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Utility of bioelectrical impedance vector analysis for assessing body composition and its association with ambulatory recovery after hip fracture

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ABSTRACT

Background: Functional recovery after hip fracture is often complicated by interrelated geriatric syndromes such as malnutrition, sarcopenia, and cognitive impairment, which alter body composition and worsen outcomes. Bioelectrical impedance vector analysis (BIVA) is a promising tool for evaluating body composition; however, its clinical relevance in post-fracture rehabilitation remains insufficiently explored. This study examined whether BIVA is associated with these conditions and functional recovery.

Methods: In this prospective observational study, 99 adults aged ≥65 years who underwent hip fracture surgery and initiated inpatient rehabilitation were evaluated. Ambulation was assessed over 12 months. Bioelectrical impedance vectors were compared among groups stratified by nutritional, sarcopenic, cognitive, and functional status. Functional recovery trajectories were plotted on reference tolerance ellipses, and prognostic value was analyzed.

Results: BIVA demonstrated significant vector shifts across nutritional, sarcopenic, cognitive, and functional categories, with poorer status associated with rightward or downward displacement. Poor ambulators frequently showed vectors outside the 95% tolerance ellipse at baseline, and these patients had lower cumulative recovery of independent ambulation. In multivariable Cox analysis, vectors outside the 95% tolerance ellipse were associated with lower likelihood of recovery at 3 months (hazard ratio [HR] 0.458; 95% confidence interval [CI] 0.262–0.800; $p = 0.006$), 6 months (HR 0.525; 95% CI 0.302–0.914; $p = 0.023$) and 12 months (HR 0.510, 95% CI: 0.297–0.877, $p = 0.015$).

Conclusions: BIVA is a feasible and informative tool for identifying body composition impairment in older adults undergoing rehabilitation after hip fracture. BIVA measurements were associated with functional recovery differences and may provide complementary information for risk stratification during pre-rehabilitation assessment.

1. Introduction

Hip fractures in older adults are associated with high mortality rates, prolonged disability, and substantial healthcare costs. One-year mortality rates range from 20% to 24%, and up to one-third of patients require institutional care because of loss of independence (Government, 2023). Although some functional recovery, including gait and balance, occurs within 6–9 months, independence in daily activities often remains impaired after 12 months (Fischer et al., 2019; Magaziner et al., 2000). Approximately 40% of patients are unable to walk independently, and 60% require assistance 1 year post-fracture (Government, 2023; Magaziner et al., 2000). Persistent functional impairment contributes to complications, delayed recovery, increased mortality, and a substantial socioeconomic burden.

Effective rehabilitation is critical for improving outcomes in older adults with hip fracture. Multidisciplinary programs focused on intensive, structured exercise improve function, reduce institutionalization, and lower mortality and healthcare utilization (Bachmann et al., 2010; Handoll et al., 2021). However, recovery is often complicated by geriatric issues, such as malnutrition, sarcopenia, and cognitive impairment, which frequently coexist and adversely affect prognosis (Sheehan et al., 2018; Xu et al., 2019). Early detection and tailored management of these

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conditions are essential. Current diagnostic guidelines for malnutrition (Cederholm et al., 2019) and sarcopenia (Kirk et al., 2024) recommend body composition analysis for accurate diagnosis and intervention. Given their strong association with cognitive impairment (Jo et al., 2022; Ye et al., 2025), assessing body composition may help identify older adults with hip fracture who are at increased risk of cognitive decline.

Bioelectrical impedance analysis (BIA) is a non-invasive and widely used method for assessing body composition by measuring the body's resistance to a small electrical current (Norman et al., 2012). It is favored for its safety, affordability, and ease of use. Conventional BIA estimates fat-free mass, muscle mass, and total body water through predictive equations that incorporate raw impedance values along with age, sex, height, and weight (Norman et al., 2012). However, its accuracy is limited in older adults and those with comorbidities because of physiological variability (e.g., hydration, body fat/muscle distribution, limb-to-torso ratio) (Camina Martín et al., 2014; Catapano et al., 2023; Norman et al., 2012) and population-specific assumptions in predictive equations (Campa et al., 2024; Norman et al., 2012). The lack of universal standardization across devices and populations further undermines its reliability (Campa et al., 2024). Conventional BIA may also overlook clinically relevant information available from raw impedance parameters because it relies solely on estimated body compartments (Akamatsu et al., 2022; Da Silva et al., 2023).

Bioelectrical impedance vector analysis (BIVA) was introduced by Piccoli et al. (1994) to address these limitations. BIVA directly analyzes the resistance (R) and reactance (Xc) standardized by height and plots them as vectors to qualitatively assess hydration, cellular integrity, and body composition (Piccoli et al., 1994). The vector orientation reflects the phase angle (PhA), a validated biomarker of nutritional and functional status (Costa Pereira et al., 2024; Norman et al., 2012). PhA has demonstrated clinical utility as a biomarker for malnutrition, sarcopenia (Sato et al., 2022; Zuo et al., 2024), and mortality risk (Lima et al., 2022), with prognostic value across various disease states (Lima et al., 2022; Norman et al., 2012). Unlike conventional BIA, BIVA is less influenced by fluid shifts and provides a more comprehensive assessment by integrating hydration, soft tissue mass, and body cell mass (BCM) (Catapano et al., 2023; Guerrini et al., 2024; Norman et al., 2012). It has shown utility in diverse populations, including older adults, athletes, dialysis and cancer patients, individuals with obesity, stroke survivors, and the critically ill (Campa et al., 2023; Catapano et al., 2023; Guerrini et al., 2025a, 2025b; Kyle et al., 2004a). BIVA can also distinguish between malnutrition (Slee et al., 2015) and sarcopenia (Jiang et al., 2023).

Despite growing evidence, BIVA remains underutilized in older adults with hip fracture, particularly in rehabilitation settings. Given the clinical importance of body composition impairment, accurate assessment is essential for timely nutritional intervention and appropriate rehabilitation planning. Few studies have systematically applied BIVA in this context. Our previous work identified distinct vector patterns in patients with hip fracture compared with healthy controls (Lim and Lim, 2025). However, that study focused primarily on cross-sectional differences in body composition and did not evaluate the relationship between BIVA parameters and functional recovery outcomes. BIVA has also been shown to be associated with differences in recovery trajectories in rehabilitation populations (Guerrini et al., 2025b) and to identify high-risk subgroups with increased mortality in hospitalized older adults (Guerrini et al., 2025a).

Building on this evidence, this study aimed to investigate the utility of BIVA in assessing key prognostic factors (malnutrition, sarcopenia, and cognitive impairment) in older adults with hip fracture initiating rehabilitation. Additionally, the study explored whether BIVA could stratify patients according to levels of functional recovery and evaluated its association with functional outcomes.

2. Methods

2.1. Study design and participants

This prospective observational secondary analysis used data from the Fragility Fracture Integrated Rehabilitation Management (FIRM) clinical trial (ClinicalTrials.gov Identifier: NCT03430193). Participants were consecutively enrolled at Seoul National University Bundang Hospital between February 2017 and February 2020 during the preliminary feasibility phase and the subsequent randomized controlled trial phase evaluating the efficacy of FIRM (Lim et al., 2025). The study was approved by the Institutional Review Board of Seoul National University Bundang Hospital (B-1603–337–002), and all participants provided written informed consent. This study used the same patient cohort as in our previously published work (Lim and Lim, 2025).

Eligible participants were adults aged ≥65 years who underwent surgery for femoral neck, intertrochanteric, or subtrochanteric fractures. Exclusion criteria were surgery for infection, arthritis, implant-related complications, avascular necrosis, periprosthetic or pathological fractures, multiple fractures, revision surgeries, severe cognitive impairment (inability to follow simple instructions or communicate effectively), refusal to participate, non-completion of the prescribed rehabilitation program, and lack of baseline BIA data.

2.2. Data collection

Baseline sociodemographic and clinical data were obtained using standardized questionnaires and a review of medical records. The collected variables included age, sex, anthropometric measures, type of surgery, postoperative complications, comorbidities (assessed using the Charlson Comorbidity Index [CCI]) (Charlson et al., 1987), osteoporosis, previous fragility hip fracture, sarcopenia, malnutrition, and cognitive impairment. Ambulatory functional status was assessed using the Functional Ambulation Category (FAC) scale (Holden et al., 1984), with a score ≥ 3 indicating independent ambulation (Barceló et al., 2024). Cognitive function was evaluated using the Mini-Mental State Examination (MMSE) (Kang et al., 1997) with education-, age-, and sex-adjusted cutoffs (Lee et al., 2004). Anthropometric measurements were performed by trained clinical staff while participants were barefoot and wearing light clothing. Body mass index (BMI) was calculated as weight divided by height squared (kg/m^2).

2.3. Outcome measures

Malnutrition and sarcopenia were assessed according to the Global Leadership Initiative on Malnutrition (GLIM) criteria (Cederholm et al., 2019) and the Asian Working Group for Sarcopenia 2019 guidelines (Chen et al., 2020), respectively. The GLIM defines malnutrition as the presence of at least one phenotypic criterion (unintentional weight loss, low BMI, or reduced muscle mass) and one etiologic criterion (reduced food intake, assimilation, or inflammation). Given the inflammatory response associated with hip fracture, all patients met the etiologic criteria (Kobayashi et al., 2022). Thus, malnutrition was classified in those who met at least one additional phenotypic criterion.

BIA was conducted using a tetrapolar system (Inbody S10; Biospace, Seoul, Korea) before the initiation of the rehabilitation program, following standardized procedures (Lukaski et al., 1985). Patients fasted for ≥8 h, avoided vigorous activity for 24 h, and removed all metallic objects before testing. Measurements were performed in the supine position with the limbs abducted. Impedance values were obtained at 50 kHz, and PhA was calculated as: PhA (°) = arctangent (Xc/R) × (180/π) (Kyle et al., 2004a).

Appendicular skeletal muscle mass (ASM) was calculated from the BIA data as the sum of the lean mass in all four limbs. Values from the non-fractured side were used for patients with lower limb implants (Kyle et al., 2004b). The ASM was normalized by height squared to derive the

ASM index. Handgrip strength (HGS) was measured using a digital dynamometer (TKK 5401 Grip-D; Takei, Niigata, Japan), according to the American Society of Hand Therapists protocol (MacDermid et al., 2015). Sarcopenia was defined as low muscle mass (ASM index <7.0 kg/m^2 for men and < 5.7 kg/m^2 for women) combined with low muscle strength (HGS <28 kg for men and < 18 kg for women) (Chen et al., 2020).

Functional recovery was defined as the achievement of independent ambulation as assessed using the FAC scale (Barceló et al., 2024). Restoration of ambulation is widely recognized as a central objective of postoperative recovery following hip fracture surgery (O'Connor and Switzer, 2022). The FAC evaluates walking independence based on the level of physical assistance required during ambulation and was selected because it enables assessment of ambulatory independence even in the early postoperative period, when gait speed may be difficult to measure because of weight-bearing restrictions, postoperative pain, or the inability to ambulate in some patients. Ambulatory status was evaluated at rehabilitation admission, discharge, and 3, 6, and 12 months postoperatively. Assessments were conducted via structured telephone interviews of participants who were unable to attend in-person follow-ups.

2.4. Rehabilitation program

The rehabilitation protocol has been previously described in detail (Lim et al., 2025). All patients participated in a standardized 2-week postoperative rehabilitation program delivered by a multidisciplinary team comprising a rehabilitation physician, physical and occupational therapists, a dietitian, a clinical nurse specialist, and a social worker. The program included 10 days of physiotherapy (PT), with two 30-min sessions per day, excluding holidays, and four sessions of occupational therapy (OT), along with fall prevention education, discharge planning, and referrals for community-based care. PT included individualized weight-bearing, strengthening, gait, aerobic, and functional training. OT focused on activities of daily living, such as transfers, bed mobility, dressing, self-care, and adaptive equipment use. Patients and caregivers received comprehensive education on postoperative exercises, activity precautions, ward routines, and home environment modifications, all based on hip fracture care guidelines.

Conventional rehabilitation focuses primarily on basic standing and gait training. Patients in this group received one 30-min physical therapy session daily, along with standard fall prevention education and discharge planning, which included postoperative and orthopedic care.

2.5. Bioelectrical impedance vector analysis (BIVA)

BIA-derived R and Xc data at an operating frequency of 50 kHz were analyzed following established BIVA protocols (Piccoli et al., 1995; Piccoli and Pastori, 2002). Values were normalized to height (R/H and Xc/H) and plotted on R-Xc graphs using BIVA-specific software (Piccoli and Pastori, 2002) and R (version 4.4.1; RStudio, Posit, Boston, MA, USA). Group comparisons were visualized using BIVA confidence ellipses, whereas BIVA tolerance ellipses (50th, 75th, and 95th percentiles) derived from a reference population enabled the assessment of individual vector distributions (Piccoli et al., 2002). In healthy individuals, impedance vectors typically fall within the 75% tolerance ellipse (Piccoli and Pastori, 2002; Piccoli et al., 1994).

The position and displacement of the impedance vector provide insights into tissue hydration and body composition. Movement along the major (longitudinal) axis reflects changes in total body water, whereas shifts along the minor (transverse) axis indicate changes in BCM and membrane integrity. Specifically, shorter vectors indicate fluid overload, whereas longer vectors indicate dehydration. Vertical displacements along the major axis of the ellipse reflect hydration status (upward = dehydration; downward = hyperhydration), whereas horizontal shifts differentiate between increased (upper left quadrant) and decreased (lower right quadrant) cellular mass (Norman et al., 2012; Piccoli et al., 1995, 1994).

As BIVA measurements are influenced by factors such as sex, ethnicity, age, BMI, and country (Catapano et al., 2023; Jensen et al., 2019; Piccoli et al., 2002), we used age- and BMI-matched reference ellipses derived from a Korean community-dwelling population without hip fracture (men, $n = 75$; age 76.6 ± 4.2 years; BMI 23.6 ± 2.3 kg/m^2; women, $n = 71$; age 75.1 ± 4.4 years; BMI 22.9 ± 2.2 kg/m^2) (Jiang et al., 2023). This reference population was selected to ensure closer demographic and anthropometric comparability with our study cohort. Additionally, the impedance vectors were converted to bivariate z-scores and plotted on R–Xc z-score graphs based on the same reference population.

2.6. Statistical analyses

Data are presented as mean ± standard deviation for continuous variables and as frequencies with percentages for categorical variables. Group comparisons were performed using independent *t*-tests and Pearson correlation coefficients for normally distributed data, and Mann–Whitney *U* tests and Spearman correlation coefficients for non-normally distributed data.

Bioimpedance vectors were compared between groups stratified by malnutrition, sarcopenia, and cognitive impairment at baseline, and ambulatory function recovery at follow-up. Bivariate 95% confidence ellipses of mean vectors were analyzed separately by sex, and intergroup differences were assessed using Hotelling's T^2 t-test. Mahalanobis distances (D) were calculated to quantify group differences, interpreted as small (0.25–0.49), medium (0.50–0.99), or large (≥1.00) (Stevens, 2002). The corresponding T^2, F-, and *p*-values were reported.

Individual bioimpedance vectors were plotted against sex-specific tolerance ellipses derived from a reference population to visualize vector distributions according to ambulatory recovery status over time. For group comparisons based on malnutrition, sarcopenia, cognitive impairment, and ambulation recovery, the mean vectors were standardized into bivariate z-scores, representing the number of standard deviations from the reference population mean.

Body composition status was categorized based on the vector location within reference tolerance ellipses: normal (<75th percentile) (Norman et al., 2012), moderately impaired (75th–95th percentiles), and severely impaired (>95th percentile), reflecting conditions such as dehydration, fluid overload, and muscle wasting (Norman et al., 2012).

Associations between body composition and malnutrition, sarcopenia, and cognitive impairment were assessed using chi-squared tests. Kaplan–Meier analyses with log-rank tests were used to compare the cumulative incidences of independent ambulation across body composition groups, with post hoc pairwise comparisons to assess between-group differences.

The association between BIVA and 12-month ambulatory recovery was evaluated using univariate and multivariate Cox proportional hazard models. Variables for multivariate analysis (backward elimination) included those with significant univariate associations, baseline group differences, or clinically relevant factors such as age, sex, BMI, malnutrition, sarcopenia, cognitive impairment, and rehabilitation method. Multicollinearity among variables was assessed using variance inflation factors (VIFs) to ensure model validity. The VIF values for BIVA-derived body composition impairment, sarcopenia, and malnutrition were 1.75, 2.32, and 3.01, respectively, indicating no evidence of problematic multicollinearity. The proportional hazards assumption was tested using Schoenfeld residuals.

To evaluate potential effect modification, interaction terms between the BIVA category and rehabilitation group (FIRM vs. conventional rehabilitation) and between the BIVA category and sex were included in the Cox regression models. Because the number of male participants was limited, the study was not powered for formal sex-stratified analyses. Missing data from loss to follow-up were handled by complete-case analysis. Only participants with available follow-up data were

included in the corresponding analyses. All statistical analyses were performed using R (version 4.4.1) in R Studio software. A p-value ≤ 0.05 was considered statistically significant.

3. Results

A total of 99 patients (24 men and 75 women; mean age, 81.5 ± 6.2 years) were included in the analysis. Seven patients were lost to follow-up at 3 months, four at 6 months, and 17 at 12 months. At baseline, 53 patients (53.5%) were malnourished, 38 (38.4%) had sarcopenia, and 50 (50.5%) had cognitive impairment, with no significant difference between the sexes. However, age, height, weight, ASMI, HGS, type of surgery, osteoporosis status, BIVA-derived body composition categories, and BIVA parameters (R and R/H) differed significantly between the sexes. Functional status (FAC ≥ 3) at discharge and at 3 months also differed significantly by sex. A significant correlation was observed between R/H and Xc/H in men ($r = 0.405$, $p < 0.05$) and in women ($r = 0.493$, $p < 0.001$). The detailed baseline characteristics are presented in Table 1.

BIVA revealed significant differences in the mean vector positions according to the nutritional, sarcopenic, cognitive (Fig. 1), and functional statuses (Fig. 2). In both sexes, impedance vectors differed between patients with malnutrition and those who were well-nourished, as well as between patients with sarcopenia and those without sarcopenia. Among women, the vectors also differed according to cognitive status, which was not observed in men. Regarding ambulation, the vector positions differed by ambulatory status at discharge in both sexes and at 3 and 6 months in women.

Notably, malnourished and sarcopenic women exhibited a marked rightward vector shift (D > 1), whereas those with cognitive impairment showed a moderate downward displacement (D = 0.9), indicating reduced soft-tissue mass and potential dehydration. Favorable ambulatory recovery was associated with leftward and upward vector shifts, indicating better hydration and cell mass—large at discharge in men and 6 months in women (D > 1), with moderate at other time points in women. These findings were supported by the raw data: women with malnutrition, sarcopenia, or cognitive impairment had significantly lower baseline PhA values ($p < 0.001$) than those without these conditions (Supplementary Table 1). Furthermore, women who achieved independent ambulation within 12 months exhibited significantly higher baseline PhA values ($p < 0.05$) than those who did not regain independent ambulation during the same period (Supplementary Table 2). Although significant differences in mean vector positions were observed between groups, partial overlap of vector distributions was present, and several comparisons showed moderate effect sizes. These findings suggest that although BIVA can characterize group-level differences in physiological status, substantial individual variability remains and should be considered when interpreting the results.

The tolerance ellipses (Fig. 3) illustrate the longitudinal changes in functional status relative to the baseline vectors. Most vectors were outside the 75% and 95% reference ellipses, mainly in the lower and upper right quadrants, suggesting a reduced BCM and fluid imbalance. In men, most vectors representing poor ambulatory status at discharge were outside the 95% tolerance ellipse. Although the number of follow-up patients declined, a general trend toward recovery was observed. All men who failed to recover ambulation at 12 months had baseline vectors outside the 95% ellipse. In women, functional trajectories were more clearly differentiated based on baseline body composition. Poor ambulators frequently exhibited vectors outside the 95% ellipse. Over time, most patients within the 75% and 95% ellipses regained independent ambulation, whereas those outside the 95% ellipse often remained non-ambulatory at 12 months.

The R–Xc z-score graphs provided additional supportive findings. In both sexes, the bivariate z-scores for malnourished, sarcopenic, and cognitively impaired groups showed rightward vector shifts beyond the 95% tolerance ellipse (Fig. 4). Among the cognitively intact patients, the

Table 1
Demographic and bioelectrical impedance characteristics of the study population.

Variables	Total (n = 99)	Men (n = 24)	Women (n = 75)	p-Value
Age (years)	81.5 ± 6.2	78.5 ± 5.2	82.5 ± 6.2	0.005
Height (cm)	156.4 ± 8.3	166.0 ± 6.6	153.3 ± 6.3	<0.001
Weight (kg)	54.2 ± 10.3	58.9 ± 12.4	52.7 ± 9.1	0.033
BMI (kg/m^2)	22.2 ± 3.8	21.4 ± 4.4	22.4 ± 3.6	0.283
ASMI (kg/m^2)	6.2 ± 1.4	6.8 ± 1.6	6.0 ± 1.3	0.037
HGS (kg)	17.1 ± 7.4	23.2 ± 7.6	15.1 ± 6.2	<0.001
Type of fracture				0.112
Femoral neck	52 (52.5)	17 (70.8)	35 (46.7)	
Intertrochanteric	46 (46.5)	7 (29.2)	39 (52.0)	
Subtrochanteric	1 (1.0)	0 (0)	1 (1.3)	
Type of surgery				0.041
Bipolar hemiarthroplasty	44 (44.4)	15 (62.5)	29 (38.7)	
Internal fixation	55 (55.6)	9 (37.5)	46 (61.3)	
Previous fragility hip fracture	12 (12.1)	2 (8.3)	10 (13.3)	0.514
Osteoporosis	72 (72.7)	11 (45.8)	61 (81.3)	0.001
CCI score				0.714
None	14 (14.1)	5 (20.8)	9 (12.0)	
Mild (1–2)	48 (48.5)	11 (45.8)	37 (49.3)	
Moderate (3–4)	21 (21.2)	4 (16.7)	17 (22.7)	
Severe (≥5)	16 (16.2)	4 (16.7)	12 (16.0)	
Postoperative complications	14 (14.1)	3 (12.5)	11 (14.7)	0.791
Rehabilitation				0.619
FIRM	66 (66.7)	15 (62.5)	51 (68.0)	
Conventional	33 (33.3)	9 (37.5)	24 (32.0)	
FAC score (≥3)				
Pre-fracture (n = 99)	88 (88.9)	23 (95.8)	65 (86.7)	0.214
Baseline (n = 99)	12 (12.1)	2 (8.3)	10 (13.3)	0.514
Discharge (n = 98)	48 (49.0)	16 (66.7)	32 (43.2)	0.046
3 months (n = 92)	64 (69.6)	18 (85.7)	46 (64.8)	0.067
6 months (n = 88)	72 (81.8)	18 (90.0)	54 (79.4)	0.280
12 months (n = 71)	57 (80.3)	14 (82.4)	43 (79.6)	0.806
Sarcopenia	38 (38.4)	12 (50)	26 (34.7)	0.179
Malnutrition	53 (53.5)	16 (66.7)	37 (49.3)	0.138
Cognitive impairment	50 (50.5)	9 (37.5)	41 (54.7)	0.143
Length of hospital stay (day)	21.3 ± 5.7	21.4 ± 4.2	21.3 ± 6.1	
Time to surgery (day)	2.6 ± 3.0	3.0 ± 2.9	2.5 ± 2.9	
Time to rehabilitation-unit transfer (day)	6.5 ± 2.7	6.2 ± 2.4	6.6 ± 2.8	
BIVA category[a]				0.037
<75% tolerance ellipse	26 (26.3)	3 (12.5)	23 (30.7)	
75–95% tolerance ellipse	17 (17.2)	2 (8.3)	15 (20.0)	
>95% tolerance ellipse	56 (56.6)	19 (79.2)	37 (49.3)	
BIVA parameters				
R (Ω)	603.4 ± 106.3	560.0 ± 108.9	617.3 ± 102.4	0.021
Xc (Ω)	40.5 ± 12.5	41.4 ± 15.8	40.3 ± 11.3	0.703
R/H (Ω/m)	388.0 ± 75.7	337.9 ± 67.6	404.0 ± 71.4	<0.001
Xc/H (Ω/m)	25.8 ± 7.6	24.4 ± 8.0	26.3 ± 7.4	0.376
PhA (°)	3.9 ± 1.1	4.3 ± 1.5	3.8 ± 0.9	0.104
Correlation (r)[b]	0.474[c]	0.405[d]	0.493[c]	

Data presented as mean ± standard deviation or number (%).
BMI, body mass index; ASMI, appendicular skeletal muscle mass index; HGS, handgrip strength; CCI, Charlson comorbidity index; FIRM, fracture integrated rehabilitation management; FAC, functional ambulation category; BIVA, bioelectrical impedance vector analysis; R, resistance; Xc, reactance; R/H, resistance/height; Xc/H, reactance/height; PhA, phase angle.
[a] Categorized based on the location of impedance vectors within reference BIVA tolerance ellipses (Jiang et al., 2023).
[b] Correlation between R/H and Xc/H.
[c] $p < 0.001$.
[d] $p < 0.05$.

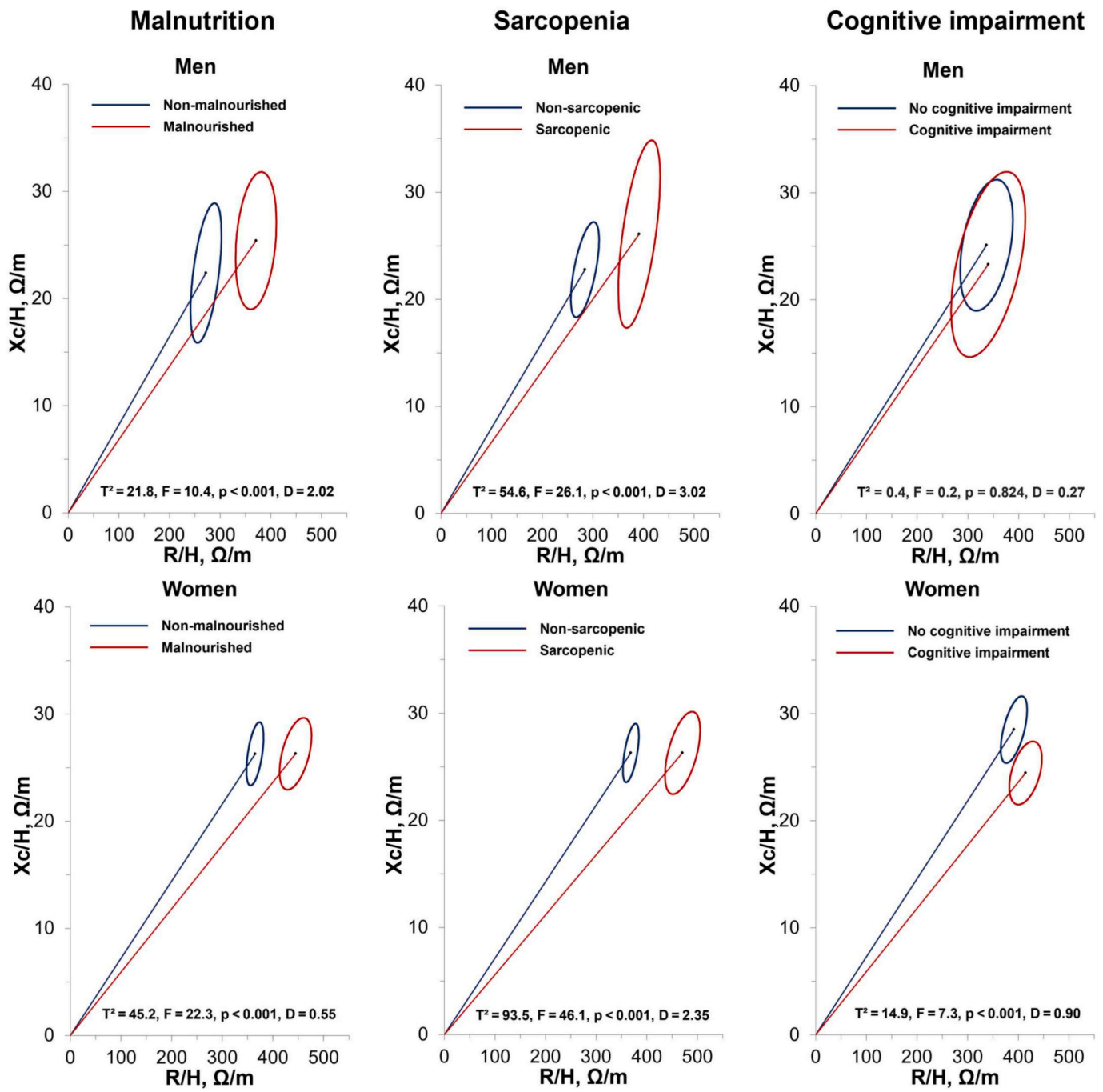


Fig. 1. Comparison of bioimpedance vectors with 95% confidence ellipses according to nutritional status, sarcopenia, and cognitive impairment. Statistical analyses include Hotelling's T^2 test, F- and *p*-values, and Mahalanobis distance (D).

vectors for women were located within the 75% ellipse, whereas those for men were positioned outside the 95% ellipse. When stratified by ambulatory function, men in the poor recovery group showed rightward displacement at discharge, 6, and 12 months. At each time point, the impedance vectors in the recovery and poor recovery groups extended beyond the 95% tolerance ellipse (Fig. 5A). Women with poor ambulatory recovery exhibited rightward and downward shifts outside the 95% ellipse, whereas the recovered individuals remained within (Fig. 5B).

Table 2 summarizes the correlations between body composition and malnutrition, sarcopenia, and cognitive impairment. Significant associations were found for malnutrition ($r = 0.547$, $p < 0.001$), sarcopenia ($r = 0.532$, $p < 0.001$), and cognitive impairment ($r = 0.359$, $p = 0.002$). Patients with vectors within the 75% ellipse had lower frequencies of these conditions, whereas those outside the 95% ellipse had higher frequencies.

Kaplan–Meier survival curves showed significantly lower ambulation recovery in patients with severe body composition impairment (>95% tolerance ellipse) (log-rank $p = 0.0028$). Post hoc comparisons confirmed lower recovery rates than those observed in the normal (<75% tolerance ellipse) and moderate impairment (75–95% tolerance ellipse) groups ($p = 0.016$ and $p = 0.015$, respectively). The absolute recovery rates at 3 months were 80.8% in patients with normal body composition, 94.1% in those with moderate impairment, and 60.7% in those with severe impairment. The corresponding recovery rates were 92.3%, 100%, and 73.2% at 6 months, and 96.2%, 100%, and 78.6% at

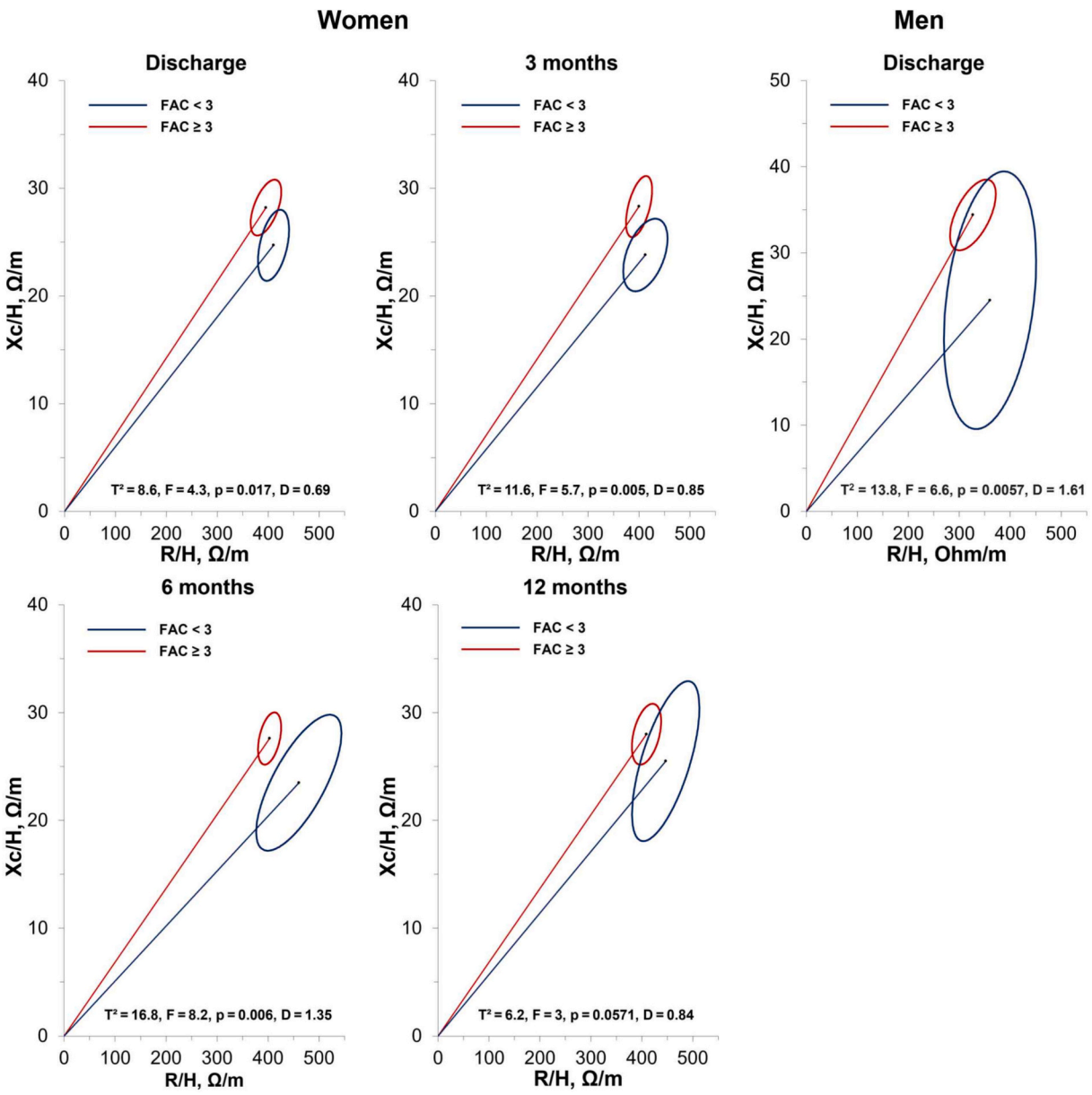


Fig. 2. Comparison of bioimpedance vectors with 95% confidence ellipses according to ambulatory status at each follow-up time point. Statistical analyses include Hotelling's T^2 test, F- and p- values, and Mahalanobis distance (D). For men, confidence ellipses at 3, 6, and 12 months could not be generated because of an insufficient sample size in the poor recovery group ($n = 3$ at 3 and 12 months; $n = 2$ at 6 months), which precluded reliable estimation of the correlation matrix.

12 months, respectively (Fig. 6).

In multivariable Cox regression analysis, severe body composition impairment showed a trend toward a lower likelihood of recovery at discharge (hazard ratio [HR] 0.493; 95% confidence interval [CI] 0.243–1.002; $p = 0.051$). Severe body composition impairment was significantly associated with a lower likelihood of recovery at 3 months (HR 0.458; 95% CI 0.262–0.800; $p = 0.006$), 6 months (HR 0.525; 95% CI 0.302–0.914; $p = 0.023$) and 12 months (HR 0.510, 95% CI: 0.297–0.877, p = 0.015). Additionally, women were less likely to regain independent ambulation. No significant interaction was observed between sex and BIVA category. However, a significant interaction between rehabilitation group and BIVA category was observed at 12 months, suggesting that patients with severe body composition impairment who received conventional rehabilitation had a lower likelihood of recovery compared with those receiving FIRM (HR 0.274; 95% CI 0.084–0.890; $p = 0.031$) (Table 3).

4. Discussion

This study builds on previous work by applying BIVA to evaluate body composition in older adults with hip fracture undergoing rehabilitation and examining its relationship with functional recovery. Our findings suggest that pre-rehabilitation BIVA assessment provides useful information on the hydration and nutritional status of this population. BIVA showed differences according to the presence of malnutrition, sarcopenia, or cognitive impairment and stratified patients by their level of functional recovery following rehabilitation, with clearer patterns observed among women. Furthermore, body composition impairment identified using BIVA was significantly associated with the likelihood of achieving independent ambulation within 1 year postoperatively. These findings suggest that BIVA may provide complementary information for risk stratification in older adults with hip fracture undergoing rehabilitation.

BIVA has demonstrated clinical utility across diverse populations,

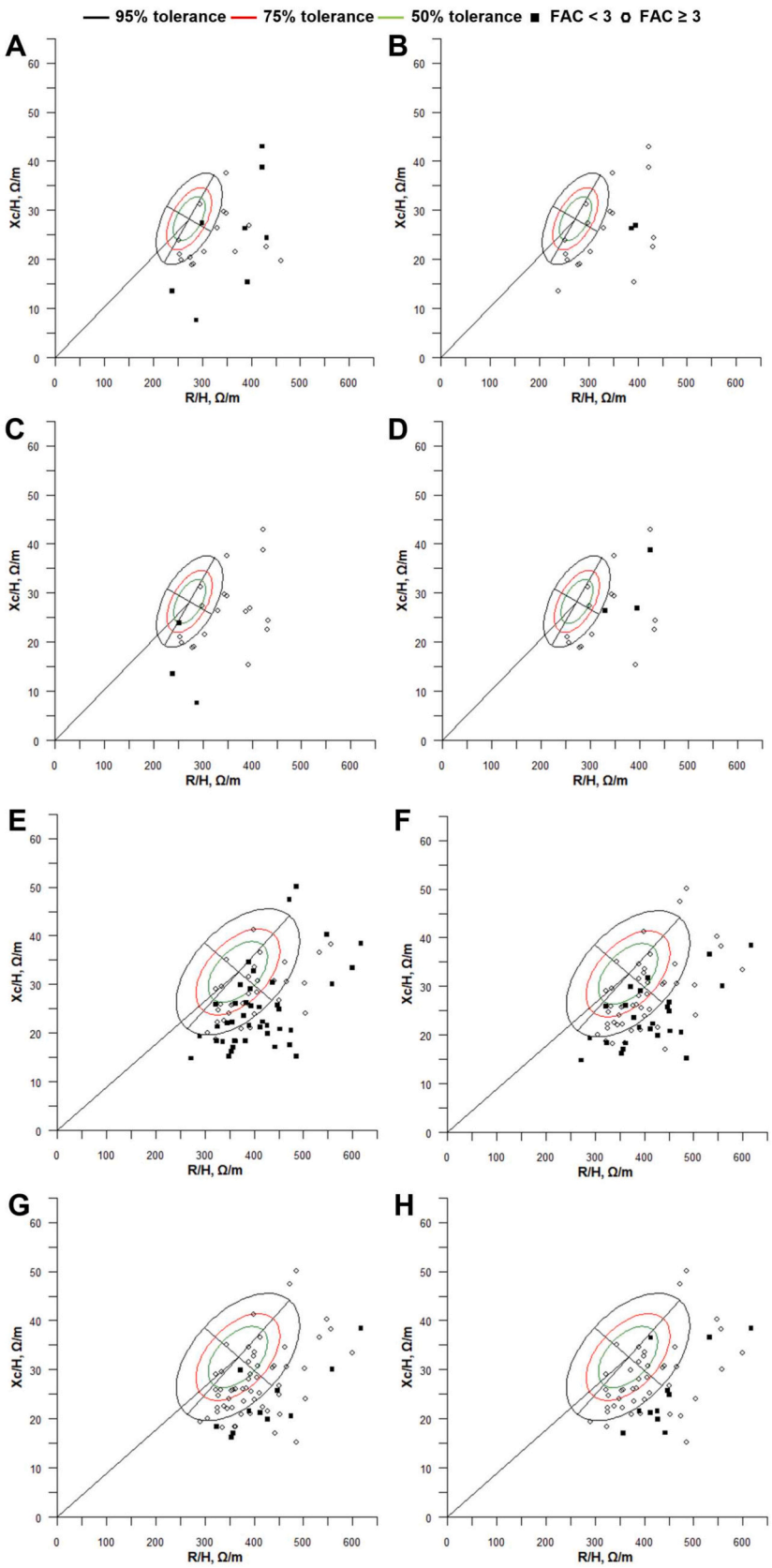


Fig. 3. Individual baseline impedance vectors for men and women plotted on reference tolerance ellipses (Jiang et al., 2023), stratified by ambulatory status at each follow-up time point. Panels represent men at (A) discharge, (B) 3 months, (C) 6 months, and (D) 12 months, and women at (E) discharge, (F) 3 months, (G) 6 months, and (H) 12 months.

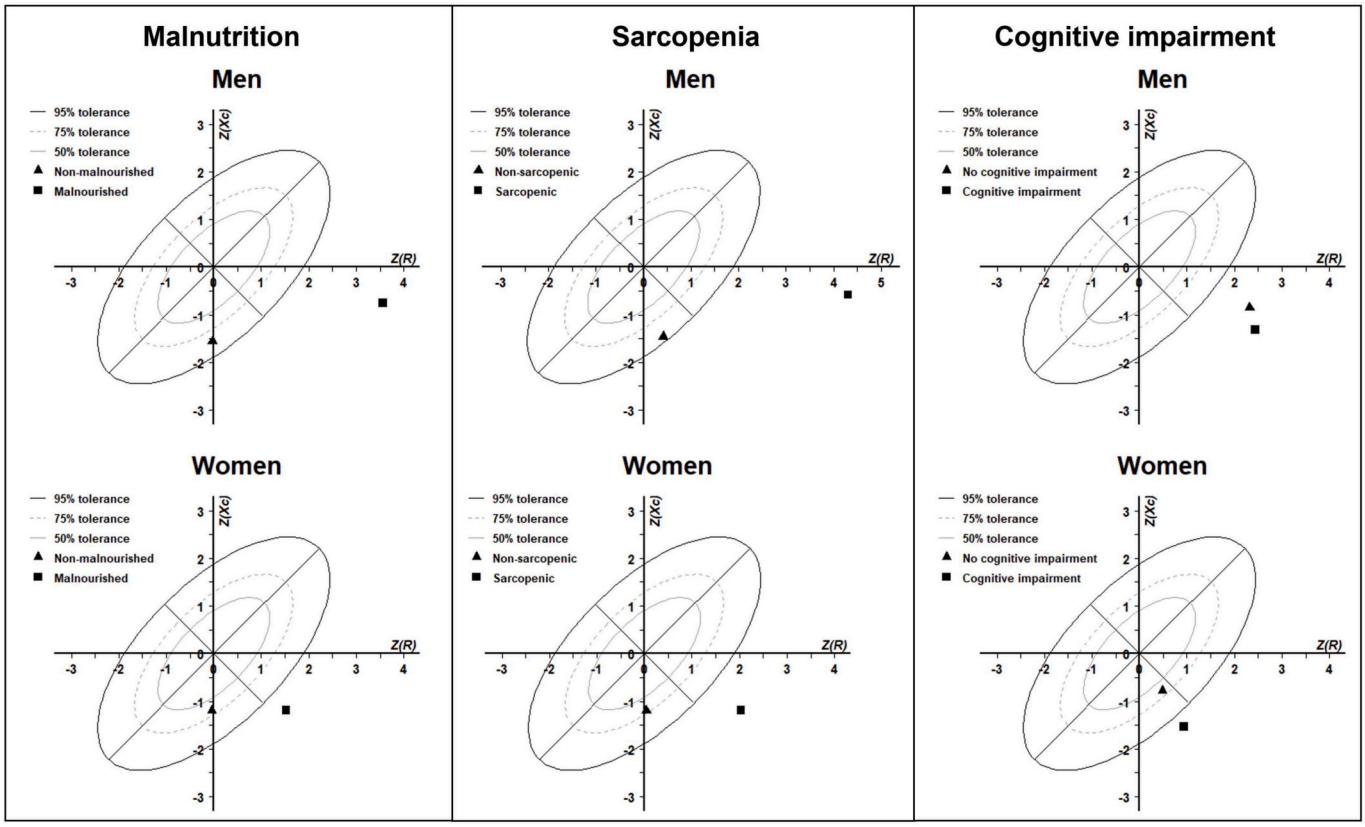


Fig. 4. BIVA Rz–Xc z-score graph showing mean vector positions of patients according to nutritional status, sarcopenia, and cognitive impairment. Mean impedance values were transformed into bivariate z-scores relative to the reference population (Jiang et al., 2023).

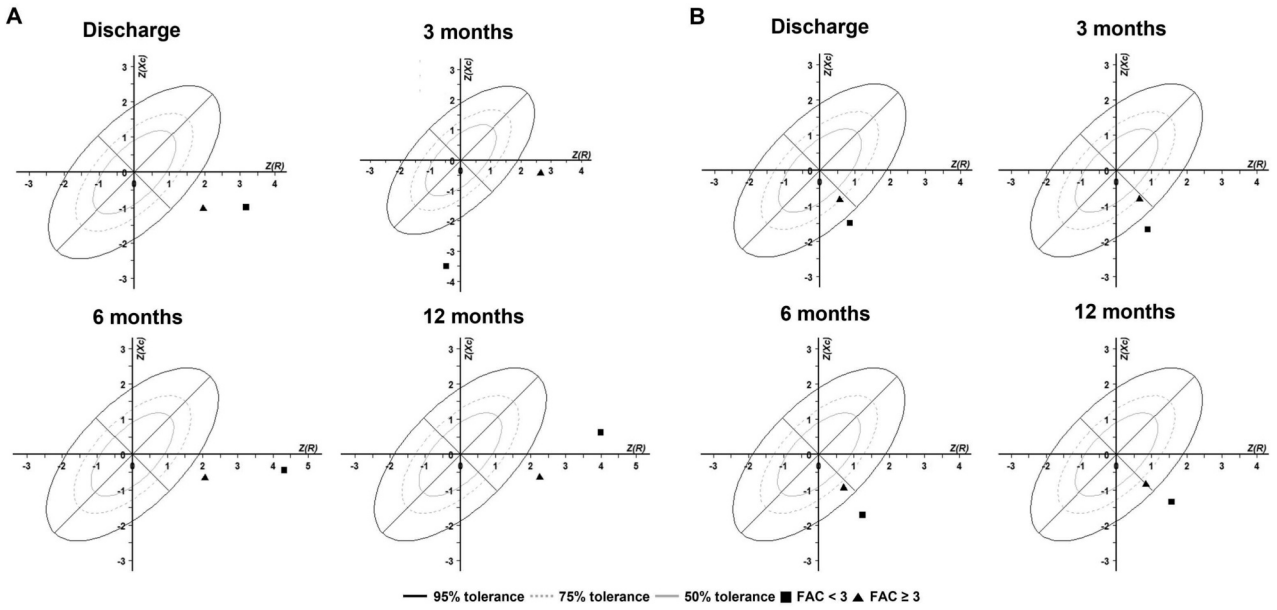


Fig. 5. BIVA Rz–Xc z-score graph showing mean vector positions of (A) men and (B) women according to ambulatory status at each follow-up time point. Mean impedance values were transformed into bivariate z-scores relative to the reference population (Jiang et al., 2023).

including older adults and individuals with various medical conditions (Catapano et al., 2023; Guerrini et al., 2025a, 2025b; Kyle et al., 2004a). In older adults with hip fracture (Lim and Lim, 2025), BIVA patterns revealed a marked reduction in Xc/H and vector displacement outside the 75% and 95% tolerance ellipses, primarily in the lower and upper right quadrants, compared with those without fractures. This distribution reflects diminished cell membrane integrity, reduced soft tissue mass, and impaired muscle function, indicating a physically vulnerable and malnourished state commonly observed in this population. In this study, men and women with malnutrition or sarcopenia exhibited a rightward shift in their bioimpedance vectors on the R–Xc graph, corroborated by R–Xc z-score analyses showing that the mean

Table 2
Associations between BIVA-derived body composition status and malnutrition, sarcopenia, and cognitive impairment.

Variables	Body composition (BIVA tolerance ellipse criteria)			r	p-Value
	<75% (n = 26)	75–95% (n = 17)	>95% (n = 56)		
Malnutrition				0.547	<0.001
Yes	4 (15.4)	6 (35.3)	43 (76.8)		
No	22 (84.6)	11 (64.7)	13 (23.2)		
Sarcopenia				0.532	<0.001
Yes	1 (3.8)	3 (17.6)	34 (60.7)		
No	25 (96.2)	14 (82.4)	22 (39.3)		
Cognitive impairment				0.359	0.002
Yes	7 (26.9)	6 (35.3)	37 (66.1)		
No	19 (73.1)	11 (64.7)	19 (33.9)		

Data presented as number (%). r: Correlation coefficient (Cramer's V or Phi). BIVA, bioelectrical impedance vector analysis.

bivariate z-scores for these groups were located outside the 95% tolerance ellipse. This displacement, characterized by increased R, indicates reduced total body water and soft tissue mass, consistent with previous studies (Guerrini et al., 2025a, 2025b). Malnutrition and sarcopenia are common in older adults with hip fracture (Inoue et al., 2020), with similarly high rates in our cohort (53.5% and 38.4%, respectively). These conditions contribute to the distinct BIVA profiles in this population, characterized by greater body composition impairment and vector displacement beyond the reference ellipses of healthy older adults without fractures.

Furthermore, cognitive impairment, particularly among women, was associated with a more pronounced downward vector shift corresponding to lower PhA values. Cognitive impairment is highly prevalent in this population and is closely linked to malnutrition and sarcopenia (Jo et al., 2022; Ye et al., 2025). These interrelated geriatric syndromes appear to produce convergent alterations in body composition detected by BIVA. Our finding that severe body composition impairment was associated with higher frequencies of malnutrition, sarcopenia, and cognitive impairment supports this observation. Although malnutrition, sarcopenia, and BIVA-derived body composition impairment represent related aspects of physiological vulnerability, they capture overlapping but not identical constructs. Together, these findings suggest that BIVA reflects shared physiological characteristics associated with geriatric syndromes such as malnutrition, sarcopenia, and cognitive impairment.

A notable strength of this study is the inter-group comparison of BIVA vectors based not only on major prognostic factors but also on ambulatory status, the primary functional outcome in older adults with hip fracture, across multiple follow-up time points. A previous study reported distinct BIVA patterns based on functional recovery after stroke rehabilitation (Guerrini et al., 2025b). Although vector differences were observed in both sexes, the patterns were more clearly identifiable among women. The relatively small number of male participants limited the statistical power for sex-specific analyses; therefore, findings in men should be interpreted cautiously and considered exploratory. Specifically, patients who achieved favorable ambulatory recovery demonstrated leftward and upward vector shifts. The R–Xc z-score analysis further supported this finding, with mean bivariate z-scores located within the 95% reference ellipse, characterized by higher Xc/H and lower R/H, indicating better hydration and greater BCM, corresponding to higher PhA.

PhA, derived from the bioimpedance vector, reflects cell membrane integrity and cellular health; lower values indicate impaired cellular function, whereas higher values are associated with preserved membrane integrity and greater BCM relative to lean mass (Norman et al., 2012). These differences are linked to improved physical performance and functional recovery (Guerrini et al., 2024). In healthy adults, PhA typically ranges between approximately 5° and 7° and declines with aging (Norman et al., 2012). Reference data from Korean older adults aged 70–80 years report mean PhA values of approximately 4.9–5.1° in men and 4.3–4.5° in women (Lee et al., 2025). In our cohort, the mean baseline PhA was lower (men, 4.3 ± 1.5°; women, 3.8 ± 0.9°), reflecting the compromised physiological and nutritional status commonly observed in patients with hip fracture. In addition, our findings showed that baseline PhA differed significantly between patients who regained independent ambulation and those who did not, supporting the potential utility of BIVA as a clinically useful tool for identifying individuals at risk of poor rehabilitation outcomes after hip fracture.

This study further highlights the potential relevance of BIVA by evaluating body composition in relation to 12-month independent ambulation in older adults undergoing rehabilitation after hip fracture. BIVA has previously demonstrated its utility in predicting clinical outcomes (Guerrini et al., 2025a; Razzera et al., 2020). In a large hospitalized cohort (Guerrini et al., 2025a), severe body composition impairment, defined as vectors beyond the 95% tolerance ellipse, was associated with a 4.79-fold increase in the risk of death. Although evidence regarding moderate impairment (75th–95th percentile) is inconsistent, our results showed that patients with vectors beyond the 95%

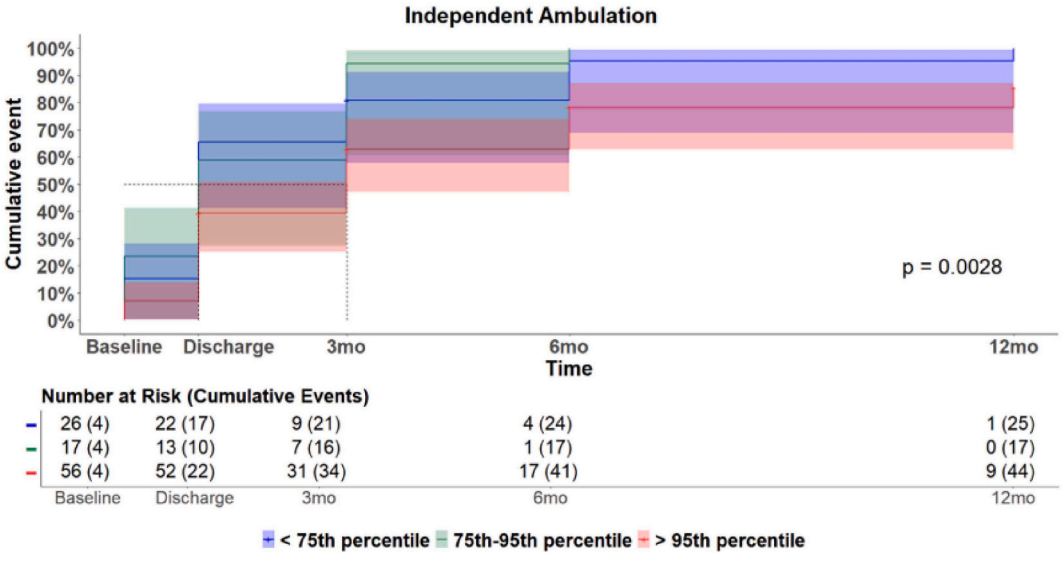


Fig. 6. Kaplan–Meier curves for the 1-year cumulative probability of achieving independent ambulation, stratified by body composition status based on BIVA.

Table 3
Multivariate Cox regression analysis of factors associated with independent ambulation at each time point within 1 year.

Variables	Category	Hazard ratio [95% CI]	p-Value
Discharge			
Body composition[a]	<75% tolerance ellipse (reference)[b]		
	75–95% tolerance ellipse[c]	1.020 [0.465, 2.238]	0.960
	>95% tolerance ellipse[d]	0.493 [0.243, 1.002]	0.051
Sex	Men (reference)		
	Women	0.593 [0.312, 1.132]	0.113
FAC	<3 (reference)		
	≥3	3.552 [0.847, 14.886]	0.083
Cognitive impairment	No (reference)		
	Yes	0.526 [0.282, 0.985]	0.045
3 months			
Body composition	<75% tolerance ellipse (reference)		
	75–95% tolerance ellipse	1.395 [0.724, 2.687]	0.320
	>95% tolerance ellipse	0.458 [0.262, 0.800]	0.006
Sex	Men (reference)		
	Women	0.369 [0.216, 0.631]	<0.001
6 months			
Body composition	<75% tolerance ellipse (reference)		
	75–95% tolerance ellipse	1.394 [0.745, 2.609]	0.299
	>95% tolerance ellipse	0.525 [0.302, 0.914]	0.023
Sex	Men (reference)		
	Women	0.424 [0.243, 0.739]	0.002
Cognitive impairment	No (reference)		
	Yes	0.611 [0.391, 1.061]	0.084
12 months			
Body composition	<75% tolerance ellipse (reference)		
	75–95% tolerance ellipse	1.335 [0.716, 2.486]	0.363
	>95% tolerance ellipse	0.510 [0.297, 0.877]	0.015
Sex	Men (reference)		
	Women	0.434 [0.250, 0.756]	0.003
Cognitive impairment	No (reference)		
	Yes	0.653 [0.398, 1.071]	0.091
Interaction	<75% tolerance ellipse × FIRM (reference)		
	>95% tolerance ellipse × conventional rehabilitation	0.274 [0.084, 0.890]	0.031

CI, confidence interval; FAC, functional ambulation category.
[a] Categorized based on the location of impedance vectors within reference BIVA tolerance ellipses (Jiang et al., 2023).
[b] Normal.
[c] Moderate impairment.
[d] Severe impairment.

ellipse were approximately 35–50% less likely to regain independent ambulation within 12 months than those with vectors within the 75% ellipse. These findings suggest that BIVA measurements may provide additional information for characterizing physiological vulnerability and supporting risk stratification in the rehabilitation setting after hip fracture.

In addition, a significant interaction between rehabilitation method and BIVA category was observed at 12 months. Patients with severe body composition impairment who received conventional rehabilitation showed a substantially lower likelihood of regaining independent ambulation compared with those who received the FIRM program. Although this finding should be interpreted cautiously because of the exploratory nature of the interaction analysis, it suggests that patients with greater physiological vulnerability may derive greater benefit from integrated multidisciplinary rehabilitation approaches.

Hip fractures represent a growing global health challenge, especially with an aging population, leading to poor outcomes and an increased socioeconomic burden (Government, 2023). Over 90% of hip fractures in older adults result from falls, and the risk is markedly increased by age-related decline in physical function and altered body composition. Patients frequently exhibit multiple interrelated risk factors, including sarcopenia, malnutrition, cognitive impairment, and various comorbidities, all of which worsen surgical and rehabilitation outcomes (Sheehan et al., 2018; Xu et al., 2019). Early and accurate assessment of prognostic factors is crucial for optimizing recovery. Although timely surgery, prevention of complications, and comprehensive rehabilitation are essential, their effectiveness may be limited without tailored approaches for frail patients. Thus, a stratified care model for identifying high-risk individuals and delivering personalized interventions is becoming increasingly important.

Our findings suggest a potential role for BIVA in pre-rehabilitation assessment. BIVA provides a practical and non-invasive method for assessing body composition and characterizing patients with malnutrition, sarcopenia, cognitive impairment, and poorer functional status. A greater displacement of impedance vectors from the normative tolerance ellipses reflects higher nutritional and physiological vulnerability, which correlates with worse functional outcomes. Given the multifactorial nature of geriatric risk in patients with hip fracture, BIVA may provide complementary information on overall physiological status and support risk stratification during pre-rehabilitation evaluation. Incorporating BIVA into routine assessments may help identify physiologically vulnerable patients and provide additional information to support clinical decision-making in post-hip fracture rehabilitation.

This study has some limitations. First, we did not assess the test–retest reliability of the BIA measurements. However, the InBody S10 device used in this study demonstrated excellent reliability and reproducibility in previous research, with an intraclass correlation coefficient exceeding 0.9 (Kim et al., 2021). Future studies should aim to standardize BIA protocols to improve the accuracy and consistency of BIVA results. Second, this was a secondary analysis of a clinical trial not originally designed for BIVA, and the sample size was relatively small and drawn from a single rehabilitation center. In particular, the limited number of male participants reduced the statistical power of the subgroup analyses, potentially limiting generalizability. Larger multicenter studies, specifically designed to evaluate BIVA, are required to validate and expand upon these findings. Third, body composition was assessed only once after hip fracture, which limited the evaluation of longitudinal changes. Repeated BIA measurements over time would provide more insight into temporal trends and the effects of rehabilitation. Finally, the accuracy of BIVA depends on the selection of an appropriate reference population. Although we used an age- and BMI-matched Korean community-dwelling reference group without hip fracture, the reference population was relatively small despite considering key factors such as sex, ethnicity, age, and BMI (Catapano et al., 2023; Piccoli et al., 2002). This finding contrasts with recent European studies that utilized large, well-characterized reference datasets (Campa et al., 2023). Future research should aim to establish updated tolerance ellipses based on a large, nationally representative Korean population to improve the accuracy and generalizability of BIVA. In addition, some follow-up assessments were conducted via telephone for participants who were unable to attend in-person visits to minimize loss to follow-up. Although this approach improved follow-up completeness, it may have introduced potential misclassification bias in the assessment of ambulatory status.

Despite these limitations, this study provides additional insights into the assessment of body composition and nutritional status in older adults with hip fracture using BIVA, an area that remains underexplored. It also contributes to the growing evidence supporting the clinical relevance of BIVA across diverse populations and highlights the potential value of incorporating BIVA as a complementary assessment tool in clinical settings.

5. Conclusion

This study suggests the potential clinical utility of BIVA for assessing body composition in older adults undergoing rehabilitation after hip fracture. BIVA showed associations with differences in functional

recovery and may provide additional information for risk stratification in pre-rehabilitation assessment. Incorporating BIVA into clinical evaluation may help identify physiologically vulnerable patients and support clinical decision-making in post-hip fracture rehabilitation.

CRediT authorship contribution statement

Seung-Kyu Lim: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation. **Jae-Young Lim:** Writing – review & editing, Resources, Project administration, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.exger.2026.113149.

Data availability

Data will be made available on request.

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