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Research Article

Continuous Monitoring of Turning Mobility and Its Association to Falls and Cognitive Function: A Pilot Study

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Abstract

Background: Difficulty turning is a major contributor to mobility disability, falls, and reduced quality of life in older people because it requires dynamic balance control that worsens with age. However, no study has quantified the quality and quantity of turning during normal daily activities in older people. The objective of this pilot study was to determine if quality of turning during daily activities is associated with falls and/or cognitive function.

Methods: Thirty-five elderly participants (85 ± 8 years) wore three Opal inertial sensors. Turning and activity rate were measured. Based on retrospective falls, participants were grouped into nonfallers ($N = 16$), single fallers ($N = 12$), and recurrent fallers ($N = 7$). We also determined which turning characteristic predicted falls in the 6 months following the week of monitoring.

Results: Quality of turning was significantly compromised in recurrent fallers compared with nonfallers ($p < .05$). In contrast, activity rate and mean number of turns per hour were similar across the three groups. Also, quality of turning during a prescribed test was similar across the three groups. Visuospatial and memory functions and the Tinetti Balance Scores were associated with quality of turning. Future falls were related to an increased variability of number of steps to turn.

Conclusions: Continuous monitoring of turning characteristics, while walking during daily activities, is feasible in older people. Turning characteristics during daily life appear to be more sensitive to fall risk than prescribed turning tasks. These findings suggest a slower, less variable, cautious turning strategy in elderly volunteers with a history of falls.

Keywords: Fall—Cognition—Continuous monitoring

Falls are the most common cause of injuries and hospitalization and one of the principal causes of death and disability in older persons (1,2). Thirty percent of community-dwelling adults over 65 years of age fall at least once a year, and 12% fall at least twice (1–3). The incidence increases further with age and mild cognitive impairment (4). Clinicians need a sensitive, objective measure of dynamic balance ability in order to predict who is at risk for a fall (5–8). A recent report on video analysis of the most common circumstances of falls in 130 elderly people residing in long-term care revealed that the most common cause of falling was incorrect transfer or shift of body weight (including turning) in 93 out of 223 recorded falls (9).

Difficulty turning during gait signals impaired dynamic balance, and could be a major contributor to falls, and reduced quality of life in older people (10). The ability to modify our locomotor trajectory by turning safely is important for functional independence and poses a much more difficult task for the nervous system to control than straight-ahead walking (10–13). Falls during turning are particularly dangerous because they usually result in contact of the femur with the ground, which results in eight times more hip fractures compared with falls during straight-line walking (14–16). Turning gradually becomes more difficult as we age due to increasing sensorimotor impairments. Exactly how many falls are associated with poorly controlled turns is unknown because it has not been possible to measure turning during daily activities, but clinicians view turning performance as a sensitive index of dynamic balance (5,17).

Turning is ubiquitous during activities of daily living. Nearly every task performed during the day requires some amount of turning (18). However, gait research has focused primarily on straight-ahead walking. The research on turning that has been performed has been limited to laboratory or clinical investigations. Previous laboratory studies, with kinematics and surface electromyography, showed that young and older adults use different strategies during turning (19–21). Specifically, older adults, more than younger adults, reduce their walking speed and increase their step width just prior to the turn, suggesting a more cautious strategy (21). Clinically, research has focused on assessing turning ability with the Timed Up and Go (TUG) test that includes a 180° turn or with the Berg Balance Scale or Tinetti Mobility assessment that include a 360° turn (10,22,23).

Recently, our group developed and validated, in a small group of Parkinson's disease and healthy control participants, an algorithm to measure turning quality continuously during the day (24).

We also found that turning characteristics can distinguish between people newly diagnosed with Parkinson's disease from control participants, even when gait speed is normal and clinical measures of balance from the Berg Balance Score or the Tinetti Mobility Assessment do not (25). We propose that continuous measures of turning may be more sensitive than clinical measures of mobility to detect decline in motor activity. Turning may be more vulnerable to impairments than straight-ahead, linear gait because turning involves more interlimb coordination, more coupling between posture and gait, and modifications of locomotor patterns requiring frontal lobe cognitive and executive function that plays an important role in postural transitions (25–27).

It is not known whether turning in daily life, specifically, is impaired in older people with fall history and/or mild cognitive deficits. Executive function is thought to play an important role in the higher-order, cognitive control of gait and posture because people with executive deficits have a high incidence of falls (28). However, Kaye and coworkers (29) recently found significant associations in the cognitive test domains of attention/processing speed, visual perceptive function, and global cognition, but not executive function, with walking speed acquired while passing under infrared sensors installed in the home. In the current study, we investigate the association between continuous monitoring of turning and fall risk as well as cognitive function.

Methods

Participants

This study recruited 35 (Table 1) participants from the Oregon Center for Aging and Technology (ORCATECH) cohort. Participants completed a weekly questionnaire about the occurrence in the past week of illness, falls, emergency room visits, medication changes, and ORCATECH participants also undergo annual clinical and neuropsychological assessments. Full details of the assessment procedures are provided in Kaye and coworkers (29).

Recruitment

A member of the ORCATECH study staff (C.D.) recruited participants from their database, only if participants had completed their annual clinical and neuropsychological assessments within the past 6 months and were without neurological disease or dementia. Dementia was defined as Clinical Dementia Rating Scale higher than 0.5 (30) and/or the Mini-Mental State Examination lower than 24. Other exclusion criteria were neurological disease and musculoskeletal impairments that could significantly affect gait or turning. Participants who used walker, cane, or wheelchair in the home were also excluded.

Cognition

Cognitive performance was assessed across five domains, according to specific z-normalized cognitive scores developed by ORCATECH: executive function (Category Fluency Animals, Categories Fluency Vegetables, and Trail Making Part B); working memory (Digit Span Backward and Digit Sequencing); attention/processing speed (Digit Span Forward, Digit-Symbol Test, and Trail Making Part A); episodic memory (Logical Memory Delayed, Visual Reproduction II, CERAD Word-List Recall); and visuospatial ability (Block Design and Picture Completion). Also, an overall global z-score was derived from all tests.

Falls

A fall was defined as any fall, including a slip or a trip, in which the participant came to rest on the floor, ground, or on a lower level (31). All falls were recorded via a weekly query of participants responding to an online questionnaire. Participants were divided into three groups: (i) single fallers (SF) were defined as participants who had recorded one fall during the 12 months preceding the study (N = 12). (ii) Recurrent fallers (RF) were defined as participants who had more than one fall in the 12 months preceding the study (N = 7), and (iii) nonfallers (NF) are defined as participants who did not experience any falls (N = 16).

In addition, prospective fallers were identified for the 6 months following the 7-day recording period. Prospectively, participants who experienced one or more falls were defined as fallers (N = 7 out of 35). Due to the small sample size and small number of prospective months, the primary analysis focused on retrospective falls collected weekly over a year. However, we also present results related to prospective falls over the 6 months following data collection at the end of the results section to validate the retrospective results.

Clinical Gait

We report the Tinetti Balance and Gait Inventories and the time to walk 9 m.

Home Protocol

Two researchers met the participants at their homes on the first morning to (i) obtain consent for participation, (ii) instruct participants how to wear movement monitors and charge them at the end of the day, and (iii) collect prescribed turns with the movement monitors using a short protocol (90 and 180° in both directions × 5). All the participants gave informed, written consent, in accordance with the declaration of Helsinki and the Institutional Review Board of Oregon Health & Science University. Participants were instructed how to put on the monitors in the morning, with and without shoes, how to take them off at the end of their day and recharge them every night. Also, they were asked to wear the monitors for seven consecutive days (except during activities such as showering and swimming). Researchers returned to the participants' homes after 7 days to pick up the movement monitors and conduct a structured interview about compliance, problems, and feedback about the system.

The movement monitors were Opals from APDM (Portland, OR). An Opal is a lightweight (about 22 g) inertial sensor, has a battery life of 16 hours, and includes 8 GB of storage. Participants wore three Opal monitors with elastic bands: one on their belt (posterior trunk at about L5) and two on shoes (on the top of each foot). Data were recorded at 128 Hz and stored in the internal memory of the Opal monitors. Data were uploaded to a laptop for data analysis in 7 days.

Data Analysis

From the monitor on the belt, periods of walking were first detected and walking periods of 10 seconds or longer were defined as gait bouts (from the 3D angular velocities) and were used by the algorithm to search for potential turns. We used the horizontal rotational rate of the lumbar sensor to detect turning events during bouts. Specifically, a turn is defined as a trunk rotation about the horizontal plane with a minimum of 45°, accompanied with at least one right and one left foot stepping. Only turns with durations between 0.5 and 10 seconds, and turn angles of 45° or more were considered. Relative turn angles were obtained by integrating the angular rate of the lumbar sensor about the vertical axis. We previously validated this turning algorithm with Motion Analysis System (Santa Rosa, CA) in a previous study in the Balance Disorders Laboratory at the Oregon Health and Science University in 15 participants with Parkinson's disease and 19 age-matched control participants. Compared with Motion Analysis, the algorithm maintained a sensitivity of 0.90 and a specificity of 0.75 for detecting turns. More details about the algorithm development and its validity can be found in El-Gohary and coworkers (24).

The turning characteristics were averaged across the week and the coefficient of variation (CV) was calculated for the following measures: (i) number of turns per hour, (ii) turn angle amplitude, (iii) turn duration, (iv) turn peak velocity, and (v) number of steps to complete a turn. In addition, activity rate was also calculated as the percent of time when participants were walking, compared with the total monitoring time per day.

Statistical Analysis

The Shapiro–Wilk normality test indicated that all data were normally distributed. One-way analysis of variance was used to determine whether differences in the continuous monitoring measures existed among the three groups (NF, SF, and RF; based on retrospective information on falls). When a significant difference was found, a post hoc analysis was performed using Bonferroni adjustment ($p < .01$) to test which groups differed from each other. In addition, a one-way analysis of variance was used to determine whether differences existed among fallers and NF, based on prospective fall information. Lastly, Pearson correlation coefficients were used to assess the relationships between turning metrics and each clinical test and each cognitive domain *z*-score obtained within 3 months of the week of assessment. All the analyses were performed using NCSS Software (Kaysville, UT) and Matlab (Mathworks).

Results

Feasibility

This study demonstrated that elderly participants can successfully wear inertial sensors on their belt and shoes for a week to obtain useful data about their mobility. All 35 participants complied with the protocol for 7 consecutive days. Participants wore the inertial monitors on average for 6.8 days (*SD*: ±0.9), 67.7 hours (*SD*: ±8.7) per week. The number of turns identified were 866.3 (minimum 300; maximum 1,511) per day and 4,525.5 (minimum 2,100; maximum 10,577) per week.

Participant demographics, clinical, and cognitive characteristics are reported in Table 1. Among the clinical tests, only the Tinetti score showed a significant difference between fallers and NF. All the cognitive test scores were similar among the three groups.

Quality, but Not Quantity, of Turning Mobility Was Impaired in RF

Quality of turning, quantified by mean turn duration, mean peak speed of turning, and mean number of steps to complete a turn were significantly compromised in RF, compared with NF (Figure 1). RF showed a significantly longer mean turn duration (SF = 3.3, $p = .05$; RF compared with NF $p = .01$) and a significantly slower mean turn peak speed compared with NF ($F = 3.6$, $p = .04$; RF compared with NF $p = .009$). Moreover, RF showed a significantly larger number of steps per turn (SF = 5.2, $p = .01$; RF compared with NF $p = .004$; RF compared with SF $p = .01$) compared with fallers and NF. The mean turn angle was similar across the groups ($F = 1$, $p = .3$); however,

Table 1. Demographics, Clinical, and Cognitive Characteristics of Nonfallers, One-time Fallers, and Recurrent Fallers (Mean and *SD* Is Reported for Each Group)

	Nonfallers (*N* = 16)		One-time Fallers (*N* = 12)		Recurrent Fallers (*N* = 7)			
	Mean	*SD*	Mean	*SD*	Mean	*SD*	*F*	*p* Value
Demographics								
Male/female	3/13		4/8		5/2			
Clinical Dementia Rating	*0.5 in 1 out of 16*		*0.5 in 1 out of 12*		*0*			
Age	83.9	7.0	86.0	7.0	88.4	8.8	0.4	.6
Mini-Mental State Examination	28.3	1.4	28.9	1.2	28.0	1.8	0.9	.4
Tinetti Gait	1.3	2.1	0.8	1.5	3.8	2.6	7.8	.002
Tinetti Balance	1.8	2.8	1.8	1.9	6.8	5.7	9.5	.0006
Time to walk 9 ft (s)	11.2	1.3	12.9	2.0	13.2	3.9	2.7	.08
Cognitive measures								
Global cognitive *z*-score	0.08	0.59	0.39	0.64	0.10	0.29	1.0	.3
Executive function *z*-score	0.08	0.77	0.54	0.83	−0.12	0.29	1.7	.2
Working memory *z*-score	−0.06	1.01	0.31	0.79	−0.11	0.76	1.3	.3
Attention/processing speed *z*-score	0.19	0.54	0.42	0.62	−0.06	0.52	1.9	.2
Memory *z*-score	0.08	0.81	0.00	1.18	0.19	0.72	0.2	.8
Visuospatial *z*-score	−0.01	0.98	0.77	0.75	0.72	0.64	2.9	.06

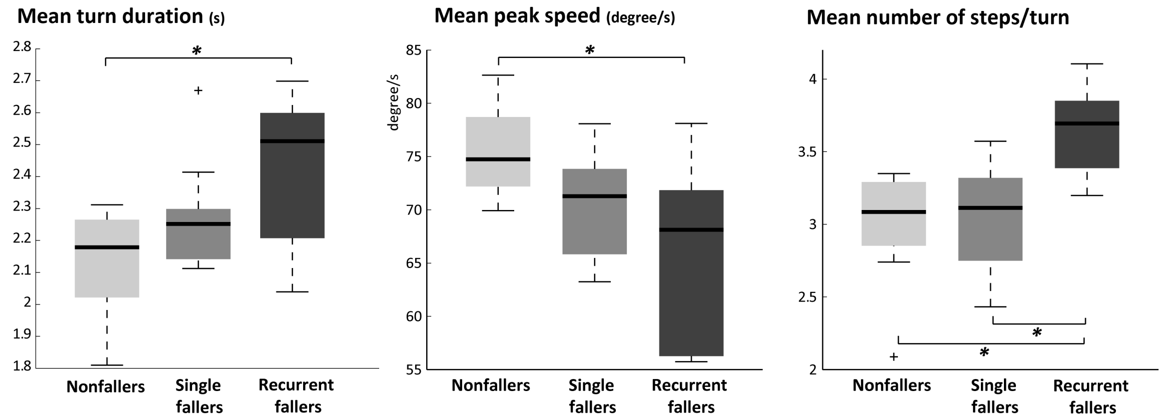

Figure 1. Quality of turning mobility across nonfallers, single fallers, and recurrent fallers. Recurrent fallers show slower turns (and more steps) than nonfallers (and single fallers). Boxes indicate the interquartile range, middle lines the median, whiskers the minimum–maximum value, outliers are plotted with +. *$p < .01$.

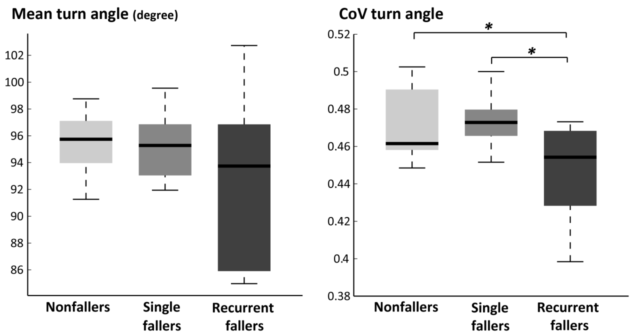

Figure 2. Quality of turning mobility across nonfallers, single fallers, and recurrent fallers. Boxes indicate the interquartile range, middle lines the median, whiskers the minimum–maximum value. *$p < .01$.

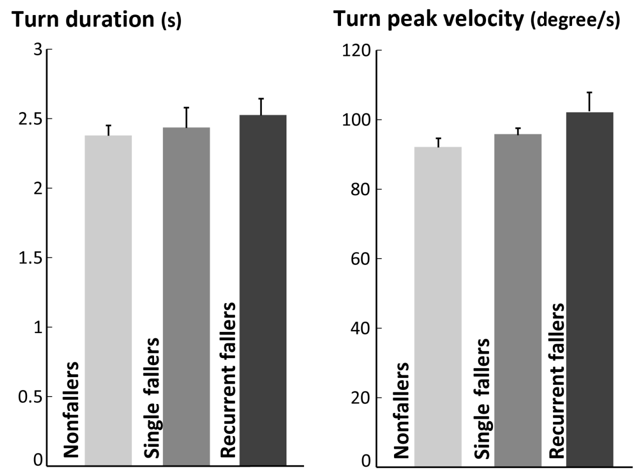

Figure 3. Prescribed turning characteristics across nonfallers, single fallers, and recurrent fallers are not different (means ± *SEM*).

RF showed a significantly lower CV of turn angle compared with NF and fallers ($F = 3.8$, $p = .03$; RF compared with NF $p = .05$; RF compared with SF $p = .02$) Figure 2.

Unlike quality of turning, quantity of turning, quantified by Active Rate (% of time when participant is walking or turning compared with the full time of monitoring during the day), and mean number of turns per hour were similar across the three groups (Active Rate, mean ± *SEM*: 20.5 ± 1.5 in NF, 18.4 ± 1.5 in SF, 18.5 ± 2.1 in RF, $F = 0.5$, $p = .6$; mean number of turns per hour, mean ± *SEM*: 65 ± 5 in NF, 56 ± 5 in SF, 46 ± 7 in RF, $F = 2.2$, $p = .1$).

Prescribed Turns Do Not Differentiate Fallers

Unlike the week of turns in the home, the prescribed mean turn duration ($F = 0.3$, $p = .7$) and peak speed ($F = 0.9$, $p = .4$) were not significantly different across the three groups, Figure 3.

Association With Clinical Scores and Cognitive Performance

Turning angle amplitude CV, mean turn peak speed, and mean number of steps per turn measured continuously for 7 days were significantly correlated with the Tinetti Balance score (r ranging from .43 to .58, $p < .01$) but not to the Tinetti Gait score ($p > .05$).

A few cognitive tests were related to turning mobility. Specifically, the visuospatial score was related to the CV of turn duration ($r = .44$, $p = .02$), whereas the episodic memory score was related to the mean turn duration ($r = -.4$, $p = .04$) and the mean turn peak speed ($r = .43$, $p = .03$). The other cognitive tests (executive function, attention-processing speed, and working memory) were not related to turning.

Variability of Number of Steps per Turn Is Larger in Prospective Fallers

In the 6 months following the mobility testing, 28 participants did not experience falls whereas 7 participants experienced one or more falls. Results in Figure 4 shows that quality of turning measured as the CV of steps per turn was significantly larger in the group that experienced one or more falls after testing, compared with the group that did not experience falls (Figure 4A and B for representative examples and Figure 4C for box-plot, $F = 6.6$, $p = .01$). In contrast, neither the Tinetti Gait nor Balance score was different in prospective fallers compared with prospective NF (Tinetti Gait score $F = 0.49$, $p = .5$; Tinetti Balance score $F = 1.1$, $p = .3$).

Discussion

This is the first study to investigate natural turning mobility during daily activities inside or outside the home in older people with or without risk for falls. Findings from this study demonstrated that

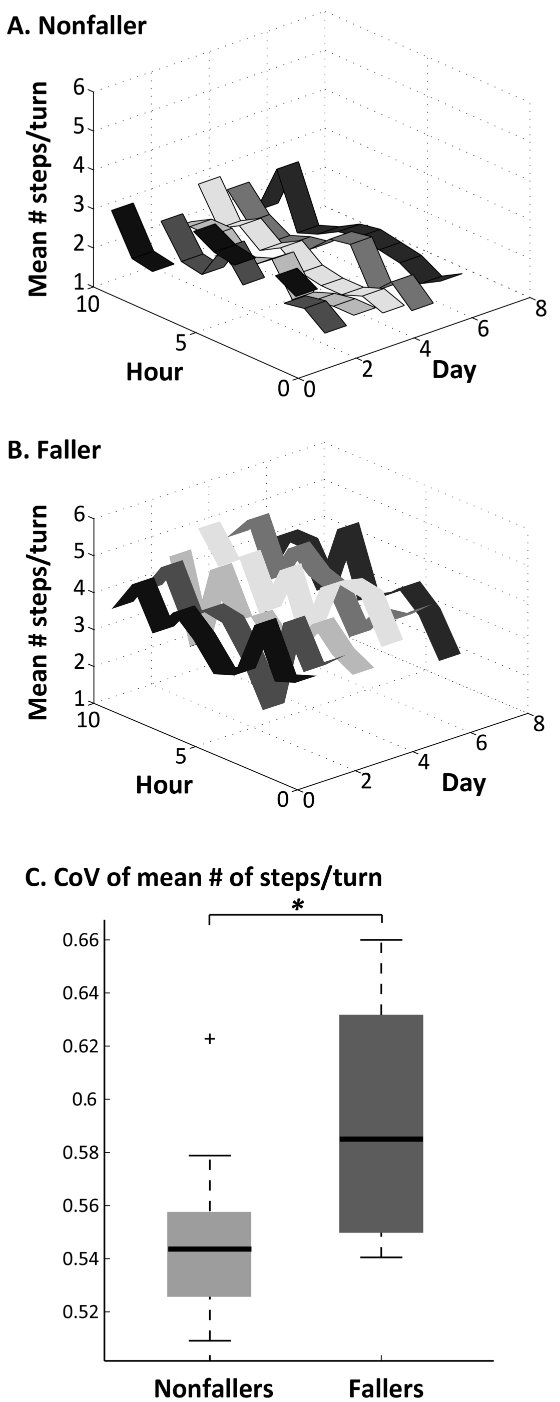

Figure 4. Mean number of steps per each turn across a week in a representative (**A**) nonfaller, (**B**) representative faller, and (**C**) between groups of nonfallers and fallers (based on prospective falls; means ± *SEM*).

(i) quality of turning is impaired in RF, (ii) continuous monitoring of turns, but not prescribed turns, differentiate between fallers and NF, (iii) turning mobility may be associated with visuospatial and memory function, and (iv) variability of steps during a turn may predict prospective falls.

We demonstrated the feasibility of using body-worn sensors to quantify turning during natural daily activities, even in elderly people who have cognitive impairment and risk for falls. We were surprised to see how often our participants turned during their daily activities (eg, a mean of 866 turns per day), although many participants primarily stayed at homes.

We showed that quality, but not quantity, of mobility is compromised in elderly fallers. Specifically, turning duration, velocity, and number of steps were compromised in retrospective, RF compared with NF. Interestingly, RF showed a similar weekly average turning angle compared with fallers and NF, but with significantly reduced turning angle variability. This reduced variability points to the tendency of fallers to repeat the same turning angle across the 7 days of continuous monitoring, which might indicate a lack of dynamic balance skills necessary to modulate turning angles for environmental situations while maintaining balance. Thus, even in this limited sample, characteristics of quality of turning mobility showed significant differences based on fall status, indicating potential of turning measures as possible markers to identify fall risk.

Many studies have characterized the quantity of mobility using activity monitors (ie, accelerometers) with measures such as duration of low, medium, and high levels of activity, total number of daily steps, percentage time spent in lying, sitting, standing, and walking (32). However, quantity of steps or walking periods do not always relate to fall risk. In fact, more recently, a few groups (33–35) have recommended the added value of measuring the quality of mobility in determining fall risk. One study found greater step-to-step timing variability in retrospective fallers, compared with NF, over 3 days of continuous monitoring, although the number of steps per day were similar between groups (35). In addition, a study in elderly people with dementia found significant differences in accelerometry-based parameters of walking and standing during 1 day of continuous monitoring between fallers and NF, without differences in conventional clinical tests (TUG time, Performance Oriented Mobility Assessment score, and five-chair stand), with the exception of "previous fallers" (33). Lastly, another report investigated the ability of accelerometry-derived gait metrics during 8 days of continuous monitoring to predict prospective falls (6 months) in a sample of 169 healthy elderly, finding that both quantity (amount of gait) and quality of gait (complexity, intensity, and smoothness) contributed substantially to the identification of individuals at risk for falls (34). The current study is the first to investigate the potential for turning characteristics to identify fallers.

Unlike a week of turning during natural activities, prescribed tasks with observed turns in the home did not differentiate fallers from NF; all three groups showed similar turning duration and velocity for the average of five 90 and 180° turns in each direction. Interestingly, we observed that RF tended to turn faster during the prescribed turns than during their natural turns. This result confirms that awareness of direct observation may, itself, affect actual mobility performance. Similarly, Kaye and coworkers (29) found elderly participants walk slower when measured unobtrusively at home, compared with a stopwatch-derived gait speed during an observed, 5-m walk. In the present study, measures of stopwatch-derived, walking speed (Time to Walk 9 ft, Table 1), turning duration, and turning velocity in a prescribed test at home were not able to differentiate NF, fallers, or RF. Thus, continuous monitoring of spontaneous activity during daily life may provide more meaningful, challenging observations related to actual, functional mobility.

Our study also found that turning is associated with distinct cognitive domains. For example, we found turn velocity, turn duration, and its variability to be associated with visuospatial and memory function. This finding is consistent with a study showing a relationship between duration and amplitude of a 180° turn, performed during an Instrumented TUG at home, with visuospatial, memory, and speed of turning (27). Turning might place demands on visuospatial processing to correctly enable directional movements required to accomplish a change in direction while walking. Although previous studies showed that gait slowing may predict the onset of cognitive impairment (27,36,37), turning-related neural control systems may predict cognitive decline even better than declines in gait (21–23).

In addition, increased variability in the number of steps per turn may be an indicator of future falls (Figure 4). Variability of gait, specifically increased stance time and step length variability, has been reported to be larger in retrospective or prospective fallers compared with NF (38–42). However, a review on gait variability in over 500 participants showed that either too little or too much step width variability can be associated with falls (43). Too much variability in turning strategy may reflect imbalance or compensation for impaired balance, whereas too little variability may be associated with a loss of the skill necessary adapt balance control for a variety of turns.

There are several limitations to this study while generating interesting questions for follow-up studies. The sample size was limited; therefore, a larger study comparing the relative value of monitoring turning versus straight gait to predict fall risk is needed. Moreover, the fact that we did not find differences in cognitive tests nor quantity of activity across groups could be due to the small sample size; therefore, our findings should be considered preliminary. In addition, we only characterized turns during gait so further algorithm development is needed to include turns during the turn-to-sit task and or turning in place. Data were collected for 7 consecutive days to include a diversity of activities; however, future studies are needed to determine if fewer days might be enough to predict fall risk. Translational activities and the location of turning events (eg, going to bed, moving to the bathroom, walking outside) could not be determined with the current protocol.

In summary, this preliminary study suggests a slower, less variable, cautious turning strategy in elderly participants with a positive history of falls. Turning mobility was related to visual-spatial function and memory, consistent with shared neural resources for cognitive and dynamic balance functions. We believe that characterizing functional turning during daily activities will address a critical barrier to clinical practice and clinical trials: objective measures of mobility in real-life environments.

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Conflict of Interest

Oregon Health & Science University (OSHU), Drs. F.B.H. and M.E. have a significant financial interest in and/or are employees of APDM, a company that may have a commercial interest in the results of this research and technology. This potential institutional and individual conflict has been reviewed and managed by OSHU.

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