Osteoporosis International
https://doi.org/10.1007/s00198-019-05110-7

ORIGINAL ARTICLE

Influence of fall environment and fall direction on risk of injury among pre-frail and frail adults

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Received: 17 January 2019 / Accepted: 24 July 2019

Abstract

Summary In this prospective study, half of all falls resulted in injury. Pre-frail adults sustained more injuries, while more frail adults had injuries requiring hospitalization or fractures. Pre-frail adults fell more often when in movement compared with frail adults who fell more often when standing and in indoor public spaces.

Purpose To assess prospectively how fall environment and direction are related to injury among pre-frail and frail adults.

Methods We included 200 community-dwelling adults with a prior fall (pre-frail, mean age 77 years) and 173 adults with acute hip fracture (frail, mean age 84 years; 77% community-dwelling). Falls were prospectively recorded using standardized protocols in monthly intervals, including date, time, fall direction and environment, and injury. We used logistic regression to assess the odds of injury adjusting for age, body mass index (BMI), and gender.

Results We recorded 513 falls and 331 fall-related injuries (64.5%) among the 373 participants. While the fall rate was similar between groups, pre-frail adults had more injuries (71% among pre-frail vs. 56% among frail, $p = 0.0004$) but a lower incidence of major injuries (9% among pre-frail vs. 27% among frail, $p = 0.003$). Pre-frail adults fell more often while in movement (84% among pre-frail vs. 55% among frail, $p < 0.0001$), and frail adults fell more often while standing (26% vs. 15% respectively, $p = 0.01$). The odds of injury among frail adults was increased 3.3-fold when falling sideways (OR = 3.29, 95% CI = 1.68–6.45) and 2.4-fold when falling in an indoor public space (OR = 2.35, 95% CI = 1.00–5.53), and was reduced when falling at home (OR = 0.55, 95% CI = 0.31–0.98). The odds of injury among pre-frail adults was not influenced by environment and was 53% lower when falling backwards (OR = 0.47, 95% CI = 0.26–0.82).

Conclusion While pre-frail adults sustain more fall-related injuries, frail adults were more likely to sustain major injuries, especially when falling sideways or outside their home.

Keywords Falls · Frail · Injuries · Pre-frail · Prospective

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Published online: 03 August 2019

Introduction

Falls are a hallmark of frailty [1] and have been associated with multiple adverse health outcomes, including hospitalization, nursing home admission, and mortality [1–3]. At age 65 years, about 30% of community-dwelling adults suffer at least one fall per year and at age 80 years, the proportion increases to 50% or more [4].

Even low trauma falls, such as falling from standing height without the interference of others or a vehicle, will cause injury in 40 to 60% of cases, and 10–20% of these injuries would be expected to be severe (i.e., fractures, brain injury) [5, 6]. This explains why 10% of all emergency room consultations among older adults are due to a fall [7].

The high incidence of falls and related injuries contributes to a substantial personal burden [8]. Notably, regardless of the severity of the injury, falls are an independent predictor of functional decline and nursing home admission [9], and are associated with increased mortality even beyond 12 months after an injurious fall [1]. The latter may in part be explained by self-imposed mobility restriction and social isolation due to fear of falling among older adults who fell [10]. Also, about 1 to 14% of falls result in hip fracture carrying a high risk of functional decline, loss of independence, and mortality [11–13].

Falls are also costly; in fact, fall injuries are among the 20 most expensive medical conditions [14]. In an international systematic review, the mean cost of falls was estimated to vary between US$ 3476 per fall and US$ 10,749 per injurious fall [8]. Therefore, both from a personal and societal perspective, reducing falls in older adults has become a public health priority.

Risk factors for falls have been categorized into intrinsic (e.g., functional limitations, advanced age, poor vision and hearing) and extrinsic factors (e.g., stairs without railing, loose carpets, poor lighting, psychoactive medications) [4]. Regarding fall environment, it has been suggested that the incidence of indoor falls was strongly associated with older age [15]. Regarding fall direction, among adults age 75 and older, hip fractures typically occur after a sideways fall from a standing height at home [16]. Thus, the body parts injured and the degree of injury may be affected by direction and fall location.

Only few previous studies have focused the risk factors of injurious falls and most of the prior studies focused on falls treated in emergency departments [17, 18] or falls that resulted in fractures [15, 19]. To our best knowledge, only two previous studies [2, 20] investigated how fall circumstances differ between frail and pre-frail adults, and one of these studies focused on home hazards only [20].

Therefore, we planned this study to gain better understanding of the complexity of falls among pre-frail and frail adults, particularly the underlying pathways on how fall direction and fall environment contribute to the risk of any injury and fractures.

Methods

Study population

Our study population arises from two separate randomized controlled trials conducted at the Centre on Aging and Mobility, University of Zurich, Switzerland. The first trial, the Zurich Disability Prevention trial (NCT01017354) [21], enrolled 200 community-dwelling adults aged 70 years and older who had a history of falls in the prior 12 months, referred to in this report as "pre-frail adults." Participants were randomly assigned to one of three monthly oral doses of vitamin D for 12 months with clinical visits at baseline, 6, and 12 months, plus an additional 6-month open follow-up after treatment cessation [21]. The second trial, the Early Rehabilitation After Hip Fracture Study (NCT00133640) [11], enrolled 173 adults aged 65 years and older with acute hip fracture, referred to here as "frail adults." Using a 2 by 2 factorial design, participants were randomly assigned to either a simple home exercise program or standard physiotherapy and to one of two daily doses of vitamin D, and were followed for 12 months with clinical visits at baseline, 6, and 12 months [11]. In both trials, participants were called in monthly intervals over the 12-month study duration to assess if they had a fall. For each fall, the same fall protocol was documented by a study nurse to assess the circumstances of the falls and related injuries. Additional information, including inclusion criteria and results for main endpoints for both trials, are described in their original published papers [11, 21].

Data collection

Information about participants' age, gender, anthropometrics, and other characteristics were collected at baseline, including a complete physical exam. Comorbid conditions were assessed with the Charlson Comorbidity Index [22]. Cognitive function was assessed using the Mini-Mental State Examination (MMSE) [23]. Pre-frail adults were required to reach a MMSE score of ≥ 27 points (of a maximum of 30 points) to be included in the original trial [21], whereas frail adults needed a score of ≥ 15 points to be enrolled [11].

Fall assessment

Falls were defined as unintentionally coming to rest on the ground, floor, or other lower levels [24]. Coming to rest against furniture or a wall was not considered a fall. Detailed information on fall circumstances and fall-related injuries were prospectively collected in monthly intervals by trained nurses using monthly telephone assessment forms and in-

person visits at 6 and 12 months. In both studies, each fall report was assessed with the same standardized fall protocol which included information about the fall environment, direction of every fall and the activity that preceded it, and the estimated fall height. Furthermore, detailed information on date and time as well as any resulting injury were assessed.

We classified the orientation of the fall as forward, backwards, or sideways. The general location of the fall was classified as outdoors, indoors in their own homes, and indoors in public spaces. The type of activity at the time of the fall was classified as sitting (getting in or out of a chair), standing, or in movement (walking at normal speed, rushing, turning, or going up- and downstairs). The level and height of the fall were categorized as falling from a sitting position (getting in or out of a chair), falling from standing position, or falling from steps, ladders, or stairs. Season during which fall occurred was categorized as winter (Dec 21–Mar 19), spring (Mar 20–Jun 20), summer (Jun 21–21 Sept), and autumn (Sept 22–Dec 20). Time of day was categorized into morning (06:00 am–noon), afternoon (noon–06:00 pm), evening (06:00 pm–midnight), and night (midnight–06:00 am).

Participants, who were injured during the fall, were asked specific questions about the type of injury and if medical care was needed. In case of several injuries associated with the same fall, we included only the most severe one. We defined an injurious fall as one that resulted in any injury, and categorized them in 3 groups: mild, if the person reported a soft tissue injury (cuts, lacerations, hematomas) but did not seek medical care; moderate, if an ambulant medical treatment was necessary for an injury other than a fracture; and major, which included all injuries requiring hospitalization and all that sustained fractures. Among those who reported fractures, fracture localization was classified in four categories: hip, upper extremity, vertebral, and other (Table 2). Missing information for any variables was coded as unknown.

Statistical analyses

Baseline characteristics of each population and fall circumstances were compared by gender using Student's t tests for continuous variables and χ^2 tests and Fischer exact tests for categorical variables. We compared fall circumstances between frail and pre-frail adults using chi-square tests. The 0.05 level was chosen to indicate statistical significance. To compare fall circumstances and resulting injuries and fractures, we used generalized estimating equations including a repeated statement for each participant accounting for multiple falls in the same participant. We present odds ratios and 95% confidence intervals adjusted for age and gender. Other potential confounders such as BMI and length of follow-up did not improve the fitness of the model and the results were virtually the same.

Results

Baseline characteristics

Population characteristics are presented in Table 1 for each group. Pre-frail and frail adults had significantly different age, BMI, cognitive status, and number of comorbidities. Pre-frail adults had a mean age of 78 years and all were community-dwelling. Frail adults had a mean age of 84 years and 77% were community-dwelling prior to their hip fracture. There were no significant differences in age, BMI, number of comorbidities, and cognitive function between men and women in both populations.

Of the total reported 513 fall events, 301 falls occurred in 121 pre-frail adults and 212 occurred among 92 frail adults. This corresponds to a rate (falls per person-year) of 1.5 in pre-frail and 1.4 in frail adults, respectively ($p = 0.72$). Participants who fell twice or more (recurrent fallers) constituted more than half of all fallers (53% in pre-frail and 59% in frail adults). Among the 200 pre-frail older adults, 15 (7.5%) sustained a fracture during the 12-month follow-up and none sustained more than one fracture within this time frame. Among the 173 frail older adults with an acute hip fracture, 18 (10.4%) sustained one fracture during the 12 months of follow-up and two frail older sustained two fractures during the same time frame. Further, among the frail older adults, 8 sustained a repeat hip fracture (4.6%).

Type of fall-related injuries among pre-frail and frail adults

Pre-frail adults had a significantly higher incidence of fall-related injuries compared with frail adults (71% among pre-frail vs. 56% among frail, $p = 0.0004$; see Table 2). Seventy-two percent of injurious falls among pre-frail and 44% among frail adults resulted in minor injury ($p < 0.0001$). Eighteen percent of injurious falls among pre-frail and 29% among frail adults resulted in moderated injuries ($p = 0.01$). Nine percent of injurious falls among pre-frail and 27% among frail adults resulted in major injury ($p < 0.0001$).

Pre-frail adults suffered 15 (5%) fractures and frail adults 22 (10%) fractures ($p = 0.02$). Fracture localization was mostly at the hip for frail adults (8 in frail and 1 in pre-frail adults, $p = 0.04$).

Table 1 Characteristics of pre-frail and frail populations

				Pre-frail older adults (with fall event)			Frail older adults (with hip fracture)		
	Pre-frail ($n = 200$)	Frail ($n = 173$)	p value	Men ($n = 66$)	Women ($n = 137$)	p value	Men ($n = 66$)	Women ($n = 137$)	p value
Age at baseline, mean years (±SD)	77.7 (5.0)	84.2 (6.9)	< 0.0001	77.9 (5.5)	77.6 (4.7)	0.67	83.9 (7.0)	84.3 (6.7)	0.75
BMI at baseline, mean kg/m^2 (±SD)	26.2 (4.0)	24.3 (4.3)	< 0.0001	26.5 (3.4)	26.1 (4.3)	0.42	24.7 (3.2)	24.2 (4.6)	0.41
MMS at baseline, mean score (±SD)[1]	28.6 (1.0)	24.7 (3.7)	< 0.0001	28.5 (1.0)	28.7 (1.0)	0.32	24.4 (4.3)	24.8 (3.5)	0.53
Living situation at baseline (%)									
Home	200 (100)	134 (77.5)	< 0.0001	66 (100)	134 (100)		29 (80.1)	105 (76.6)	0.62
Assisted living	0	29 (16.8)		–	–		5 (13.9)	24 (17.5)	0.60
Nursing home	0	10 (5.8)		–	–		2 (5.6)	8 (5.8)	0.99
Charlson Comorbidity Index, N (%)[2]									
0	127 (63.5)	18 (10.5)	< 0.0001	35 (53.0)	92 (67.2)	0.05	2 (5.6)	16 (11.2)	0.36
1	40 (20.0)	32 (18.7)	0.75	18 (27.3)	22 (16.1)	0.06	5 (13.4)	27 (20.0)	0.40
2	25 (12.5)	40 (23.4)	0.01	10 (15.2)	15 (11.0)	0.39	9 (25.0)	31 (22.3)	0.80
≥3	7 (3.5)	81 (47.4)	< 0.0001	3 (4.6)	5 (3.4)	0.69	20 (55.6)	61 (45.2)	0.27
Falls during follow-up (%)									
No falls	79 (39.5)	81 (46.8)	0.15	27 (40.9)	52 (40.2)	0.77	18 (50.0)	63 (46.0)	0.66
One fall	57 (28.5)	38 (22.0)	0.15	22 (33.3)	35 (25.6)	0.29	11 (30.6)	27 (19.7)	0.16
Two or more falls	64 (32.0)	54 (31.2)	0.87	17 (25.8)	47 (34.3)	0.18	7 (19.4)	47 (34.3)	0.09

BMI, body mass index; *MMS*, Mini-Mental State Examination

[1] Measurement of cognitive impairment (range 0–30)

[2] Predicts the 10-year mortality for a patient who has a range of comorbid conditions (range 0–37)

Data given as numbers and percentages unless otherwise noted

p values from the Student t test for continuous variables and χ^2 or Fisher exact tests for categorical variables

Fall direction and fall-related injury among pre-frail and frail adults

With regard to the direction of the falls, forward falls occurred more frequently in pre-frail adults compared with frail adults (48% among pre-frail vs. 17% among frail, $p < 0.0001$; Table 3). In contrast, sideways falls occurred more frequently in frail adults compared with pre-frail adults (45% among frail vs. 28% among pre-frail, $p = 0.001$).

Notably, sideways falls carried a high risk of injury (OR = 3.29 (1.68, 6.45)) and fracture (OR = 3.25 (1.09, 9.68)) among frail adults. Among pre-frail adults, there was no significantly increased risk of injury by direction of the fall. However, pre-frail older adults who fell backward appeared to have a lower odds of injury (OR = 0.47 (0.26, 0.82)).

Among frail adults, falling sideways was 3.3-fold more likely to result in any injury (OR = 3.29, 95% CI = 1.68–6.45) and 3.3-fold more likely to result in a fracture (OR = 3.25, 95% CI = 1.09–9.68) compared with falling backward or forward (Table 4), and after adjusting for age and gender. Among frail adults, falling indoors in a public space increased the odds of injury 2.4-fold (OR = 2.35, 95% CI = 1.00–5.53), whereas falling inside their home decreased the odds of injury by 45% (OR = 0.55, 95% CI = 0.31–0.98) (Table 4). There were no significant associations between the activities before the fall, season or time of the day, and injuries or fractures.

Fall environment and fall-related injury among pre-frail and frail adults

With regard to the environment where falls occurred, more pre-frail adults fell outdoors (58% among pre-frail vs. 21% among frail, $p < 0.0001$; Table 3) and indoors in a public space compared with frail adults (19% vs. 10%, $p = 0.03$). On the other hand, more frail adults fell indoors at home compared with pre-frail adults (67% among frail vs. 23% among pre-frail, $p < 0.0001$).

Frail adults fell more frequently while sitting (15%) and standing (26%) compared with pre-frail adults (1% and 15% respectively, $p < 0.05$ for both). In contrast, pre-frail adults fell more often while in movement (84% among pre-frail vs. 55% among frail, $p < 0.0001$; Table 3).

Frail adults fell more often from sitting height compared with pre-frail adults (18% in frail vs. 7% in pre-frail adults, $p < 0.001$; Table 3). Pre-frail adults fell more often from a

Table 2 Type of fall-related injuries among pre-frail and frail adults

	Pre-frail adults *n* (%)	Frail adults *n* (%)	*p* value	Adjusted *p* value[1]
Fallers	121 (60.5)	92 (53.2)	0.21	
Recurrent fallers	64 (52.9)	54 (58.7)	0.4	
Total falls	301	212		
Injurious falls				
Any injury	213 (70.8)	118 (55.6)	0.0004	0.003
None	88 (29.2)	94 (44.3)		
Type of injury[2]				
Minor	154 (72.3)	52 (44.1)	< 0.0001	< 0.0001
Moderate	39 (18.3)	34 (28.8)	0.01	0.01
Major	20 (9.4)	32 (27.1)	< 0.0001	0.003
Falls with fracture				
Fracture	15 (5.0)	22 (10.2)	0.02	0.04
No fracture	286 (95.0)	190 (89.8)		
Fracture location[3]				
Hip	1 (6.7)	8 (36.4)	0.04	0.01
Upper extremity	7 (46.7)	5 (22.7)	0.13	0.12
Vertebral	1 (6.7)	2 (9.1)	0.79	0.42
Other	6 (40.0)	7 (31.8)	0.61	0.78

[1] Results from generalized linear models adjusting for age, gender, and days of follow-up

[2] Among those with injury only

[3] Among those with fractures only

standing height compared with frail adults but this difference only approached significance (82% among pre-frail vs. 73% among frail, $p = 0.08$). Frail adults who fell at home had more frequently non-injurious falls vs. injurious falls (78% vs. 64%, $p = 0.03$), whereas adults who fell outdoors or indoors in a public space were injured more frequently (7% vs. 15%, $p = 0.05$; and 9% vs. 20%, $p = 0.03$, respectively). While there were no significant differences regarding the activity during the fall, all falls on stairs were injurious (total 9 falls).

Among pre-frail adults, fall environment, activity, and height of fall were not significantly associated with the odds of any injury or fracture (Table 4). Among frail adults, activity and fall height also did not increase the odds of any injury or fracture. However, falling indoors at home reduced the odds of injury (OR = 0.55 (0.31, 0.98)) and falling indoors in public spaces increased the odds of injury (OR = 2.35 (1.00, 5.53)).

Season, time of day, and fall-related injury among pre-frail and frail adults

There was no statistically significant difference in the frequency of falls across seasons between pre-frail and frail adults. Regarding day time, frail adults fell more during night time compared with pre-frail adults (12 pm–6 am; 13% among frail vs. 3% among pre-frail adults, $p = 0.0005$; Table 3). Pre-frail adults fell more frequently in the afternoon (12 am–6 pm) compared with frail adults (57% vs. 45%, $p = 0.04$). There were no significant differences regarding morning and evening falls.

Pre-frail adults who fell during autumn had more frequently injurious falls compared with non-injurious falls (26% with injury vs. 11% without injury, $p = 0.01$; Table 3). In contrast, pre-frail adults who fell during the summer had less injuries (24% in without injury vs. 36% with injury, $p = 0.02$).

There were no associations between time of the day and the odds of injury with falling among pre-frail or frail adults (Table 4). However, there was a lower odds of injury when pre-frail older adults fell during the summer (OR = 0.51 (0.29, 0.9)) and a higher odds of injury when they fell during fall (OR = 2.56 (1.15, 5.7)).

Discussion

In this large prospective study evaluating 513 falls and 331 fall-related injuries, the mean rate of falling among pre-frail and frail adults was about one and a half times per year. Notably, more than half of all falls were associated with an injury, both among pre-frail and frail older adults. While more fall-related injuries occurred in pre-frail adults, frail adults had a higher frequency of major injury requiring hospitalization or resulting in a fracture, and eight participants (4.6%) reported a second hip fracture during the first year of follow-up. Among pre-frail adults, environment did not influence their odds of injury when falling, although they fell more often when in movement compared with frail adults who fell more often when standing. Among frail adults, fall direction contributed to a 3.3-fold increased odds of injury if the fall was sideways, and sideways falls also contributed to a 3.3-fold increased odds to sustain a fracture when falling. In contrast, among pre-frail adults, fall direction and environment did not increase the odds of injury. In fact, backward falls appeared to be protective with regard to injury among pre-frail adults. With regard to environment, the odds of injury increased 2.4-fold among frail adults if they fell outside their home, in indoor public spaces.

Regarding the direction of a fall and related injury, our results are in line with previous studies suggesting that sideways falls are associated with a higher risk of injury, in particular hip fractures [16, 25, 26]. However, in our study, only frail adults who fell sideways had a 3.3-fold increased risk of fracture, while sideways falls did not contribute to increased odds of injury among pre-frail adults. Also consistent with prior studies [27, 28], we found that the most common type of falls among pre-frail adults is forward falls during movement, although forward falls in our study did not contribute to an increased odds of injury among pre-frail and frail adults. In a recent study by Crenshaw et al. [27] conducted among community-dwelling women age 65 years and older, forward

Table 3 Frequency of injurious falls among pre-frail and frail adults by fall direction, environment, activity, fall height, and season

	Falls total population					Injurious falls										Fractures									
	Pre-frail adults		Frail adults		*p* value	Pre-frail adults					Frail adults					Pre-frail adults					Frail adults				
						No		Yes		*p* value	No		Yes		*p* value	None		Yes		*p* value	None		Yes		*p* value
	N	%	*N*	%		*N*	%	*N*	%		*N*	%	*N*	%		*N*	%	*N*	%		*N*	%	*N*	%	
Fall direction																									
Forward	140	48.1	34	16.9	< 0.0001	35	39.8	105	49.3	0.13	13	13.8	21	18.1	0.40	135	47.2	5	33.3	0.29	32	16.8	2	10.0	0.43
Backward	56	18.1	42	20.9	0.53	21	23.9	35	16.4	0.13	20	21.3	22	19.0	0.68	53	18.5	3	20.0	0.89	39	20.5	3	15.0	0.56
Sideways	89	27.6	83	45.3	0.001	27	30.7	62	29.1	0.79	24	25.5	59	50.9	0.0002	83	29.0	6	40.0	0.36	70	36.8	13	65.0	0.01
Environment																									
Indoors home	64	23.0	143	67.1	< 0.0001	20	22.7	44	20.7	0.69	72	78.3	71	64.0	0.03	61	21.3	3	20.0	0.90	130	70.7	13	68.4	0.84
Outdoors	182	58.0	23	20.6	< 0.0001	54	61.4	128	60.1	0.84	6	6.5	17	15.3	0.05	172	60.1	10	66.7	0.61	21	11.4	2	10.5	0.91
Indoors public space	55	18.9	30	9.9	0.03	14	15.9	41	19.2	0.50	8	8.7	22	19.8	0.03	53	18.5	2	13.3	0.61	27	14.7	3	15.8	0.90
Activity before fall																									
Sitting	0	0.7	33	14.8	< 0.0001						17	18.1	16	13.6	0.37						30	15.8	3	13.6	0.79
Standing	43	14.8	56	26.2	0.01	15	17.0	28	13.1	0.38	25	26.6	31	26.3	0.96	41	14.3	2	13.3	0.91	49	25.8	7	31.8	0.54
Movement	258	84.2	101	55.0	< 0.0001	73	83.0	185	86.9	0.38	38	40.4	63	53.4	0.06	245	85.7	13	86.7	0.91	92	48.4	9	40.9	0.50
Fall height																									
From siting	19	6.5	38	17.7	0.001	6	6.8	13	6.1	0.82	19	20.2	19	16.1	0.44	18	6.3	1	6.7	0.95	35	18.4	3	13.6	0.58
From standing	245	81.6	144	73.2	0.08	74	84.1	171	80.3	0.44	63	67.0	81	68.6	0.80	232	81.1	13	86.7	0.59	129	67.9	15	68.2	0.98
Stairs	33	9.7	9	6.1	0.28	7	8.0	26	12.2	0.28	0	0.0	9	7.6	0.01	32	11.2	1	6.7	0.58	8	4.2	1	4.5	0.94
Season																									
Spring	93	31.5	49	27.2	0.42	27	30.7	66	31.1	0.94	19	20.2	30	25.4	0.37	90	31.6	3	20.0	0.34	45	23.7	4	18.2	0.56
Summer	82	27.7	62	29.7	0.70	32	36.4	50	23.6	0.02	32	34.0	30	25.4	0.17	80	28.1	2	13.3	0.21	55	28.9	7	31.8	0.78
Autumn	64	21.8	59	21.1	0.88	10	11.4	54	25.5	0.01	24	25.5	35	29.7	0.51	58	20.4	6	40.0	0.07	53	27.9	6	27.3	0.95
Winter	61	18.9	42	22.0	0.51	19	21.6	42	19.8	0.73	19	20.2	23	19.5	0.90	57	20.0	4	26.7	0.53	37	19.5	5	22.7	0.72
Time of day																									
Morning	81	28.1	45	28.3	0.96	23	27.4	58	28.4	0.86	17	23.9	28	30.4	0.36	79	28.8	2	14.3	0.24	43	29.1	2	13.3	0.19
Afternoon	164	56.8	70	44.7	0.04	48	57.1	116	56.9	0.97	33	46.5	37	40.2	0.42	154	56.2	10	71.4	0.26	63	42.6	7	46.7	0.76
Evening	36	12.2	23	14.3	0.59	11	13.1	25	12.3	0.84	10	14.1	13	14.1	0.99	34	12.4	2	14.3	0.84	21	14.2	2	13.3	0.93
Night	7	2.9	25	12.6	0.0005	2	2.4	5	2.5	0.97	11	15.5	14	15.2	0.96	7	2.6	0	0.0	0.54	21	14.2	4	26.7	0.20

Adjusted for age, gender, days in the study, and repeated falls per person

Table 4 Odds of injurious falls and fractures by fall direction, environment, activity, fall height, and season among pre-frail and frail adults

	Injurious falls						Fractures					
	Pre-frail adults			Frail adults			Pre-frail adults			Frail adults		
	No. of injurious falls	No. of non-injurious falls	OR (95% CI)	No. of injurious falls	No. of non-injurious falls	OR (95% CI)	No. of fractures	No. of non-fractures	OR (95% CI)	No. of fractures	No. of non-fractures	OR (95% CI)
Fall direction												
Forward	105	35	1.56 (0.93, 2.65)	21	13	1.08 (0.48, 2.43)	5	135	0.56 (0.18, 1.73)	2	32	0.59 (0.15, 2.3)
Backward	35	21	0.47 (0.26, 0.82)	22	20	0.74 (0.41, 1.35)	3	53	1.14 (0.31, 4.17)	3	39	0.74 (0.23, 2.4)
Sideways	62	27	1.11 (0.60, 2.07)	59	24	3.29 (1.68, 6.45)	6	83	1.61 (0.56, 4.59)	13	70	3.25 (1.09, 9.68)
Environment												
Indoors home	44	20	0.96 (0.47, 1.96)	71	72	0.55 (0.31, 0.98)	3	61	0.93 (0.26, 3.38)	13	130	0.82 (0.31, 2.15)
Outdoors	128	54	0.94 (0.57, 1.56)	17	6	2.19 (0.87, 5.54)	10	172	1.32 (0.46, 3.75)	2	21	0.99 (0.24, 4.06)
Indoors public space	41	14	1.16 (0.52, 2.57)	22	8	2.35 (1.00, 5.53)	2	53	0.68 (0.15, 3.07)	3	27	1.17 (0.37, 3.68)
Activity before fall												
Sitting	0			16	17	0.69 (0.33, 1.44)				3	30	1.02 (0.32, 3.23)
Standing	28	15	0.79 (0.39, 1.6)	31	25	1.19 (0.67, 2.11)	2	41	0.92 (0.2, 4.24)	7	49	1.3 (0.6, 2.84)
Movement	185	73	1.27 (0.63, 2.58)	63	38	1.44 (0.89, 2.35)	13	245	1.09 (0.24, 5.00)	9	92	0.68 (0.31, 1.52)
Fall height												
From siting	13	6	0.91 (0.32, 2.6)	19	19	0.81 (0.41, 1.60)	1	18	1.06 (0.14, 8.23)	3	35	0.86 (0.28, 2.67)
From standing	171	74	0.72 (0.35, 1.48)	81	63	1.08 (0.59, 1.95)	13	232	1.54 (0.33, 7.08)	15	129	
Stairs	26	7	1.87 (0.75, 4.65)	9	0		1	32	0.55 (0.07, 4.61)	1	8	0.98 (0.12, 7.77)
Season												
Spring	66	27	0.98 (0.57, 1.71)	30	19	1.32 (0.77, 2.27)	3	90	0.54 (0.15, 1.94)	4	45	0.65 (0.24, 1.76)
Summer	50	32	0.51 (0.29, 0.9)	30	32	0.77 (0.41, 1.45)	2	80	0.39 (0.07, 2.06)	7	55	1.55 (0.65, 3.72)
Fall	54	10	2.56 (1.15, 5.7)	35	24	1.13 (0.61, 2.09)	6	58	2.68 (0.89, 8.04)	6	53	
Winter	42	19	1.06 (0.55, 2.03)	23	19	0.87 (0.41, 1.85)	4	57	1.43 (0.39, 5.19)	5	37	1.08 (0.4, 2.9)
Time of day												
Morning	58	23	1.15 (0.7, 1.89)	28	17	1.08 (0.57, 2.03)	2	79	0.4 (0.09, 1.89)	2	43	0.31 (0.07, 1.45)
Afternoon	116	48	0.85 (0.53, 1.38)	37	33	0.69 (0.36, 1.32)	10	154	1.95 (0.59, 6.53)	7	63	1.26 (0.44, 3.67)
Evening	25	11	0.98 (0.47, 2.03)	13	10	1.33 (0.53, 3.36)	2	34	1.22 (0.25, 5.85)	2	21	1.03 (0.24, 4.46)
Night	5	2	1.66 (0.13, 20.76)	14	11	1.39 (0.48, 4.04)	0	7		4	21	2.26 (0.9, 5.64)

Adjusted for age, gender, and repeated falls per person

falls were the most common falls (44%) and about one-third of them were injurious, which is similar to the frequency observed among pre-frail adults in our study. Notably, in three prior studies exploring fall direction, backward falls were associated with a lower risk of injury if compared with sideways or forward falls [28–30]. Two prior studies reported that backward falls were associated with lower odds of hip fracture if compared with sideways falls [29, 30]. In addition, in our study, backward falls were associated with a significant 53% lower odds of injury among pre-frail adults and a non-significant 26% lower odds of injury among frail adults. However, not all studies support an association between direction of the fall and risk of injury [31] and one recent study suggested an increased odds of injury with backward falls [27]. These discrepancies may in part be explained by rotation of falls initially directed sideways to land backward and rotation of falls initially directed forward to land sideways [26]. Falling backwards might be an effective safe-landing strategy if combined with a squad motion leading to lower impact velocity and force [32]. On the other hand, falling sideways implies more direct impact to the bone [33] especially in the case of diminished trochanteric soft tissue thickness among frail older adults [34].

Our findings highlight the need for prevention strategies for sideway falls among frail older adults as especially sideways falls were associated with higher odds of fracture. Among sideways falls that lead to fractures, recurrent hip fractures are the most serious [35]. In our population of 173 frail older adults with acute hip fracture, 4.6% sustained a repeat hip fracture within the first 12 months of the acute first hip fracture. This somewhat lower rate than described in the literature (10% [36]) may be explained by the fact that this is a secondary analysis of a clinical trial where all participants received either 800 or 2000 IU vitamin D per day plus standard of care physiotherapy with or without a simple home-based exercise program [11].

In our study, more than two-thirds of frail study participants fell indoors, while pre-frail participants mostly fell outdoors. This is consistent with previous studies showing that relatively healthy and active older adults fall more often outdoors whereas frail older adults are more likely to fall indoors [37–39]. These differences may be best explained by differences in health status and level of physical activity between pre-frail and frail adults. For example, older adults who fall outdoors more often walk for exercise, have better health, and take less prescribed drugs [39], whereas adults who fall indoors are less likely to go for walks outside due to impaired mobility, have poorer health, and take more prescribed drugs [3].

Despite the consistent observation that most falls among frail older adults occurred indoors at home, we observed that the odds of injury was 2.4-fold higher among those who fell indoors in a public space whereas falls inside their home reduced the odds of injury by half compared with falling outdoors or in a public space. In contrast, others studies report a higher prevalence of injurious falls in the home environment compared with other places among frail older adults [2, 20, 40, 41]. Nevertheless, our results are in line with a study conducted in a similar population to our frail participants where older adults (mean age = 80 years) recruited shortly after hospital discharge reported 70% of indoor falls at home [40]. Among these falls, 49% were injurious, whereas 73% of the falls occurred in the community were injurious [40]. In another study on the circumstances of falls among patients age 75 and older in an emergency department, more falls were reported indoors at home but, similar to our study, with a lower risk of severe injury [42]. A potential explanation is that falls at home may not involve further hazards that may cause additional injury [42].

Frail adults had a higher percentage of falls from sitting height and fell more frequently during sitting or standing compared with pre-frail adults. On the other hand, pre-frail adults had twice as many falls during movement compared with frail adults. Similar to our results, Speechley et al. also reported that frail adults were less likely to fall during movement [2]. Conversely, other previous studies in community-dwelling adults age 65 years and older have reported an increased frequency of falls while walking [3, 6, 37]. In our study, frail adults reported 9 falls from stairs; all of them lead to injuries. Otherwise, we found no association between the activity and height of the fall and the risk of injury among frail adults and pre-frail adults.

The association between season and falls is still controversial. While several studies have reported no significant associations between seasons and all falls [18], injurious falls [43], and hip fractures [44], others reported more falls [6, 45] and radius plus humerus fractures [44] during winter. In our study, we observed more falls during spring and summer in both pre-frail and frail adults. Despite the higher number of falls in summer, pre-frail adults had a 49% lower odds of injury when they fell in the summer season, but a 2.6-fold increased odds of injury when the fall occurred in the autumn season. Our observation that pre-frail older adults have an increased risk of falling in spring and summer may be best explained by higher activity levels among community-dwelling older adults as described in several studies [46, 47]. On the other hand, greater sunshine exposure during spring and summer may have contributed to less injuries [44] by less environmental hazards such as ice and slippery leafs plus improvement in 25(OH) D status [48] contributing to less fractures as described in several studies [44, 49, 50]. The increased risk of fall-related injuries in the fall season may be related to an increase in outdoor falls and related

environmental hazards (58% of pre-frail older adults reported falling outdoors). Consistently, a prior study among community-dwelling older adults found that falling outdoors was more frequent among more physically active older adults [5].

In our study, pre-frail adults fell more frequently in the afternoon compared with frail adults. Our results are in line with previous studies among community-dwelling active older adults reporting more falls during day-time hours, in particular in the afternoon [27, 51]. Also consistent with the literature, in our study, frail adults were more likely to fall at night [41, 52]. Environmental factors such as poor lighting combined with poor visual acuity [53] or nocturia [54] may increase the risk of nightly falls especially among frail older adults.

Our study has several strengths. It is one of few studies to present a comprehensive prospective evaluation of fall circumstances in a large sample of both pre-frail and frail adults, using the same fall protocol, applied in person and in monthly intervals. Also, each of the 513 falls was assessed with a detailed fall protocol regarding the description of circumstances and injuries. A limitation of our study is that we relied mostly on self-report of falls, and we might have missed some fall events. However, the rate of falls among our study population is consistent with the literature [4], and the monthly in-person assessment of falls with a detailed protocol for each fall, supported by diaries, reduced the risk for falls to be forgotten or recorded repeatedly [55]. While we asked about detailed information on the circumstances of each fall (direction, height, time, location), we did not evaluate the exact reasons behind each fall. In addition, misreporting of the characteristics of the fall is possible, for example, in a recent study comparing self-report of the direction of the fall and video surveillance reported up to 50% of discrepancies [56]. Finally, while we excluded adults with severe cognitive impairment in both trials, there is a possibility that, due to moderate cognitive impairment in our frail study sample, the circumstances surrounding the fall event may have been reported incorrectly. However, our finding that sideways falls carry a high odds of injury among frail older adults is reassuring as this finding is very consistent with the literature [16].

The results of our study contribute to better understanding of the different circumstances surrounding falls in pre-frail and frail adults and to establish better fall prevention measures targeting specific subgroups of older adults at increased risk of falling. Further studies should evaluate the circumstances related to recurrent fractures among hip fracture patients.

Funding information The analysis was supported by the Baugarten Centre Grant to the Centre on Aging and Mobility. Regarding the pre-frail dataset, the primary funding sources were a Swiss National Foundations Professorship Grant PP00B-114864 (Bischoff-Ferrari) and The VELUX Foundation (Bischoff-Ferrari). Regarding the frail dataset, the primary funding sources were the Swiss National Foundation Grant NFP-53 (Bischoff-Ferrari) and Vontobel Foundation (Bischoff-Ferrari HA).

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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