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Research paper

Longitudinal changes in daily patterns of objectively measured physical activity after falls in older adults with varying degrees of glaucoma

Jian-Yu E[a,b], Aleksandra Mihailovic[a], Jennifer A. Schrack[b,d], Catalina Garzon[a], Tianjing Li[c], David S. Friedman[e], Sheila K. West[a], Laura N. Gitlin[f], Pradeep Y. Ramulu[a,b,d,*]

[a] Wilmer Eye Institute, Johns Hopkins School of Medicine, Baltimore, Maryland, USA
[b] Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA
[c] Department of Ophthalmology, School of Medicine, University of Colorado Anschutz Medical Campus, Aurora, Colorado, USA
[d] Center on Aging and Health, Johns Hopkins University, Baltimore, Maryland, USA
[e] Massachusetts Eye and Ear, Harvard Medical School, Boston, Massachusetts, USA
[f] College of Nursing and Health Professions, Drexel University, Philadelphia, Pennsylvania, USA

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A B S T R A C T

Background: Visually impaired older adults have a greater risk of falling, making them particularly susceptible to fall-related health consequences and restricted physical activity. Unclear however, is the relationship between having falls and longitudinal changes in daily patterns of objectively measured physical activity in older adults with visual impairments.

Methods: We created a three-year prospective cohort study (Falls in Glaucoma Study) of older adults with primary or suspected glaucoma at the Johns Hopkins Wilmer Eye Institute from 2013 to 2015. Cumulative incidence of falls was determined through self-reported fall calendars over 12 months. Participants were then classified into one of three groups: multiple fallers (≥2 falls), single fallers (1 fall), and non-fallers (0). Daily physical activity was measured over 1 week using a waist-bound accelerometer during baseline and three-year follow-ups. Activity fragmentation was defined as the reciprocal of the mean activity bout length, with higher fragmentation reflecting shorter, more fractured bouts of continuous activity. Multivariate linear mixed-effects models were used to assess three-year longitudinal changes in: 1) activity fragmentation, and 2) accumulation of activity across six three-hour intervals from 5 AM to 11 PM.

Findings: In adjusted models accounting for visual field damage and other factors, multiple fallers demonstrated greater annual declines (per year) in daily active bouts (-1.79 bouts/day, 95% confidence interval [CI]: -3.35, -0.22), daily active minutes (-17.15 min/day, 95% CI: -26.35, -7.94), and increased fragmentation (1%, 95% CI: 0, 2%) over the three-year follow-up period as compared to non-fallers; no such changes were seen when comparing single fallers and non-fallers. In time-of-day analyses, multiple fallers experienced greater annual declines in average hourly steps over all periods of the day, though the rate of decline was only significant between 5 PM and 8 PM (-27.07 steps/hour, 95% CI: -51.15, -2.99) compared to non-fallers.

Interpretation: In an older population with visual impairment, multiple falls over 12 months were associated with more transient and fragmented activity over a subsequent three-year period, and activity declines during evening hours, compared to non-fallers. These findings suggest that multiple fallers with visual impairment may be at high risk for a decline in physical capacity and endurance, warranting clinical interventions.

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Introduction

Falls are the most common and severe injury-related medical issues facing older adults.[1] One in three community-dwelling individuals aged 65 or older fall every year and roughly half of such cases suffer from recurrent falls, which are associated with increased hospital admission, discharge to a rehabilitation facility, and death.[2,3] The risk of falling doubles (or triples) for individuals with visual impairment compared to those with normal vision.[4–6] The American Geriatric Society (AGS) recommends that older persons who experience recurrent falls over a year have a physician conduct a

* Corresponding author.
E-mail address: pramulu@jhmi.edu (P.Y. Ramulu).

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Research in context

Evidence before this study

Falls are the most common issues facing older adults, particularly for individuals with visual impairment who have a higher risk of falling. Although previous research has demonstrated the restricted physical activity after falls, including several aspects of physical activity such as type, duration, and frequency that are vital for overall health, the impact of falls on long-lasting changes in accelerometry-derived daily patterns of physical activity, such as activity fragmentation, has been less well studied.

Added value of this study

In this clinical cohort of older adults with varying degrees of visual impairment, multiple fallers identified prospectively over 12 months developed more transient and fragmented activity over a subsequent three-year period, with activity declines occurring throughout the day but most pronounced during evening hours. However, longitudinal changes in activity fragmentation and patterns of daily activity were not observed in those with only one fall or no fall over a 12-month period.

Implications of all the available evidence

This study suggests that multiple fallers with visual impairment may be at high risk for a decline in physical capacity and endurance. Future research is warranted to focus on interventions to prevent recurrent falls and reductions in activity in high-risk older individuals, i.e., those with visual impairment with multiple falls.

multifactorial fall risk assessment, including evaluation of vision.[7] Better understanding of the long-term implications of experiencing repeated and single falls is important for establishing the detrimental health consequences following falls in high-risk older adults with visual limitations and enable targeting of those most at risk for physical decline.

One downstream consequence of falls may be restricted or altered physical activity levels. Physical activity is vital for overall health and quality of life,[8] especially for older adults whose functional capacity declines, independence of daily living decreases, and risk of mortality increases at lower physical activity levels.[9–11] Previous research has demonstrated several aspects of physical activity including type, duration, and frequency, are essential to maintain well-being; however, recent evidence suggests that accelerometry-derived daily patterns of physical activity may shed more light on physical function and overall well-being beyond traditional activity measures, especially among older adults who engage in limited amounts of activity.[12–17] Compared with self-reported measures of physical activity, which is subject to recall bias and activity misclassification,[18] accelerometer-derived activity measures allow for unique activity metrics that quantify minute-by-minute activity levels and patterns throughout the day.[19] Moreover, activity fragmentation, a compromised physiological state marker, can serve as an assessment tool for early identification of decline in functionality and health.[5]

Prior cross-sectional research has reported that people who fall recently have low levels of self-reported physical activity,[1] and those who conduct less activity are at high risk of having recurrent falls;[20] yet, the evidence objectively quantifying the longitudinal changes in daily patterns of physical activity after one or more falls is sparse. For instance, older adults demonstrate more sedentary, fragmented, and transient behaviors, rather than sustained activity with aging. These aspects of activity are indicators of poor physical function,[13,21] lower endurance capacity,[22] and a higher risk of disability and mortality.[12,23] Although our prior research has demonstrated that injurious falls are associated with a significant decline in activity levels among visually impaired older adults,[24] the impact of fall frequency on long-lasting changes in objective metrics of activity patterns, such as fragmentation, is less studied.

This study aims to characterize and quantify the longitudinal changes in patterns of free-living physical activity as a consequence of fall frequency in a population of older adults with visual impairment. We hypothesize that older people with visual impairment who experienced either a single fall or 2 or more falls over a 12 month period would show (1) a worsening in activity fragmentation, and (2) lower levels of activity during waking hours over a three-year follow-up period as compared to their counterparts who did not fall. Understanding the impact of falls on subsequent physical activity levels can inform who is at most risk and the design of targeted interventions to restore/maintain physical function and activity after falls in older people with a common eye disease such as glaucoma.

Methods

Participants

Participants were enrolled from a prospective cohort study known as Falls in Glaucoma Study (FIGS), conducted at the Johns Hopkins Wilmer Eye Institute from 2013 to 2015. As described in detail previously,[25] eligibility criteria for study participation included: (1) being 60 years of age or older by the conclusion of the study, (2) living within 60 miles of Johns Hopkins hospital, (3) having a diagnosis of glaucoma or suspected glaucoma, and (4) being able to conduct visual field testing. Participants were excluded if they (1) had visual acuity worse than 20/40 resulting from any diseases other than glaucoma, (2) were restricted to a bed or wheelchair, (3) were hospitalized in the last month, or (4) had ocular or non-ocular surgery within the last two months. We excluded participants with visual acuity worse than 20/40 because 20/40 is used as the cutoff for driving licensure in many states in US, and the level of visual impairment at which reading ability generally declines.[26] The study was approved by the Johns Hopkins Institutional Review Board and all participants provided written informed consent. The manuscript adhered strictly to STROBE guidelines.

To determine the representativeness of the FIGS study sample, the characteristics of participants were compared to 258 patients visiting the same hospital over a one-week period. The FIGS study sample had similar characteristics including age, race and sex as the clinic population that would have also been eligible to participate in the study. However, the FIGS study population were more likely to report falling within the past year than the eligible study population (42% vs 22%, $p < 0.01$) suggesting this study sample was more fall-prone (Supplementary Table S1).

Measures of falls and multiple falls

A fall was described as unintentionally coming to rest on the ground or a lower level and participants viewed an instructional video to assure their understanding of its definition.[27,28] After baseline assessment, participants were provided a calendar and were instructed to mark the occurrence of any falls and return calendars via email or mail. Follow-up calls were initiated weekly to people not returning calendars to maximize the collection of fall occurrences. For this study, participants were classified into three groups – multiple fallers (two or more falls), single fallers (exactly one fall), and non-fallers according to falls data collected in the first study year.

Assessment of physical activity patterns

To measure physical activity, participants wore a waist-bound accelerometer (Actical, Respironics Inc., Murrysville, PA) for seven days during four annual visits (at baseline and then at each yearly follow-up for three years). Participants were instructed to wear the device during waking hours except when bathing or swimming. Study coordinators called participants at least twice during seven-day wear period to maximize adherence to accelerometer. Accelerometer data were used for analysis from participants who wore the device for a minimum of four valid days, each consisting of at least eight hours of wear time.[29,30] Physical activity was estimated to infer the amount of activity for that year.

We used steps from minute-by-minute level accelerometer data to calculate the total amount of activity per day and amount of activity over various time periods of the day. Active minutes were defined as minutes with any steps recorded, and minutes with no steps were deemed as sedentary minutes.[31] Consistent with the prior literature, active bouts lengths were defined by the number of consecutive minutes in an active stage (minutes with one or more steps). Active bout duration was calculated as the sum of active minutes per day divided by the number of active bouts per day. Activity fragmentation (i.e., the active-to-sedentary transition probability), reflecting the likelihood of transition from an active state to a sedentary state, was computed as the reciprocal of mean active bout duration for each individual. A higher value of fragmentation indicates more fragmented, and transient activity, as opposed to sustained activity, and thus a metric of physiological compromise.

Evaluation of vision function and covariates

Visual acuity and visual field were measured with ETDRS chart and Humphrey HFA-2 perimeter (Carl Zeiss Meditec, Carlsbad, California, USA), respectively. We derived integrated VF (IVF) sensitivity by combining pointwise sensitivities from 24−2 tests in both eyes to generate a sensitivity at each spatial coordination by the maximum sensitivity method.[25] Then, we transformed IVF with decibel values to raw sensitivity values, averaged all points in the entire visual field, and finally reconverted average raw sensitivity back to decibel values to obtain the average IVF sensitivity. Participants with average IVF $\geq$ 31 dB were considered to have normal visual fields, while IVF $<$ 31 dB suggested visual field damage. We further classified the severity of visual field damage in three categories: normal/mild (IVF > 28 dB), moderate (IVF 23−28 dB), or severe (IVF $<$ 23 dB).[32]

Demographic characteristics, including age, sex, race, living arrangement, education level, and fall occurrence in the past year were gathered through a self-reported questionnaire at baseline visit. Polypharmacy was determined as taking a minimum of five systematic prescription medications. The number of comorbidities was calculated as the sum of comorbidities identified from a list of 15 comorbid conditions (including arthritis, hip fracture, back problems, heart attack, angina/chest pain, congestive heart failure, peripheral vascular disease, hypertension, diabetes, emphysema, asthma, stroke, Parkinson's, nonskin cancer, or vertigo/Meniere's).[33] Cognitive status was assessed with the Mini-Mental State Examination for visually impaired (MMSE-VI), which classified dementia as the score $\leq$16 and no dementia as 17−22.[34]

Statistical analysis

Participants who had valid accelerometer data at baseline and at least one follow-up visit were included in the analysis. Group differences in demographic and health features by fall category were analyzed using chi-squared testing for categorical variables and *t*-test for continuous variables.

Post-hoc power calculations were conducted to determine the sample size needed to identify an effect size of 2% activity fragmentation at the 5% significance level, on the basis of findings of prior literature which assumed the mean activity fragmentation was 32% (SD = 3%) in glaucoma patients.[5] Using a two-tail *t*-test power calculation, we computed that as compared to non-fallers, a sample size of a total 237 would provide a 90% power for multiple-fallers and 96% power for single-fallers to detect an increase of 2% activity fragmentation, assuming 9% loss to follow-up per year.

Physical activity patterns (e.g., activity fragmentation) over the three-year study period were fitted to visualize the trend and magnitude of longitudinal changes stratified within each fall category. Based on the appearance of activity change over time, linear mixed-effects models were used to explore the longitudinal changes in each activity outcome (including active bout/day, active minutes/day and fragmentation) in response to first-year fall category (multiple faller, single faller, or non-faller). An interaction between fall category and follow-up time (reflected in years) was included in each model to capture differences in activity changes between fall categories. For these models, autoregression correlation was used, and standardized residuals were compared to predicted estimates to secure goodness of fit. Factor including age, race, sex, living arrangement, education, fall occurrence last year, integrated vision field (IVF) sensitivity, comorbidity, polypharmacy, and cognitive function were fixed as model covariates given their associations with vision and/or physical activity.[5]

The mean steps taken for every three-hour interval during typical waking hours (5:00 AM to 10:59 PM) were calculated for each individual. To examine whether changes in activity levels at each three-hour interval varied by fall category, linear mixed-effects models accounting for correlation between daily periods and days of the week were applied. Time-of-day intervals were treated as random effects and an unstructured covariance model was used to justify within-individual clustering. A three-way interaction between fall category, follow-up years, and time-of-day intervals was added to assess whether three-year changes in average steps across six time-of-day intervals differed by fall categories. The contrast statements were employed to compute coefficients and 95% confidence intervals (CIs) for such changes in average steps at each time-of-day interval for three fall categories, respectively. Statistical significance was defined using two-tail hypothesis at $p < 0.05$. All analyses were performed using STATA/SE-16 (StataCorp LLC, College Station, TX).

Role of funding sources

The funding agency had no role in study design, data collection, data analysis, data interpretation, or writing of this report.

Results

FIGS cohort had a total of 245 participants, those without complete vision (n = 2) and physical activity (n = 6) assessments at baseline were excluded (Fig. 1). For the 237 participants (633 person-years) enrolled in the study, mean age at baseline was 70.6 years (Standard Deviation [SD]=7.6), approximately half (51.5%) were male, 29.1% were African American, 20.2% lived alone, 70.9% had a bachelor degree or higher, and 42.2% reported a falling occurrence in last year. The average better-eye visual acuity-logMAR was 0.10 (SD = 0.23). The mean IVF sensitivity was 27.0 dB (SD = 4.5), and close to half of the sample (49.0%) had normal/mild visual field damage, while 40.5% and 10.5% had moderate and severe visual field damage, respectively. 32.9% took five or more non-eye prescription drugs, 65.0% of participants had two or more comorbidities; mean MMSE-VI score was 20.0 (SD = 1.9). During the first study year, 18.6% (N = 44) and 26.6% (N = 63) of participants were classified as multiple fallers and single fallers, respectively, while 54.9% (N = 130) were non-fallers. Of these

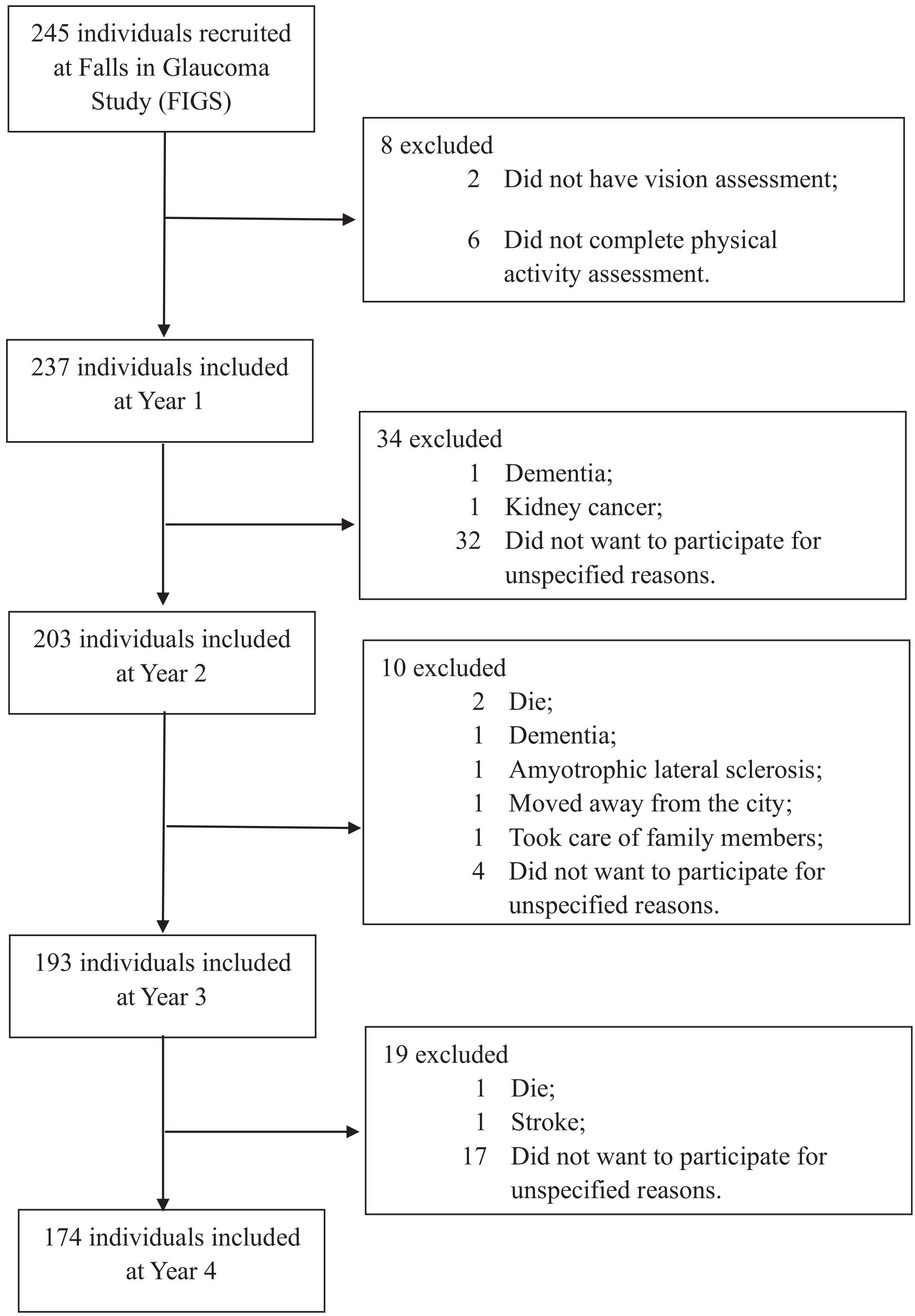

Fig. 1. Participant flowchart.

multiple fallers (N = 44), 5% were admitted into the hospital, 7% had joint dislocation, 16% had a bone fracture, 16% sprained a ligament, 20% pulled a muscle, 43% had swelling, 66% had bruising, and 75% had pain. Participants in each fall category did not differ with regards to demographic and health characteristics at baseline (all ANOVA $p > 0.05$) (Table 1).

Assessments of baseline physical activity were available for all 237 participants, while 203 (85.7%), 193 (81.4%), 174 (73.4%) had physical

Table 1
Participant demographic and health characteristics by non-faller, single-faller and multiple-faller at baseline.

	All participants *N* = 237	Non-fallers *N* = 130	Single fallers *N* = 63	Multiple fallers *N* = 44	*p*-value
Demographic characteristics					
Age, mean (SD)	70.6 (7.6)	69.8 (7.8)	71.4 (7.2)	71.8 (7.7)	0.19
Male, n (%)	122 (51)	71 (55)	31 (49)	20 (46)	0.53
African American, n (%)	69 (29)	41 (32)	20 (32)	8 (18)	0.21
Live alone, n (%)	48 (20)	26 (20)	13 (21)	9 (21)	0.99
Education					0.25
≤ Some college, n (%)	69 (29)	41 (32)	21 (33)	7 (16)	
Bachelor, n (%)	59 (25)	35 (27)	16 (25)	8 (18)	
≥ Master, n (%)	109 (46)	54 (42)	26 (41)	29 (66)	
Any fall occurrence last year, n (%)	100 (42)	52 (40)	27 (43)	21 (47)	0.66
Health characteristics					
Better-eye visual-acuity logMAR, mean (SD)	0.10 (0.23)	0.12 (0.26)	0.08 (0.21)	0.09 (0.13)	0.46
IVF sensitivity, mean (SD)	27.0 (4.5)	27.1 (4.9)	27.2 (3.6)	26.7 (4.4)	0.86
Normal/mild VF damage, n (%)	116 (49)	65 (50)	32 (51)	19 (43)	
Moderate VF damage, n (%)	96 (41)	50 (39)	25 (40)	21 (48)	
Severe VF damage, n (%)	25 (10)	15 (12)	6 (10)	4 (9)	
Polypharmacy, n (%)	78 (33)	38 (29)	26 (41)	14 (32)	0.24
No. of comorbidities					0.13
≤ 1, n (%)	83 (35)	55 (42)	16 (25)	12 (27)	
2–3, n (%)	105 (44)	51 (39)	30 (48)	24 (55)	
4–5, n (%)	49 (21)	24 (18)	17 (27)	8 (18)	
MMSE-VI, mean (SD)	20.0 (1.9)	20.1 (1.7)	20.0 (2.0)	19.9 (2.2)	0.90

SD: standard deviation; IVF: integrated vision field (in decibels); VF: visual field; Normal/mild VF damage: IVF >28 dB; Moderate VF damage: IVF: 23–28 dB; Severe VF damage: IVF <23 dB; Polypharmacy: ≥ 5 systemic prescription medications; MMSE-VI: Mini-Mental State Examination-Vision Impairment (maximum as 22).
Note: participants without complete vision (*n* = 2) and physical activity (*n* = 6) assessments at baseline were excluded.

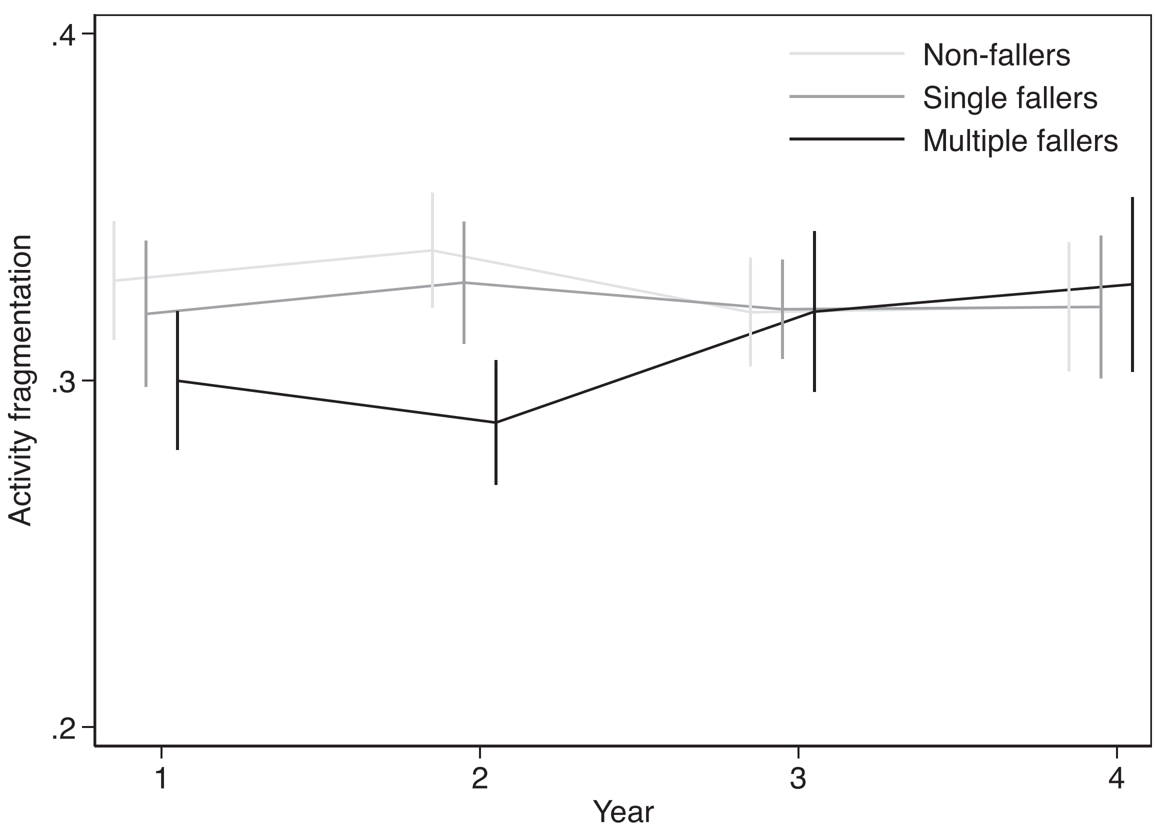

Fig. 2. Activity fragmentation by fall categories over the three-year follow-up period (error bars represent 95% confidence intervals) Fig. 2 Legend: N = 237 at Year 1, 203 for Year 2, 193 for Year 3, and 174 for Year 4.

Table 2
Longitudinal changes in activity outcomes for participants within each group of fall categories.

Activity outcomes	Falls category (β, 95% CI)		
	None	Single	Multiple
Active bouts/day	−0.35 (−1.18, 0.49)	0.03 (−1.18, 1.24)	−2.13 (−3.46, −0.80)*
Active minutes/day	3.19 (−1.68, 8.05)	−0.95 (−8.03, 6.12)	−13.96 (−21.77, −6.15)*
Fragmentation	0 (−0.01, 0)	0 (0, 0.01)	0.01 (0, 0.02)*

Mixed-effects estimates adjusted for age, race, sex, living arrangement, education, fall occurrence last year, integrated vision field (IVF) sensitivity, comorbidity, polypharmacy, and cognitive function.
CI: confidence interval.
*$p < 0.01$.

activity data recorded at the end of the first, second, and third follow-up years, respectively. The percentage of dropout at each year ($p > 0.05$) did not differ across three fall categories, suggesting that dropout was not differential across fall status. When examining continuous three-year longitudinal changes in activity patterns for people stratified within each first-year fall category, annual decline (i.e., rate of change per year) in daily active bouts (−2.13 bouts/day/year, 95% CI: −3.46, −0.80) and active minutes (−13.96 min/day/year 95% CI: −21.77, −6.15), and increased fragmentation (1% higher/year, 95% CI: 0, 2%) (Fig. 2) were observed for multiple fallers; however, none of the three activity measures (including daily active bouts, active minutes, and fragmentation) changed in single fallers or non-fallers ($p > 0.20$ for all) (Table 2). When comparing longitudinal changes over three years in activity patterns across fall categories (multiple, single or no fall groups), multiple fallers demonstrated greater declines in daily active bouts (−1.79 bouts/day/year, 95% CI: −3.35, −0.22) and daily active minutes (−17.15 min/day/year, 95% CI: −26.35, 7.94), and increased fragmentation (1% higher/year, 95% CI: 0, 2%) over the three-year follow-up period as compared to non-fallers; single fallers, however, did not display significant differences in the rate of change in these three activity measures compared to non-fallers (p>0.21 for all) (Table 3).

When assessing changes in activity levels over various waking periods between fall categories, multiple fallers appeared to show initiation of activity at 7:00 AM to 9:00 AM, peak at 12:00 PM to 2:00 PM, and decline in afternoon and evening, and the longitudinal declines in average hourly steps over the three-year follow-up for all waking periods (Fig. 3). In adjusted models accounting for age, race, sex, living arrangement, education, fall occurrence last year, IVF sensitivity, comorbidity, polypharmacy, and cognitive function, multiple fallers experienced greater annual declines in average hourly steps as compared to non-fallers over all waking periods of the day, though the rate of decline was only significantly faster for the evening period (5:00 PM to 8:00 PM: −27.07 steps/hour/year [95% CI: −51.15, −2.99]). However, when compared to non-fallers, single fallers did not show significant differences in the rate of activity decline over time for any time-of-day interval ($p > 0.13$ for all) (Table 4).

Table 3
Comparison of longitudinal changes in activity outcomes across fall categories.

Activity outcomes	Falls category (β, 95% CI)		
	None	Single	Multiple
Active bouts/day	Reference	0.38 (−1.09, 1.84)	−1.79 (−3.35, −0.22)*
Active minutes/day	Reference	−4.14 (−12.72, 4.44)	−17.15 (−26.35, −7.94)**
Fragmentation	Reference	0 (0, 0.01)	0.01 (0, 0.02)**

Mixed-effects estimates adjusted for age, race, sex, living arrangement, education, fall occurrence last year, integrated vision field (IVF) sensitivity, comorbidity, polypharmacy, and cognitive function.
CI: confidence interval.
*$p < 0.05$, **$p < 0.01$.

Discussion

In this clinical sample of older adults with varying degrees of visual impairment, we found that physical activity in those who had multiple falls over a year became more transient and fragmented over the subsequent three-year period. Overall activity levels also declined, with most pronounced declines occurring during the evening hours. However, changes in fragmentation and patterns of daily activity were not observed in those with only one fall or no fall over a 12 month period. Collectively, our results suggest that, in a group largely consisting of persons with visual impairment from glaucoma, multiple fallers experience a more decline in physical capacity and endurance over time (as suggested by changes in fragmentation and evening activity) as compared to non-fallers.

Our study provides important information on quantifying the longitudinal changes in patterns of free-living physical activity as a consequence of fall frequency in a population of older adults with visual impairment. The strengths of this study include: (1) use of objective measurement of physical activity to capture a variety of metrics – e.g., number of steps, minutes of activity, and bouts of activity, (2) quantification of daily activity patterns in a sample at higher risk of falling because of their visual impairments, (3) assessment of three-year activity changes as the effect of fall occurrences– e.g., effects are enduring and dramatic at least for multiple fallers. The results of our study indicate that, more resources and practice guidelines should be directed to multiple fallers, such as investigation on falling at least twice in the past 12 months should be a screening step in identifying multiple fallers who are in need of early treatment; further, given single fallers may fall again in subsequent years – attention to them should be noted as well.

Our findings add to the literature suggesting that older adults experience functional declines[35] and reduced daily activity[36] after falling, and this extends out to three years from falling. A previous cross-sectional study in a well-functioning population of older adults found that people who reported falling in the past year exhibited a similar amount of accelerometer-measured physical activity compared to their comparators who did not fall. However, fall measurement through a health interview questionnaire is subject to substantial recall bias,[18] and the consequence of prospectively collected and continuously monitored falls on long-term changes in physical activity was not described. Another study with a large sample of independently mobile and community-dwelling older men reported that recurrent falls were cross-sectionally associated with fewer daily steps, less moderate and vigorous activity, and more sedentary behavior;[37] however, daily patterns of physical activity, such as fragmentation, which reflects a metric of overall health and physiologic decline, were not evaluated.

Prior evidence has demonstrated that greater activity fragmentation (i.e., shorter episodes of activity) is associated with older age, slower gait speed, higher fatigability, poor functionality, and shorter lifespan – all independent of total activity.[12,13,22] Our prospective three-year study provides novel insights as to the long-term consequences of falls on changing physical activity patterns, demonstrating

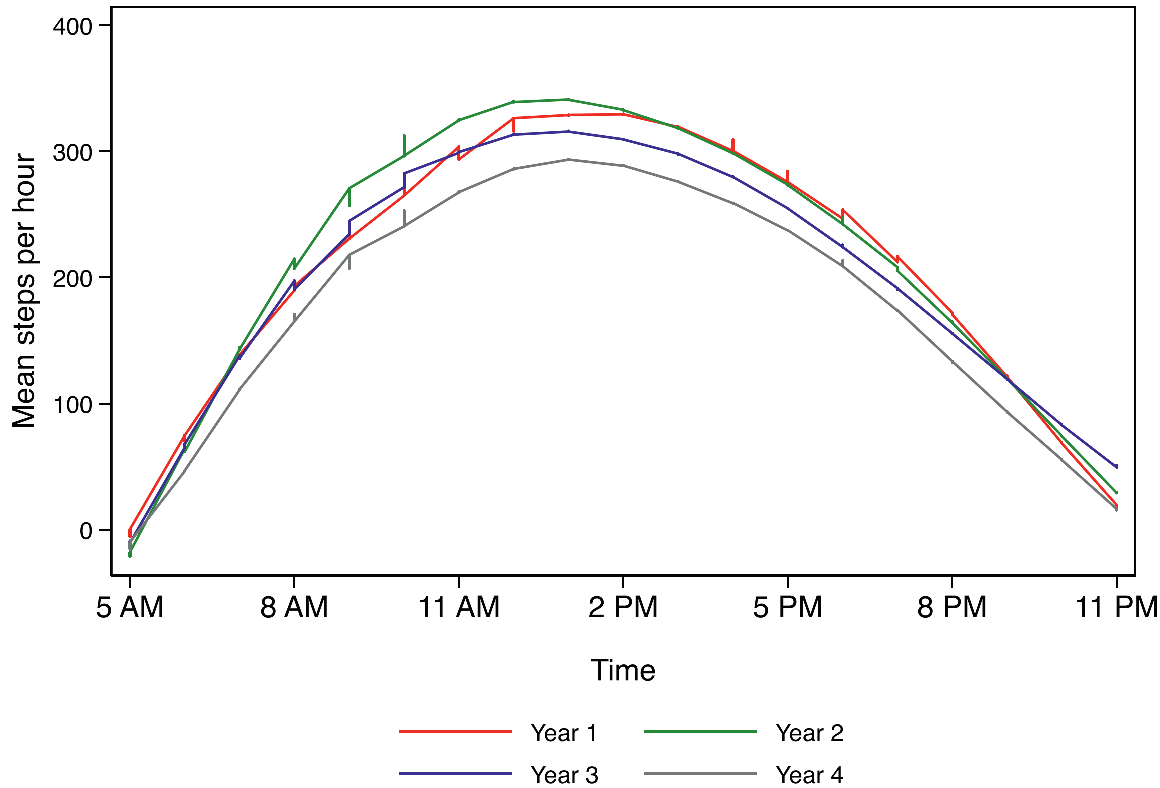

Fig. 3. Average number of steps per hour from 5:00 AM to 11:00 PM over four-year study period for multiple fallers.

that multiple falls over 12 months appear to be associated with more transient and fragmented activity over a three-year period compared to individuals experiencing only one or no falls. However, it remained unclear that if falls were the cause of changes in activity or simply a marker of physical activity changes that were happening as a result of other systemic issues, and might have taken place even if the fall did not occur. Further, these results suggest that multiple falls should be targeted for intervention to prevent the possibility of greater functional challenges with daily activities and/or lower endurance capacity through fatigue as a result of these multiple falls, or in combination with risk factors that both increase the risk of falls and alter physical activity patterns.

Previous research has noted that older people who have a higher risk of falling (e.g., balance problems) and perceived fatigability display altered and downshifting diurnal patterns of physical activity (e.g. lower activity levels).[14,38,39] Consistent with prior research based on accelerometer measurement of physical activity, the distribution of daily activity in our study showed a similar pattern at each of four annual visits for our first-year multiple fallers. Furthermore, our study examined changes in activity levels across fall categories and demonstrated that long-term declines of activity after multiple falls occurred over all waking periods of the day, with activity declines most pronounced during evening hours (5:00 PM to 8:00 PM). Such declines in late-day activity over time suggest multiple fallers with glaucoma may have more difficulties in performing activity and optimizing functionality after sunset when it is darker; alternately, it may indicate greater late-day fatigue in this group. Further research is warranted to study whether declines in late-day activity is associated with fatigability in glaucoma patients.

Our study has several limitations. First, although our study population was mostly representative of patients seeking eye care at Johns Hopkins, where participants were recruited, it is unclear if our findings are generalizable to other older adults in general or even to others with visual impairment. Second, our ability to assess other

Table 4
Comparison of longitudinal changes in average steps at time-of-day intervals (5:00 AM to 11:00 PM) across fall categories.

Time	Falls category (β, 95% CI)		
	None	Single	Multiple
5:00 AM–8:00 AM	Reference	−2.35 (−24.06, 19.36)	−5.45 (−29.60, 18.70)
8:00 AM–11:00 AM	Reference	−10.71 (−32.29, 10.87)	−17.05 (−41.15, 7.04)
11:00 AM–2:00 PM	Reference	7.23 (−14.28, 28.75)	−18.40 (−42.47, 5.66)
2:00 PM–5:00 PM	Reference	−11.75 (−33.25, 9.75)	−16.76 (−40.81, 7.30)
5:00 PM–8:00 PM	Reference	−16.68 (−38.23, 4.87)	−27.07 (−51.15, −2.99)*
8:00 PM–11:00 PM	Reference	−1.88 (−23.54, 19.77)	−6.37 (−30.50, 17.75)

Mixed-effects estimates adjusted for age, race, sex, living arrangement, education, fall occurrence last year, integrated vision field (IVF) sensitivity, comorbidity, polypharmacy, and cognitive function.
CI: confidence interval.
*$p < 0.05$.

potential confounders (home hazards, lighting conditions) was limited, and it is unclear if environmental conditions differed across the three fall categories. Additionally, although the longitudinal cohort study traditionally allowed stronger inferences than cross-sectional studies, our study design was unable to account for reverse causality. For instance, declining physical function may result in less activity and promote falls, such that falls only serve as a marker for declining functionality and do not necessarily cause it. Third, our prior research has described the circumstances and location of falls in this cohort;[40] however, given that not all falls could be explained by participants, we did not collect the information as to whether falls could be explained or unexplained and the exact timing of the falls. Moreover, although prior research demonstrated that falls per activity exposure (e.g., falls per hours walked) complemented falls per person time,[41,42] we did not incorporate this measurement in present study as it was our hypothesis that it was the fall itself, not the rate of falling per unit of activity, that would result in changes in activity. Fourth, we did not obtain individual comorbid condition that may impact daily physical activity, such as severity and duration of each comorbidity and the interaction between these comorbidities. Fifth, although the dropout rate over three years did not differ by fall frequency categories, we did not perform complex analysis using joint models for longitudinal and censoring data approach.[43] Sixth, it was possible that vision loss varied over time; however, as this was a treated cohort, changes in vision loss were infrequent, making it difficult to judge changes in vision measures and changes in physical activity. Seventh, the original objective of our grant was to determine the impact of falling in the first year on the long-term (three-year) mobility in a glaucoma cohort; a limitation of this pre-planned design is that it does not incorporate information regarding falls during follow-up years and thus it is not clear if falls in subsequent years contributed to observed activity patterns over the three years. It is possible that in real-world settings participants who were initial fallers might not fall in follow-up years and those who were non-fallers might transition to become fallers. However, the cumulative incidence of falls for each year was similar over the three-year study period, and risk of staying multiple fallers was higher for multiple fallers as opposed to non-fallers in the first year, suggesting that first-year fall data may be a good surrogate for events occurring in later years. Of note, multiple faller group started out with less fragmentation of activity than the other groups and ended with only slightly more fragmentation. However, this lower fragmentation at baseline was likely true as it persisted for two years of measurement. This might reflect that multiple fallers did enough activity to have these falls and thus made them more susceptible to greater fragmentation over time.

In conclusion, our study found that in an older population enriched for visual impairment, multiple fallers identified prospectively over 12 months developed more transient and fragmented activity over a subsequent three-year period, with activity declines occurring throughout the day but most pronounced during evening hours. However, longitudinal changes in fragmentation and patterns of daily activity were not observed in those identified in the first 12 study months as single or non-fallers. Future research is warranted to focus on interventions to prevent recurrent falls and reductions in activity in high risk older individuals, i.e. those with visual impairment with multiple falls.

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Data sharing statement

The datasets used for these analyses are not public available, but access can be requested to the authors.

Contributors

Conceptualization: JE, JS, PR; Data curation: JE, AM, PR; Formal Analysis: JE, AM, PR; Funding acquisition: DF, SW, LG, PR; Investigation: JE, AM, JS, PR; Methodology: JE, AM, JS, CG; PR; Project administration: JE, AM, DF, SW, LG, PR; Resources: JE, AM, PR; Software: JE, AM; Supervision: JS, TL, PR; Validation: JE, AM, CG, PR; Visualization: JE, PR; Writing – original draft: JE; Writing – review & editing: all authors. JE, AM, PR are responsible for, and can validate the raw datasets associated with the study.

Declaration of Competing Interest

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.eclinm.2021.101097.

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