tomlinson and Irving, 1977). Older adults have demonstrated lower CMC in voluntary movements or isometric contraction of the upper extremity, compared to young adults, with lower CMC associated with lower strength (Bayram et al., 2015; Kamp et al., 2013). Furthermore, decreases in β (20–30) and lower γ (30–40) CMC have been observed in adults with amyotrophic lateral sclerosis and stroke, relative to healthy controls (Proudfoot et al., 2018; Fang et al., 2009). However, increased β band CMC in older adults, relative to young adults, has been found in dual task conditions, where concurrent cognitive and fine motor tasks are performed (Johnson and Shinohara, 2012). Furthermore, increased β CMC has been associated with increased accuracy in dual task conditions but only in young adults (Johnson and Shinohara, 2012). While less is known about gamma frequency changes with aging, increased γ-range CMC has been associated with increased demands in sensorimotor integration processes (Omlor et al., 2007) that may be expected in older vs. younger adults.

Considering the inconsistencies observed in the examination of the effects of aging on CMC and the few studies that have examined the neuromuscular basis of Tai Chi practice benefits on postural control, the purpose of this study was to evaluate the effects of Tai Chi practice and healthy aging on cortical and neuromuscular function, as evaluated by CMC, while standing in realistic and challenging environments. This study investigated the connection between cortical activation, lower limb muscle activities, and underlying postural control in novel standing balance conditions to achieve this goal. We hypothesized that (1) compared to young adults and older adults with Tai Chi practice, older adults would demonstrate significantly lower β CMC and higher γ CMC, specifically in less challenging conditions, given decreases in β CMC seen in older adults (Bayram et al., 2015; Kamp et al., 2013) and increases in γ CMC seen when tasks require increased sensorimotor integration (Omlor et al., 2007), (2) β CMC would be significantly correlated with the center of pressure indices in conditions that required isometric contractions, and that (3) γ CMC would be significantly correlated with the center of pressure indices in conditions that required non-isometric contractions , given observed changes in β and γ range CMC in lower extremity isometric and isotonic exercises (Gwin and Ferris, 2012).

2 Methods

2.1 Study participants

Ten healthy young adults, ten healthy older adults, and ten healthy older adults with Tai Chi practice experience were recruited for this study (Table 1). An a-priori power analysis using G-power, based on the effect of Tai chi on cortical electrical activity across central and occipital channels during a postural control task in beta oscillatory activity (Liu et al., 2003), which demonstrated

TABLE 1 Characteristics of study participants.

Characteristic	Young adult	Older adult	TCP
	Mean (SD)	Mean (SD)	Mean (SD)
Age	20(2)	71(5)*	76(6)*
Sex (F/M)	5/5	6/4	6/4
BMI	24.30 (6.03)	24.86 (5.55)	22.81 (2.53)
TCP hours	0	0	61–9,360
TMT-A	20.86 (6.27)	27.71 (7.78)	34.00 (6.99)*
TMT-B	45.80 (19.19)	57.05 (16.93)	65.30 (22.36)
FES-I	17.40 (2.12)	19.20 (3.01)	21.30 (4.08)*
Acrophobia	29.55 (34.58)	20.40 (13.28)	35.30 (21.40)
miniBEST	26.00 (1.25)	24.90 (1.97)	23.50 (2.76)*

SD, standard deviation; BMI, body mass index; TCP, Tai Chi practice; TMT, trail making test; FES-I, falls efficacy scale-international.
*Cohort difference relative to young adults, $p < 0.05$.

a medium effect size, $f = 0.25$, was used to establish the 30 person sample size for a within-between group interaction for F tests at 80% power at $alpha = 0.05$ for three groups and four repeated measures. Participant inclusion criteria were as follows: (1) right-handed; (2) over 18 years old; (3) free of chronic or acute neurological conditions, such as Parkinson's disease, Huntington's disease, stroke, epilepsy, and seizures; (4) and free of severe heart conditions, such as history of heart attack, heart failure, and angina; (5) no lower limb injury in the past 3 months; and (6) normal or corrected vision. Exclusion criteria were as follows: (1) cognitive dysfunction, determined by a Modified Telephone Interview for Cognitive Status (TICS-M) questionnaire score lower than 18 (Cook et al., 2009); (2) severe chronic pain that limits physical activity; or (3) severe motion sickness. Furthermore, younger adults were limited to 18–30 years, while older adults were limited to individuals over 65 years of age, and older adults with Tai Chi practice were over 65 years of age while currently practicing Tai Chi and having Tai Chi practice of at least 2 h per week in the past 16 weeks. Once included in the study, all participants signed a written informed consent form. The protocol and procedures have been reviewed and approved by the Institutional Review Board of the University of Illinois at Urbana Champaign (IRB Protocol No. 15317, Approved 08/15/2023).

2.2 Experimental paradigm

This study consisted of a single session cross-sectional experimental design. Ground conditions, 30 s in duration, were provided before 90 s height conditions within each 240 s block. Four counter-balanced blocks consisting of no perturbation (blocks 1 and 4) or perturbation (blocks 2–3) conditions were provided (Figure 1). To incorporate sensory and mechanical perturbations, VR was used to provide a simulation of virtual height changes, which introduced sensory perturbations and integrated an actuator to provide mechanical perturbations. Participants were asked to stand as still as possible without taking steps while EEG, EMG, and center of pressure (COP) data were recorded. Multimodal data were synchronized using Vizard (WorldViz, Inc) scripts that provided TTL pulses for EEG data, initiated force plate data collection at the start of each block, and use of a specific pseudorandomized perturbation profile, as previously described (Widdowson et al., 2016). Additional functional tests and questionnaires were conducted to control for potentially confounding factors.

2.3 Virtual reality height control test

The virtual reality height control test (VR-HCT) combined sensory input and mechanical perturbation through the use of a head-mounted display (HTC Vive, HTC Corp.). The mechanical perturbations were induced by the SMART EquiTest-Clinical Research System (SECRS, Neurocom, a division of Natus) as a 10-degree, 2.5 s, toe-down perturbations. This perturbation was similar to the perturbations incorporated in the clinical adaptation test (ADT), designed to engage the brainstem and cortex. An industrial lift in a barren factory floor was created by the researchers using Vizard, with a ground or virtual height condition (3-m, 6-m, or 9-m height, as seen in Figure 1).

To incorporate the VR sensory manipulation and mechanical perturbation and to minimize the order of heights affecting the experiment results, the height changes were provided in a pseudo-randomized pattern to the participants and the toe-down perturbation was induced at each height during the second and third blocks. Thus, each participant experienced all height conditions with and without mechanical perturbation. Based on the height and perturbation onset, all conditions within the four blocks were further classified into four overarching conditions, which were ground condition, height condition, ground with perturbation condition, and height with perturbation condition. These four overarching conditions were used to label and perform grand averages for primary outcome measurements and used as condition levels in subsequent statistical analyses.

2.4 Data acquisition and pre-processing

High-density EEG data from a 64-channel active system (actiChamp system, Brain Vision LLC, Morrisville, NC USA) were recorded during each condition to assess the cortical activations of the participants. The EEG system consisted of a cap plus two electrooculography (EOG) electrodes, temporal to and inferior to the right eye, two EMG electrodes on the right and left trapezius, one reference electrode on the right mastoid, and a ground electrode on the left mastoid. Data were recorded at 1,000 Hz and referenced to the average of the left and right mastoid electrodes. The positions of the EEG sensors on the head were based and modified from international 10–10 systems. For EMG, bilateral ankle flexor and extensor muscle activities were recorded with Trigno wireless EMG system (Delsys Inc, Natick MA, USA) with a sampling rate of 1,926 Hz. EMG sensors were applied to bilateral tibialis anterior (TA), gastrocnemius medial head (GAM), gastrocnemius lateral head (GAL), and soleus (S) muscles. The

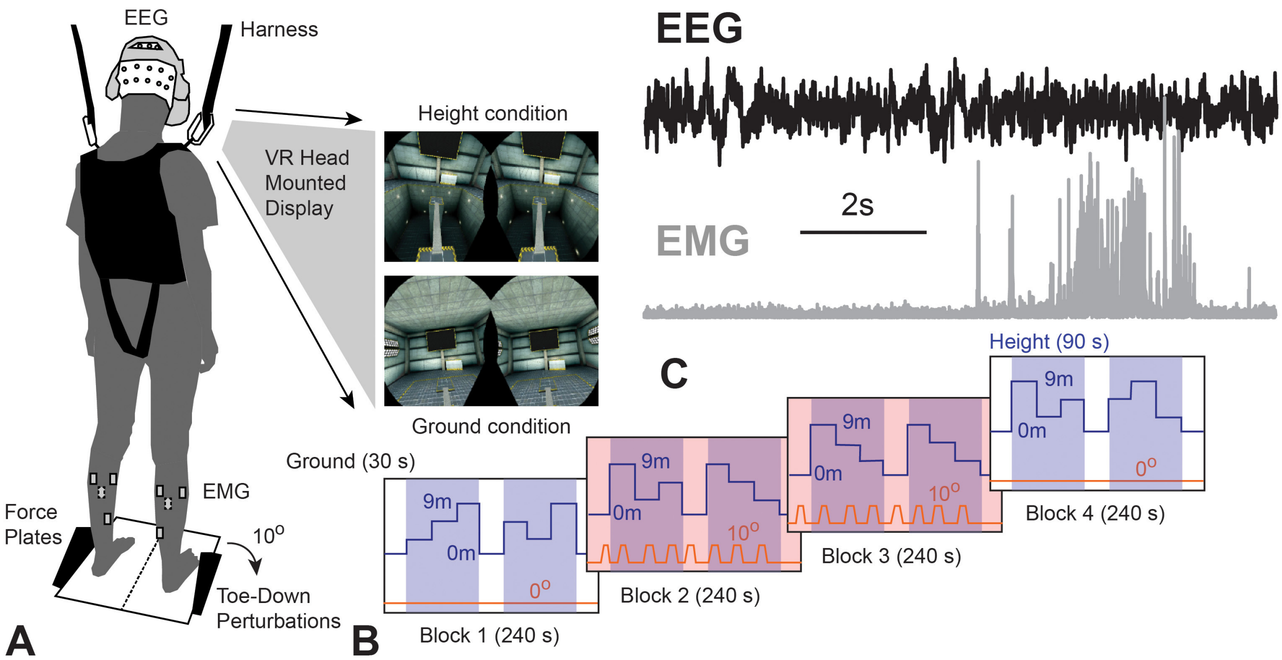

FIGURE 1
(A) Experimental setup and example of VR environment; **(B)** schematic of experimental protocol, with white regions (30 s in duration) representing ground conditions, blue shaded regions (90 s in duration) representing height conditions, and orange shaded regions (240 s in duration) representing perturbations in blocks 2–4; **(C)** sample electroencephalography (EEG) and electromyography (EMG) segment during perturbation in a representative older adult with Tai Chi practice.

SECRS research module was used to acquire COP data with a 100 Hz sampling rate while providing toe-down perturbations synchronized with VR environment.

All data processing was performed with customized MATLAB scripts (MathWorks, Natick, MA, USA). Raw EEG data were high-pass filtered at 1Hz to remove drift and low-pass filtered at 55 Hz to remove line noise. A band-specific filter for 60 Hz was applied due to the environment line noise in the lab. EEG artifacts associated with eye and other muscle movements were removed using independent component analysis (ICA). Based on the topography, spectra, and trial-to-trial characteristics of ICA components, good fit ICA components were selected and used to generate back-projected EEG data, referred to as clean EEG. The clean EEG data were further trimmed based on the synchronization time stamps into segmented EEG data corresponding to each VR-HCT condition in each block for each participant. EMG raw data were first resampled to 1,000 Hz (the EEG sampling rate) and then low pass filtered with a cutoff frequency of 400 Hz (Mello et al., 2007). After being corrected by the average signal over the entire recording, the EMG data were rectified. The signals from GAL and GAM were grand averaged as one gastrocnemius signal (GA). The EMG data were further segmented based on the timestamps of the onset and offset of each VR-HCT condition in each block for each participant. COP raw data were low pass filtered using a Butterworth filter with a cutoff frequency of 10 Hz. Then, the COP data were segmented based on the 30-s conditions in each block. The average anterior-posterior and medial-lateral positions in each segmented block in each block were calculated as the standing center point and used to correct the COP raw data in the corresponding block. The corrected COP data were referred to as segmented COP data.

2.5 Primary measures

2.5.1 Corticomuscular coherence assessment

For each VR-HCT condition (30 s), the power spectral density of EEG and rectified EMG was computed using Welch's method with 500 ms non-overlapping Hanning windows (Gwin and Ferris, 2012). CMC was evaluated using the magnitude square coherence for each EEG channel/EMG channel paired using Equation 1:

$$coh_{c1c2}(f) = \frac{|s_{c1c2}(f)|^2}{s_{c1c1}(f) \cdot s_{c2c2}(f)} \quad (1)$$

where s_{c1c1} and s_{c2c2} are the auto-spectra of each signal; s_{c1c2} is the cross-spectra; and (f) denote the band of interest, which were β (13–30 Hz) and γ (31–45 Hz). CMC was calculated for each paired EEG and EMG signal and was further grand averaged based on corresponding cortical regions with specific ankle muscles as follows: frontal (Fz, F5, and F6), central (Cz, C5, and C6), parietal (Pz, P5, and P6), and occipital (Oz, O5, and O6).

2.5.2 Postural control assessment

Based on the segmented COP data, the following COP indices were extracted to describe the postural control abilities. The range of COP displacement was defined as the differences between the maximal COP positions, which were extracted in the anteroposterior (R_{AP}) and mediolateral (R_{ML}) directions separately. The total root mean square (RMS) of COP displacements was calculated using

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \quad (2)$$

where n denotes the number of measurements, and x_i denotes each displacement value. The RMS of COP displacement from each position to the center point (COP_{rms}), COP displacement in the anterior-posterior direction (COP_{rmsAP}), and COP displacement in medial-lateral direction (COP_{rmsML}) was extracted. Sway energy was also calculated in each unique condition in each block. Specifically, the following equation was used:

$$SwayEnergy = C1 \times RMS(PY') + C2 \times RMS(PY'') \quad (3)$$

where the constants $C1$ and $C2$ are defined as $C1 = 1/(inches/second)$ and $C2 = 0.025/(inches/second^2)$. While PY denotes COP displacement in AP direction, PY' denotes the first derivative of PY, and PY'' denotes the second derivative of PY. This equation was based on the SECRS system equations that are used to estimate the unitless sway energy in the clinical adaption test (Mcguirk, 2005).

2.6 Secondary measures

Furthermore, baseline physical, cognitive, and psychological function was evaluated to help control for potential covariates in cortical activation and postural control. Before the VR-HCT test, the MiniBESTest battery was conducted to evaluate the functional balance of the participants. The MiniBESTest test score was used to quantify functional balance. Participants' executive function was evaluated using the Trail Making Test (TMT). The fall risk of the participants was assessed by the Falls Efficacy Scale-International (FES-I). The fear of height was assessed by the Acrophobia Questionnaire-Anxiety Subscale. This questionnaire is a 20-item self-report questionnaire that asks participants to rate their anxiety related to height-relevant situations using a 0 (not at all anxious; calm and relaxed) to 6 (extremely anxious) scale. A Tai Chi experience questionnaire was given to participants during the pre-screening phone interview. The questions include (1) "Have you practiced Tai Chi or Taijiquan before?"; (2) "Are you currently actively practicing Tai Chi?"; (3) "How long have you practiced Tai Chi? in weeks or years."; (4) "In total, how many hours have you practiced Tai Chi?"; (5) "Currently, on average, how many hours do you practice Tai Chi every week?". Questions three to five were used to quantify the Tai Chi practitioner's experience into total hours.

2.7 Statistical analysis

All the statistical analyses were performed using R (R 4.4.0, RStudio 2024.12.0+467). There were three sets of statistical analyses performed to answer the research questions. The one-way ANOVA was used to test the cohort demographic differences and secondary measurement differences. For primary outcome measurements, outliers were detected and removed using an Interquartile Range (IQR) method with a 1.5 IQR cutoff. To achieve residual normality, log or square-root data transformation were performed based on the direction and level of skewness of the data set. A positive square-root transformation was used on sway energy, anteroposterior COP RMS, and β and γ CMC. Linear mixed effect models (LMMs) were used to identify the cohort differences for cortical activities and postural control performance, using subject as a random factor, and cohort (young adult, older adult, and Tai Chi practice groups), condition (ground, height, ground with perturbation, and height with perturbation), cortical region (frontal, central, parietal, and occipital), and muscle (TA, GAM, GAL, and S) as fixed effects. Model significance was evaluated using the likelihood ratio test. Linear mixed model assumptions were confirmed using visual inspection. The best model identified included all one-way factors, two-way interactions with cohort, and cohort $\times$ muscle $\times$ condition three-way interaction. Least square means *post-hoc* comparisons were performed using a p-value of < 0.05 and reported in Supplementary material. Moreover, Spearman's correlations were used to investigate the relationship between CMC and COP indices in each test.

3 Results

Statistically significant differences in anteroposterior COP range (R_{AP}), mediolateral COP range (R_{ML}), anteroposterior COP RMS (COP_{rmsAP}), mediolateral COP RMS (COP_{rmsML}), sway energy, and overall COP RMS (COP_{rms}) were observed across different conditions ($p < 0.01$, Figure 2). In particular, higher R_{AP}, R_{ML}, COP_{rmsAP}, COP_{rmsML}, sway energy, and COP_{rms} were found in ground and height with perturbation conditions, relative to ground condition. In addition, a significant cohort effect on COP_{rmsML} was observed ($p < 0.05$), with Tai Chi practitioners demonstrating a lower COP_{rmsML} than older adults. Furthermore, a statistically significant cohort by condition interaction effect was observed in R_{ML} ($p < 0.05$) and sway energy ($p < 0.01$), such that older adults had a higher R_{ML} and sway energy than young adults in the height with perturbation condition, relative to ground condition (Figure 2). No other statistically significant effects were detected in postural control metrics.

3.1 Corticomuscular coherence

The β range coherence peaks occurred at 21.5 ± 5.39 Hz for young adults, 21.6 ± 5.37 Hz for older adults, and 21.7 ± 5.38 Hz for Tai Chi practitioners. The γ range coherence peaks occurred at 37.9 ± 4.48 Hz for young adults, 38.0 ± 4.50 Hz for older adults, and 28.0 ± 4.49 Hz for Tai Chi practitioners. These frequency peaks were not harmonics of each other across the frequency ranges.

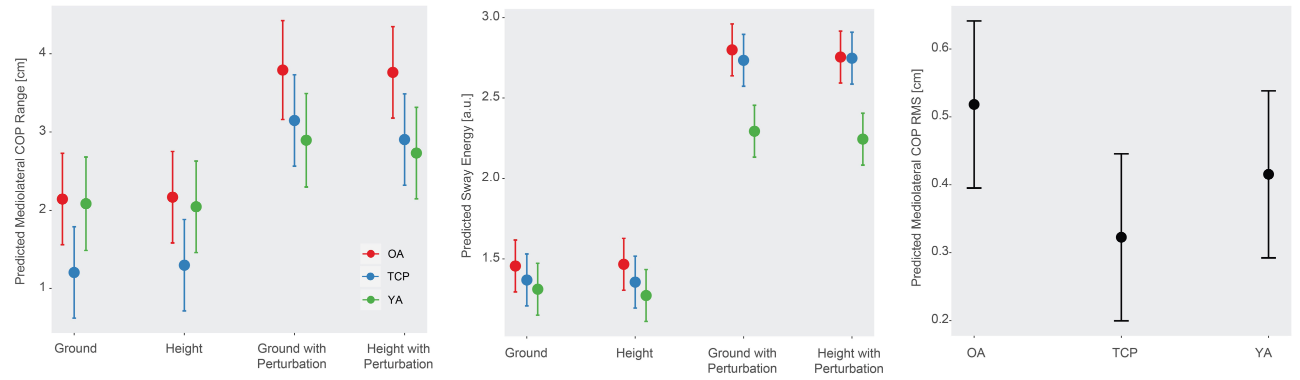

FIGURE 2
(Left) Predicted mediolateral COP range across conditions and cohorts, **(Center)** sway energy across conditions and cohorts, and **(Right)** mediolateral COP RMS changes across cohorts.

Peaks in the β EMG spectral power occurred at 18.0 $\pm$ 5.29 Hz for young adults, 16.0 $\pm$ 4.63 Hz for older adults, and 16.4 $\pm$ 5.26 Hz for Tai Chi practitioners. Peaks in the γ EMG spectral power occurred at 35.6 $\pm$ 4.27 Hz for young adults, 35.3 $\pm$ 4.29 Hz for older adults, and 34.7 $\pm$ 3.87 Hz for Tai Chi practitioners. Peaks in the β EEG spectral power occurred at 14.3 $\pm$ 3.22 Hz for young adults, 15.5 $\pm$ 2.88 Hz for older adults, and 15.2 $\pm$ 2.94 Hz for Tai Chi practitioners. Peaks in the γ EEG spectral power occurred at 31.9 $\pm$ 1.72 Hz for young adults, 32.0 $\pm$ 1.66 Hz for older adults, and 31.7 $\pm$ 1.46 Hz for Tai Chi practitioners (Supplementary Table S1).

3.1.1 β corticomuscular coherence

Overall, a statistically significant condition effect ($p < 0.05$), muscle effect ($p < 0.001$), cohort-condition interaction effect ($p < 0.01$), condition-muscle interaction effect ($p < 0.001$), and cohort-muscle-condition interaction effect ($p < 0.001$) were observed on β CMCbased on linear mixed models (Figure 3, Table 2).

3.1.1.1 *Post-hoc* results

Based on *post-hoc* contrasts, increased β CMC was observed in height with perturbation relative to ground with perturbation conditions and in gastrocnemius and soleus muscles relative to tibialis anterior (see Supplementary Table S2). In particular, older adults demonstrated increased β CMC in height with perturbation relative to ground conditions. Furthermore, during ground conditions, decreased β CMC was observed in older adults, relative to both young adults and Tai Chi practitioners. Further examination of cohort differences by muscle and condition demonstrated that tibialis anterior β CMC during ground conditions significantly increased in Tai Chi practitioners and young adults, relative to older adults, and in young adults relative to Tai Chi practitioners. In contrast, tibialis anterior β CMC during ground and height with perturbation conditions significantly decreased in young adults relative to older adults and in young adults relative to Tai Chi practitioners in ground with perturbation conditions. Furthermore, in gastrocnemius β CMC during ground and ground with perturbation conditions significantly decreased in young adults relative to older adults and in young adults relative to Tai Chi practitioners in ground conditions. Finally, in soleus β CMC during ground condition significantly increased in Tai Chi practitioners and young adults relative to older adults.

3.1.2 γ corticomuscular coherence

Overall, a statistically significant cohort effect ($p < 0.001$), condition effect ($p < 0.01$), muscle effect ($p < 0.05$), cohort-condition interaction effect ($p < 0.001$), cohort-muscle interaction effect ($p < 0.001$), and cohort-muscle-condition interaction effect ($p < 0.001$) was observed on square-root transformed γ CMC.

3.1.2.1 *Post-hoc* results

Based on *post-hoc* contrasts, increased γ CMC was found in both older adults and Tai Chi practitioners, relative to young adults (see Supplementary Table S3). Furthermore, increased γ CMC was observed in height with perturbation relative to height conditions and in gastrocnemius relative to tibialis anterior. In particular, older adults demonstrated increased γ CMC in height with perturbation relative to height and ground with perturbation conditions, while decreased γ CMC was observed in height and ground with perturbation conditions, relative to ground conditions. Furthermore, Tai chi practitioners demonstrated increased γ CMC in ground with perturbation conditions relative to ground conditions. Furthermore, during both ground and height with perturbation conditions, increased γ CMC was observed in older adults, relative to both young adults and Tai Chi practitioners. In addition, in both height and ground with perturbation conditions, Tai Chi practitioners had increased γ CMC, relative to young adults. Further examination of cohort differences by muscle and condition demonstrated that tibialis anterior γ CMC during ground conditions significantly decreased in Tai Chi practitioners and young adults, relative to older adults, and in young adults relative to Tai Chi practitioners. Similarly, tibialis anterior γ CMC during height conditions significantly decreased in younger adults, relative to older adults and Tai Chi practitioners, and in younger adults, relative to Tai Chi practitioners in ground with perturbation conditions.

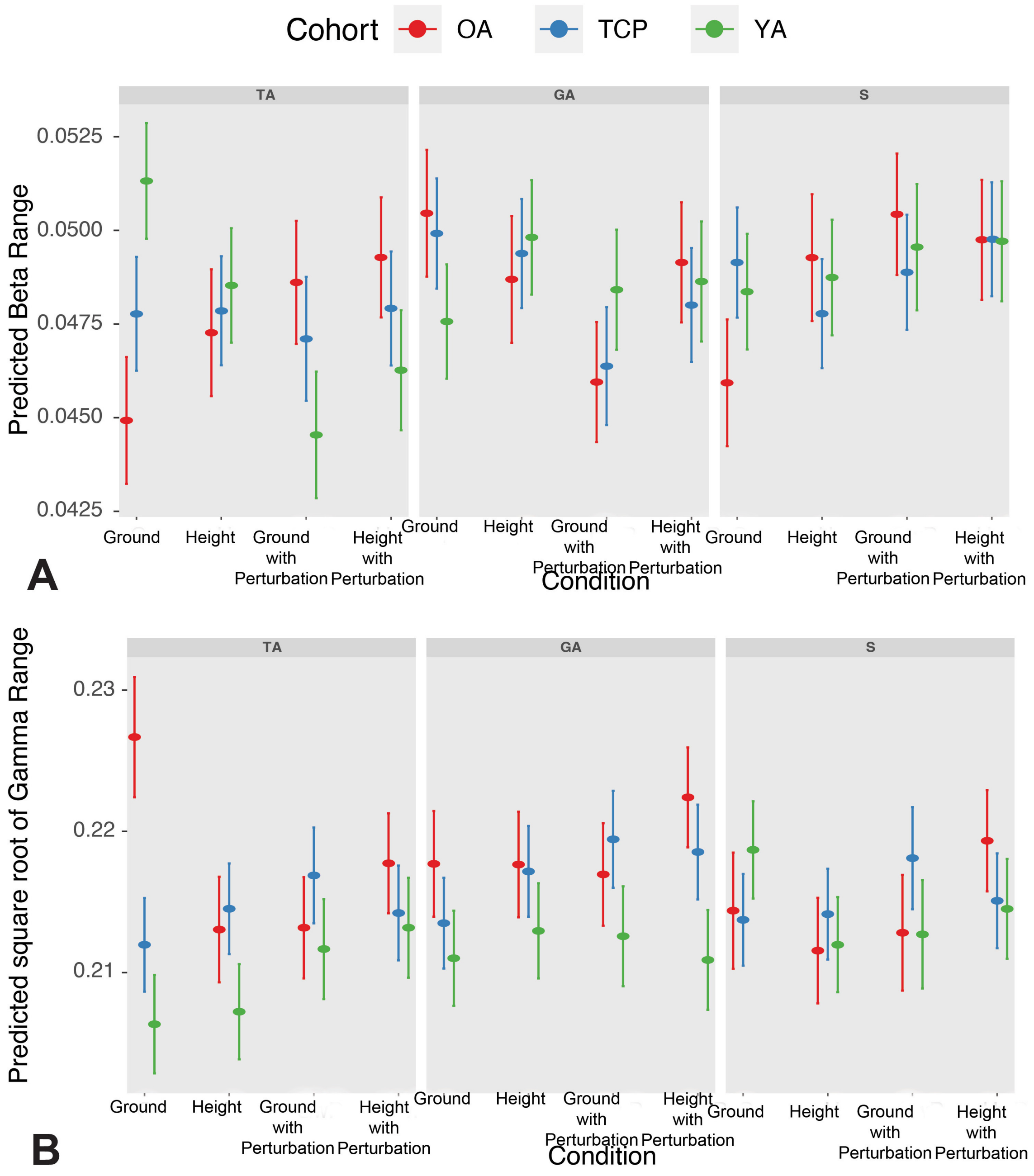

FIGURE 3
(A) Predicted β CMC range across conditions and cohorts; and **(B)** Predicted square root of γ CMC range across conditions and cohorts. YA, young adult; OA, older adult; TCP, older adult with Tai Chi practice; TA, tibialis anterior; GA, gastrocnemius; S, soleus.

3.2 Correlation between corticomuscular coherence and postural control

The correlation between corticomuscular coherence meausures and postural control measures that was found to have significant cohort effects or interactions was examined using Spearman's correlation. A negative association was found between β CMC and COP_{rmsML} in the ground condition (ρ = -0.120, $p < 0.05$). Specifically, subgroup analysis found a negative correlation in Tai Chi practitioners ($\rho = -0.31$, $p < 0.01$). A negative correlation was found between γ CMC and COP_{rmsML} in the ground condition ($\rho = -0.156$, $p < 0.01$). Specifically, subgroup analysis found a negative correlation in older adults ($\rho = -0.38$, $p < 0.01$) and Tai Chi practitioners (ρ=-0.39, $p < 0.01$) and a positive correlation in young adults ($\rho = 0.3$, $p < 0.01$). A negative correlation was found between γ CMC and R_{ML} in the ground condition ($\rho = -0.115$, $p < 0.05$). Specifically, subgroup analysis found a negative correlation in older adults ($\rho = -0.28$, $p < 0.01$) and Tai Chi practitioners ($\rho = -0.39$, $p < 0.01$) and a positive correlation in young adults (ρ=0.28, $p < 0.01$). A positive correlation was found between γ CMC and

TABLE 2 Linear mixed effect model type III analysis of variance table with Satterthwaite's method.

Factor	*F* value	*p*-value	Signif.
β Corticomuscular coherence:			
Cohort	0.0434	0.9576	
Condition	2.8269	0.0375	*
Muscle	9.9350	0.0001	***
Regions	0.3117	0.8169	
Cohort: Condition	3.2049	0.0040	**
Cohort: Regions	0.2044	0.9755	
Cohort: Muscle	0.0515	0.9950	
Condition: Muscle	5.1341	0.0000	***
Cohort: Condition: Muscle	5.8546	0.0000	***
γ Corticomuscular coherence:			
Cohort	9.5949	0.0007	***
Condition	4.4722	0.0039	**
Muscle	4.4705	0.0116	*
Regions	0.0608	0.9804	
Cohort: condition	5.7160	0.0000	***
Cohort: regions	0.4541	0.8424	
Cohort: muscle	6.3317	0.0000	***
Condition: muscle	1.6507	0.1298	
Cohort: condition: muscle	3.1125	0.0002	***

Significance codes: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

sway energy in ground with perturbation condition ($\rho = 0.275$, $p < 0.001$) and in height with perturbation condition ($\rho = 0.251$, $p < 0.001$). Specifically, subgroup analysis found a positive correlation in older adults in the ground with perturbation condition ($\rho = 0.41$, $p < 0.01$) and in older adults in height with perturbation condition ($\rho = 0.24$, $p < 0.05$).

4 Discussion

This study furthered our understanding of the effects of Tai Chi practice and healthy aging on cortical and neuromuscular function, as evaluated by CMC, while standing in balance-demanding virtual reality environments. Partly consistent with our hypotheses, we found that (1) compared to young adults and Tai Chi practitioners, older adults demonstrated significantly lower β CMC in ground conditions and higher γ CMC in both ground and height with perturbation conditions; (2) β CMC was significantly correlated with center of pressure indices in ground conditions; and (3) γ CMC was significantly correlated with center of pressure indices in ground, ground with perturbation, and height with perturbation conditions, consistent with observed changes in β and γ range CMC in lower extremity isometric and isotonic exercises (Gwin and Ferris, 2012).

We found older adults, relative to young adults and Tai Chi practitioners, to have decreased β CMC in ground conditions, which was consistent with decreases in β CMC previously seen in older adults (Bayram et al., 2015; Kamp et al., 2013). Furthermore, relative to young adults and Tai Chi practitioners, older adults were found to have increased γ CMC in both ground and height with perturbation conditions, consistent with tasks requiring increased sensorimotor integration (Omlor et al., 2007). In addition, Tai Chi practitioners had increased γ CMC, relative to young adults, in both height and ground with perturbation conditions, which may reflect an adaptive change in Tai Chi practitioners. Combined, these findings suggest aging might be associated with loss of isometric ankle strategy in upright postural control, and this effect might be partly overcome by practicing Tai Chi as an older adult. As β CMC was associated with isometric contraction and constant force output, and γ CMC was related to strong contraction and isokinetic contraction (Gwin and Ferris, 2012), these relevant CMC changes indicated stronger contraction and less isometric contraction presented in older adults compared to Tai Chi practitioners and young adults. In this study, as all participants were instructed to stand as still as possible, an isometric ankle strategy with minimal lower limb joint flexion and extension was expected to maintain upright postural. However, the significantly higher γ CMC in soleus and higher γ and β CMC in gastrocnemius relative to tibialis anterior indicated a potential shift to voluntary plantarflexor control to maintain balance during quiet standing in older adults. Alternatively, Tai Chi practice may contribute to more efficient cortical control by enhancing temporal precision, focused engagement, and the economical structuring of movement, a theoretical possibility supported by prior accounts of resource-sensitive motor regulation in aging and under energetic constraints (Schumann et al., 2022; Tomporowski, 2008). This effect may arise from two interrelated processes: the targeted mobilization of cognitive resources for motor coordination, and the refinement of control strategies that optimize the alternation between muscular tension and relaxation, thereby supporting a dynamic and context-sensitive regulation of effort within the movement flow (Schumann et al., 2022).

Confirming the second hypothesis, in ground condition, higher β CMC was associated with lower postural sway (COP_{rmsML}), and subgroup analyses suggest this relationship was enhanced and significant in TCP while there was non-relationship in older adults and young adults. At the same time, higher γ CMC was associated with lower postural sway and COP displacement range (R_{ML}) in the ground condition. However, while higher γ CMC was associated with lower postural sway and COP displacement range in both older adults and Tai Chi practitioners, higher γ CMC was associated with higher postural sway and COP displacement range in young adults. These results suggest that corticomuscular coupling might be essential in postural stability, especially during quiet standing in older adults, which might be explained by compensation theories of aging (Seidler et al., 2010). Specifically, the opposite directionalities in the γ CMC and postural stability relationships between young adults and older adults' groups may suggest γ corticomuscular coupling was engaged in regulating the postural stability in older adults. γ corticomuscular coupling might be related to the initiation of voluntary movement in ML direction in young adults. This is supported by the similar postural sway level that was found in young adults compared to Tai Chi practitioners, and larger COP displacement ranges that were found in YA compared to Tai Chi practitioners. Moreover, while older adults and Tai Chi practitioners' CMC γ increased along with reduced postural sway, a significantly higher postural sway was still found in older adults compared to Tai Chi practitioners. In addition, as the correlation between β CMC and postural sway was only significant in Tai Chi practitioners, combined with the significant differences between older adults, Tai Chi practitioners, and young adults in β CMC levels discussed above, the ability to maintain β corticomuscular coupling might be a key for successfully maintaining balance while standing in older adults.

Confirming the third hypothesis, γ CMC was positively correlated with COP sway energy in both ground with perturbation condition and height with perturbation condition. Interestingly, subgroup analyses suggest these relationships were enhanced and only significant in older adults while there was non-relationship in Tai Chi practitioners and young adults. These results suggest a potential unsuccessful γ cortical coupling compensation might be presented in older adults to regulate postural stability under perturbation. As sway energy was calculated based on RMS of the first and second derivative of COP position along AP direction, sway energy describes the ability to regulate the movement velocity in AP direction. Higher sway energy presented during perturbation conditions indicated that perturbations induced higher COP velocity and acceleration changes in AP direction in older adults and Tai Chi practitioners than young adults.

The positive relationship between γ CMC and sway energy might indicate older adults failed to control the COP velocity and accelerations. As previous study suggested that γ CMC is associated with isokinetic contraction and strong muscle contractions (Gwin and Ferris, 2012), our results suggested older adults might had strong muscle contractions which involved lower limb joints' angle changes, which might be linked with passively response to the irregulated COP movement in AP direction under perturbation. On the other hand, as these relationships were not established in young adults and Tai Chi practitioners, they were not engaging in γ corticomuscular coupling to regulate COP movement under perturbation conditions. The positive relationship between γ corticomuscular coupling and COP sway energy in older adults also suggests that the high γ CMC was unsuccessful compensations for control of the COP movement, which can be explained by the aging-related unsuccessful compensation behavior under the framework of the Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model (Cabeza and Dennis, 2013).

There are several limitations of this study. First, the anteroposterior COP features might be dominated by the pre-programed perturbation profile, thus failed to detect the impacts other than the condition effect in the LMMs. Specifically, during the perturbation conditions, the period of perturbation onset (~3 s) and the perturbation offset period (~27 s) were not separated, which might allow the preprogrammed mechanical perturbation amplitude to overwrite the underlying cohort differences. The drastic effect during the 3 s could overwrite the underlying cohort differences, specifically when the indices were closely linked with the absolute position, such as range of position and total COP sway. Future analysis should segment the perturbation condition further to perturbation onset or offset period. It might help to provide additional insight into cohort differences in response to perturbation in the anterior-posterior direction. Second, as a cohort study, the Tai Chi practitioners has a large range of Tai Chi practice time and a large variance of Tai Chi style of practice, which might introduce potential confounding variables into the data analysis. In addition, the increased time needed to complete the trail making test—form A suggests differences in complex attention or selective decline in cognitive and attentional functions among the Tai Chi practitioners (McMorris, 2016) but may also reflect age-related changes in motoric performance, given the strong contribution of age on TMT A and B performance (Tombaugh, 2004). Future work should implement a randomized clinical trial design to minimize these confounding factors and utilize repeated observations to improve design-level constraints and allow for the evaluation of differential effectiveness in Tai Chi practice.

5 Conclusion

This study investigated the corticomuscular coherence between cortical areas and ankle plantarflexor and dorsiflexor muscles during novel virtual reality height control tests. To our knowledge, this is the first study to investigate the effect of Tai Chi and older age on corticomuscular coherence during standing postural challenges. In particular, this study demonstrated how corticomuscular coherence patterns may reflect compensatory mechanisms in aging and how these might be modifiable through structured movement practice. Thus, through the integration of modern technologies, such as virtual reality and neuromechanics, with traditional movement practices, we can refine our conceptual understanding of embodied cognition and adaptive motor control. While the dose-response relationship of Tai Chi training and temporal dynamics of cortical recruitment after Tai Chi practice remain open questions, these findings support Tai Chi as a low-impact, accessible, and culturally meaningful, form of physical activity that may help stabilize postural control in 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 University of Illinois Urbana-Champaign Institutional Review Board. 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

YH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. EH-W: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. MH: Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Visualization, 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

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EDITED BY
Roshan Joy Martis,
Manipal Institute of Technology Bengaluru,
India

REVIEWED BY
Rüdiger Christoph Pryss,
Julius Maximilian University of Würzburg,
Germany
Balachandra Achar,
Manipal Institute of Technology Bengaluru,
India

*CORRESPONDENCE
Konstantinos Georgas
✉ kostasgeo@biomed.ntua.gr
Konstantinos Bromis
✉ konbromis@biomed.ntua.gr

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eHealth literacy assessment as a promoter of user adherence in using digital health systems and services. A case study for balance physiotherapy in the TeleRehaB DSS project

Konstantinos Georgas*, Konstantinos Bromis*, Theodoros P. Vagenas, Olympia Giannakopoulou, Nikolaos Vasileiou, Ioannis Kouris, Maria Haritou and George K. Matsopoulos

Biomedical Engineering Laboratory, Institute of Communication and Computer Systems, NTUA, Athens, Greece

Improving patient adherence and compliance with digital health interventions requires the creation of eHealth literacy resources. This study examines the creation and application of a novel eHealth literacy tool for home-based balance physiotherapy as part of the TeleRehaB DSS project. This tool evaluates patients' digital literacy, in particular their ability to use the Internet of Things (IoT), Augmented Reality (AR) and smart device technologies. The tool addresses the challenge of low treatment adherence by utilizing models to monitor compliance in real time and adjust treatment recommendations accordingly. The TeleRehaB DSS integrates this literacy tool to maximize resource allocation and improve patient engagement. Testing and validation has shown the system's ability to improve therapeutic outcomes and increase patient involvement. This strategy not only addresses the real-world difficulties of implementing digital health systems, but also advances the growing body of knowledge on improving treatment adherence through customized digital literacy assessments. When developing effective health technologies, the capabilities of users must be taken into account, especially for older people or those with limited digital literacy, as this study highlights.

KEYWORDS

digital health, eHealth literacy, health technology, mobile health (mHealth), patient adherence, telerehabilitation

1 Introduction

Digital technologies have become a critical component of patient-centered care in the dynamic healthcare landscape, enabling innovative approaches to diagnosis, treatment and rehabilitation. A key factor in this transformation is health literacy, which is the ability of an individual to understand and apply health information effectively to make decisions about their care (1). The ability to find, evaluate and use health information from electronic sources is referred to as eHealth literacy, which is a subset of health literacy (2). EHealth literacy is essential for patient participation and adherence as the use of digital health interventions increases, especially for populations that manage chronic diseases or undergo rehabilitation (3).

Despite the obvious advantages of digital health technologies, differences in the digital literacy of the population remain a major obstacle to their widespread adoption. Navigating digital health systems can be difficult for many patients, especially the elderly (4). This can lead to non-adherence to treatment programs and suboptimal health outcomes. Research has repeatedly shown that people with low eHealth literacy are less likely to participate in digital health interventions, which has a direct impact on their ability to manage their health successfully (5). Long-term patient engagement is critical to a successful recovery in rehabilitation, so this issue is of particular concern in this regard (6). To ensure more equitable access to these technologies, there is therefore an urgent need for apps that not only provide digital health services, but also assess and improve the digital literacy of users.

Assessing users' eHealth literacy and digital skills is the main goal of the eHealth Literacy App created as part of the TeleRehaB DSS project. This assessment serves as the basis for customizing interventions in home-based balance physiotherapy programs. In particular, the app evaluates patients' competency with Internet of Things (IoT), augmented reality (AR) and smart device technologies, enabling medical practitioners to customize treatment regimens according to patients' degree of digital literacy. In addition, it offers actionable insights that let doctors modify treatments as necessary during real-time patient monitoring, guaranteeing that interventions are available and efficient for all users with varying technological capabilities. According to research, lack of digital literacy frequently leads to lower patient engagement and worse health outcomes, so this is crucial (7, 8).

The app's capacity to incorporate eHealth literacy evaluations into the therapeutic process guarantees individualized treatment plans from the beginning improving adherence and health outcomes. This is where the significance of the study lies. The app addresses health equity issues by tackling digital literacy early, increasing the inclusion and accessibility of digital health technologies for users of all levels of technological skills. This is consistent with research in the larger body of literature showing that a major obstacle to accessing healthcare is a lack of digital literacy that exacerbates disparities (9). This strategy is an important step in making sure that technology supports care rather than hinders it, especially as digital health solutions proliferate in the medical field.

2 Related works

With the increasing reliance on mobile and web platforms for healthcare, eHealth literacy has emerged as a critical element in shaping digital health interventions. Tools such as the eHealth Literacy Scale (eHEALS) are commonly used to assess an individual's ability to seek, understand and use health information from digital sources. However, the fact that eHEALS mostly emphasizes perceived ability over actual performance, limits its ability to accurately represent users' actual digital abilities. This is a major criticism of the system. To obtain a more complete picture of eHealth literacy, recent research suggests that it is necessary to combine self-reported measures with tools that assess real-world performance (2, 10, 11).

Pavan et al. (12) investigated the effectiveness of two tele-rehabilitation (TR) models aimed at improving recovery from subacute upper limb disability following stroke. While the other cohort used non-robotic techniques, the first cohort received robot-assisted TR. Both groups showed remarkable progress in their cognitive and motor abilities, although the motor outcomes of the non-robotic group were slightly better. This suggests that despite the potential of robotic systems, conventional non-robotic methods can still achieve better results in certain rehabilitation settings.

Bok et al. (13) studied the effectiveness of home-based high-tech rehabilitation programs for stroke patients that focused on interventions such as virtual reality (VR), robotic devices and game-based techniques. According to the results, VR-based rehabilitation outperformed robotic and game-based interventions in terms of improving physical function, especially in upper limb recovery. This demonstrates the potential of immersive virtual reality technologies in rehabilitation programs conducted at home.

Jaramillo-Isaza et al. (14) implemented a comprehensive analysis of wearable sensors and artificial intelligence in tele-rehabilitation and presented how these technologies can enhance remote rehabilitation initiatives. Clinicians were able to make dynamic adjustments to treatment protocols using wearable devices that continuously monitored patients' movements and provided real-time feedback. In home-based rehabilitation, this strategy significantly improved patient's adherence and results, particularly for patients with mobility impairments.

Xie and Mo (15) conducted a meta-analysis comparing the Digital Health Literacy Instrument (DHLI) and the eHealth Literacy Scale (eHEALS) in the context of tele-rehabilitation of older adults. Their results showed that although both instruments measure perceived eHealth literacy well, the DHLI is better at identifying the practical digital skills required to successfully use tele-rehabilitation platforms. This research emphasizes the importance of using performance-based assessments to ensure that patients can interact with complicated digital health environments, which ultimately increases the effectiveness of tele-rehabilitation treatments.

3 Materials and methods

The eHealth Literacy App was developed using a comprehensive methodological approach that addresses both technical and user-centered requirements. Before detailing the individual components, it is important to understand the overall structure and workflow of the app. The app operates in dual-mode, incorporating the patient mode for clinical use with specific patient data and session tracking, and the demo mode for training or demonstration purposes without patient data requirements. Figure 1 illustrates the overall workflow of the app and shows how the user progresses through the stages of data collection, exercise-questionnaires-quizzes completion and data synchronization. This workflow

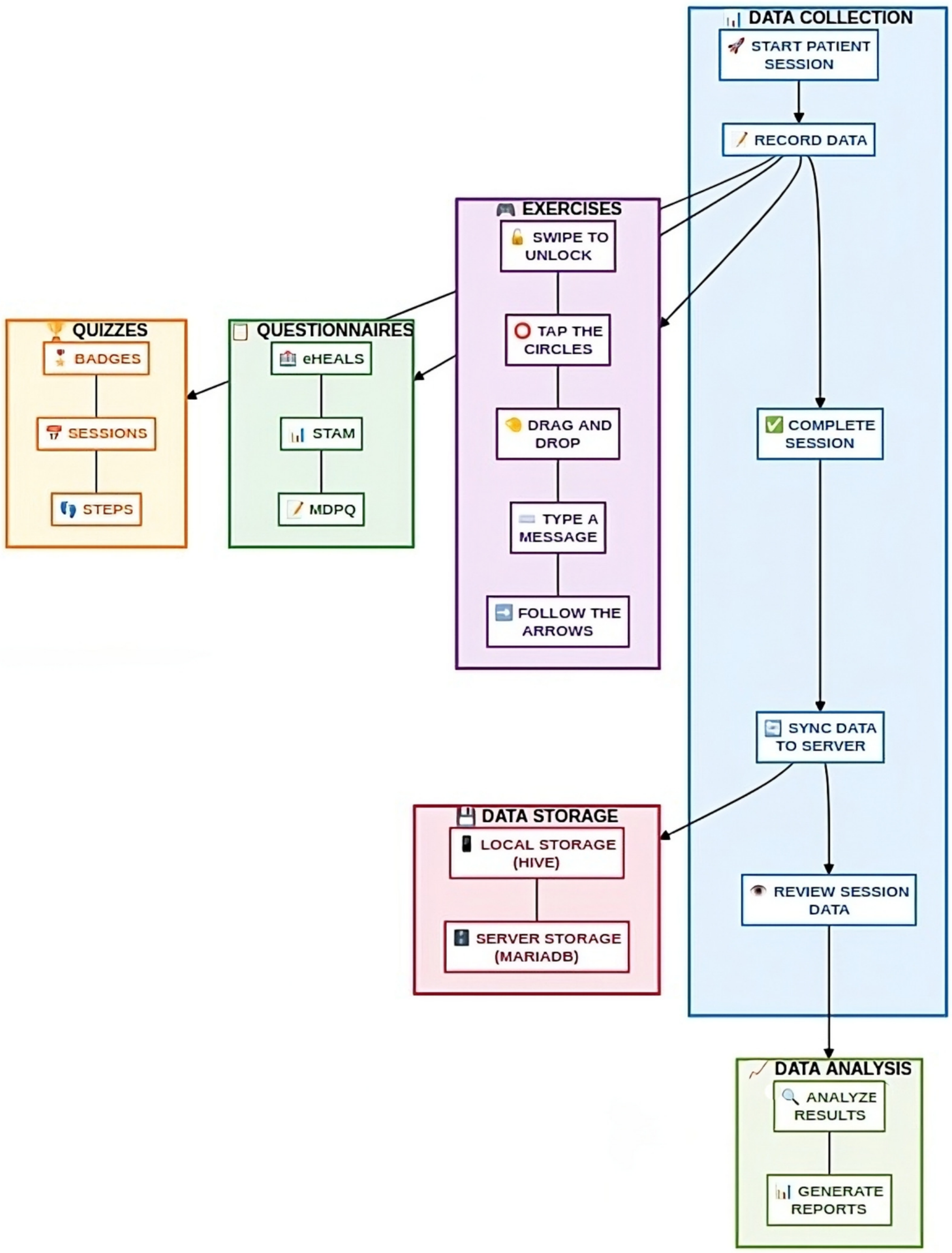

FIGURE 1
The Workflow diagram of the eHealth Literacy App.

forms the foundation for all technical implementation decisions described in the following subsections.

3.1 System architecture

To guarantee cross-platform functionality, data security and effective synchronization, a strong technology stack was used during the development of the eHealth Literacy App. The Flutter framework, which enables the development of natively compiled applications for iOS and Android platforms from a single codebase, was used to implement the frontend (16). This method streamlines development and improves usability. .NET Core was chosen for the backend implementation as it has excellent performance characteristics, built-in security features, and efficient resource utilization with high concurrent load (17). The architectural flexibility of the framework allows the implementation of robust authentication protocols and encrypted data transfers, which are essential for handling sensitive patient data, while the modular design facilitated integration with healthcare-specific data processing modules. REST APIs ensure reliable and effective data exchange by enabling seamless communication between the frontend and backend, supporting the real-time synchronization required for patient monitoring and assessment.

3.2 Data management and security protocols

To maintain availability and persistence of data, the application uses a dual-database architecture. The main server-side database MariaDB is used to safely store exercise results, session data and patient records. Hive, a lightweight NoSQL database, is utilized for local storage within the application to guarantee offline functioning, automatically synchronizing all data upon reconnection (18). Strict data security procedures such as encryption and secure API communication are implemented in accordance with industry best practices for health data protection (19) in order to protect sensitive patient information.

3.3 Multilingual support and accessibility

Using the Slang package, the system automatically adjusts the language settings to the nation of the clinic identified by the logged-in clinician's credentials (20). With support for English, Greek, German, Portuguese and Thai, this feature improves accessibility and user convenience by displaying the app in the user's preferred language.

3.4 User interface

The app has several screens designed to guide the user through exercises and questionnaires to assess their eHealth literacy. One of the most important screens is the login screen, where clinicians can enter their credentials. Patient mode and demo mode are the two different operating modes that are displayed after logging in, as shown in Figure 2. Each patient in patient mode is linked to a unique patient ID and session, so it is intended for use in a clinical environment (21). On the other hand, in demo mode, no patient-specific credentials are required to test and explore the app. This two-mode system is intended for research or demonstration purposes in addition to practical clinical use. In the Patient Mode, clinicians can see a list of their patients. Each patient can have multiple sessions, with an overview of completed and pending exercises. The interface allows clinicians to select patients and review their progress across different therapy sessions.

3.5 Metrics

The selection of metrics to assess digital literacy and motor skills was based on established frameworks and previous research on eHealth literacy (9). Each metric was specifically selected to assess particular aspects of user interaction with the app, ensuring a comprehensive assessment of both digital literacy and practical abilities. The exercises were designed to reflect real-life scenarios that patients might face when using digital health resources, providing relevant insights into their skills. The evaluation intended to provide an expanded overview of the ability to implement eHealth solutions by combining performance-based metrics with self-reported responses.

Upon selecting a particular patient, the patient is presented with a series of exercises, as displayed in Figure 3 and questionnaires, as displayed in Figure 5. The metrics of both exercises and questionnaires, as being captured by the app, are shown in Table 1.

The performance-based exercises are designed to assess different aspects of digital literacy and motor skills (22). The "Swipe to Unlock" exercise measures the user's ability to interact with touchscreen surfaces and records the time it takes to perform the action. The "Tap the Circles" exercise assesses fine motor skills and reaction time, recording both successful and failed touches. The "Drag and Drop" exercise assesses the user's ability to manipulate objects onthe screen and measures the time it takes to arrange the objects correctly. The "Type a Message" exercise assesses typing skill by measuring time to completion, typing errors, time to first backspace and total number of backspaces. Finally, the "Follow the Arrows" exercise tests the user's ability to follow the on-screen instructions and records the score and the total number of arrows displayed.

In addition to the performance-based exercises, three gamification-focused quizzes were integrated to enhance user engagement and evaluate comprehension of digital health concepts. The "Badges Quiz" evaluates users' understanding of achievement in systems commonly employed in digital health platforms, by presenting scenarios where users must distinguish between collected and uncollected badges (23). The "Sessions Quiz" assesses the user's ability to interpret session-based information and track progress over time. It requires users to calculate the remaining sessions based on visual progress indicators (24). The "Steps Quiz" measures the user's understanding of activity tracking interfaces and tests their ability to read and interpret pedometer displays and daily goals (25). These gamification-based assessments, shown in Figure 4, provide an interactive approach to evaluating users' ability to navigate common elements found in contemporary digital health applications.

The integration of questionnaires such as the eHealth Literacy Scale (eHEALS), the Senior Technology Acceptance Model (STAM), and the Mobile Device Proficiency Questionnaire (MDPQ) into digital health literacy tools is critical for enhancing their efficacy and user engagement. These questionnaires, shown in Figure 5, serve a dual purpose: they not only facilitate the customization of digital health resources by evaluating users' internet utilization patterns, technology acceptance levels, and ability in mobile device operations, but they also contribute to the overall improvement of health literacy. By systematically identifying the unique challenges faced by elders in the adoption

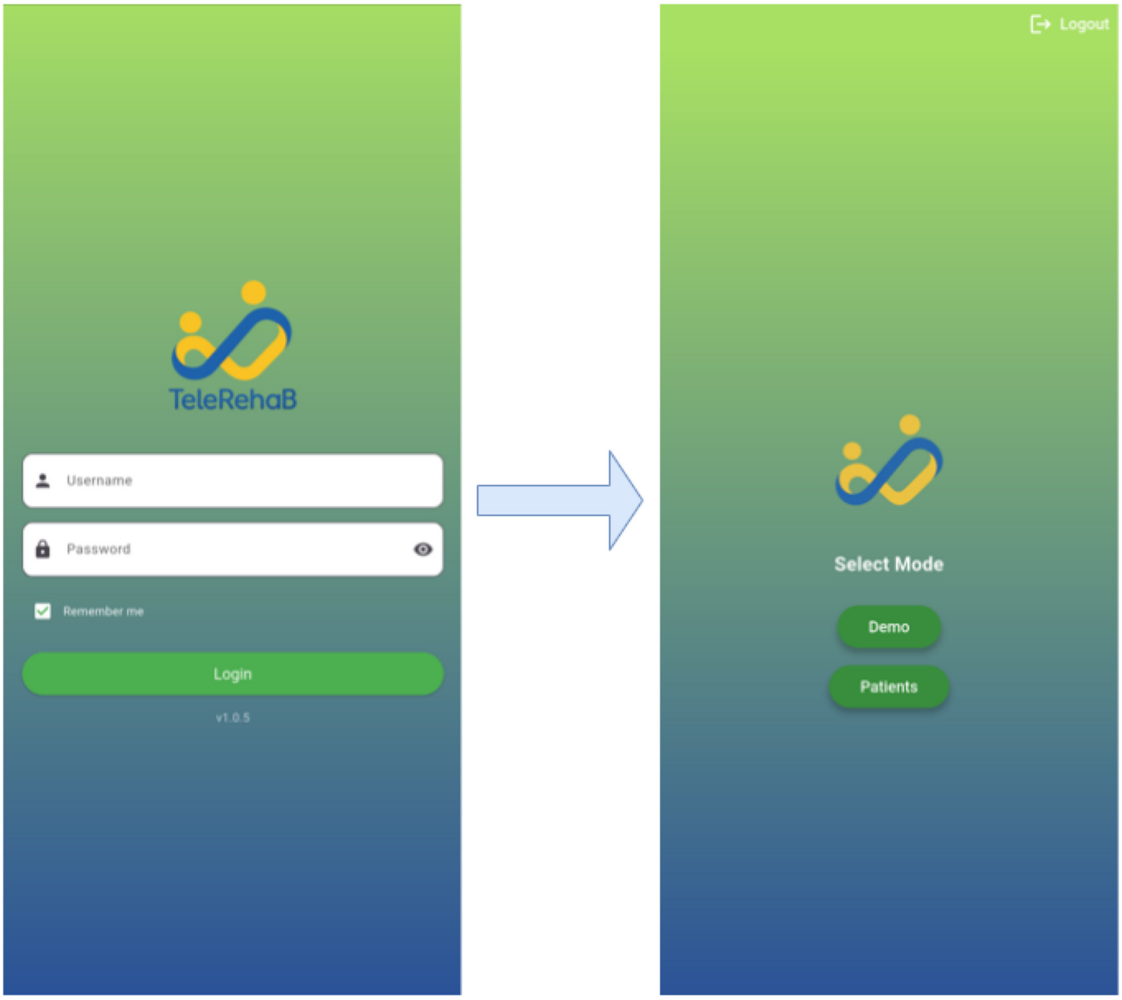

FIGURE 2
Login interface displaying patient and demo modes.

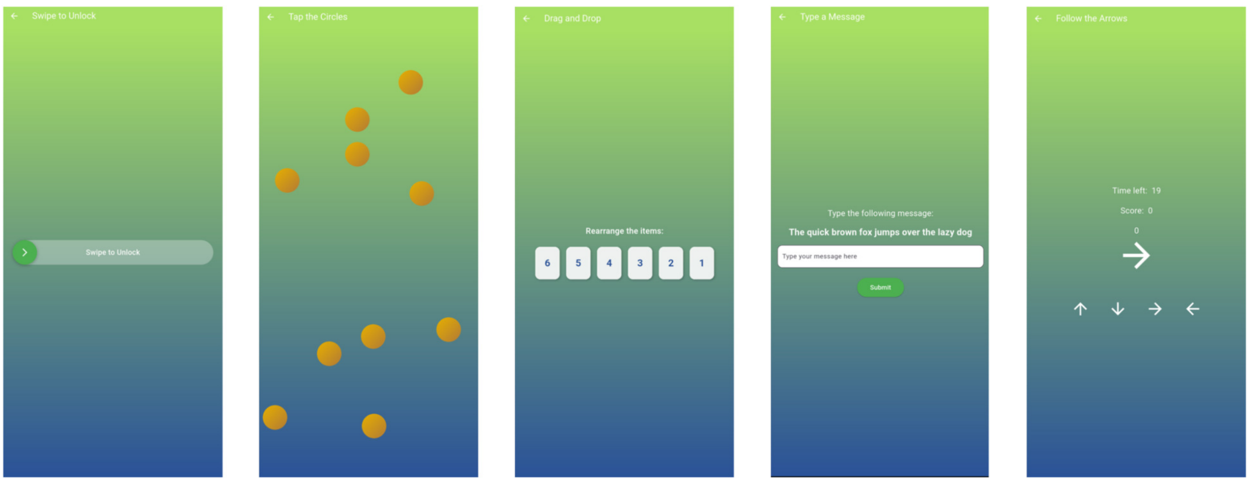

FIGURE 3
User interface displaying exercises.

TABLE 1 Metrics captured by the App.

Exercise/quiz/ questionnaire	Metrics	Description
Swipe to unlock	Time to unlock	Time taken for the user to swipe and unlock the screen
Tap the circles	Taps completed, missed taps	Number of circles successfully tapped and missed
Drag and drop	Time to complete	Time taken for the user to correctly rearrange items
Type a message	Time to complete, typing mistakes, time until first backspace, backspace count	Time taken to type the message, number of errors, time until first correction, total corrections made
Follow the arrows	Score, total arrows shown	User's score and total number of arrows displayed
Badges quiz	Correct responses, response time	Number of correct identifications of badge status and time taken per question
Sessions quiz	Correct responses, response time	Accuracy in interpreting session progress and time taken per calculation
Steps quiz	Correct responses, response time	Accuracy in reading step counter displays and time taken per question
eHEALS questionnaire	Responses	Likert-scale responses assessing eHealth literacy
STAM questionnaire	Responses	Likert-scale responses evaluating attitude towards technology
MDPQ questionnaire	Responses	Responses evaluating mobile device proficiency

of digital technologies, these questionnaires can uncover specific needs and barriers to effective engagement.

The eHEALS questionnaire (26) begins with an introductory question asking users if they use the Internet to find health-related resources. Based on the answer to this question, the app decides whether to proceed with the full eHEALS assessment. This adaptive approach ensures that the assessment is relevant to each user's digital habits.

The STAM (Senior Technology Acceptance Model) questionnaire (27) was developed to assess older adults' acceptance of and comfort with using digital health technologies. It assesses the key factors that influence technology acceptance, including perceived usefulness, ease of use and social influence. The questionnaire contains a series of questions on a Likert scale (from 1 to 10) that allow users to indicate their level of agreement or disagreement with statements about their experiences and attitudes towards technology. This assessment is specifically designed for older adults and focuses on variables such as age-related factors and self-efficacy in using digital tools for health-related purposes.

The Mobile Device Proficiency Questionnaire (MDPQ) (28) was integrated to obtain a comprehensive assessment of the user's ability to perform various tasks on mobile devices. This questionnaire covers a range of activities, from basic operations such as adjusting screen brightness to more complex tasks such as managing app installations and using cloud storage services.

Before each questionnaire is started, the patient is shown an instructions' screen (28). This screen is designed to provide clear and concise information about the purpose of the questionnaire and instructions on how to complete the questionnaire. For example, before the eHealth Literacy Scale (eHEALS), the introductory screen explains the importance of assessing the user's confidence in accessing and understanding online health information. Similarly, before the Senior Technology Acceptance Model (STAM) and the Mobile Device Proficiency Questionnaire (MDPQ), the user gets informed of the specific objectives of the questionnaires, that might involve evaluating the benefits of using mobile devices or measuring the usability of the equipment (29).

3.6 Sessions' functionality

Throughout the course of treatment, clinicians can track progress and changes in eHealth literacy according to the app's support during numerous sessions (30, 31). A new session begins or an incomplete one is carried over, each time a patient finishes a series of exercises and questionnaires. This feature acknowledges potential weariness or time limits of older individuals using digital tools by allowing assessments to be resumed after interruption.

When an internet connection is available, the Hive-stored session data is synchronized with the MariaDB database on the server. Healthcare professionals always have access to the most recent data regarding the status of their patients due to this synchronization (32). The methodology by which the sessions are organized also makes it easier to create progress reports, which helps doctors evaluate patient outcomes as they progress.

On the other hand, while an application's Demo mode is intended for one-time use or demonstration, it does not make use of the session process. The app's adaptability in meeting clinical and instructional demands is highlighted by the difference in session management between the demo and patient modes.

3.7 Deployment and platform availability

The eHealth Literacy App is distributed to clinical sites through controlled installation packages for both Android and iOS devices. This deployment strategy ensures that only authorized clinical sites receive the application and enables consistent version management across all installations. The backend system is hosted centrally at the Biomedical Engineering Laboratory, NTUA, Athens, as part of the overall TeleRehaB DSS project infrastructure. Authentication is managed through clinician credentials, so that only authorized healthcare professionals within the TeleRehaB project can access the system. This centralized model simplifies maintenance while maintaining security protocols for handling sensitive patient data.

4 Results

The eHealth Literacy Application was made available to the organization's internal users in the first test phase. This group included employees with different functions and technical knowledge. The pre-pilot phase was used to evaluate the usability

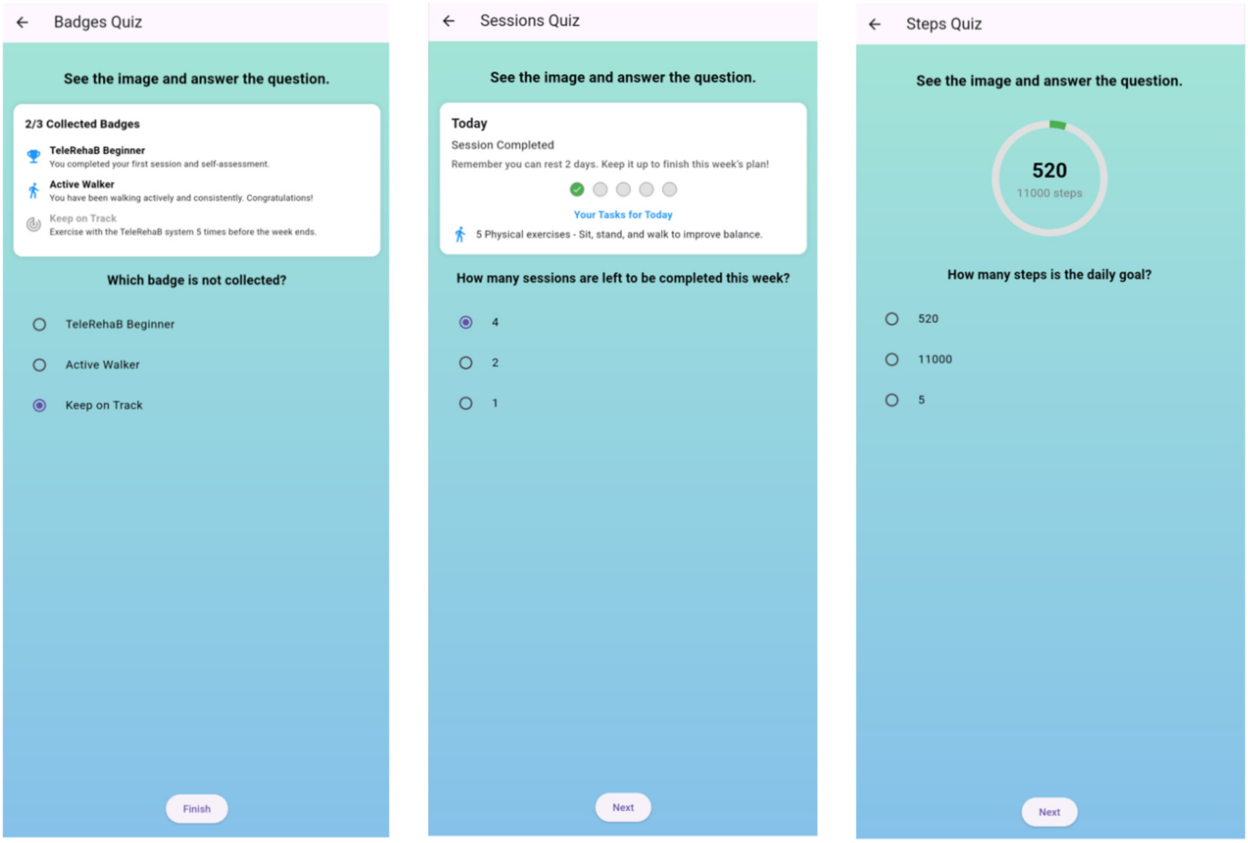

FIGURE 4
User interface displaying Gamification quizzes: (a) badges quiz, (b) sessions quiz, (c) steps quiz.

and overall user experience of the app before the pilot phase for patients initialized. The software was used by internal users who answered the questionnaires, completed the exercises, and performed the gamification quizzes. This diverse group provided comprehensive usability by providing insightful feedback on the app's performance in terms of various technical backgrounds, interface design and navigation.

4.1 Usability and functionality testing

Usability of the eHealth Literacy App was assessed using the System Usability Scale (SUS) (33), a widely recognized tool that provides a reliable measure of user satisfaction and ease of use. After interacting with the app, participants completed the SUS (34), which consists of ten items that evaluate various aspects of usability. This approach allows for quantitative analysis of user feedback, offering insights into the app's overall effectiveness and areas for improvement (35). The SUS scores were subsequently analyzed to identify strengths and weaknesses in the user interface and overall experience.

The diverse group of internal users could be valuable sources of perspective regarding usability, interface design, and general user experience, even if they are not the targeted audience. It was expected that their comments would indicate weaknesses related to navigation, engagement, or the flow of interaction processes in the app. The focus of this study was to assess how well the participants would be able to perform the set exercises, complete the posed questions, respond to the gamification quizzes, as well as to assess the connectivity between the local database (Hive) and the backend APIs for session data storage and synchronization.

The data gathered through this testing phase were mostly aimed at the time taken to perform each exercise, the number of completed exercises and opinions regarding the app's features. In addition, the participants were invited to submit open-ended comments on the transparency of the instructions, the app's navigation and interactivity during live performance (36). Furthermore, the data connected with how well the multilingual feature (using Slang) operated was also noted.

Insights gained from this phase enabled improvement of particular features of the app. In particular, the content of the introductory screens that accompanied each questionnaire was modified, as well as translation of some terminologies, based on user comments. Such observations will constitute the foundation for the full pilot study where the application will be used with real patients in a clinical setting.

This phase established that the application is technically sound, as data was managed seamlessly between the local device and Hive storage

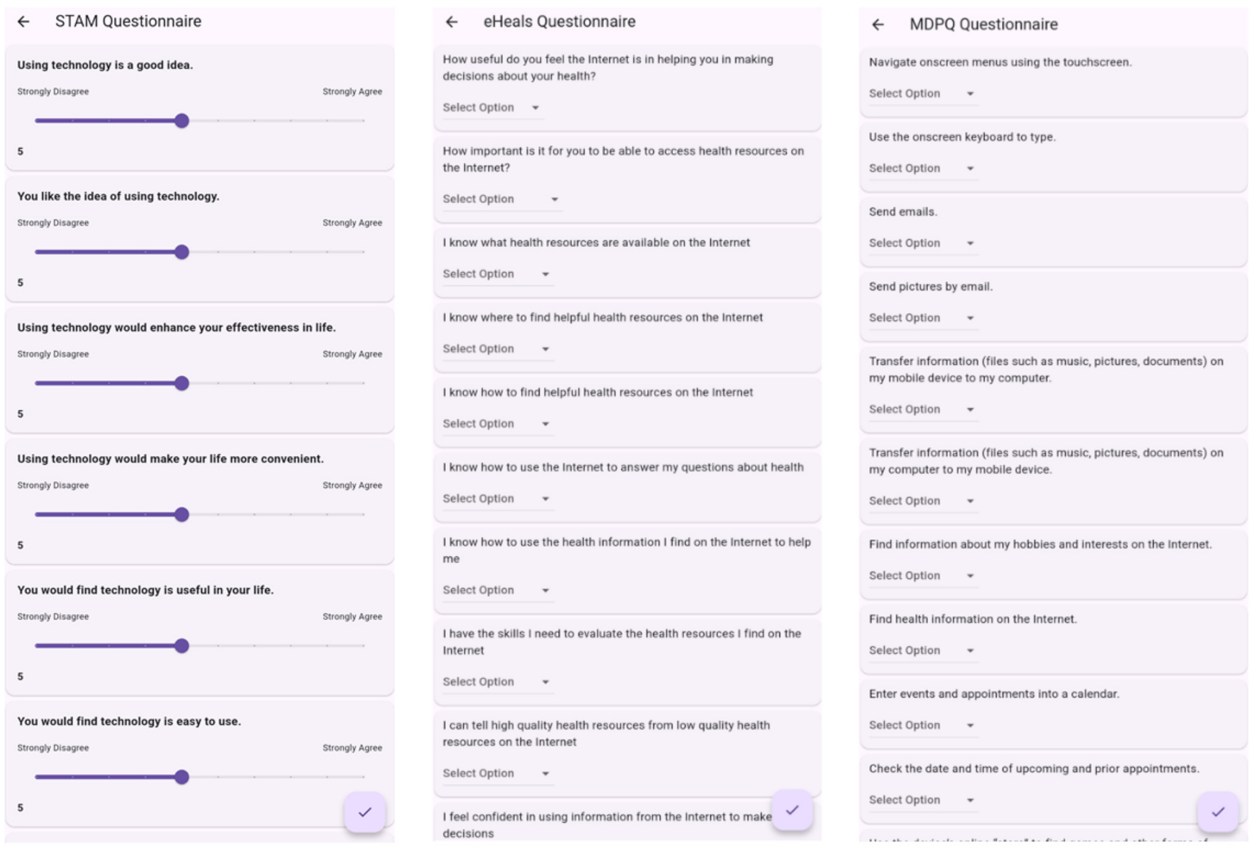

FIGURE 5
User interface displaying questionnaires.

and the backend server. The testing subjects involved lost scenarios when the internet was available for the first portion of the session but ceased for the latter section of it. This was done in three variations; whenever the device was disconnected from the network, the data stored locally on it was always synchronized with the server once the connection was restored. Such validation steps allow for a usage scenario where an application will run in environments where internet connection is poor and data loss would otherwise occur.

4.2 System stability

The REST APIs created in C# language for communication between the application and the backend server were successfully completed within an average data exchange time of less than 1 s under stable internet connections. With the help of these APIs, patient records can be updated immediately, allowing clinicians to keep track of patients' needs and modify the treatment if necessary (37).

4.3 Assesment of risk of bias

Potential sources of bias in the evaluation of the eHealth Literacy App were thoroughly addressed during the internal testing phase. We considered selection bias in participant recruitment, potential inconsistencies in exercise administration, and limitations of self-reported data. To mitigate these concerns, we included internal users with varying technical backgrounds, standardized testing protocols, and compared self-reported assessments with observed performance. This internal testing was primarily designed to validate technical functionality rather than comprehensively evaluate eHealth literacy outcomes. These preliminary findings have strengthened the app's design, preparing it for the upcoming multicentric clinical study where comprehensive quantitative data will be collected from 230 patients comprising the intervention arm of the study.

5 Discussion

Within the TeleRehaB DSS project, the development and pilot study of the eHealth Literacy App demonstrates its relevance in overcoming the existing digital and eHealth literacy challenges of patients receiving balance physiotherapy. These issues have been resolved through eHealth literacy, which has been shown to enable patients to participate appropriately in health interventions delivered via the internet, directly impacting adherence to a prescribed treatment regime. The use of an app that assesses the level of digital and eHealth literacy of patients helps healthcare providers to develop appropriate management strategies to avoid patients having difficulties in using the digital platforms that are helpful to their rehabilitation.

The implementation of all of the above, including the app's exercises, self-reported questionnaires, and gamification quizzes, illuminates the readiness of technologically literate patients to use technology for their health. This combination of self-reported ease, practice-based competence, and interactive assessments explores a key limitation of existing digital health solutions where patients self-assess 'comfort' with technology without clearly outlining basic skills.

The inclusion of gamification-oriented quizzes (Badges Quiz, Sessions Quiz, and Steps Quiz) fills a critical gap in existing assessments of eHealth literacy by assessing users' understanding of the interaction mechanisms common in modern digital health platforms. These elements are becoming increasingly important as health apps employ game-like features to improve user motivation and adherence to treatment protocols. The quizzes showed that participants could effectively interpret visual progress indicators and success systems. This suggests that gamification elements, when properly designed, do not present additional barriers to target audience engagement with digital health applications. This finding is particularly relevant for the TeleRehaB DSS project, as the integration of motivational elements through gamification can potentially improve patients' long-term engagement in rehabilitation protocols.

During the testing phase involving internal users, it was noted that session data was not lost in even the hardest of conditions thanks to Hive which maintained local data storage even in the absence of a stable internet connection. This is an important factor in remote or low-resource settings where internet connection is very unreliable and data integrity remains important. The use of Slang for bringing automatic language adaptation through the region of the doctor's clinic also worked well as it made the application more usable in different languages and cultures. This functionality compliments the aim of increasing engagement and participation especially of otherwise underserved patients in such digital health interventions.

The application was built with dual-mode functionality which is one of the most useful features of the application as it allows for use by self-identified patients in specific sessions or in anonymous demo. This offered convenience to clinicians, as the app can be used in different patient rehabilitation scenarios or purely educational or training aspects. Further, the ability to perform multiple sessions per patient allows the clinicians to have more information concerning the patients over time and make better decisions regarding their further treatment and the interventions that need to be made.

When comparing our approach to existing work in eHealth literacy assessment, our study offers several novel contributions to the field. Unlike tools such as eHEALS (2) that primarily rely on self-reported capabilities, our eHealth Literacy App integrates performance-based exercises, gamification quizzes, and standardized questionnaires, addressing the need for real-world performance assessment. Pavan et al. (12) investigated robotic and non-robotic tele-rehabilitation models and demonstrated significant recovery of cognitive and motor function in stroke patients. Bok et al. (13) focused on home-based high-tech rehabilitation programs and highlighted the effectiveness of virtual reality in improving upper limb recovery. Jaramillo-Isaza et al. (14) investigated the use of wearable sensors and emphasized their role in providing real-time feedback to improve patient adherence to therapy. In contrast to these studies, our research introduces the eHealth Literacy App, which not only incorporates elements of these innovative technologies, but also prioritizes eHealth literacy and enables patients to effectively engage with digital health interventions. Furthermore, while (15) identified the importance of performance-based assessments, our work extends this finding by creating a comprehensive framework that translates assessment results directly into personalized treatment recommendations—a capability not present in existing eHealth literacy tools. Additionally, the incorporation of automated multilingual support distinguishes our approach from existing solutions, directly addressing the cultural and linguistic barriers highlighted by (9) as determinants of health disparities. Finally, through dual-mode functionality and the integration of self-assessments, our study presents a comprehensive solution that has the potential to improve both patient engagement and treatment adherence in rehabilitation settings.

5.1 Limitations and future perspectives

The application had practical exercise-based assessments that measured motor and cognitive skills relevant to the proficiency of digital literacy. However, some changes would enhance the interface, primarily the start up screens of the questionnaires. Additionally, the current implementation assumes relatively stable network connectivity for optimal data synchronization, which may present challenges in some clinical environments. These limitations emphasize the importance of progressive enhancement of the app to ensure it achieves its objectives whilst being simple and easy to use.

Moreover, while the initial results are promising, there are limitations to the current findings as the tests were conducted in a controlled organizational setting and not with the patient population intended for the app. As the pilot study progresses and the app is used in a clinical setting, further evaluation will be required to assess the impact of the app on patient adherence, engagement and health outcomes in practice. The upcoming clinical validation will provide more comprehensive insights into the effectiveness and scalability of the app.

5.2 Conclusions

In conclusion, the eHealth Literacy App developed as part of the TeleRehaB DSS project, represents a significant advancement in addressing the digital and eHealth literacy of patients undergoing balance physiotherapy. By incorporating self-assessments, performance-based exercises, and interactive gamification quizzes, the app provides a comprehensive assessment of a patient's digital skills and enables healthcare providers to develop tailored management strategies. The results of the initial testing phase show that the app is technically robust, well received by users and adaptable to different cultural contexts. In addition, the dual-mode functionality improves accessibility, allowing both self-identified patients and anonymous users to benefit from the app's features. Ultimately, this innovative approach is expected to enhance patient adherence to rehabilitation protocols and could contribute to better health outcomes, highlighting the importance of integrating technology into healthcare. Future studies will further expand on these findings by evaluating the app's effectiveness in real-world clinical settings, which may pave the way for improved patient care in an increasingly digital healthcare landscape.

Data availability statement

The datasets presented in this article are not readily available because still on process/under project progress. Requests to access the datasets should be directed to kostasgeo@biomed.ntua.gr.

Author contributions

KG: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. KB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. TV: Methodology, Project administration, Validation, Writing – review & editing. OG: Methodology, Validation, Writing – review & editing. NV: Conceptualization, Formal analysis, Methodology, Project administration, Validation, Writing – review & editing. IK: Formal analysis, Methodology, Project administration, Software, Validation, Writing – review & editing. MH: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. GM: 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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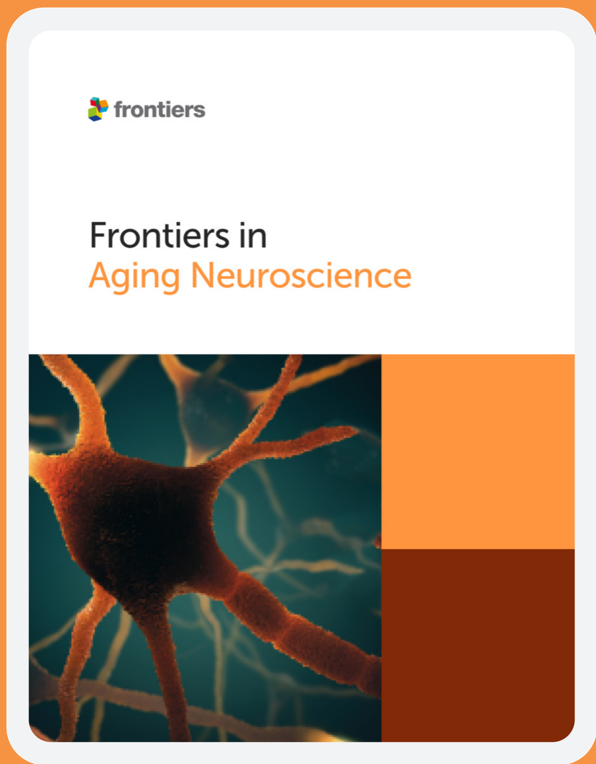

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