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RESEARCH ARTICLE

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Association between fall location and postoperative clinical outcomes after fragility hip fracture: a multicentre cohort study

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ABSTRACT

Background: Fall location may serve as a marker of underlying vulnerability in adults with fragility hip fractures; however, its association with postoperative outcomes remains unclear. This study investigated this association using multicentre prospective registry data.

Materials and Methods: This retrospective multicentre cohort study analysed Korean Hip Fracture Registry data, including patients aged ≥50 years with proximal femoral fractures treated between June 2016 and December 2024. Fall location was classified as indoor or outdoor. Primary outcomes were functional dependence, gait impairment, and mortality, whereas secondary outcomes included postoperative complications and discharge destination. Logistic regression analysed functional dependence, gait impairment, complications, and discharge destination, whereas Cox proportional hazard regression analysed mortality. Adjusted odds ratios (ORs), hazard ratios (HRs), and 95% confidence intervals (CIs) were calculated; sequential adjustment analyses assessed potential confounding.

Results: Among 5,391 patients with fragility hip fractures, 3,480 (64.6%) sustained indoor falls and 1,911 (35.4%) sustained outdoor falls. Mean follow-up was approximately six months, and most indoor falls occurred at home (80.8%). Compared with outdoor fallers, indoor fallers were older, more often female, had poorer pre-fracture function, and greater comorbidity burden (all $p<0.001$). Indoor falls were independently associated with higher risks of functional dependence (adjusted OR 1.19, 95% CI 1.01–1.40, $p=0.043$), gait impairment (adjusted OR 1.34, 95% CI 1.18–1.52, $p<0.001$), and mortality (adjusted HR 2.27, 95% CI 1.45–3.54, $p<0.001$). Discharge destination and postoperative complications were not significantly associated with fall location after full adjustment. Associations were attenuated after adjustment for demographic and clinical factors, but those for functional dependence, gait impairment, and mortality remained significant.

Conclusion: Patients sustaining indoor falls represent a vulnerable subgroup with poorer functional recovery and higher mortality after fragility hip fractures. Fall location may serve as an additional marker of frailty and postoperative risk, contributing to risk stratification following hip fracture.

KEY MESSAGES

- Indoor fall location was associated with poorer functional recovery, gait impairment, and higher mortality after fragility hip fractures in adults.
- Indoor falls may reflect underlying frailty, reduced physiological reserves, and poorer pre-fracture functional status rather than environmental exposure alone.
- Fall location is a simple, routinely available clinical marker that may complement established frailty-related assessments when identifying patients at an increased risk of adverse postoperative outcomes.

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Introduction

Hip fractures in older adults are associated with poor outcomes and impose substantial clinical and socioeconomic burdens worldwide [1], particularly in rapidly aging societies such as Korea, where demographic shifts are expected to markedly increase the incidence of fragility fractures [2]. These injuries are characterized by high morbidity, mortality, and prolonged recovery: 1-year mortality is approximately 20%–24%, nearly one-third of patients require long-term institutional care [3], and only 40–60% regain their pre-fracture mobility [4]. With the global hip fracture incidence projected to reach approximately 4.5 million cases annually by 2050, these burdens are expected to escalate further [5].

Falls are the predominant cause of injury among older adults, accounting for more than 90% of hip fractures, most of which result from low-energy trauma, such as falls from a standing height [6]. In Korea, falls are the most common cause of injury in older adults and are associated with substantially higher rates of emergency department visits, hospitalizations, and fall-related mortality than those in younger populations [7]. Reflecting rapid population aging, fall-related injuries increased markedly from 2016 to 2020, with an average annual rise of 24.6% and nearly 60% occurring in individuals aged ≥60 years [8]. Between 2011 and 2020, 15.8% of Korean adults aged ≥65 years who presented to the emergency department after unintentional falls sustained by hip fractures [9].

Fall location varies according to age, activity level, and environmental exposure. Individuals who sustain outdoor falls are typically younger, more often male, and have a lower burden of chronic comorbidities, suggesting that these falls frequently occur during mobility in relatively healthier, more physically active individuals. In contrast, indoor fallers are typically older, more often female, and exhibit greater baseline vulnerability, including more comorbidities, poorer pre-fracture functional status, and reduced physiological reserve. Consequently, outdoor falls are more closely related to environmental exposure during daily activities, whereas indoor falls are more likely to reflect underlying frailty and functional decline [10–15].

Consistent with these observations, indoor falls account for many hip fracture–related injuries, particularly in the oldest adults [16]. With advancing age, declines in physical and cognitive functions often restrict mobility; increase time spent indoors, particularly at home or in care facilities; and reduce outdoor exposure, reflecting underlying functional decline and greater susceptibility to fragility fractures [14,16]. Indoor falls have also been associated with higher post–hip fracture mortality rates than outdoor falls [17,18]. Collectively, these findings suggest that fall location may reflect biological vulnerability rather than environmental exposure alone, supporting its use as a clinically meaningful marker for targeted prevention, postoperative risk stratification, and prognostic assessment.

However, fall location remains poorly studied as a predictor of postoperative outcomes, particularly functional recovery, after fragility hip fractures. To address this gap, we analysed data from the Korean Hip Fracture Registry (KHFR), a multicentre cohort study evaluating clinical outcomes, mobility, mortality, and fracture-related risks among patients with proximal femoral fractures in Korea. The primary objective of this study was to examine the association between fall location and postoperative functional dependence, gait impairment, and mortality among adults with fragility hip fractures. Postoperative complications and discharge destination were evaluated as secondary outcomes. We hypothesized that patients who sustained indoor falls would demonstrate poorer functional recovery and higher mortality rates than those who sustained outdoor falls.

Material and methods

Study design and participants

This retrospective study analysed data from the KHFR, a multicentre prospective registry of patients aged ≥50 years treated for proximal femur fractures in Korea. The dataset was accessed through the Internet-based Clinical Research and Trial Management System (iCReaT) of the Korean National Institutes of Health. Established in 2014, the KHFR prospectively collects standardized clinical, radiologic, laboratory, surgical, and follow-up data from 22 tertiary hospitals across Korea to evaluate patients with hip fractures [19]. This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of Soonchunhyang University Cheonan Hospital (SCHCA 2025-05-038).

The ethics committees of all participating hospitals approved the study protocol. Written informed consent was obtained at registry enrollment. Additional consent for this analysis was waived because de-identified data were used in this study.

Data collection

KHFR data were collected at baseline, during hospitalization, and at scheduled follow-ups. Trained research coordinators prospectively collected and entered data using standardized case report forms based on patient interviews, physical examinations, laboratory assessments, radiological evaluations, and medical record reviews. The central registry management team periodically reviews the registry data to ensure completeness and consistency. The participating centres consecutively enrolled patients according to standardized registry procedures.

The baseline data included demographic characteristics, fracture-related radiological findings, medical comorbidities, pre-fracture functional status, laboratory findings, nutritional status, and surgical characteristics. Overall comorbidity burden was quantified using the Charlson Comorbidity Index (CCI) [20]. Detailed descriptions of the registry variables and operational definitions have been previously reported [19]. Nutritional status was assessed using Global Leadership Initiative on Malnutrition (GLIM) criteria [21]. According to the GLIM recommendations, malnutrition is diagnosed when there is at least one phenotypic criterion (unintentional weight loss, low body mass index, or reduced muscle mass) and one etiological criterion (reduced food intake, reduced assimilation, or inflammation). Because hip fractures are associated with an acute inflammatory response, all patients were considered to meet the etiologic criterion [22]; therefore, malnutrition was defined as the presence of at least one phenotypic criterion in this study. For patients who were unable to communicate because of cognitive impairment or medical conditions, relevant information was obtained from family members or extracted from medical records.

Fall characteristics

Fall characteristics were categorized primarily according to fall location (indoor or outdoor). The timing of the fall was recorded as daytime or nighttime. Fall-related information, including fall location, was collected at enrollment by trained research coordinators through interviews with patients and/or caregivers and a review of medical records. Fall location was a predefined registry variable prospectively recorded using standardized case report forms.

Given the substantial variability in the reported fall environments, the original registry data were reviewed and reclassified according to predefined classification rules developed for the present study. Because the reported fall circumstances frequently contained mixed descriptions of location, activity, and mechanism, the classification was based primarily on whether the fall occurred within an enclosed built environment. Indoor falls were defined as those occurring within enclosed structures, including private residences, hospitals, residential facilities, workplaces, commercial buildings, and public indoor facilities. Outdoor falls were defined as falls occurring in open environments such as roads, sidewalks, parks, gardens, playgrounds, and other outdoor spaces. When the original descriptions were ambiguous, the classification was determined according to predefined rules. Detailed environmental subclassifications were available only for indoor fall settings; therefore, subsequent analyses of specific fall environments were restricted to indoor falls.

Indoor fall settings were categorized as follows: (1) private home, (2) residential facility or long-term care facility or day-care centre, (3) hospital, (4) public, welfare, or religious community facilities, (5) commercial or service facilities, (6) sports or exercise facilities (e.g. gymnasium or swimming pool), (7) workplace, (8) parking area, (9) other public indoor places, and (10) unknown location.

To better characterize specific indoor environments, indoor fall locations were additionally grouped into functional micro-environments: (1) transfer zones (bed or chair), (2) living areas (living room or bedroom), (3) bathroom/toilet areas (including public bath facilities), (4) stairs or steps, (5) kitchen or food preparation areas, (6) balcony, (7) entry or corridor areas (entrance, hallway, thresholds, or access points), (8) hospital ward or therapy areas (including rehabilitation rooms), (9) office or indoor workplace areas, and (10) other or unknown locations.

Outcome assessment

Follow-up assessments were primarily conducted through outpatient clinic visits. When in-person assessments were not feasible, home visits, telephone interviews, or proxy interviews with family members or caregivers were performed according to the KHFR protocol. When patients were unable to communicate directly, the outcome information was obtained from family members or caregivers.

Ambulatory status was assessed using the Koval classification, a 7-grade scale in which lower scores reflect better walking ability [23]. Functional independence was assessed using a 7-level functional independence scale based on the Functional Independence Measure (FIM) grading system [24]. For a descriptive comparison of the postoperative clinical courses between patients with indoor and outdoor falls, we evaluated time to postoperative ambulation, post-fracture ambulatory status, post-fracture functional independence, postoperative complications, delirium, discharge destination, and follow-up mortality.

The primary clinical outcomes were functional dependence, gait impairment, and mortality during follow-up. Functional dependence was defined as a functional independence level ≤5, whereas levels 6–7 represented modified or complete independence [24]. Gait impairment was defined as a Koval grade ≥5, representing the inability to ambulate independently in the community [23]. These thresholds were selected a priori to identify clinically meaningful losses of independence and mobility following hip fracture. Mortality was defined as death occurring during the follow-up period. At the follow-up assessment, vital status and the exact date of death were obtained through interviews with family members or other proxies and verified against available hospital records whenever possible. The mortality data were not linked to the national death registry. The secondary outcomes included postoperative complications during hospitalization and discharge destination (home vs. non-home facilities). The postoperative complications included systemic (hypovolemic shock, cardiac arrest, hemorrhagic complications, fat embolism, pulmonary embolism, pneumonia, acute renal failure, and other medical complications) and local (pressure sores, skin necrosis, nerve injury, vascular injury, deep vein thrombosis, infection, and pseudoaneurysm) complications, which were prospectively recorded in the KHFR during hospitalization.

Statistical analysis

Continuous variables were presented as means ± standard deviation, and categorical variables as frequencies with percentages. Baseline characteristics were compared between the indoor and outdoor fall groups using independent *t*-tests for continuous variables and chi-square tests for categorical variables.

To examine the association between fall location and functional dependence, gait impairment, postoperative complications, and discharge destination, logistic regression models with cluster-robust standard errors were used to account for potential between-centre variability. For mortality, Cox proportional hazards regression was performed using the time from surgery to death or last follow-up as the time scale, with robust standard errors to account for clustering by the participating centre. The proportional hazards assumption was assessed using scaled Schoenfeld residuals, and no significant violations were observed. Odds ratios (ORs) and hazard ratios (HRs) were presented with 95% confidence intervals (CIs). Both unadjusted and fully adjusted models were constructed. The fully adjusted models included demographic factors (age and sex), comorbidity burden (CCI categories and selected comorbid conditions including dementia, Parkinson's disease, cerebrovascular accident, hemiplegia/paraplegia, chronic kidney disease, spinal disease, and ophthalmologic disease), prior hip fracture history, pre-fracture functional status (walking ability and functional independence), fracture, and surgical characteristics (fracture type, operation type, transfusion, and ASA physical status score), and nutritional status. Covariates were selected based on previous literature and clinical relevance as established predictors of postoperative outcomes after hip fracture [25–28], with additional consideration given to variables demonstrating meaningful baseline differences between indoor and outdoor fall groups. These variables were considered potential confounders of the association between fall location and postoperative clinical outcomes and were included in the multivariable models. All analyses used complete-case approach. The baseline characteristics of the included and excluded participants were compared to evaluate the potential for selection bias associated with the complete-case analysis.

Sequential adjustment models were constructed for the primary outcomes to explore the contribution of potential confounders. Covariates were introduced stepwise across the following clinically relevant domains: demographic factors (M1), comorbidity burden (M2), pre-fracture functional status (M3), fracture and surgical characteristics (M4), and nutritional status (M5). The M5 model included all covariate domains and corresponded to the fully adjusted model used as the primary model for inference. The analytic cohort was fixed according to the fully adjusted dataset to maintain comparability across models. All statistical analyses were performed using R software (version 4.4.3; R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was defined as a two-sided p-value <0.05.

Results

Study population

A total of 7,467 patients aged ≥50 years with proximal femoral fractures who completed follow-up were identified from the KHFR between June 2016 and December 2024. After excluding patients who had no follow-up assessment, high-energy trauma, unknown mechanisms of injury, missing fall characteristic data, and those who did not undergo surgical treatment, 5,391 patients with fragility hip fractures were included in the final analytic cohort. Of these, 3,480 (64.6%) sustained indoor falls and 1,911 (35.4%) sustained outdoor falls (Figure 1). The baseline characteristics of the included and excluded participants are presented in Table S1. The excluded participants differed from the analytic cohort in terms of their demographic and clinical characteristics. Although the excluded participants demonstrated poorer mobility and functional status on some measurements, they had a lower prevalence of several major comorbidities.

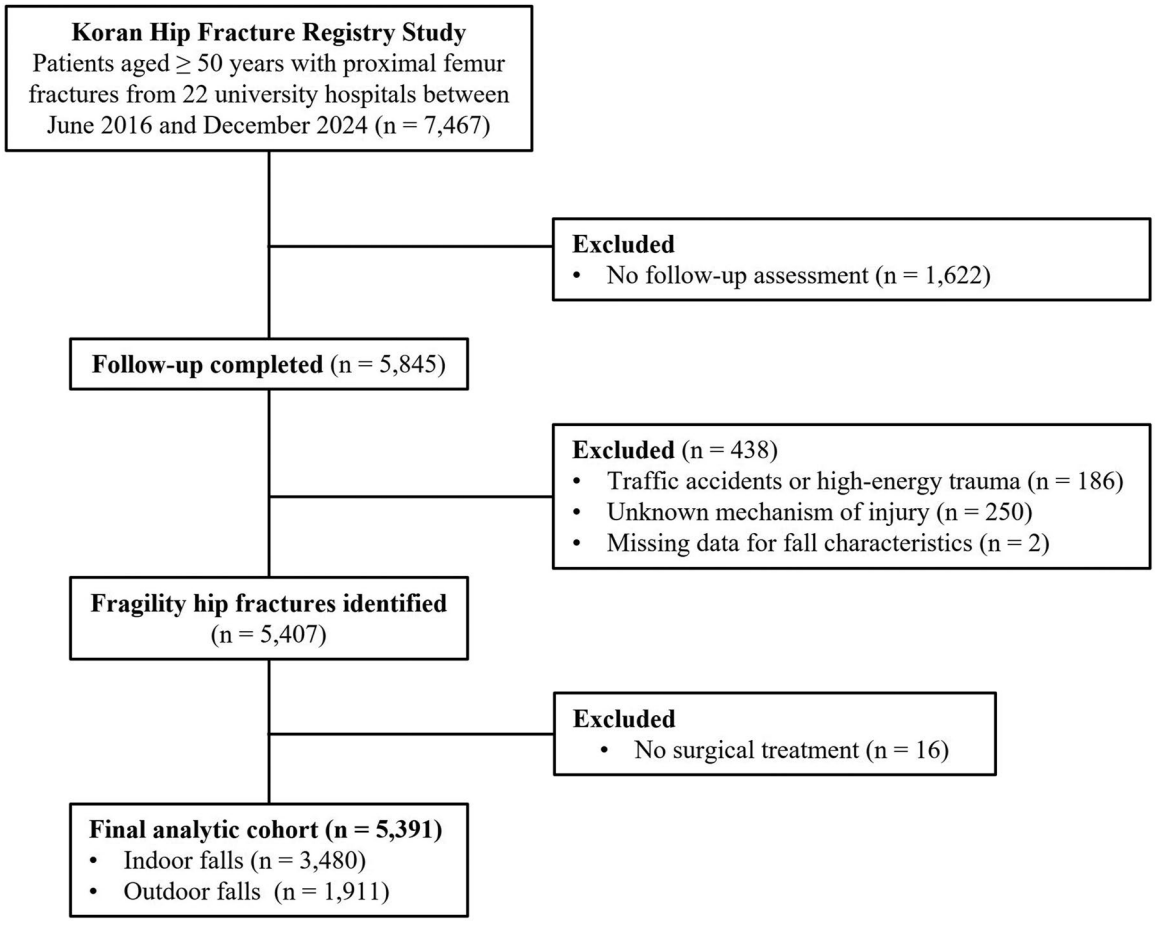


Figure 1. Selection of the study population.

Baseline characteristics according to fall location

Patients who sustained indoor falls were older and more frequently female than those who sustained outdoor falls (mean age 80.0 vs 75.9 years; female 78.2% vs. 64.8%; both $p < 0.001$). Indoor falls occurred more frequently at night than during the daytime. Compared with outdoor fallers, patients with indoor falls demonstrated poorer pre-fracture mobility and functional independence, a greater comorbidity burden, and a higher prevalence of chronic neurological and systemic conditions. Malnutrition was also more common among indoor fallers (all $p < 0.001$). With regard to fracture- and surgery-related characteristics, intertrochanteric fractures, higher transfusion rates ($p = 0.003$), and higher American Society of Anaesthesiologists (ASA) physical status scores were observed more frequently in patients with indoor falls. Arthroplasty was more common in the indoor fall group, whereas internal fixation was performed more frequently among the outdoor fall group (all $p < 0.001$) (Table 1).

Characteristics of indoor fall environments

Detailed environmental characterization was available only for indoor fall settings in the registry. Indoor falls most commonly occurred at home (80.8%), followed by residential care facilities (8.3%) and hospitals (4.0%). Within indoor settings, the most frequent specific locations were bathrooms or toilets (50.6%) and transfer zones (21.9%), with smaller proportions occurring in living areas, corridors, kitchens, and staircases (Figure 2).

Postoperative clinical courses by fall location

The timing of postoperative walking initiation and the incidence of postoperative delirium did not differ significantly between the groups. Compared to outdoor fallers, patients with indoor falls demonstrated higher rates of gait impairment (48.5% vs. 29.6%) and functional dependence (62.0% vs. 44.4%) at follow-up (both $p < 0.001$). During follow-up, mortality was higher among indoor fallers than among outdoor fallers (68 [2.0%] vs. 12 [0.6%]; $p < 0.001$). In addition, patients with indoor falls experienced more postoperative complications (12.2% vs. 8.7%, $p < 0.001$) and were less frequently discharged home (47.4% vs. 54.6%, $p < 0.001$) than those with outdoor falls (Table 2).

Multivariable associations between fall location and clinical outcomes

Associations between fall location and primary clinical outcomes were significant in both unadjusted and adjusted analyses. In cluster-robust regression models adjusted for demographic factors, comorbidities, pre-fracture functional status, fracture and surgical characteristics, and nutritional status, indoor falls remained associated with an increased risk of worse clinical outcomes than outdoor falls. Specifically, indoor falls were associated with higher odds of functional dependence at follow-up (adjusted OR 1.19, 95% CI 1.01–1.40, $p = 0.043$), gait impairment (adjusted OR 1.34, 95% CI 1.18–1.52, $p < 0.001$), as well as a higher risk of mortality (adjusted HR 2.27, 95% CI 1.45–3.54, $p < 0.001$) (Figure 3). The fully adjusted multivariable regression models for the primary clinical outcomes according to the fall location are presented in Table S2. By contrast, the associations between fall location and discharge to a facility, as well as postoperative complications, were attenuated after full adjustment and were no longer statistically significant (Table S3).

Sequential adjustment analyses

Sequential adjustment analyses showed that the associations between indoor falls and adverse outcomes were progressively attenuated after adjusting for demographic characteristics, comorbidity burden, pre-fracture functional status, fracture and surgical factors, and nutritional status. The greatest attenuation occurred after adjusting for demographic factors, baseline functional status, and comorbidity burden, suggesting that these factors partially explain the observed associations. Nevertheless, indoor falls

Table 1. Baseline characteristics of study group.

Variable	Outdoor falls ($n = 1,911$)	Indoor falls ($n = 3,480$)	p-value
Age, mean (SD), years	75.9 (10.3)	80.0 (8.9)	<0.001
Sex, *n* (%) (female)	1238 (64.8)	2721 (78.2)	<0.001
Height, mean (SD), cm	159.2 (8.7)	156.5 (8.2)	<0.001
Weight, mean (SD), kg	57.0 (10.6)	54.2 (10.4)	<0.001
BMI, mean (SD), kg/m^2	22.4 (3.4)	22.1 (3.6)	<0.001
Living with family, *n* (%)	1498 (78.4)	2484 (71.4)	<0.001
Time of fracture			<0.001
Day	1502 (78.7)	2149 (61.8)	
Night	406 (21.3)	1329 (38.2)	
Previous history of hip fracture, *n* (%)	138 (7.2)	365 (10.6)	<0.001
Previous history of compression fracture	462 (31.1)	1189 (43.4)	<0.001
Pre-fracture ambulation, *n* (%)[a]			<0.001
Independent community ambulation	1341 (70.2)	1471 (42.3)	
Community ambulator with cane	297 (15.5)	654 (18.8)	
Community ambulator with walker/crutches	76 (4.0)	218 (6.3)	
Independent household ambulator	42 (2.2)	342 (9.8)	
Household ambulator with cane	24 (1.3)	202 (5.8)	
Household ambulator with walker/crutches	31 (1.6)	318 (9.1)	
Non-functional ambulator	100 (5.2)	275 (7.9)	
Pre-fracture function, *n* (%)[b]			<0.001
Total dependent	41 (2.1)	166 (4.8)	
Maximal dependent	71 (3.7)	205 (5.9)	
Moderate dependent	40 (2.1)	348 (10.0)	
Minimal dependent	81 (4.2)	345 (9.9)	
Supervision	51 (2.7)	197 (5.7)	
Modified independent	371 (19.4)	905 (26.0)	
Independent	1256 (65.7)	1314 (37.8)	
Charlson Comorbidity Index, *n* (%)			<0.001
None	812 (42.5)	1103 (31.7)	
Mild (1–2)	864 (45.2)	1760 (50.6)	
Moderate (3–4)	190 (9.9)	500 (14.4)	
Severe (≥ 5)	45 (2.4)	117 (3.4)	
Osteoporosis, *n* (%)	981 (51.3)	2071 (59.5)	<0.001
Parkinson disease, *n* (%)	41 (2.1)	158 (4.5)	<0.001
Dementia, *n* (%)	139 (7.3)	551 (15.8)	<0.001
Cerebrovascular accident, *n* (%)	206 (10.8)	587 (16.9)	<0.001
Hemiplegia/paraplegia, *n* (%)	7 (0.4)	69 (2.0)	<0.001
Heart failure, *n* (%)	32 (1.7)	146 (4.2)	<0.001
DM without complication, *n* (%)	531 (27.8)	1088 (31.5)	0.008
Chronic pulmonary disease, *n* (%)	111 (5.8)	236 (6.8)	0.182
DM with complication, *n* (%)	9 (0.5)	32 (0.9)	0.099
Chronic kidney disease, *n* (%)	122 (6.4)	318 (9.1)	<0.001
Incontinence, *n* (%)	2 (0.1)	8 (0.2)	0.489
Ophthalmologic disease, *n* (%)	40 (2.1)	104 (3.0)	0.063
Spine disease, *n* (%)	226 (11.8)	624 (17.9)	<0.001
Malnutrition, *n* (%)[b]	382 (20.0)	966 (27.8)	<0.001
Fracture type, *n* (%)			<0.001
Femur neck	866 (45.4)	1470 (42.6)	
Intertrochanteric	890 (46.7)	1850 (53.7)	
Subtrochanteric	96 (5.0)	83 (2.4)	
Femur shaft	54 (2.8)	44 (1.3)	
Combined fracture, *n* (%)	151 (7.9)	195 (5.7)	0.002
ASA score, *n* (%)			<0.001
0	4 (0.2)	2 (0.1)	
1	178 (9.3)	131 (3.8)	
2	1166 (61.0)	1846 (53.0)	
3	536 (28.0)	1408 (40.5)	
4	27 (1.4)	92 (2.6)	
5	0 (0.0)	1 (0.0)	
Operation type, *n* (%)			<0.001
Internal fixation	988 (51.8)	1681 (48.8)	
Bipolar hemiarthroplasty	694 (36.4)	1552 (45.0)	
Total hip replacement	226 (11.8)	215 (6.2)	
Anaesthesia, *n* (%)			0.204
General	1047 (54.8)	1838 (52.9)	
Spinal	834 (43.7)	1595 (45.9)	
Epidural	28 (1.5)	40 (1.2)	
Cement, *n* (%)	27 (2.9)	57 (3.2)	0.772
Transfusion, *n* (%)	266 (13.9)	591 (17.0)	0.003
Pre-OP 25-OH Vitamin D, mean (SD), ng/mL	20.7 (41.5)	20.9 (118.7)	0.948
Pre-OP Albumin, mean (SD), g/dL	3.9 (4.1)	3.9 (6.4)	0.747
Days to surgery, mean (SD), days	4.9 (9.0)	5.4 (8.9)	0.075

(*Continued*)

Table 1. Continued.

Variable	Outdoor falls ($n = 1,911$)	Indoor falls ($n = 3,480$)	p-value
Length of hospital stay, mean (SD), days	18.7 (13.3)	19.3 (14.8)	0.114
Follow-up duration, mean (SD), days	185.3 (44.3)	184.3 (50.1)	0.469

BMI: body mass index; DM: diabetes mellitus; ASA: American Society of Anaesthesiologists.
[a]KOVAL classification.
[b]Defined by Global Leadership Initiative on Malnutrition (GLIM) criteria.

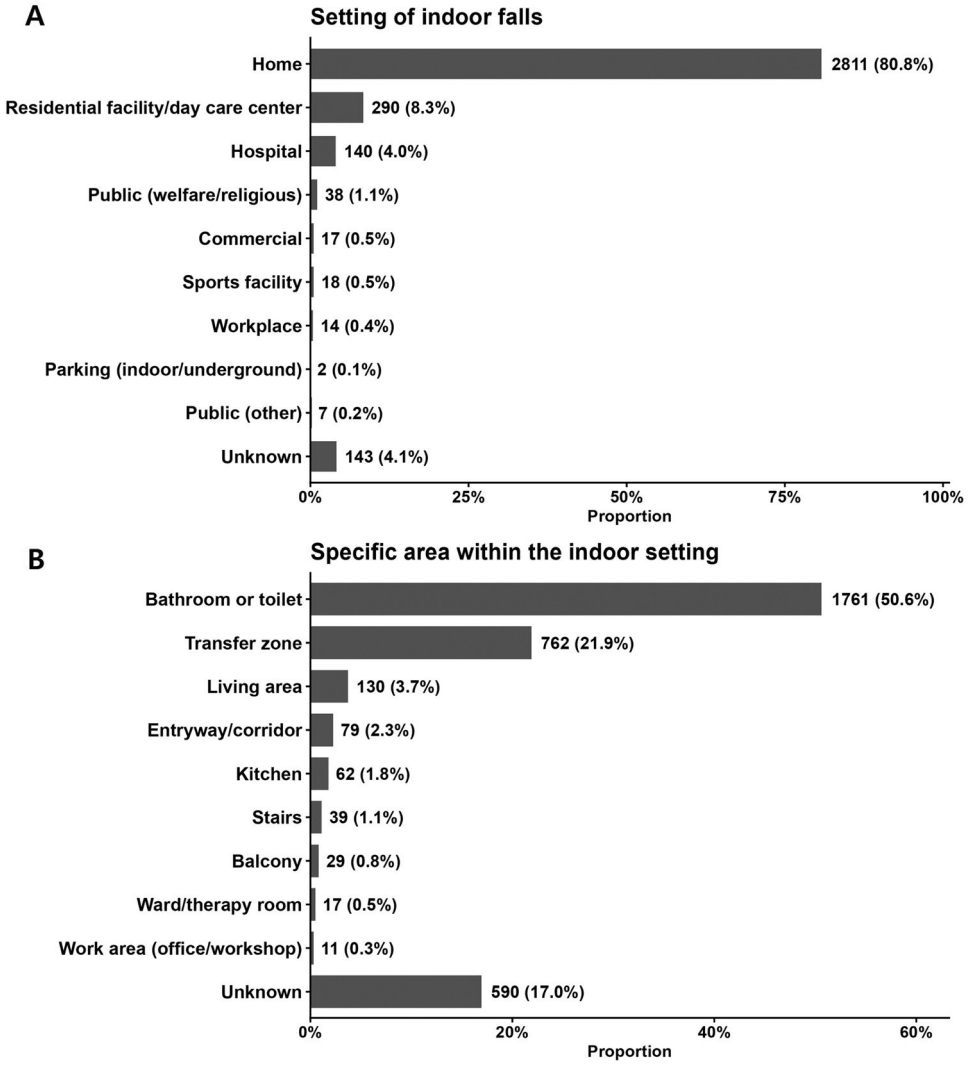


Figure 2. Characteristics of indoor falls among patients with hip fracture. (A) Distribution of indoor fall settings. (B) Specific locations within indoor environments where falls occurred. Percentages are calculated within the indoor fall subgroup.

remained independently associated with gait impairment, functional dependence, and mortality in the fully adjusted models (Table S4).

Discussion

This multicentre cohort study showed that fall location is a clinically meaningful prognostic marker in adults with fragility hip fractures. Patients who sustained indoor falls had a more vulnerable clinical profile than outdoor fallers, including poorer baseline health, heavier comorbidity burden, worse pre-fracture function, and more frequent malnutrition. Importantly, even after extensive adjustments for demographic, clinical, functional, fracture-related, surgical, and nutritional factors, indoor falls remained independently

Table 2. Postoperative clinical outcomes by fall location.

Variable	Outdoor falls ($n = 1,911$)	Indoor falls ($n = 3,480$)	p-value
Walking initiation date, *n* (%)			0.930
POD 1–2	325 (20.6)	550 (21.1)	
POD 3–4	521 (33.0)	845 (32.5)	
POD 5–7	277 (17.6)	470 (18.1)	
POD ≥ 8	454 (28.8)	736 (28.3)	
Post-fracture ambulation, *n* (%)[a]			<0.001
Independent community ambulation	512 (27.0)	506 (14.9)	
Community ambulator with cane	441 (23.3)	594 (17.5)	
Community ambulator with walker/crutches	325 (17.2)	539 (15.9)	
Independent household ambulator	55 (2.9)	107 (3.1)	
Household ambulator with cane	97 (5.1)	239 (7.0)	
Household ambulator with walker/crutches	319 (16.9)	847 (24.9)	
Non-functional ambulator	144 (7.6)	565 (16.6)	
Post-fracture function, *n* (%)			<0.001
Total dependent	63 (3.3)	287 (8.4)	
Maximal dependent	139 (7.3)	474 (14.0)	
Moderate dependent	239 (12.6)	624 (18.4)	
Minimal dependent	219 (11.6)	381 (11.2)	
Supervision	181 (9.6)	339 (10.0)	
Modified independent	562 (29.7)	820 (24.1)	
Independent	490 (25.9)	472 (13.9)	
Postoperative complication, *n* (%)	166 (8.7)	420 (12.2)	<0.001
Postoperative delirium, *n* (%)	37 (8.8)	64 (7.9)	0.668
Discharge location			<0.001
Hospital	652 (34.1)	1280 (36.8)	
Residential facility	211 (11.0)	533 (15.3)	
Home	1044 (54.6)	1647 (47.4)	
Others	4 (0.2)	16 (0.5)	
Death during follow-up	12 (0.6)	68 (2.0)	<0.001

POD: post-operative day.
[a]KOVAL classification.

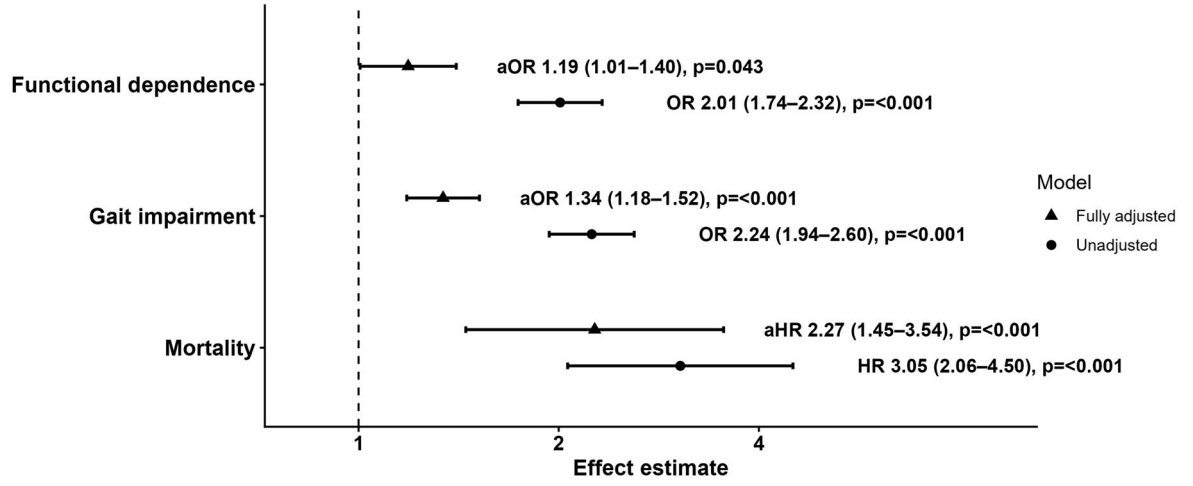


Figure 3. Associations between fall location and primary clinical outcomes after hip fracture. Forest plot showing effect estimates with 95% confidence intervals (CIs) for indoor versus outdoor falls (reference). Odds ratios (ORs) are presented for functional dependence and gait impairment, and hazard ratios (HRs) for mortality. Fully adjusted models included demographic factors, comorbidities, pre-fracture functional status, fracture and surgical characteristics, and nutritional status.

associated with an increased risk of functional dependence, gait impairment, and mortality during follow-up. These findings suggest that fall location may reflect biological vulnerability beyond environmental exposure and may provide a simple and readily available indicator of physiological reserve in patients with fragility hip fractures.

Our findings align with previous evidence that indoor falls are clustered among older frail adults with multiple chronic conditions. Falls occur during diverse daily activities in community-dwelling older adults. However, outdoor falls are more frequently reported during walking or other dynamic activities among

relatively younger older individuals, whereas indoor falls increase with age [10–15]. This shift likely reflects declining physiological reserves, reduced mobility, and increased dependence on daily activities, leading older adults to spend more time indoors and to fall during lower-demand activities. Unlike outdoor falls, which often involve dynamic environmental hazards such as slipping or tripping during ambulation, indoor falls commonly occur during routine low-intensity activities such as transfers, toileting, or indoor ambulation and thus may reflect underlying functional vulnerability rather than environmental exposure alone [16].

Most hip fractures in older adults occur after indoor falls [16]. However, only a small proportion of falls cause clinically significant injuries, and hip fractures remain uncommon among community-dwelling older adults [11,16]. The occurrence of fractures depends on whether the all-related impact energy exceeds the bone strength, which is influenced by fall characteristics, protective responses, shock absorption, and skeletal integrity. Conditions such as sarcopenia, osteoporosis, and impaired physiological homoeostasis, reduce muscle shock absorption, compromise bone strength, and diminish the ability to respond effectively to injury [29,30]. Accordingly, a hip fracture following a relatively low-energy indoor fall likely indicates substantial underlying frailty and a diminished physiological reserve.

In our cohort, indoor falls most frequently occurred at home, particularly in bathrooms and transfer zones such as bed–chair transitions, indicating that the home is a major site of hip fracture–related falls and not necessarily a protected environment for older adults. Bathrooms may be especially hazardous owing to their frequent use, balance-challenging activities, and environmental factors such as slippery floors, confined spaces, thresholds, and insufficient grab support, particularly among individuals with age-related declines in strength and balance. Similarly, previous studies have shown that fragility hip fracture–related falls predominantly occur indoors from standing height during routine activities, and often involve a loss of balance due to positional changes or weakness [16]. Falls associated with incorrect weight-shifting, collapse during low-intensity activities, and slipping during walking have been linked to increased mortality after hip fracture [17]. Indoor falls are also common in hospitals and long-term care facilities, where environmental unfamiliarity, multimorbidity, polypharmacy, cognitive impairment, and functional decline further increase risk [31]. Fall rates in long-term care facilities are substantially higher than those in community settings [31], with a higher incidence of hip fractures and worse prognosis [32], underscoring the need for prevention strategies tailored to institutional and home environments.

Indoor falls in our cohort were also more likely to occur at night, which is consistent with the evidence that frail older adults are particularly vulnerable to nocturnal falls [14]. Nighttime falls are associated with nocturia, sleep disturbance, and inadequate lighting [14,33,34]. Beyond the immediate injury, nocturnal falls may lead to prolonged “long-lie” situations, particularly among older adults living alone, resulting in delayed discovery and adverse complications such as rhabdomyolysis [35]. These observations support targeted prevention strategies centred on high-risk indoor environments, night-time safety measures, and modifiable clinical risk factors, including frailty, functional decline, and medication burden, across home, hospital, and long-term care settings.

The association between indoor fall location and adverse postoperative outcomes was attenuated after adjusting for demographic characteristics, baseline functional status, comorbidities, and nutritional status, indicating that underlying health status and functional reserve partly explain this relationship [18,36]. The greatest attenuation occurred after accounting for age, sex, functional capacity, and comorbidity burden; however, indoor falls remained significantly associated with functional impairment and mortality in the fully adjusted models. This persistent association is consistent with previous studies showing that indoor falls identify older adults with greater frailty, poorer physical function, and higher mortality risk, independent of established clinical risk factors [14,18]. These findings suggest that fall location may capture dimensions of vulnerability not fully reflected by conventional clinical assessments, including pre-fracture functional status, comorbidity burden, and nutritional status, which are commonly used surrogate markers of frailty [36,37]. Because fall location reflects the interaction between an individual’s functional capacity and the environment in which daily activities occur, it may provide complementary prognostic information beyond established frailty-related measures [12,14]. Although we did not formally evaluate whether fall location improves risk prediction beyond conventional frailty markers, the persistence of the association after extensive adjustment suggests that it captures dimensions of vulnerability that are not fully reflected in standard clinical assessments. Residual associations may reflect unmeasured dimensions of vulnerability, such as balance impairment, environmental barriers, additional

functional limitations, or limited familial and social support [38]. Alternatively, fall location itself may serve as a composite proxy for frailty, functional decline, and diminished physiological reserve [12,18]. Accordingly, fall location may represent a clinically meaningful risk marker that integrates biological reserves, functional capacity, environmental context, and social support.

Our findings have several important clinical implications. Fall location is readily available and may provide a practical, low-cost marker for early postoperative risk stratification after hip fractures [18,36]. These findings suggest that fall location may help identify patients at an increased risk of adverse outcomes and may complement established clinical assessments when considering postoperative care planning and fall-prevention strategies [18,36,39]. Particular attention should be directed toward modifiable indoor hazards such as slippery surfaces, inadequate lighting, insufficient grab supports, and environmental barriers [40,41]. Prevention strategies should adopt a staged approach: preventing falls through risk factor modification and environmental safety, reducing indoor fall risk through home hazard assessment and functional support [42], minimizing severe consequences by optimizing bone health and protective responses [41], and systematically evaluating fall causes to guide rehabilitation, secondary fracture prevention, and long-term management [43]. These approaches should be tailored according to the care settings, including private homes, residential facilities, and hospitals [40].

This study has several limitations. Although fall environments were categorized using predefined criteria with additional indoor subcategories, some responses lacked sufficient clarity for precise classification and misclassification could not be excluded. Because the indoor and outdoor classifications were based on registry descriptions rather than direct environmental assessments, some degree of misclassification may have occurred, particularly in settings that could be either indoor or outdoor. Detailed fall characteristics such as mechanism, activity at the time of the fall, protective responses, and environmental triggers were not systematically captured; however, specific fall locations may partially reflect these contextual factors and function as composite proxies for functional vulnerability and environmental exposure. The final analytical cohort was derived after excluding patients without follow-up assessment, those with missing fall-related information, unknown injury mechanisms or fall locations, and those whose fractures were managed nonoperatively. A comparison of the included and excluded participants revealed several baseline differences. Although the excluded participants did not consistently exhibit greater frailty or poorer health status across all measures, selection bias could not be excluded. In addition, because non-operative management is often reserved for patients with severe frailty, advanced comorbidities, or limited physiological reserve, the findings may not be fully generalizable to all patients with fragility hip fractures.

Potential mediating effects among clinical, functional, and environmental factors were not formally examined, and information on rehabilitation exposure, including inpatient rehabilitation intensity and post-discharge rehabilitation services, was unavailable, which may have influenced the observed functional outcomes. Although KHFR data are prospectively collected by trained research coordinators using standardized case report forms and undergo periodic quality reviews, some degree of underreporting remains possible. Comorbidities were obtained from registry records and medical documentation rather than from comprehensive geriatric assessments. Therefore, some conditions may have been under-reported, potentially leading to residual misclassification. The observed low mortality rate may partly reflect the mean follow-up duration of approximately 6 months. In addition, because the mortality analysis was restricted to participants with available follow-up assessments, selection bias cannot be excluded. Furthermore, because mortality was not confirmed through linkage with a national death registry, underascertainment of mortality cannot be excluded. The KHFR database contains information only for enrolled participants and does not capture the total number of hip fracture surgeries performed at the participating hospitals or the characteristics of patients who were not enrolled in the registry. Therefore, the recruitment rates and potential differences between participants and non-participants could not be assessed. In addition, the study population was exclusively derived from a Korean multicentre prospective registry. Differences in healthcare systems, rehabilitation practices, living environments, and population characteristics may limit the generalizability of these findings to other countries or ethnic populations.

Despite these limitations, our multicentre cohort analysis, incorporating standardized clinical and functional assessments across participating institutions, extends the existing evidence by demonstrating that fall location may serve as a clinically meaningful marker of the underlying vulnerability associated with both functional recovery and survival after hip fracture surgery.

Conclusions

In conclusion, fall location is strongly associated with postoperative functional recovery and mortality after fragility hip fractures and may reflect the underlying physiological reserve, functional vulnerability, and environmental context. Rather than being a simple geographic descriptor, fall location may serve as a clinically meaningful marker that integrates biological reserves, functional capacity, and environmental exposure. As an additional marker of frailty and postoperative risk, the fall location may complement established prognostic factors and contribute to risk stratification in adults with fragility hip fractures.

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Author contributions statement

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Data availability statement

The KHFR dataset is accessible through the Internet-based Clinical Research and Trial Management System (iCReaT) of the Korea National Institute of Health (https://icreat.nih.go.kr). Access to the database is available upon reasonable request with approval from the KHFR committee.

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