In-home Assessment of Turning and Transitions using Inertial Sensors in Older Adults with Dementia and Older Caregivers

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Abstract

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This project consisted of two studies: Study 1 and Study 2.

STUDY 1: *Background/Objectives:* Mobility problems progressively worsen with advancing stages of dementia. Cognitive decline, along with age-associated impairments in muscle weakness and balance, present significant challenges in the performance of everyday tasks which contribute to the incidence of falls. The aim of the study was to determine whether spatiotemporal parameters of turning and transitions differ between older adults with dementia compared to those without dementia, using portable inertial sensor technology in the home environment. *Participants*: Older adults with dementia [n=37 (Instrumented Timed-Up-and-Go), 29 (360° turns)] and caregivers [n=38 (Instrumented Timed-Up-and-Go), n=40 (360° turns)]. *Outcomes Measures*: *Performance-based tests*: Instrumented Timed-Up-and-Go (iTUG), and

360° turns clockwise (CW) and counterclockwise (CCW) and spatiotemporal measures of sit-to-stand, stand-to-sit, and turning were derived from the Ambulatory Parkinson's Disease Monitoring (APDM) inertial sensors. *Results:* Participants with dementia took a significantly longer time to complete the sit-to-stand and stand-to-sit transitions compared to the caregivers ($p < 0.05$). However, there was no significant difference between the groups in trunk lean angle, average velocity or trunk displacement for either of the transitions between sitting and standing. Participants with dementia demonstrated a slower peak turning velocity and longer turning duration to complete the iTUG turn and 360° turns CW and CCW, compared to the older caregivers ($p < 0.001$). The mean turning angle was less (wider) in participants with dementia. *Conclusion:* Participants with dementia were slower while turning and transitioning between sitting and standing compared to the older caregivers. In addition, participants with dementia had a wider turning angle, suggesting differences in movement strategy.

STUDY 2: *Background/Objectives:* With a surge in the number of studies utilizing the Ambulatory Parkinson's Disease Monitoring (APDM) portable sensor system for investigation of movement in older adults, an investigation of concurrent validity between the laboratory-based motion analysis system (Qualisys, the criterion measure) and the APDM inertial sensor system (proposed alternative) is warranted. The aim of the study was to examine concurrent validity between measures of turning performance obtained from the APDM portable inertial sensor system and the laboratory-based motion analysis system, in people with mild cognitive impairment, in the laboratory setting. *Participants*: Older adults with mild cognitive impairment (MCI) [n=10]. *Performance based tests:* 360° turn counterclockwise (CCW) and spatiotemporal measures of turning derived from the APDM inertial sensors and the laboratory-based Qualisys motion analysis system. *Results:* Measures of turn duration and peak velocity demonstrated good

to excellent positive correlations, $r = 0.952$, $p < 0.001$ and $r = 0.976$, $p < 0.001$, respectively. There was no correlation between the measure of turn angle obtained from the two motion analysis systems ($r_s = -0.139$). *Conclusions*: Turn duration and peak velocity measures of APDM system demonstrate excellent correlation with Qualisys measures on the 360° turn, in older adults with MCI, in the laboratory. Further statistical analysis is needed to examine the absolute agreement on the turn angle measures.

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Chapter 1

In-home assessment of turning and transitions using inertial sensors in older adults with dementia and older caregivers

1.1 INTRODUCTION

Dementia is related to a high incidence of falls and injuries among older adults (Delbaere, 2012; Tyrovolas, 2016). In addition to cognitive decline, age-associated impairments in muscle weakness and balance present significant challenges in performance of everyday tasks which contribute to the incidence of falls (Robinovitch, 2013; Talbot, 2005). Care for people who experience mobility problems and falls presents a substantial financial burden (Hurd, 2013). Since a majority of falls occur at the homes of older adults (Connell, 1997; Josephson, 1991), it is important to study mobility skills within the home environment. Several mobility skills, such as turning and sit to stand transitions, require complex balance control while modulating speed and direction in small spaces at home.

Global brain atrophy has been reported as a risk factors for falls in older adults with cognitive impairment (Yamada, 2013). Mobility problems progressively worsens with advancing stages of dementia (Aggarwal, 2006). Certain transitions in everyday tasks, such as turning and transition between positions place a greater demand upon the neuromuscular system, putting older adults at risk for instability and falls. Evidence supports that older adults with cognitive impairment demonstrate significant reduction in gait speed (Aggarwal, 2006; Moretti, 2015). Eggermont et al (2010) reported that older adults demonstrate reduced functional mobility as compared to cognitively healthy older adults.

Using laboratory-based video graphic observational analysis, several studies have reported differences in turning characteristics, in older adult compared to younger adult populations, including longer turning duration and increased number of steps (Meinhart-Shibata, 2006; Thigpen, 2000; Yamada, 2012). A few studies have investigated the turning performance of older adults using laboratory-based 3-D motion capture systems (Akram, 2010; Braid, 2009; Wright, 2012), and telemetry/EMG combination (Kuo, 2014; Lin, 2014). There are differences in timing and sequence of inter-segmental motion that result in greater movement of center of mass in older adults as compared to younger adults (Braid, 2009). Older adults adjust velocities of various body segments to maintain stability while turning (Akram, 2010; Kuo, 2014; Lin, 2014; Wright 2012). Despite these advances in understanding of functional mobility in older adults, there is limited research comparing differences in turning characteristics between cognitively healthy older adults versus those with dementia.

Characterizing parameters of turning and sit-to-stand transition in older adults with cognitive impairment compared to the older caregivers is important in developing a greater understanding of mobility-related problems that contribute to falls. There are no known studies that have examined turns and transitions in the home environment in people with cognitive impairment. Moreover, it is unknown whether findings from studies using laboratory-based quantitative motion analysis are directly applicable to the home environment, where most fall incidents are reported (Connell, 1997; Josephson, 1991).

Portable body-worn inertial sensors consist of an accelerometer, gyroscope, and magnetometer. Due to their many advantages, such as portability, wireless synchronization of multiple body-worn sensors, cost-effectiveness, ease of set-up, and compact storage size, a portable body-worn inertial sensor system provides an alternative to the laboratory-based motion

capture system for data collection within the home environment. Inertial sensors have been used to collect real-time data on gait and balance in young adults and patients with Parkinson's disease (Baston 2014; El-Gohary, 2014; Mancini, 2012), however, the use of this technology in older adults with cognitive impairment has been reported in only one study and they examined functional mobility in the individuals with mild cognitive impairment (Mirelman, 2014).

The overall purpose of this study was to develop a greater understanding of mobility problems related to turning and transitions in older adults with dementia. The aim of this study was to determine whether spatiotemporal parameters of turning and transitions differ between older adults with dementia compared to those without dementia, using portable inertial sensor technology in the home environment. The hypothesis of this study was that the spatiotemporal parameters of turns and transitions would be impaired to a greater extent in older adults with dementia compared to older caregivers.

1.2 METHOD

This study used a cross-sectional design to compare turns and transitions in older adults with dementia to those of their caregivers. It involved secondary analysis of baseline data from an intervention study "Translational Research to Help Older Adults Maintain their Health and Independence in the Community" (1RO1 AG041716, PI: Linda Teri, PhD, Co-investigator, Ellen McGough, PT, PhD). Older adults with dementia and their older caregivers were recruited for this study. The inclusion criteria for people with dementia, for the larger exercise intervention study, included: 1) 60 years of age or older, 2) an established diagnosis of dementia, consistent with the DSM IV-R criteria (diagnosed by their physician), 3) able to walk household distances with or without an assistive device, and 4) living in the community with a caregiver (not a

retirement community). The inclusion criteria for the caregivers was: 1) 60 years or older; 2) no diagnosis of dementia, 3) primary family caregiver for the person with dementia. Potential participants for the dementia or caregiver group were excluded if they: 1) had a known, terminal illness (with death anticipated within the next 12 months); 2) were hospitalized for a psychiatric disorder in the 12 months prior to baseline, 3) actively suicidal, hallucinating, or delusional, blind, deaf, 4) not ambulatory, or 5) had a neurological diagnosis other than dementia (e.g., Parkinson's disease or stroke). All assessments were conducted by trained research assistants in homes of the study participants in Northwest Washington between September 2014 and April 2016. This study was approved by the Institutional Review Board at the University of Washington. A written informed consent was obtained from the eligible participants prior to participating in the study.

Demographic and Health Data: Information on age, gender, and health history was gathered through self-report from the participants or caregivers. The Self-Administered Comorbidity Questionnaire (SCQ) was used for health conditions (Sangha O, 2003). The Mini-Mental Status Exam (MMSE), a measure of global cognitive impairment, was administered to participants with dementia to describe their level of cognitive function (Folstein, 1975).

Instrumentation**:** The Ambulatory Parkinson's Disease Monitoring (APDM) Mobility Lab™ (APDM Inc, USA), a portable motion analysis system, was utilized to collect in-home mobility data in persons with dementia and their caregivers. APDM software was installed on a Windows laptop. Six wireless inertial sensors were secured on each participants' body using Velcro straps at six pre-determined anatomical locations (i.e., sternum, waist [lumbar spine levels 4-5], bilateral wrists, and dorsum of the feet).

Instrumented performance based assessment:

Instrumented Timed Up-and-Go (iTUG): The Timed Up-and-Go (TUG) is a test of functional mobility in which participants are instructed to stand up from a standard height chair, walk 3 m, turn, and walk back to the chair, and sit down (Podsiadlo, 1991). Participants were instrumented with 6 APDM sensors as described above to perform two trials of the iTUG test. Subjects were instructed to perform the trials as fast as they safely can. The TUG has demonstrated excellent test-retest reliability (ICC = 0.99) in community-dwelling older adults (Steffen, 2002), and good test-retest reliability (ICC = 0.87) in older adults with moderate to severe dementia (Ries et al., 2009). Test-retest reliability of iTUG has been reported in patients with Parkinson’s disease (Salarian, 2010), with low values for the sit-to-stand transition (ICC = 0.04) and excellent reliability for the iTUG turn (ICC = 0.89).

The operational definitions for the variables of data collected with the APDM system and utilized for this study are described in Table 1.1.

Instrumented 360° turns: The participants were instrumented with APDM sensors as described above and stood on a firm surface with shoes on, their feet positioned in a comfortable stance width, and their arms at their side, with their gaze focused on a fixed reference point on the wall. The participants stood at least 2 feet from the wall to allow sufficient space to complete the turn. The participants were instructed to make a 360° turn in the clockwise direction and return to their starting position to focus on the point on the wall. After a 5 second waiting period, the participants were instructed to make a 360° turn in the counter-clockwise direction. All participants performed one turn in each direction, clockwise (CW) and counter-clockwise

(CCW). Data utilized for the current analysis, include turn angle (degrees), turn duration (seconds), and peak velocity (degrees/second) (Table 1.1).

Statistical analysis: SPSS Statistics for Windows, Version 22.0 (Armonk, NY: IBM Corp.) was used to perform the statistical analysis. An independent t-test was used to determine group difference in age. Fisher's Exact test was used to describe the difference in the proportion of gender and health conditions. In addition, Levene's test was used to assess the equality of variances between the two participant groups. Differences in the iTUG and 360° turn parameters between older adults with dementia and their older caregivers were determined using independent t-tests (Table 1.1).

1.3 RESULTS

Demographics: Participant demographics and health condition characteristics are reported in Table 1.2.

***Participant demographics for the iTUG analysis*:** Thirty-seven participants with dementia and 38 caregivers were included in the iTUG analysis (Figure 1.1). Participants with dementia were significantly older than the caregivers (mean difference = 6 years, $p < 0.001$). Among participants with dementia, 35.1 % were female, whereas 64.9 % of the caregivers were female. The average score for MMSE for participants with dementia was 17.13 (SD = 6.6). No MMSE was available for the caregivers, though there were no cases of reported or diagnosed dementia in their health history. Comparing the dementia and caregiver groups, there were no significant differences in the percentage of participants with co-morbid health conditions including cardiopulmonary, musculoskeletal, diabetes, hypertension.

Participant demographics for the 360° Turn analysis: Twenty-nine participants with dementia and 40 caregivers were included in the 360° Turn analysis (Figure 1.1). Participants with dementia were significantly older than the caregivers (mean difference = 6 years, $p < 0.001$). Among participants with dementia, 27.6 % were female, whereas 73 % of caregivers were female. The average score of MMSE for the participants with dementia was 18.20 (SD = 6.6). There were no significant differences in the percentage of participants with co-morbid health conditions including cardiopulmonary, musculoskeletal, diabetes, or hypertension between the dementia and caregiver groups.

Instrumented Timed Up-and-Go: Group differences between participants with dementia and the caregivers in the iTUG measures are reported in Table 1.3.

Sit-to-Stand Transitions: Participants with dementia took a significantly longer time to complete the transition from sitting to standing compared to the caregivers (mean difference = 0.22 seconds; $p < 0.05$). However, there were no significant differences between the groups in the trunk lean angle measured at the sternum sensor (mean difference = 2.16 degrees, $p = 0.391$), the average velocity (mean difference = 0.03 m/s, $p = 0.181$), or the trunk displacement measured at the lumbar sensor (mean difference = 0.02 meters, $p = 0.278$).

Stand-to-Sit Transitions: Participants with dementia took a significantly longer time to complete the transition from standing to sitting compared to the caregivers (mean difference = 0.13 seconds; $p = 0.02$). The trunk lean angle was greater in the dementia group and approached significance, the difference between participants with dementia and the caregivers was not statistically significant. (mean difference = 7.31 degrees; $p = 0.053$). Differences in trunk displacement (mean difference = .02 meters, $p = 0.284$) and average velocity (mean difference = .03 m/s, $p = 0.117$) were not statistically significant between the groups.

iTUG turns: The participants with dementia took a significantly longer time to complete the 360°turn and demonstrated a lower peak turning velocity compared to the caregivers, mean difference = 0.45 seconds, $p < 0.001$ and mean difference = 174.14 degrees/s, $p < 0.001$, respectively. The turn degrees detected were significantly less in the participants with dementia than the caregivers, mean = 165.42 degrees DM; 181.01 degrees CG, $p < 0.001$.

Summary of results for the iTUG: On transitions between sitting and standing, participants with dementia were slower when moving form sitting to standing and from standing to sitting; however, there were no statistically significant differences between participants with dementia and their caregivers in the trunk lean angle, trunk displacement, or average velocity in either transition. Participants with dementia demonstrated a slower peak turning velocity and longer turning duration to complete iTUG turn, compared to the older caregivers. The mean turning angle was less (wider) in participants with dementia.

Instrumented 360° turns: Group differences between participants with dementia and the caregivers in the 360° turn measures are reported in Table 1.4. The peak turning velocity was significantly slower in participants with dementia compared to the caregivers in both the CW and CCW turns (mean difference = 44.05 degrees/s CW, $p < 0.001$; 63.49 degrees/s CCW, $p < 0.001$). Participants with dementia took a significantly longer time to complete the turns compared to the caregivers, mean difference = 1.11 seconds CW, $p < 0.001$; 1.38 seconds CCW, $p < 0.001$. There was significantly lower (wider) mean CCW turn angles in participants with dementia compared to the caregivers, mean difference = 14.44 degrees, $p < 0.05$. In the CW direction, the mean turn angle was less (i.e., wider) in participants with dementia compared to caregivers, but the difference was not statistically significant (mean difference = 8.44 degrees, $p = 0.059$).

Summary of results for the 360° Turn analysis: Participants with dementia demonstrated a slower peak turning velocity and longer turning duration to complete 360° clockwise and counterclockwise turns, compared to the older caregivers. The mean turning angle was less (i.e., wider) in participants with dementia.

1.4 DISCUSSION

The aim of this study was to determine whether spatiotemporal parameters of turning and transitions differ between older adults with dementia compared to those without dementia (older caregivers), using portable inertial sensor technology in the home environment. This study demonstrated that participants with dementia had longer turn duration and slower peak turning velocity on the iTUG and 360° turn tests compared to the older caregivers. In addition, participants with dementia had a smaller (wider) turning angle, suggesting differences in movement strategy as well as speed.

The two groups of participants had similarities in the trunk displacement and lean angle of the trunk in the sit-to-stand and stand-to-sit components of the iTUG, however, the participants with dementia performed these transitional movements at a significantly slower speed as compared to the caregiver group, suggesting a similar sitting to standing strategy, but a difference in movement velocity. Mirelman et al. (2014) reported that the duration of total iTUG duration, sit-to-stand transition, and stand-to-sit transition did not differentiate older adults with and without mild cognitive impairment, but consistent with the current study, older adults with mild cognitive impairment were slower on the iTUG turn. In the present study, participants had a greater impairment in the cognitive function, as evident from the MMSE scores (Table 1.2) and the iTUG was performed at a fast speed which may have resulted in a significant impact on the

performance of the sit-to-stand and stand-to-sit transitions. Kuo FC et al. (2014) utilized electro-goniometers to compare the performance of young and older adults on the TUG test, and suggested that the older adults decreased the velocity to control the destabilizing forces during the performance of the TUG. This mechanism may also be relevant in explaining differences in older adults with and without dementia.

The present study found that older adults with dementia performed the transitions and turns more slowly than those without dementia, however, the underlying mechanism for this difference remains unclear. Although several mechanisms may help to explain the differences, cognitive impairment alone may be a major contributing factor due to atrophy of brain and decreased ability to withstand age related pathology (Whalley, 2016). Differences in age also likely contribute to performance differences, however, age-related decline may be accelerated in people with dementia due to reduced physical activity (Fratiglioni, 2000). In addition, stronger knee extensor muscles have been associated with better cognition in older adults (Chen, 2015). A reduction in speed in older adults with cognitive impairment may be a compensatory strategy to decrease ground reaction forces and change the pattern of muscle activity, resulting in reduced loading on the joints (de David, 2015).

Older adults are more susceptible to dual-task mobility decrements in tasks involving cognitive and physical modalities (Porciuncula, 2016). Previously, dual task assessment has also been used as a marker of gait and posture disturbances in dementia (Montero-Odasso et al, 2014). Here, the study demonstrated that the subcomponents of the iTUG and 360° turn tests illuminate the decline in the physical performance in older adults with dementia in absence of a dual task condition competing for cognitive reserve. A recent PET study (Campo N, 2016) provided evidence on the potential direct effects of regional brain pathology in Alzheimer's

disease on motor function. Del Campo N. et al (2016) found a significant association between amyloid beta in the posterior and anterior putamen, occipital cortex, precuneus, and anterior cingulate and slow gait speed. Reduction in cortical grey matter and total hippocampal volumes has been associated with reduced gait velocity (Ezzati A, 2015).

James Lin et al (2014) had tested performance of older adults on the TUG test using electro-goniometers and inclinometers, and reported that along with velocity and timing, the older adults also changed the amount of trunk movement to control their motion. In the present study, between-group difference in the trunk lean angle during the sit-to-stand and stand-to-sit subcomponents of the iTUG did not reach significance. These differences between our findings and Lin's may have resulted because of different instrumentation used for measurements. The inertial sensors used in the present study included three axes accelerometers, gyroscopes, and magnetometers as compared to the electro-goniometers used by James Lin et al (2014).

Previously, Shibbata et al. (2005) used an optoelectronic camera system to study turns in older adults, and concluded that the older adults execute the 180° turns at a slower speed as compared to young adults. Similarly, Wright et al. (2012) using a motion capture system, reported that the older adults with history of falls take longer time to complete 360° turns. The current study demonstrates that older adults with dementia move more slowly during transitions between sitting and standing; and they turn more slowly using a wider turn angle compared to older adults without known dementia cognitive deficits. This suggests that people with dementia are not only slower, but they use a different motor strategy. Moving forward, performance on the iTUG turn and the 360° turn may be a robust indicator of mobility decline in older adults with dementia.

A slower speed and wider turning angle may have enabled participants with dementia to control the destabilizing forces during the turn. Previous research comparing performance of young and older adults suggests that older adults adjust velocities of various body segments to maintain stability while turning (Akram, 2010; Kuo, 2014; Lin, 2014; Wright 2012). Potential mechanism underlying these results may be peripheral or central, including (1) greater biomechanical cost placed on the neuromuscular system during the execution of turning tasks. During turning, knee muscle activity of the stance leg provides body support and knee control, which may be difficult to achieve in older adults with dementia due to reduced quadriceps strength (Chen, 2015), and decreased lower limb function associated with social isolation (Fratiglioni, 2000). Loading patterns of the lower extremity are affected by turn angle during turn actions (Xu, 2006). Wider turn angle may be a strategy to decrease joint loading in older adults with dementia. (2) a difference in the strategy to maintain balance during turning due to atrophy of brain and decreasing structural complexity of cortex (reduction in structural connectivity), which may leads to slowness of information processing, impairments in sensory systems and decreased ability to withstand age related pathology (Whalley, 2016).

Inertial sensors provide valuable data for analysis of mobility in older adults in their home environment. However, there were some limitations in the study. There were more females in the caregiver group compared to the dementia group. The group with dementia was older than the caregiver group. Instead of being limited due to age and gender differences, the study was benefitted by inclusion of the caregivers, considering the similarity in the daily environmental and social factors for the dementia-caregiver pairs. The sample size limited our ability to perform further statistical analysis using age matched groups. Studies with larger sample size would be better powered to conduct age matched analysis.

Table 1.1 Instrumented Timed Up-and-Go, and 360° Turns: Variable Definitions

Test	*Variable*	*Definition (units)*	*Sensor*
Sit-to-stand	displacement	displacement of trunk during standing up from the sitting position (meters)	lumbar
Stand-to-sit	duration	time taken to stand up from the sitting position (seconds)	lumbar
	average velocity	computed using the displacement and duration (m/s)	lumbar
	lean angle	angle of trunk lean during standing up from the sitting position (degrees)	sternum
iTUG turn;	turn angle	angle of rotation of the trunk (degrees)	lumbar
360° turn CW;	turn duration	time taken to complete the turn (seconds)	lumbar
360° turn CCW	peak velocity	peak angular velocity of trunk during turning (degrees/s)	lumbar

CW = Clockwise; CCW = Counter-clockwise

Table 1.2 Demographics and Health

	Instrumented Timed Up & Go			*360° Turns*		
	Dementia (n=37)	Caregiver (n=38)	p-value	Dementia (n=29)	Caregiver (n=40)	p-value
Age; mean (SD)	78.49 (6.7)	72.15 (6.7)	.000**	79.19 (6.8)	73.00 (6.4)	.000**
Sex (% female)	35.1%	64.9%	.001*	27.6%	73%	.000**
MMSE; mean (SD)	17.13 (6.6)	----	----	18.20 (6.6)	----	----
Health Conditions; % (n)						
Cardiopulmonary	24.3% (9)	31.0%(13)	.618	27.6%(8)	29.7%(11)	1.000
Musculoskeletal	59.5% (22)	64.3% (27)	.817	58.6 %(17)	67.6 %(25)	.607
Diabetes	13.5 % (5)	7.1 % (3)	.463	13.8 % (4)	8.1 % (3)	.690
HTN	43.2 %(16)	42.2% (19)	1.000	48.3% (14)	45.9% (17)	1.000

MMSE: Mini Mental State Examination; HTN: Hypertension; ** : $p < .001$; * $p < .05$

Table 1.3 iTUG Components

		Dementia (DM) mean (SD)	*Caregiver (CG)* mean (SD)	*p-value*
Sit to stand (n=37 CG; n=42 DM)	Displacement (m)	.404 (.06)	0.386 (0.07)	.278
	Duration (sec)	1.117 (.23)	0.986 (0.19)	.006*
	Average velocity (m/s)	0.375 (0.08)	0.402 (0.09)	.181
	Lean angle (degrees)	35.27 (11.29)	37.43 (10.65)	.391
Stand to sit (n=37 CG; n=42 DM)	Displacement (m)	0.32 (.06)	0.30 (0.05)	.284
	Duration (sec)	0.91 (0.26)	0.78 (0.21)	.020*
	Average velocity (m/s)	0.37 (0.09)	0.40 (0.8)	.117
	Lean Angle(degrees)	41.06 (16.37)	34.37 (12.87)	.053
iTUG turn (n=37 CG; n=42 DM)	Turn angle (degrees)	165.42 (23.06)	181.01 (6.49)	.000**
	Turn duration (sec)	2.47 (0.57)	2.02 (0.45)	.000**
	Peak velocity (degrees/s)	152.58 (49.23)	226.72 (64.88)	.000**

** : p < .001; * : p < .05

Table 1.4 360° Turns

	Dementia (DM) mean (SD)	*Caregiver (CG)* mean (SD)	*p-value*	*Dementia (DM)* mean (SD)	*Caregiver (CG)* mean (SD)	*p-value*
	Clockwise, n= 40 CG; 29 DM			*Counter-clockwise, n= 40 CG; 29 DM*		
Turn angle (degrees)	349.73 (26.29)	358.17 (7.85)	.059	345.41 (34.15)	359.83 (7.84)	.031*
Duration (sec)	4.47 (1.18)	3.36 (0.67)	.000**	4.61 (1.45)	3.23 (0.67)	.000**
Peak turning velocity (degrees/s)	148.04 (40.47)	192.09 (53.98)	.002*	146.89 (40.31)	210.38 (64.48)	.000**

** : $p < .001$; * : $p < .05$

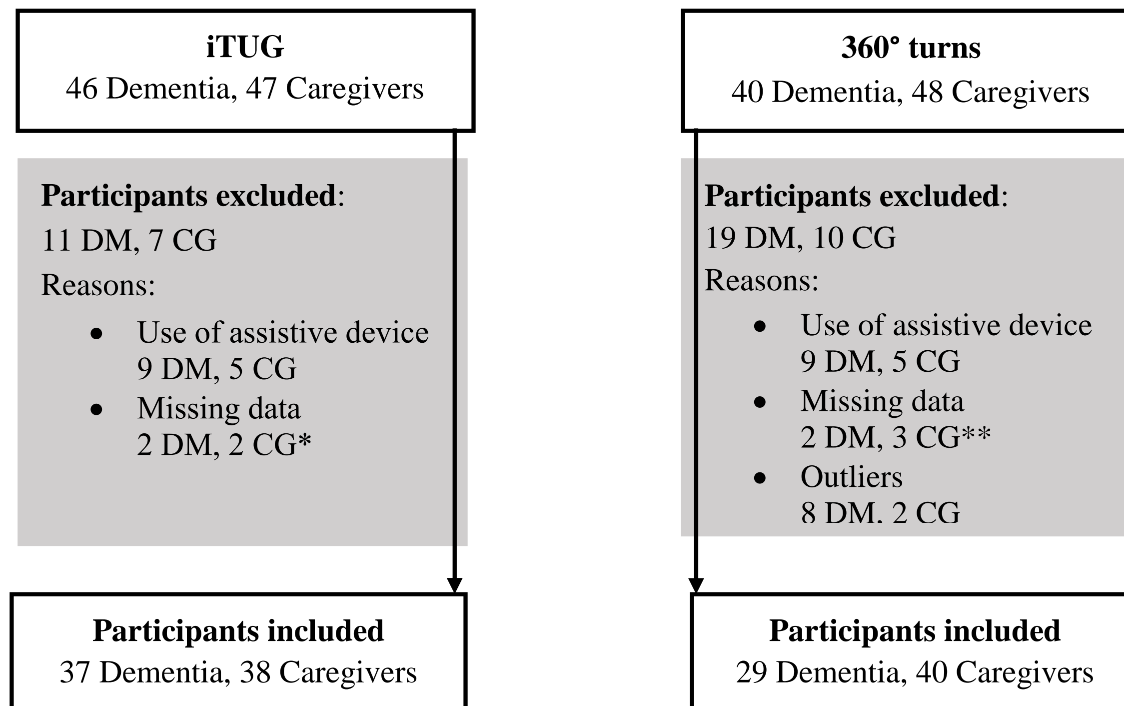

Figure 1.1 Flow diagram of subject inclusion. * TUG data missing for 4 participants due to technical issues related to equipment or software.**360° turns data missing for 2 participants due to inability of the subject to understand the test instructions; 360° turns data missing for 3 participants due to technical issues related to equipment or software.

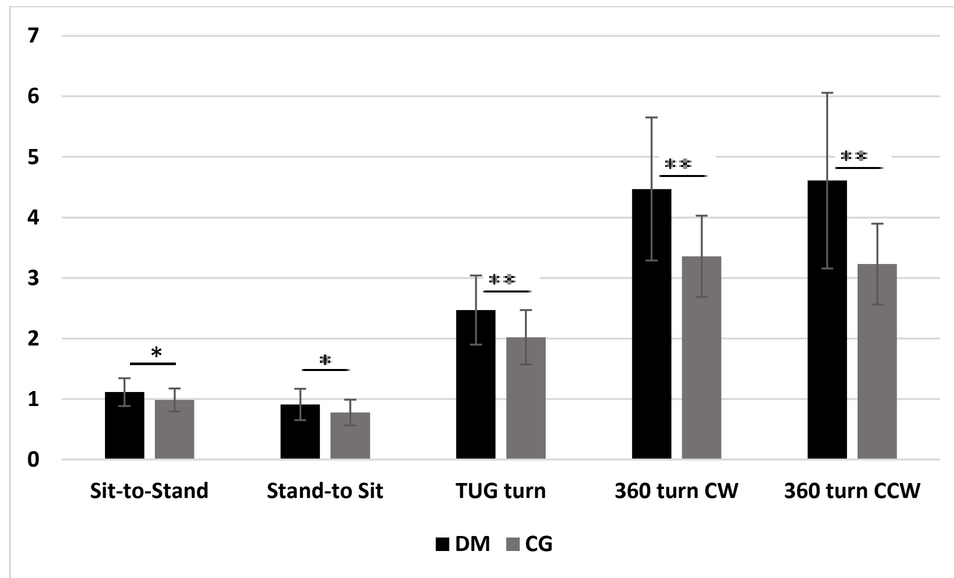

Figure 1.2 Comparison of duration for iTUG components and 360° clockwise (CW) and counterclockwise (CCW) turns between the participants with dementia (DM) and older caregivers (CG). ** : $p < .001$; * : $p < .05$

Chapter 2

Concurrent validity between a portable inertial sensor system and a laboratory-based motion analysis system during a 360° turn test in older adults with cognitive impairment

2.1 INTRODUCTION

Advancement of cutting edge sensor based applications for the healthcare sector has potential to benefit scientific research and clinical practice by providing cost effective, faster methods of objective assessment of health-related outcomes. Wearable sensor technology allows home-based assessments and will likely increase subject recruitment in elderly populations.

Older adults with dementia demonstrate worsening mobility problems with advancing stages of the disease (Aggarwal, 2006). Certain functional tasks of everyday routine put older adults at risk for instability and falls. Atrophy of the brain is one of the risk factors for falls in older adults with cognitive impairment (Yamada, 2013). Therefore, investigation of functional mobility is important to reduce incidence of falls in this patient population. The laboratory-based multi-camera motion analysis system has been considered as a gold-standard for objective quantification of mobility (Kim, 2012). However, the multi-camera motion analysis system is a resource intensive method, which requires significant time and effort to process the data. Body-worn inertial sensors are a portable, low-cost alternative to the laboratory based 3-dimensional multiple camera systems. Recently, there has been a surge in the number of studies utilizing the Ambulatory Parkinson's Disease Monitoring (APDM) portable sensor system for investigation of movement in various patient populations (Horak, 2015; Mancini, 2012; Ramsperger, 2016; Spain 2012). This necessitates examination of concurrent validity between the portable APDM system and the laboratory based motion analysis system.

Concurrent validity is studied when the measurement to be validated and the criterion measure are taken at relatively the same time so that they reflect the same incident behavior (Portney & Watkins, 2009). This method is useful when a new or untested tool is potentially more efficient, easier to administer, more practical than another more established method and is being proposed as an alternative (Portney & Watkins, 2009). The purpose of this study was to examine concurrent validity between quantitative motion analysis of 360° turns obtained from the 8-camera Qualisys Motion Capture System (criterion measure) and the portable APDM Mobility Lab™ motion analysis system (alternative method), in older adults with mild cognitive impairment, in the laboratory setting. The hypothesis of this study was that the spatiotemporal measures of turning performance from APDM system will correlate with those obtained from the Qualisys system demonstrating that both systems measure the same set of parameters.

2.2 METHODS

This study used a cross-sectional design to examine the concurrent validity between the spatiotemporal measures of 360° counterclockwise (CCW) turns obtained from the laboratory-based Qualisys motion analysis versus the portable APDM Mobility Lab motion analysis system. The study was been approved by the Institutional Review Board at the University of Washington. A written informed consent was obtained from the eligible participants prior to participating in the study.

Participants: This project represents preliminary analysis of data from a larger study, "Functional Markers of Mobility Disability in Older Adults With Cognitive Impairment" (P.I., Ellen McGough, PT, PhD, pilot study funded by NIH/NIA P30 AGO34592-03).

Ten older adults with mild cognitive impairment (MCI) and mild dementia were randomly selected from a database of 40 subjects who had undergone concurrent APDM and Qualisys motion analysis testing. *Inclusion criteria* were: 1) 70 years of age or older; 2) a diagnosis of MCI or mild dementia, consistent with the DSM IV-R criteria; 3) able to walk household distances without an assistive device. *Exclusion criteria* were: 1) a known terminal illness (with death anticipated within the next 12 months); 2) hospitalization for a psychiatric disorder in the 12 months prior to baseline; was actively suicidal, hallucinating, or delusional; blind; deaf; or not ambulatory; or 3) a neurological diagnosis other than dementia (e.g., Parkinson's disease or stroke). The data were collected in the University of Washington Human Motion Analysis Laboratory within in the Department of Rehabilitation Medicine (Director: Valerie Kelly, PT, PhD). Two motion analysis systems, the APDM and the Qualisys, were used simultaneously to collect data on turns.

Demographic and health data: Information on age, gender, height, weight, health conditions, sensation and lower extremity function was gathered.

Instrumentation:

APDM Instrumentation: A portable gait and balance laboratory called APDM Mobility Lab™ was utilized to collect, and store the in-lab mobility data. APDM software was installed on an encrypted Windows laptop. Six wireless inertial sensors were secured on the subject's body using Velcro straps at six pre-determined anatomical locations (i.e., sternum, waist [lumbar spine levels 4-5], bilateral wrists, and dorsum of the feet).

Qualisys Instrumentation: A set of 42 retroreflective markers were placed on the bony landmarks of the feet, legs, pelvis, trunk, arms, and head. An eight-camera motion analysis system

(Gothenburg, Sweden) was used to collect three-dimensional (3-D) marker position data at 120 Hz.

Instrumented performance based assessment:

Instrumented 360° turns: The participants were instrumented with APDM sensors as described above and stood on a firm surface with shoes on, their feet positioned in a comfortable stance width and their arms at their side, with their gaze focused on a fixed reference point on the wall. The participants stood at least 2 feet from the wall to allow sufficient space to complete the turn. The participants were instructed to make a 360° turn in the clockwise direction and return to their starting position to focus on the point on the wall. After a 5 second waiting period, the participants were instructed to make a 360° turn in the counter-clockwise direction. . All participants performed one turn in clockwise (CW) direction, followed by the counter-clockwise (CCW). Only CCW turn trials were used for the data analysis in this study. Data utilized for the current analysis, included turn angle (degrees), turn duration (seconds), and peak velocity (degrees/second) (Table 1.1).

Data processing: Qualisys Track Manager was used to identify markers. Visual 3D motion analysis software (C-Motion Inc., Rockville, MD, USA) was used to filter marker position data, build link-segment models, label heel strike and toe-off events, and compute spatiotemporal outcomes. APDM Mobility Lab™ (APDM Inc, USA) data was exported to the Microsoft Excel files for analysis.

Statistical analysis: To test the concurrent validity between the portable APDM inertial sensor system and the laboratory-based Qualisys motion capture system, Spearman’s rank correlations between measures tested by the two systems was examined because of the small sample size

[n=10] (Portney & Watkins, 2009). Strength of correlation was defined as: 0.00 to 0.25 = little or no relationship; 0.25 to 0.50 = fair relationship; 0.50 to 0.75 = moderate to good relationship; above 0.75 = good tp excellent relationship (Portney & Watkins, 2009). SPSS Statistics for Windows, Version 22.0 (Armonk, NY: IBM Corp.) was used to perform the statistical analysis.

2.3 RESULTS

Demographics: Participant demographics and health condition characteristics are reported in Table 2.1. Ten participants with MCI and mild dementia were included in this study. Mean age of participants was 85.2 years (SD = 6.28). 60% of the participants were female. The average score of MMSE for the participants was 26.60 (SD = 2.06). In this cohort, percentage of reported history of cardiopulmonary conditions was 30%, musculoskeletal was 50%, diabetes was 10%, hypertension was 20%.

Correlation between APDM and Qualisys measures: 360° turn CCW data from the APDM and the Qualisys measures are presented in Table 2.2. Concurrent validity of the 360° turn CCW measures obtained from the APDM and the Qualisys motion analysis systems is summarized in Table 2.3 and Figure 2.1. Measures of turn duration and peak velocity demonstrated good to excellent correlations, $r_s = 0.952$, $p < 0.001$ and $r_s = 0.976$, $p < 0.001$, respectively. Change in the APDM measures of turn duration and peak velocity is proportional to the change in those obtained from the Qualisys. There was no correlation between the measure of turn angle obtained from the two motion analysis systems ($r_s = -0.139$). However, the turn angle measures showed reasonable absolute agreement (Table 2.2).

2.4 DISCUSSION

The aim of this study was to examine concurrent validity between the spatiotemporal measures of 360° turns CCW obtained from the laboratory-based Qualisys motion analysis versus the portable APDM Mobility Lab™ (APDM Inc, USA) motion analysis system. For 10 participants with MCI and mild dementia, APDM measures of the 360° turns CCW were correlated with Qualisys measures of the 360° CCW turn. Good to excellent correlation was found between the measures of turn duration and peak velocity for the two motion analysis systems. However, the measure of turn angle showed no correlation. However, the magnitude of the correlation must be considered in context of the variable being measured. Considering that this is a 360° turn, even differences of 15 degrees is only a 7% error, which is reasonably acceptable for practical purposes.

The APDM system utilizes acceleration data from the lumbar sensor for the turning tasks. The APDM algorithm for calculation of the measures takes into consideration the time of start and stop of turn, which is automatically defined as the time of start and stop of the rotation of pelvis in the vertical direction. Anterior or posterior pelvic tilt could result in a small tilt of a few degrees of the accelerometer, which is prone to interpret acceleration due to gravity as part of the acceleration around the vertical axis. This error compounds when calculations are made from acceleration to derive angular position. The Qualisys system derives the measures of turning using the position data obtained from the retroreflective markers. The start and stop times for calculation of turn measures in the Qualisys algorithm are not automatically derived. Instead, these times depend on the manually labeled start and stop times based on the marker position data. The manual labeling is performed on the basis of operational definition of turn start and stop times. Individual variations in the position of sensor, or manual differences in the start and

stop events could be possible sources of error which must be considered while interpreting the association of turn angle measure between the two motion analysis systems.

While correlation tells us how the measures vary together, it cannot tell us the extent of agreement between the two sets of measurements. For research and clinical applications, it is important to know of actual values obtained by the two measurements are the same and not just proportional to each other. It is advisable to use intraclass correlation coefficient in conjunction with correlation analysis. The intraclass correlation analysis would be a more appropriate approach to analyzing this data. With a larger sample size, this statistical approach will be more applicable.

The APDM data analysis software is pre-programmed to use the lumbar sensor for turning related tests. On the contrary, the Qualisys system can be programmed and allows flexibility to plan the analysis based on the requirements of a particular study. It may be advisable to use turn start and stop times based on the position of pelvis, instead of feet, for processing of the position data in the Qualisys system in order to minimize sources of methodological error in studies examining the concurrent validity.

This study had a few limitations. Information on individual variations in the angle of tilt of the pelvis was not available for the study sample to account for the small error in the turn angle measurements in a segment of the study sample. Due to a small sample size, the results of this study should be interpreted with caution. However Despite the small sample size, the results of this study are encouraging.

In conclusion, this is promising preliminary work suggesting that the APDM inertial sensor system may afford a practical alternative to laboratory-based motion analysis, and provide

sensitive measures of movement. It is a faster and easier method of in-home assessment of mobility that reduces barriers for participants, researchers, and clinicians. It would be important to conduct larger concurrent validity studies on a wider range of functional mobility parameters. Future research should also investigate concurrent validity between the laboratory-based motion analysis system and the APDM inertial sensor system tested in the home environment.

Table 2.1 Demographics and Health

	MCI and mild dementia (n=10)
Age; mean (SD)	85.2 (6.28)
Sex (% female)	60%
MMSE; mean (SD)	26.6 (2.06)
Health Conditions; % (n)	
Cardiopulmonary	30% (3)
Musculoskeletal	50% (5)
Diabetes	10 % (1)
HTN	20 % (2)

MMSE: Mini Mental State Examination; HTN: Hypertension

Table 2.2 360° Turn CCW Data Obtained from APDM and Qualisys Motion Analysis Systems

Subject ID	*APDM turn angle (degrees)*	*Qualisys turn angle (degrees)*	*APDM turn duration (seconds)*	*Qualisys turn duration (seconds)*	*APDM turn peak velocity (degrees/s)*	*Qualisys turn peak velocity (degrees/s)*
1007	358.98	366.23	3.3	3.48	179.93	172.19
1012	361.25	361.28	2.88	2.96	228.23	211.47
1014	367.12	365.9	2.7	2.78	272.33	253.58
1016	359.93	359.87	3.09	3.78	233.07	204.18
1019	359.23	360.62	7.58	8.09	89.6	75.31
1020	351.54	357.71	5.23	5.92	125.33	116
1021	350.9	355.49	3.95	4.16	156.46	146.84
1026	369.83	351.53	6.61	6.63	108.26	93.12
1029	363.94	352.66	3.69	3.73	198.72	169.26
1035	353.78	361.91	3.91	4.58	132.92	134.93

Table 2.3 Spearman’s Rank Correlations

	Qualisys turn peak velocity	*Qualisys turn duration*	*Qualisys turn angle*
APDM turn peak velocity	.976**		
APDM turn duration		.952**	
APDM turn angle			-.139

** p<.001

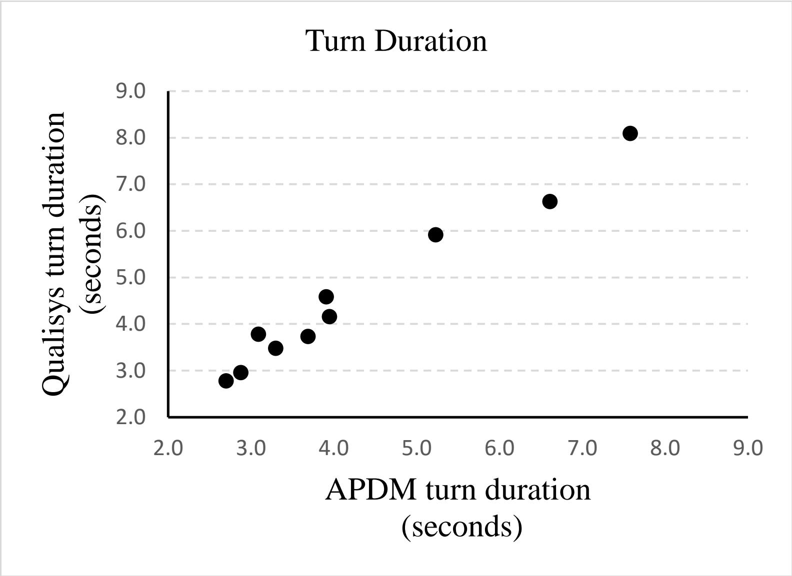

Figure 2.1 a: Spearman’s rank correlation between the measures of turn duration obtained from the APDM and Qualisys systems.

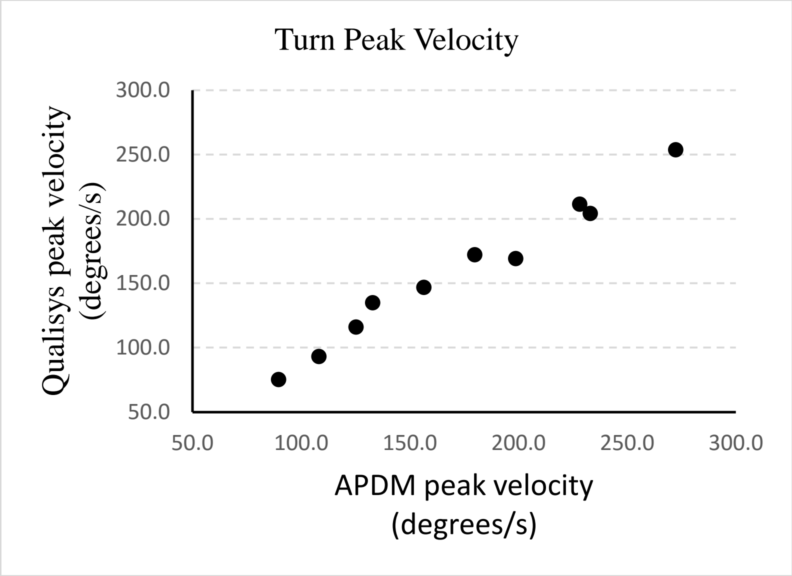

Figure 2.1 b: Spearman's rank correlation between the measures of turn peak velocity obtained from the APDM and Qualisys systems.

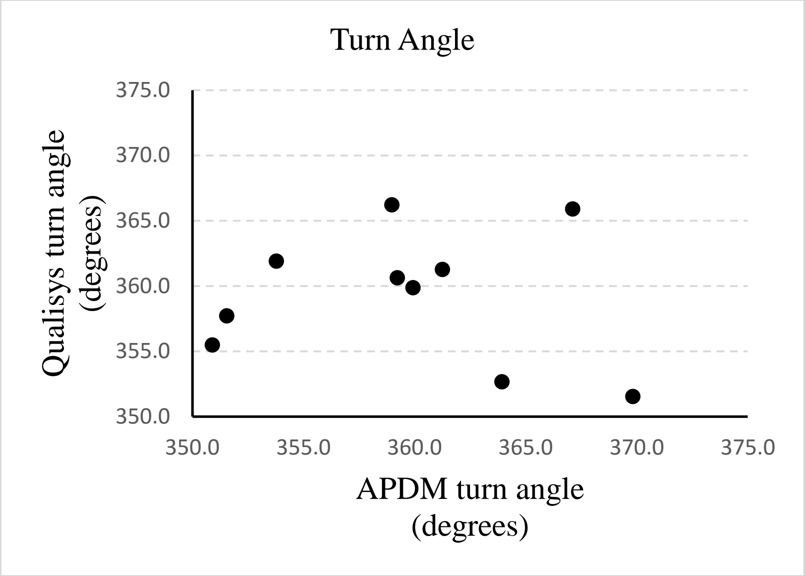

Figure 2.1 c: Spearman's rank correlation between the measures of turn angle obtained from the APDM and Qualisys systems.

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