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ORIGINAL ARTICLE

Association between walking and hip fracture in women aged 65 and older: 20-year follow-up from the study of osteoporotic fractures

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Abstract

Summary Hip fractures in elderly women pose significant healthcare challenges. Promoting walking for exercise as a cost-effective intervention may help reduce the risk of fractures in this population.

Purpose This study aimed to examine the relationship between walking and hip fracture risk among women aged 65 years and older.

Methods A 20-year prospective study (1986–2006) included 9704 women from the Study of Osteoporotic Fractures (SOF) in the USA. Participants were followed biennially, and walking exposure was assessed by the number of city blocks walked for exercise, routine activity, and total blocks walked daily. Cox regression models with time-varying covariates assessed associations, with competing risks addressed using Fine and Gray models. Penalized splines were used to explore dose–response relationships.

Results In total, 1419 hip fractures were identified through the study period. The mean and median follow-up times for hip fractures or censoring were 15.0 and 15.8 years in the walking for exercise group, vs. 13.2 and 13.7 years in the not walking for exercise group. The hip fracture incidence rate was 10.0 cases per 1000 person-years (py) in the walking for exercise group compared to 10.9 per 1000 py in the not walking for exercise group. All-cause mortality was 37.1 per 1000 py in the walking for exercise group compared to 46.4 per 1000 py in the not walking for exercise group. Adjusted models showed that walking for exercise significantly reduced hip fracture risk (HR, 0.864; 95% CI, 0.762–0.980; $P=0.0230$), with each additional block walked for exercise reducing risk (HR per block, 0.986; 95% CI, 0.978–0.995; $P=0.0022$). Walking for routine activities showed no significant association. Spline analysis indicated walking 16 blocks (≈3200 steps) daily significantly lowered hip fracture risk.

Conclusion Walking for exercise is linked to a reduced risk of hip fractures in elderly women. Walking the equivalent of 16 blocks or more (> 3200 steps) per day might be an effective way to reduce the risk of hip fractures in this vulnerable population.

Keywords Elderly women · Hip fracture · Osteoporotic fractures

Introduction

Hip fractures in older adults often cause disability, reduced quality of life, increased risk of death, and are associated with high economic costs[1–4]. Current fracture prevention strategies include adequate calcium intake through diet and supplements, pharmacologic interventions, hormone replacement therapy, bone mineral density (BMD) screening, fracture risk assessment, and exercise[5–7]. Exercise plays an important role in the management of medical conditions, especially for older people[8–10]. In the context of osteoporosis, many studies have shown that combination exercise programmes, which include weight-bearing and resistance strengthening exercise, reduce bone loss in the femoral neck and lumbar spine in post-menopausal women[11–15]. Although less well-studied, similar effects of exercise interventions on BMD have been found in men[16,17]. Exercise is recommended in many guidelines for the management of osteoporosis and fractures[18–20]. Walking is a simple and free form of exercise, and studies have shown that walking can preserve bone mineral density in postmenopausal women[21–24].

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In addition to its beneficial effects on bone mineral density (BMD), walking is associated with a reduced risk of hip fractures in elderly women. Feskanich et al.[25] demonstrated that walking for at least 4 h per week among postmenopausal women was associated with a 41% lower risk of hip fracture compared to walking less than 1 h per week. Similarly, LaMonte et al.[26] found an inverse association between walking and hip fracture risk among postmenopausal women aged 50–79 years (> 7.5 MET hours/week vs. none: HR, 0.88; 95% CI, 0.78–0.98; *P* for trend = 0.01). Furthermore, elderly women who walked for exercise at baseline were less likely to sustain a second hip fracture, with a relative risk (RR) of 0.5 (95% CI, 0.3–0.9)[27]. Results from the SUPERB study indicated that older women who walked 3 to 4 days per week for 1–2 h each time could significantly lower their risk of hip fracture[28]. Conversely, Bliuc et al. [29] reported that older women with self-reported significant walking limitations had more than a twofold higher risk of hip and vertebral fractures compared to those without walking limitation.

The aim of this analysis was to examine the associations between walking distance and the risk of hip fracture among women aged 65 years or older in the Study of Osteoporotic Fractures (SOF).

Methods

The SOF is an ongoing cohort of community-dwelling women aged 65 years and older. Launched in 1986, SOF enrolled 9704 primarily Caucasian women and continues to follow these women with clinical visits approximately every 2 years. Details of the design of the SOF study have been published previously[30,31]. In this study, we analysed data from nine completed visits to assess the impact of walking on the incidence of hip fracture.

Outcomes

The outcome variable for this analysis was the first incident of either a hip fracture or any other type of fracture (excluding hip fractures) occurring after Visit 1 (baseline). Fractures were adjudicated through a three-step process: (1) the clinic Principal Investigator's initial diagnosis, (2) pre-adjudication by the Endpoints Specialists of the Coordinating Center, and (3) final adjudication by a physician.

For this study, the overall follow-up times were calculated as the number of days from the first visit to the first hip or any other fracture or the last contact date minus the first visit date. Since we used Cox models with time-varying covariates for the analysis, we divided the overall follow-up time into smaller intervals corresponding to Visits 1, 2, 4, 5, 6, 8, and 9. Visits 3 and 7 were not considered because there was no information on walking at Visit 3 and no fracture information at Visit 7.

Walking

Four measurements related to walking were analysed. The first measurement was "Do you take walks for exercise?" which was a binary variable (yes vs. no). This variable was available for visits 1, 2, 4, 5, 6, 7, 8, and 9. The second measurement was "If walking for exercise, on average, how many city-blocks or their equivalent do you walk each day for exercise?" We treated this variable as a continuous variable. This variable was available for visits 1, 2, 4, 5, 6, 7, 8, and 9.

The third measurement was "How many city blocks or their equivalent do you walk each day as part of your normal routine (not including walking for exercise)." This variable was available at visit 1, 2, 4, 5, 6, 7, and 8. The fourth measurement was a derived variable, which was the total blocks walked each day, combining both walking for exercise and walking as part of a normal routine. One city block is equivalent to approximately 147 yards (which equals 134 m or about 200 steps).

Time-dependent and independent covariates

The time-dependent covariates considered in this analysis included: age, recorded at Visits 1 through 9; femoral neck BMD (g/cm^2), measured using the Hologic QDR 1000 workstation at Visits 2, 4, 5, 6, 7, 8, and 9; body mass index (BMI, kg/m^2), assessed at Visits 1 through 9; falls in the past 12 months, ascertained at Visits 1 through 9; history of any other fracture since the last visit, asked at Visit 1,2, 4, 5, 6, 8, and 9; and walking problems, such as issues related to walking due to recent surgery, injury, or other health conditions that might impede activities like standing up from a chair or mobility, documented at Visits 1 through 9. Additionally, the status of currently smoking cigarettes (yes/no) was recorded at Visits 1, 2, 4, 5, 6, 8, and 9. Alcohol drinking in the past 30 days (at least one drink of any kind of alcoholic beverage, yes/no) was recorded at Visits 1, 4, 5, 6, 8, and 9. The Charlson Comorbidity Index[31], derived from subjects' medical history, was assessed at Visits 1, 2, 4, 5, 6, 8, and 9 (see Supplementary Tables S2 and S3 for detailed information). Menopause age was treated as a time-independent covariate, and its value did not change over the visits. Another time-independent variable was the "Total number of times physical activity per year over a lifetime (teen + 30 + 50 + now), weighted by activity intensity". This variable was calculated based on activities such as walking, hiking, jogging, running, swimming, skiing, cycling, skating, racquetball, squash, badminton, dance exercise, aerobic dance, square dancing, other forms of dancing, gardening, golf (walking), golf (with a cart), bowling, rowing, shuffleboard, canoeing, calisthenics, softball, field hockey, basketball, tennis (singles and doubles), weightlifting, Nautilus, volleyball, horseback riding, and others. Each activity was weighted by its intensity (light, moderate, or heavy). This variable was collected at baseline.

Ethics approval

The Southern Adelaide Clinical Human Research Ethics Committee granted ethics approval for the secondary analysis of the data and granted a waiver of informed consent (application number: 762.2).

Statistical analysis

The incidence of hip and any other fracture since the first visit was quantified by the number of first hip and any other fractures and their corresponding follow-up time, expressed as an incidence rate per 1000 person-years (py). Walking and covariates measured at each visit were categorical or continuous variables and were presented as frequencies (percentages) or means (standard deviations), respectively.

Fully conditional specification (FCS), also known as multiple imputation by chained equations (MICE) was used to impute missing data in the primary analysis. This method can handle missing data patterns for both continuous and categorical variables[33]. Multiple imputations were conducted using the SAS procedures proc mi and proc mianalyze. All variables included in the multivariable analysis model were also used in the imputation models. For binary variables (smoking cigarettes, alcohol drinking, walking problem, falls and history of fracture), imputation was performed under a generalized logit distribution. Twenty imputed datasets were used for the primary analysis[34]. Sensitivity analyses were performed on complete cases.

The association between hip and any fracture incidence and various walking metrics—walking for exercise (yes vs. no), blocks walked for exercise, blocks walked as part of a normal routine, and total blocks walked (exercise and routine combined)—was assessed using cause-specific Cox hazard regression models with time-varying covariates and a counting process style of data input, both with and without imputed datasets[35,36]. Follow-up time since the first visit was divided into seven intervals corresponding to different visits: from Visit 1 to Visit 2, Visit 2 to Visit 4, Visit 4 to Visit 5, Visit 5 to Visit 6, Visit 6 to Visit 8, Visit 8 to Visit 9, and Visit 9 to the last contact. Therefore, one participant could have up to seven rows of data[35,36]. Hip and any fracture were treated as the event, while time at risk was otherwise censored at loss to follow-up, the end of the study interval, or death. Both unadjusted (with walking as the sole predictor) and adjusted analyses were performed. Covariates in the adjusted models were selected based on prior knowledge and data availability. Time-dependent covariates included age, femoral neck BMD, BMI, falls in the past 12 months, history of fracture, walking problems, current cigarette smoking, alcohol consumption, and the Charlson Comorbidity Index, allowing these variables to change across different visits. Conversely, menopause age and the total number of times of physical activity per year over a lifetime were treated as time-independent variables, maintaining consistent values across all visits. Interactions between the exposure and covariates were tested by including interaction terms (product of the exposure and covariates) in the multiple Cox regression models.

Penalized splines with four degrees of freedom were used to examine the dose–response effect of blocks walked per day on hip fracture, with hazard ratios estimated from Cox regression models[37,38]. The selection of degrees of freedom was based on a trade-off between smoothness and model fit (see supplementary Fig. S1). Sensitivity analysis to assess the competing risks between deaths and hip/any fracture was conducted using the Fine and Gray sub-distribution hazard models, using both imputed datasets and complete cases[39,40].

To compare the calculated expected difference in mean BMD between those who walked for exercise versus those who did not, with the actual difference ascertained from the data, we used the following equation to calculate the proportion of risk attributed to a low BMD:

$$\frac{[\log HR_a/\log GR] - [\log HR_b/\log GR]}{[\log HR_a/\log GR]}$$

In this equation, HR_a is the unadjusted hazard ratio for walking exercise, HR_b is the hazard ratio adjusted for BMD, and GR is the gradient of risk for femoral neck BMD. The gradient was obtained from a meta-analysis of BMD and fracture risk, which found that the risk of hip fracture increased 2.07-fold for each SD decrease in femoral neck BMD[41,42].

All statistical analyses were performed using SAS statistical software (Version 9.4; SAS Institute Inc., Cary, NC) and R Software v4.4.0 (R Core Team, Vienna, Austria).

Results

Table 1 presents the characteristics of participants at each visit, categorized by their walking exercise status. On average, participants in the walking for exercise group were younger at each visit compared to those in the not walking for exercise group. There were no significant differences in femoral neck BMD between the two groups at any visit. The walking for exercise group had a lower BMI than the

Table 1 Distribution of covariates at each visit, categorized by exercise participation

Covariates	Walking for exercise		*P*-value*
	Yes	No	
Age (year), mean (SD)			
Visit 1	71.0 (4.9)	72.2 (5.5)	**< 0.0001**
Visit 2	72.6 (4.7)	73.6 (4.9)	**0.0029**
Visit 4	76.1 (4.4)	77.5 (5.1)	**< 0.0001**
Visit 5	78.1 (4.3)	79.0 (4.7)	**< 0.0001**
Visit 6	79.9 (4.0)	80.7 (4.4)	**< 0.0001**
Visit 8	83.7 (3.2)	84.4 (3.5)	**< 0.0001**
Visit 9	88.0 (2.6)	88.4 (2.9)	**0.0018**
Femoral Neck BMD (g/cm^2), mean (SD)			
Visit 2	0.65 (0.11)	0.64 (0.11)	0.3257
Visit 4	0.64 (0.11)	0.63 (0.12)	0.1418
Visit 5	0.63 (0.11)	0.63 (0.12)	0.7194
Visit 6	0.63 (0.12)	0.63 (0.12)	0.8064
Visit 8	0.63 (0.11)	0.63 (0.12)	0.7382
Visit 9	0.64 (0.11)	0.63 (0.12)	0.1179
BMI (kg/m^2)			
Visit 1	25.9 (4.1)	26.9 (4.8)	**< 0.0001**
Visit 2	25.8 (4.1)	26.8 (4.8)	**0.0010**
Visit 4	25.8 (4.2)	27.1 (4.8)	**< 0.0001**
Visit 5	25.7 (4.1)	27.1 (4.9)	**< 0.0001**
Visit 6	25.6 (4.0)	27.0 (4.8)	**< 0.0001**
Visit 8	25.8 (3.9)	27.1 (4.6)	**< 0.0001**
Visit 9	25.5 (3.7)	26.5 (4.1)	**< 0.0001**
Fall in past 12 months, % (yes/*n*)			
Visit 1	30.3 (1465/4832)	29.9 (1437/4813)	0.6208
Visit 2	30.8 (143/464)	28.5 (125/439)	0.4407
Visit 4	28.3 (1064/3755)	30.6 (1248/4081)	**0.0295**
Visit 5	29.7 (841/2836)	32.4 (1376/4247)	**0.0146**
Visit 6	29.6 (691/2334)	32.1 (1194/3717)	**0.0396**
Visit 8	34.9 (465/1334)	39.0 (942/2416)	**0.0123**
Visit 9	37.3 (249/667)	42.5 (459/1081)	**0.0338**
History of fracture, % (yes/*n*)			
Visit 1	50.1 (2418/4827)	53.3 (2559/4802)	**0.0017**
Visit 2	5.4 (25/463)	4.8 (21/439)	0.6743
Visit 4	7.3 (274/3752)	8.4 (342/4082)	0.0773
Visit 5	7.5 (213/2835)	9.6 (409/4251)	**0.0021**
Visit 6	8.3 (194/2339)	10.4 (1194/3715)	**0.0063**
Visit 8	8.5 (113/1332)	10.1 (243/2416)	0.1156
Visit 9	8.9 (59/665)	9.0 (97/1082)	0.9474
Walking problem, % (yes/*n*)			
Visit 1	7.6 (366/4838)	15.5 (747/4814)	**< 0.0001**
Visit 2	14.5 (37/255)	25.6 (69/270)	**0.0016**
Visit 4	14.5 (476/3285)	29.1 (967/3329)	**< 0.0001**
Visit 5	13.7 (340/2474)	28.1 (1010/3598)	**< 0.0001**
Visit 6	15.3 (310/2026)	32.0 (996/2116)	**< 0.0001**
Visit 8	22.7 (252/1108)	36.4 (684/1879)	**< 0.0001**
Visit 9	20.9 (108/518)	35.8 (246/687)	**< 0.0001**

Table 1 (continued)

Covariates	Walking for exercise		*P*-value*
	Yes	No	
Currently smoke cigarettes, % (yes/*n*)			
Visit 1	7.6 (366/4823)	12.4 (596/4809)	**< 0.0001**
Visit 2	3.2 (15/464)	9.3 (41/439)	**0.0001**
Visit 4	4.3 (160/3761)	7.5 (306/4088)	**< 0.0001**
Visit 5	3.5 (98/2838)	6.2 (265/4256)	**< 0.0001**
Visit 6	2.4 (57/2341)	5.4 (202/3719)	**< 0.0001**
Visit 8	1.7 (23/1340)	3.2 (78/2428)	**0.0065**
Visit 9	1.4 (9/668)	1.3 (14/1083)	0.9223
During the past 30 days had at least one drink of any kind of alcoholic beverage, % (yes/*n*)			
Visit 1	57.3 (2774/4840)	51.7 (2493/4819)	**< 0.0001**
Visit 4	49.5 (1861/3760)	38.2 (1561/4087)	**< 0.0001**
Visit 5	47.0 (1333/2837)	38.8 (1649/4253)	**< 0.0001**
Visit 6	47.7 (1116/2340)	37.6 (1398/3716)	**< 0.0001**
Visit 8	48.1 (645/1340)	36.6 (888/2426)	**< 0.0001**
Visit 9	42.1 (281/668)	27.8 (300/1078)	**< 0.0001**
Charlson comorbidity index, mean (Sd)			
Visit 1	1.1 (1.7)	1.1 (1.5)	0.7194
Visit 2	1.2 (1.6)	1.4 (1.7)	0.1100
Visit 4	2.6 (2.8)	2.9 (2.8)	**< 0.0001**
Visit 5	2.8 (2.9)	3.0 (2.8)	**0.0036**
Visit 6	2.8 (2.8)	3.2 (2.9)	**< 0.0001**
Visit 8	3.4 (3.0)	3.6 (3.0)	**0.0384**
Visit 9	3.7 (3.2)	3.9 (3.0)	0.2795
Menopause age, mean (SD)			
Visit 1	48.2 (5.7)	47.7 (5.8)	**< 0.0001**
Total number of times of physical activity per year over lifetime (teen, 30, 50, now), weighted by intensity of activity level, mean (SD)			
Visit 1	5175.4 (3384.2)	3442.5 (3034.4)	**< 0.0001**
Death since the visit, % (yes/*n*)			
Visit1	58.2 (2832/4866)	64.7 (3127/4836)	**< 0.0001**
Visit2	56.9 (267/469)	65.8 (293/445)	**0.0057**
Visit 4	51.3 (1967/3837)	64.1 (2722/4244)	**< 0.0001**
Visit 5	49.4 (1446/2926)	59.4 (2660/4475)	**< 0.0001**
Visit 6	42.7 (1040/2431)	56.3 (2222/3944)	**< 0.0001**
Visit 8	32.4 (464/1431)	41.6 (1098/2640)	**< 0.0001**
Visit 9	12.8 (94/734)	25.7 (318/1239)	**< 0.0001**

**P*-values were calculated using two-sample t-tests for continuous variables at each visit. For categorical variables, *p*-values were determined using Chi-square tests for each visit. *SD* standard deviation

not walking for exercise group. At Visits 1 and 2, there were no differences in the number of falls reported in the past 12 months between the two groups. However, from Visit 4 onward, the walking for exercise group reported fewer falls. At baseline, Visit 5, and Visit 6, the walking for exercise group reported a history of fewer fractures compared to the not walking for exercise group. No differences in the history of fracture were observed between the groups at Visits 2, 4, 8, and 9.

Participants in the walking for exercise group reported fewer walking-related problems compared to the not walking for exercise group across all visits. They also smoked less than those in the not walking for exercise group, except at the last visit. In the past 30 days, a higher proportion of women in the walking for exercise group reported alcohol consumption compared to the not walking for exercise group across all visits. The walking for exercise group had fewer comorbidities at Visits 4, 5, 6, and 8 compared to the not walking for exercise group. Additionally, participants in the walking for exercise group experienced later menopause than those in the not walking for exercise group. Finally, the walking for exercise group engaged in more weighted physical activity and had a lower mortality rate compared to the not walking for exercise group.

Approximately 50% of participants reported walking as exercise at baseline, which decreased to 37.2% at later visits among surviving participants. The number of city blocks or their equivalent walked daily by participants who engaged in walking for exercise decreased from 12.0 ± 10.2 at baseline to 7.3 ± 6.9 at the last recorded visit. The number of city blocks or their equivalent walked each day as part of the normal routine (excluding walking for exercise) remained relatively constant during the follow-up period. The total number of blocks walked per day for both exercise and normal routine showed a decreasing trend with additional visits, as shown in supplementary Table S1. The follow-up time in days since each visit, and the number of deaths since each visit, are also shown in Table S1.

Table 2 presents data on the incidence of hip fracture and any other fracture, as well as mortality in the walking for exercise group. The mean and median follow-up times to hip fracture or censor were 15.0 and 15.8 years for the walking for exercise group, compared to 13.2 and 13.7 years for the not walking for exercise group. For any other fracture, the mean and median follow-up times were 11.9 and 11.7 years for the walking for exercise group, and 10.7 and 10.2 years for the not walking for exercise group. Regarding mortality, the mean and median follow-up times were 15.7 and 16.9 years for the walking for exercise group, compared to 13.9 and 14.6 years for the not walking for exercise group. The overall incidence rate of hip fracture was 10.0 per 1000 person-years (py) for the walking for exercise group, compared to 10.9 per 1000 person-years for the not walking for exercise group. For any other fracture, the incidence rate was lower in the walking for exercise group than in the not walking for exercise group (32.9 per 1000 py vs. 34.5 per 1000 py). Finally, the overall all-cause mortality rate was 37.1

Table 2 Incidence rate of the first hip, any other fracture, and mortality rate since baseline

Fracture site	Walking for exercise (yes)					Walking for exercise (no)				
	Cases	Mean follow-up time (year)	Median follow-up time (year)	Total person years	Incidence/mortality rate (cases/1000 py)	Cases	Mean follow-up time (year)	Median follow-up time (year)	Total person years	Incidence/mortality rate (cases/1000 py)
Hip	723	15.0	15.8	72,455.9	10.0	696	13.2	13.7	63,877.0	10.9
Any other*	1518	11.9	11.7	46,060.2	32.9	1427	10.7	10.2	41,329.9	34.5
Death¶	2832	15.7	16.9	76,238.5	37.1	3127	13.9	14.6	67,372.0	46.4

*In total, there were 2946 other incidence fractures (excluding hip fractures), with one patient missing walking exercise data¶In total, there were 5961 deaths, with 2 patients missing walking exercise data per 1000 person-years for the walking for exercise group, compared to 46.4 per 1,000 person-years for the not walking for exercise group.

Table 3 shows both the unadjusted and adjusted results from Cox regression models. In the unadjusted analyses, all four walking measures were associated with a decreased risk of hip fracture. In the adjusted analyses (excluding femoral neck BMD), walking for exercise (yes vs. no) was associated with a reduced risk of hip fracture (HR, 0.849; 95% CI, 0.749–0.963; $P = 0.0109$). After accounting for BMD, the hazard ratio increased slightly by about 2% (from 0.849 to 0.864). Given that the risk of hip fracture increases 2.07-fold per standard deviation (SD) decrease in femoral neck BMD (gradient of risk), low BMD accounted for only a small portion (10.7%) of the difference in hip fracture risk between those who walked for exercise and those who did not.

In the adjusted analyses (excluding femoral neck BMD), walking more city blocks each day for exercise was associated with a lower risk of both hip and any fractures. Each additional block walked for exercise per day was linked to a reduced risk of hip fracture (HR *p*er 1 block, 0.984; 95% CI, 0.976–0.993; $P = 0.0004$). The number of city blocks walked each day as part of a normal routine was not associated with a lower risk of hip. Walking more total city blocks each day (combining both exercise and routine) was linked to a reduced risk of hip fracture (HR *p*er block, 0.987; 95% CI, 0.980–0.994; $P = 0.0003$).

After adjusting for femoral neck BMD, walking for exercise (yes vs. no) remained associated with a lower hip fracture risk (HR, 0.864; 95% CI, 0.762–0.980; $P = 0.0230$) indicating that there is a BMD-independent effect. Walking more city blocks daily for exercise continued to show an association with reduced hip fracture risk (HR per 1 block, 0.986; 95% CI, 0.978–0.995; $P = 0.0022$). City blocks walked as part of a normal routine were not associated with hip fracture risk (HR,0.997; 95% CI, 0.983–1.011; $P = 0.6359$). More total city blocks walked each day (combining exercise and normal routine) remained linked to a lower risk of hip fracture (HR per block, 0.988; 95% CI, 0.981–0.995; $P = 0.0008$). The adjusted analysis showed that none of the four walking measures were associated with any other fracture.

Detailed adjusted Cox regression model results are provided in Supplementary Tables S4 and S5. There were no significant interactions between walking exposure and any of the other covariates, and therefore, interaction terms were not included in our regression models.

Penalized spline regressions revealed linear dose–response effects of blocks walked per day on hip fracture risk. The analysis indicated that walking for exercise

Table 3 Associations between walking and hip, any fracture risk

Fracture	Walking measurement (exposure)	Unadjusted models		Adjusted models* (not adjust BMD)		Adjusted models *(adjust BMD)	
		HR (95% CI)	*p*-value	HR (95% CI)	*p*-value	HR (95% CI)	*p*-value
Hip	Walking for exercise at visit (yes vs. no)	0.763(0.677–0.859)	**< 0.0001**	0.849(0.749–0.963)	**0.0109**	0.864(0.762–0.980)	**0.0230**
	City block[¶] or their equivalent walked each day for exercise	0.974(0.965–0.982)ǂ	**< 0.0001**	0.984(0.976–0.993)	**0.0004**	0.986(0.978–0.995)	**0.0022**
	City block walked each day as normal routine (not include walking for exercise)	0.980(0.966–0.994)ǂ	**0.0049**	0.996(0.983–1.010)	0.5989	0.997(0.983–1.011)	0.6359
	Total city block walked each day (exercise and normal routine combined)	0.978(0.971–0.985)ǂ	**< 0.0001**	0.987(0.980–0.994)	**0.0003**	0.988(0.981–0.995)	**0.0008**
Any other	Walking for exercise at visit (yes vs. no)	0.917(0.846–0.995)	**0.0374**	0.967(0.886–1.054)	0.4429	0.974(0.894–1.062)	0.5538
	City block[¶] or their equivalent walked each day for exercise	0.993(0.989–0.998)	**0.0097**	0.997(0.991–1.002)	0.1964	0.997(0.992–1.003)	0.3107
	City block walked each day as normal routine (not include walking for exercise)	0.997(0.987–1.007)	0.5182	1.002(0.992–1.012)	0.7316	1.002(0.992–1.012)	0.7178
	Total city block walked each day (exercise and normal routine combined)	0.995(0.991–0.999)	**0.0119**	0.998(0.994–1.002)	0.3207	0.998(0.994–1.002)	0.4116

[*]Adjusted for age, BMI, menopause age, fall during the last 12 months, history of fracture, walking problems, current smoking, alcohol drinking in the past 30 days, Charlson comorbidity index, weighted total number of times of activity per year over a lifetime, and with/without adjusting for femoral neck BMD; detailed results are shown in Table S3[¶]1 city block ≈ 1/12 mile, 147 yards, 134 m, or about 200 steps[ǂ]HR: hazard ratio for per 1 block walked; CI: confidence interval

between 8.0 blocks (HR, 0.821; 95% CI, 0.678–0.995) and 17.5 blocks (HR, 0.707; 95% CI, 0.503–0.994) was significantly associated with a lower risk of hip fracture. The total walking blocks (combining normal routine and exercise) between 16 blocks (HR, 0.853; 95% CI, 0.728–0.999) and 33 blocks (HR, 0.686; 95% CI, 0.467–0.989) per day were significantly associated with a decreased risk of hip fracture (Fig. 1).

Sensitivity analyses using complete cases and the Fine and Gray models showed estimates similar to those of the primary analysis (Supplementary Tables S6 to S14).

Discussion

In this 20-year prospective study involving 9704 women aged 65 years and older, we found a significant association between walking and a reduced risk of hip fractures. Participants who engaged in walking for exercise experienced a notable reduction in hip fracture risk, compared to those who did not walk for exercise. Furthermore, both the number of blocks walked for exercise and the total number of blocks walked daily (exercise and routine combined) were associated with a decreased risk of hip fractures. However, after adjusting for covariates, the number of blocks walked each day as part of a normal routine (excluding walking for exercise) was not linked to hip fracture risk, possibly because the amount of walking, averaging five blocks per day, was relatively low.

While numerous studies have demonstrated the positive impact of walking on bone mineral density (BMD) among older women[43–45], the present investigation is among the first to explore comprehensively the relationship between walking and hip fracture risk within a large cohort study. Previous research indicated that women engaging in at least 4 h of walking per week had a 41% reduction in hip fracture risk compared to those not participating in other forms of exercise[25]. Furthermore, women who walked for exercise at baseline were less likely to sustain a second hip fracture from the same SOF population[28]. Our study confirms the association between walking and reduced hip fracture risk, and it also identifies thresholds where the dose–response effects of walking within certain ranges can result in a significant reduction in estimated hip fracture risk.

The effect of walking for exercise on fracture risk could be influenced by various factors such as walking dose, speed, environment, and concurrent activities[46–49]. For example, recent research found that walking with leashed dogs increased fracture risk among individuals aged 65 or older[50]. In practice, exercise in older people must be carefully evaluated, as high-impact activities that benefit younger individuals might not be suitable or beneficial for older adults[51]. There have been concerns that high levels of exercise may be counterproductive, with the exercise dose–response curve potentially exhibiting a reverse J or U

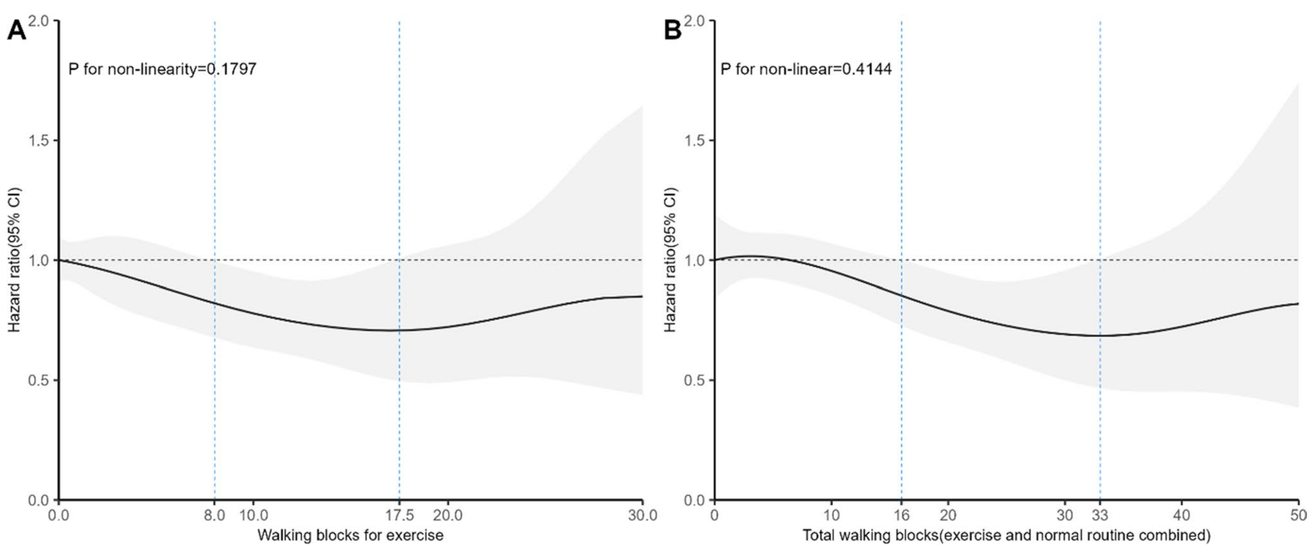

Fig. 1 Association between **A** the number of blocks walked for exercise per day and **B** the total number of blocks walked per day (exercise and normal routine combined). Penalized spline curves illustrate the dose–response relationship between the number of blocks walked per day and the risk of hip fracture. Hazard ratios were estimated using Cox proportional hazards models, with blocks walked per day modeled as a spline and adjusted for age, body mass index, age at menopause, falls, history of fracture, walking problems, current smoking status, alcohol consumption, Charlson comorbidity index, intensity-weighted physical activity, and femoral neck BMD. Walking zero blocks per day was set as the reference, with the hazard ratio fixed at 1. The curve lines represent the hazard ratio, while the shaded area indicates the 95% confidence interval (CI). The two vertical dashed lines delineate the range that significantly reduces hip fracture risk (where the hazard ratio is less than 1 and the 95% CI does not include 1). Note that 1 block is approximately equivalent to 200 steps

shape, where the highest exercise regimens do not confer additional health benefits[52–54]. Although this study did not demonstrate a nonlinear dose–response effect of walking on hip fracture risk, the spline curves suggest there may be threshold effects. At low doses, no benefit was observed, but a significant beneficial effect emerged after reaching a threshold of 16 blocks (≈3200 steps) per day, with no further significant benefit beyond 33 blocks (≈6600 steps) per day. This range of steps is close to the findings reported in the Women's Health Study, which showed that walking between 4400 and 7500 steps per day significantly lowered all-cause mortality among 16,741 older women[55].

Figure 1B shows that the risk of hip fractures increases from zero blocks, indicating that if someone has been sedentary for a long time and suddenly starts walking, it may pose a risk for hip fractures. Although causality cannot be inferred from our observational analyses, our findings are consistent with the importance of walking as an exercise for older adults and suggest that strategies promoting physical activity should prioritize walking as a cost-effective intervention. Additionally, our results may inform the development of appropriate guidelines by suggesting that a minimum dose of walking is necessary to effectively reduce hip fracture risk in older adults. However, the mechanism whereby exercise might reduce the risk of hip fracture could not be determined from this study, aside from a modest impact on femoral neck bone mineral density. Other factors might include effects on muscle strength and coordination, which in turn reduce the risk of injurious falls [56,57].

This study has several significant strengths. The study population was a large and representative sample of older Caucasian women in the US. The population was frequently followed up, and exposure and covariates were repeatedly measured, allowing adjustment for age, BMI, menopause age, falls during the last 12 months, history of fracture, walking problems, current smoking, alcohol drinking, comorbidity, and lifetime physical activity. The study design made it possible to analyze variables that could change during the follow-up period in a counting process data input style[58], without needing to assume that variables measured at baseline were always the same during the follow-up period. This statistical method for addressing time-varying exposures and covariates has a distinct advantage over traditional methods that incorporate follow-up time and covariate interaction terms into the regression model, as it does not require assuming that changes in covariates have a linear relationship with follow-up time.

Our study also has several limitations. First, not all exposures and covariates were measured at each visit, and some visits had limited participants, resulting in missing values. Although multiple imputations were performed, it requires the assumption that missing values were missing at random, an assumption that is untestable[59]. However, by using a counting process structure for the data, these missing values did not require the listwise deletion of subjects, allowing us to utilize available information from different visits in the partial likelihood estimations of Cox models. Second, while we adjusted for several important confounders based on prior knowledge, other confounding factors might not have been accounted for in our analysis. Third, walking data was self-reported through questionnaires, which may result in measurement error. Fourth, our analysis focused exclusively on Caucasian women aged 65 years and older, so the findings may not be generalizable to other populations. Finally, while our study provides valuable insights, causality cannot be established from this observational cohort study. The case for causality is, however, strengthened by the persisting effect after adjustment for other forms of exercise, but establishing causality would require a randomized controlled trial (RCT), which would necessitate a very large sample size.

In conclusion, our study highlights the potential benefits of walking in reducing hip fracture risk among women aged 65 years or older. We recommend promoting walking exercise as an effective preventive measure against hip fracture in this vulnerable demographic.

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Data availability The data associated with the paper are publicly available at https://sofonline.ucsf.edu/

Declarations

Conflicts of interest None.

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