Grant Final Report

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Evaluation and Integration of an Automatic Fall Prediction System

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Structured Abstract

Purpose: The objectives were to evaluate the relationship of standardized gait and balance assessments used to estimate fall risk and the Fractal dimension (Fractal D) measure of voluntary movement path variability gathered during everyday activities; evaluate the hypothesis that Fractal D would increase prior to an elderly person's fall; and create a practical system for automatically and unobtrusively detecting changes in Fractal D and movement path distance duration and speed.

Scope: Falls and fear of falling are about two times more frequent in elderly persons living in nursing homes and assisted living facilities (ALF) than in community-dwelling aged peers. The research determined if Fractal D would increase fall predictability beyond estimates provided by fall history, gait and balance assessments, cognitive impairments, and psychoactive medication use.

Methods: The voluntary movements of 53 elderly (M=76.6, SD=11.1 years, 83% female) residents in two ALFs were monitored for one year; their falls were recorded.

Results: Mean Fractal D during the week preceding a fall in 23 fallers was statistically significantly higher than for 30 non-fallers whose week represented the midpoint of their observation period. Logistic regression analysis showed only Fractal D and a history of one or more previous falls were significant fall predictors, results supporting the hypotheses tied to the first two objectives of the research. The system for measuring movement path variability was awarded a patent in 2011.

Key Words: fall risk prediction in elderly; movement path variability; fractal dimension

Final Report

Purpose

Objectives of Study

The objectives of the project were the specific aims of the original competing application. The *first* objective was to evaluate the relationship between conventional fall risk assessment measures (elders' performance on standardized gait and balance [SGB] tests) and Fractal D movement tortuosity gathered by real-time movement tracking system (MTS) in their home living (ALF) environment. We hypothesized SGB would share significant variance with coinciding MTS tortuosity measures allowing tortuosity to be a proxy for SGB assessments while yielding improved fall prediction.

The *second* objective was to evaluate tortuosity changes preceding a fall. Consenting volunteers' movements in a common living area were monitored daily for 12 months and individual daily tortuosity measures calculated. The key hypothesis was that increased path tortuosity would predict falls, and that changes in tortuosity occurring in close temporal proximity to the fall will be more predictive than more distal changes. Similarly, current path tortuosity and falls was expected to be related to past fall history, hence falls occurring in the 12-month period prior to the study interval were evaluated for their relationship to movement tortuosity measures taken at SGB assessment. In addition to SGB and fall history, the relationship between other known risk factors and falls were evaluated, including the use of psychoactive medications and difficulties completing activities of daily living. Stated another way, the overall purpose was to determine if changes in path tortuosity prior to a fall improved fall prediction beyond that provided by other known risk factors.

The *third* objective was to determine the software and hardware requirements for an MTS that automatically estimates fall risk in moving elders in community-based settings. In addition to presenting fall risk information to ALF or nursing home staff, the integrated system sends frequent fall risk updates electronically to healthcare providers monitoring persons in ambulatory settings.

Scope

Changes in Movement Patterns and Other Risk Factors for Falls

While risk of falling and fear of falling increase sharply in community-dwelling adults, particularly for those in their eighties,[1] the risk of falls for same aged residents in nursing homes is estimated at two to three times greater.[2-4] Falls are expensive adverse events for the elderly, costing the US economy over $19 billion in 2000; cost estimates increase to $55 billion by 2020.[5] The mix of environmental and predisposing factors for falls and available preventive measures vary widely across living situations.[6, 7] Wagner and colleagues[8] note that even though falls are the most frequent adverse event in nursing homes, there is little consistency in reporting contributing factors. Most falls are related to faller predispositions to unsteadiness, impaired gait, muscle weakness, impaired cognitive and sensory functioning, and prior fall history.[2-4, 9] Antipsychotic and antidepressant drugs contribute to fall risk by affecting cognitive and perceptual motor processes. In a large study of fall risk in nursing homes, French et al.[10] identified 18 fall risk factors; the top three—unsteady gait, need for extensive assistance in activities of daily living (ADL), and wandering—were related to movement patterns. In community-based studies, increased variability in stride-to-stride velocity has been identified as a potent risk factor for subsequent falls in persons with and without cognitive impairments.[11-13]

In sum, changes in the quality and quantity of movement are prominent features associated with changes in health, medication regimens, cognitive impairment, and other predisposing factors involved in fall risk.[14]

Standardized Gait and Balance Assessments (SGB) and Impaired Cognitive Functioning as Predictors of Fall Risk

These two risk factors received careful consideration in the research program. With respect to specific aim 1 listed above, a trained expert performed SGB assessments on all consenting participants at the beginning of the year-long observation period of the research. Assessments of static (balance while not moving) and dynamic (balance while moving in a straight line and making a 180d turn) balance and gait—speed and stride-to-stride variability—while walking on a gait mat were performed. Based on the literature cited above, it was hypothesized that poor SGB performance would predict subsequent falls. The usefulness of SGB as a predictor of later falls varies on the length of the interval between assessment and fall. For example, Hill and colleagues[15] used SGB to identify a group of women with an average age of 74 years who were at low risk for falls. Over the one-year period following the assessment, 49% of the women fell one or more times.

The procedures used to assess movement pattern variability in the present research were originally developed to study the association of movement path variability and cognitive functioning. Impairments in spatial orientation and executive function related to navigation through familiar spaces were factors contributing to elevated movement path variability; both factors have been implicated in risk for falls.[16] As reported by Kearns[17] and Kearns and Fozard,[16] and the original proposal for the completed research program, auxiliary analyses of the two studies cited revealed cases of greater path variability and falls related to impaired cognitive function.

Increased Movement Pattern Variability Prior to a Fall

With respect to specific aim 2, the task was to identify what, when, where or how the changes in movement patterns leading up to the fall event occurred. The major hypothesis of the present research program was that major changes in movement patterns associated with fall risk will occur fairly close in time to the fall event. To evaluate the hypothesis, the voluntary movement paths of persons traveling within common areas of assisted living facilities (ALF) were monitored with a UWB telesurveillance system described in the Methods section and in earlier publications.[18, 19] Briefly, changes in the location of a transponder worn by the person were grouped into paths, each bounded by a 60-second period at the beginning and end of a movement of the transponder. The distance, duration, velocity and vector changes in each movement path was automatically calculated and cumulated over time using Craighead's Real Time Fractal Path Analysis algorithm.[20] Random changes in path direction reflecting uncorrelated turns increase path "tortuosity" and were captured in the Fractal D measure, which ranges from 1.0 when a movement path is perfectly straight (and therefore can be described by a line having a single dimension, of length) to a value of 2.0 when the path is so tortuous (e.g., random) that fully two dimensions of a plane (length and width) are required to describe it. We hypothesized that the contribution of path tortuosity to fall risk would improve estimates of fall risk beyond that provided by previously identified fall risk factors: age;[1] impaired gait and balance;[12, 15, 21, 22] prior fall history;[8, 10, 23] number of ADLs requiring supervision or assistance in community;[1, 8] impaired cognition;[22] and the use of cardiac and analgesic medications,[24, 25] antidepressants,[26, 27] and antipsychotics.[10, 28]

Operational Definition of a Fall

To our knowledge, there are no published data on falls among residents in ALFs which provide hotel services and assistance with ADLs,[29] but not nursing services. Kallin et al.[9] reported a Swedish study of falls in residential care facilities for elderly persons that included various settings from independent living apartments to skilled nursing home care and specialized dementia care units. Following a baseline assessment, 140 women and 59 men in the various settings named were followed for a year; approximately 57% had one or more falls during the observation period, a figure slightly lower than that reported for nursing homes in the United States.

Falls involving voluntary movement were our primary focus. Falls are defined as an unintended movement from an elevated position to a position on the surface on which the person was either standing or from a lower surface such as a chair, with no elaboration of the circumstances surrounding the fall.[30, 31] In prospective fall risk studies in community and some nursing homes, self-report provides the basis for defining injury related falls.[1, 7, 32] In Kallin et al.,[9] a team comprising a physician, nurse and a physiotherapist determined fall circumstances using faller self-reports and eyewitness accounts. In the present study, fall information was obtained from records maintained by state of Florida licensed ALFs providing data on when and where the fall occurred, precipitating circumstances as provided by staff or self-report, and the fall's consequences. Because the focus of the study on relating movement patterns to falls, the present study restricted the definition of a fall to investigators' consensus that the fall occurred during active voluntary movement and not simply sliding from a chair or bed as when dozing or resting.

Research Setting

ALFs were chosen for the research. Some, but not all residents had one or more falls over a year; on average, residents were more capable of self-initiated movements than comparable residents in nursing homes. Good data were available for the other risk factors. The setting provided an economy of scale.

Development of an automatic movement tracking system for measuring variability in human walking. The instrumentation for the research completed under the grant was designed to provide a continuous, automatic and unobtrusive measure of spatial variability in the voluntary movements of ALF residents in the public areas of the ALF. This technology represents an advance over two other broad approaches to studying gait. The first is the use of various devices to measure characteristics of stride velocity and other features of the mechanics of walking. These require the people to adhere to a prescribed path which contains the necessary sensors used to describe the movements. Hausdorff and colleagues[21] have used this approach to demonstrate that increased variations in stride to stride velocity is related to impaired cognition and increased risk for falls, findings that were to a degree replicated in the present study as well as by Verghese and colleagues[12] and Hayes and colleagues.[11]

In order to describe the spatial dimension of movement variability, Algase and colleagues[33] used trained observers to rate the movements of persons with dementia in a nursing home setting. With high inter-rater reliability, the observers were able to distinguish among purposeful movements, e.g., going to the dining area or a bathroom (50%), random wandering (27%), and walking in repetitive or lapping patterns. The descriptions of movements used by the raters were incorporated into the 40-item Algase Wandering Scale—Community Version—for use by untrained observers.[34] The community version of the scale does not include “purposeful” movements, but includes items on elopement attempts and wandering away from the table during meals.

Algase and colleagues[35] described 23 variations on the definition of dementia-related wandering, the most robust of which is randomness in movement patterns. In order to develop a more objective approach to measuring spatial dimension of movement patterns as well as information about the distance, duration and velocity of movements, we developed the procedures described below. Changes in direction of movement paths during movement are described using Fractal mathematics developed to characterize exploratory and food-seeking behavior of wild animals.[36, 37] The system of commercially available hardware and custom designed software used in the research was awarded a United States patent in 2011. A local company, Silent Partner, has licensed the development rights for the patent owned by the University of South Florida.

In summary, the present study investigated the relationship of falls by ALF residents over a one-year observation period to their movement path variability over the same period. The main hypothesis tested was that movement path variability would be greater in persons the week before they fell compared to those not experiencing a fall. To do so, a novel adaptation of location aware telesurveillance technology capable of measuring small directional changes, rate of travel and duration of free movements over long durations[18] was employed. The contribution of these movement dimensions to fall risk was investigated in the context of previously established risk factors for falls.

Methods

Study Design

The main hypothesis of the research was that variability in voluntary movement paths of ALF residents would be greater in the week preceding a fall compared to residents who did not fall. To evaluate this hypothesis, a prospective, observational study using telesurveillance technology was employed.

Participants. The study included 69 ALF residents (53 female) aged 76.9 (SD ±11.9 years), with a mean MMSE of 18.3 (SD ± 7.2). Following University of South Florida IRB approval, recruits were informed the study would examine health changes related to movement patterns over one year using a small lightweight transponder, and their ALF records would be monitored for fall incidents, medications, and health changes. They were informed they would receive a standardized gait and balance (SGB) assessment and short test of cognitive ability, and that the results would be placed in their ALF health records. Proxy consent was obtained for those unable to provide informed consent.

Participants’ classified as Fallers had at least one validated fall (fell during ambulation) and tracking data in the seven prior days. Non-fallers had no validated falls; their data’s midpoint date was substituted and tracking data from the preceding seven days was used. This procedure yielded 23 fallers and 30 non-fallers (16 could not be classified using the validation protocol) for analysis; the characteristics of these 53 mirrored the full group─83% female, mean MMSE=18, SD ± 7 and mean age, 76.6 years, SD ±11.5.

Table 1. Demographic Characteristics of Faller and Non-faller Groups

Characteristic	Fallers n=23	Non-Fallers n=30
Percentage Female	82.6	83.3
Age (+/- 95% CI)	75.61 (+/- 4.60)	75.40 (+/- 4.29)
MMSE (+/- 95% CI)	16.8 (+/- 3.08)	19.00 (+/- 2.34)
% Hispanic	8.7	3.3%
% Black	4.3	10%
ADL’s Needing Assistance (+/- 95% CI)	3.91 (+/- 0.92)	2.50 (+/- 0.60)
% with Dementia Diagnosis	47.8	60.0

Apparatus and movement path data. A Ubisense Ultra-Wideband Real-Time Location System (see http://www.ubisense.net/en/resources/factsheets.html#rtls) with four sensors was installed in two ALFs in a roughly rectangular configuration;18 one Ubisense Compact Tag was assigned to each participant. Some participants with moderate cognitive impairment who routinely removed tags were provided with Wanderguard, Inc. locking wrist straps to reduce data loss. Twenty-six participants (38%) disliked wearing wristbands; prior testing19 revealed no significant differences between positional data generated from tags on wrist straps or on personal assistive devices required for ambulation, so for these participants the tag was attached to their personal assistive devices. Tag position data was recorded on a notebook computer running

Ubisense Platform Ver. 2.1.7. A movement path was defined as 60 s with no tag movement at start and finish; durations of inactivity less than 60 s were considered part of the movement path. Custom written software, “FractalTracker”, implementing Craighead’s Real Time Fractal Path Analysis (RTFPA) algorithm20 calculated Fractal D for each movement path. The calculated Fractal D value represents the degree of non-linearity of a path between two points in space. RTFPA calculates this value by estimating the path length using multiple minimum units of length (spatial scales). These spatial scales vary along the path as a multiple of the mean distance between points that make up the path. These estimated path lengths are then transformed using the following function: f(length, scale) = log(length)/log(scale). D is the slope of the line between two estimates on a log/log plot of estimates transformed by the previous function. RTFPA takes path duration, rate and total distance into account, as rate of travel directly affects the spatial scales used in the estimation of the total path length at the various spatial scales; this path length is a function of rate and path duration. Section 3 of Craighead’s article20 provides a detailed discussion of the RTFPA implementation, and a comparison to other algorithms for estimating D. Movement path duration, rate and distance were also recorded. Data acquisition was remotely managed at each site and automated scripts daily uploaded data to HIPAA compliant storage at the University of South Florida.

Orientation sensor. During SGB participants wore a wireless 9 df orientation sensor (Inertia Cube 3 [IC3], Intersense, Billerica, MA) containing a rate gyroscope, uniaxial accelerometer, and magnetometer.[38] Maximum static accuracy at 255Hz update rate was 0.25° in pitch and roll, and 1° in yaw, with pitch aligned with the body COM sagittal axis thus representing forward and backward sway. An 8M GaitRite mat (CIR Systems, Clifton, NJ) calculated gait parameters.[39, 40]

Procedure. The Mini Mental State Exam (MMSE)[41] was administered at recruitment. The standardized gait and balance (SGB) had several parts; static balance—standing but not moving—was assessed with a modified Clinical Test of Sensory Interaction on Balance (mCTSIB)[42] that included four conditions: 1) eyes open standing on a solid surface, 2) eyes closed standing on a solid surface, 3) eyes open standing on a foam pad, and 4) eyes closed standing on a foam pad. Dynamic balance was assessed by the Timed Get Up and Go Test[43, 44] and the Timed 180° Degree Turn Test.[45] Gait velocity was determined by the Dual-Task Walking Test.[46] Sway (IC3) was recorded during all tests, the presentation order of which was randomized. Cognitively impaired participants unable to understand instructions were not tested. The Timed Get Up and Go Test required participants to rise unassisted, walk rapidly unaided 3M, turn about a cone without touching, return and sit. Participants requiring walking aids or unable to rise unassisted were excluded. Trials completed, duration, maximum and mean turn rate at cone and chair were recorded. In the 180° Turn Test, the participant was asked to rotate exactly 180° while standing. Trials completed, degrees rotated, number of steps and time to complete the turn were recorded. For the Dual-Task Walking Test, participants strode self-paced 8M on a gait mat under single task (no cognitive load) or a dual task condition in which the participant listened to a randomized audio sequence for “X”, and repeated the letter aloud. Number of strides, stride velocity and coefficient of variation (COV), time to traverse the mat, and trials completed were recorded.

Tracking data collection. Following SGB assessment, each participant was instructed to wear their tag during waking hours but remove it for bathing; those with tags on assistive devices were asked to not remove it. Participants were told the tag emitted weak radio signals revealing its location only in the common area between domiciles and the dining area. Data quality control occurred thrice weekly; missing data lasting more than a day resulted in an email message to the ALF operator with a request to determine if tag failure or protocol noncompliance was at issue; in the first instance, the battery or tag was replaced; in the second, the participant was counseled to resume wearing the tag. The tag was worn for as long as the person was in the study. Not every subject completed the year-long participation; some dropped out because of illness, death or movement to a higher level of care.

Fall validation protocol. Investigators independently evaluated fall records to identify falls occurring while ambulating, attempting to stand or transferring, but not sliding from one's seat or bed to the floor; 75% investigator agreement was required. Fall incident reports for the baseline year preceding the study were evaluated using the same criteria. Medications and clinical diagnosis of dementia medication prescription start and stop dates from ALF records were extracted for baseline and observation periods. Medications were classified as psychoactive by an RN/PhD in psychiatric nursing (MB). Participant's clinical diagnosis of dementia was also extracted. Standardized ADL assessments of ambulation, bathing, dressing, toileting, eating, and transferring, characterizing the participant as 'independent', 'needs supervision', 'needs assistance' or 'needs total help' were obtained from ALF records and coded by assessment date.

Data reduction and statistical analyses. Of the 69 participants recruited, seven died; four were discharged to skilled nursing, hospice or other care facilities; and nine voluntarily discontinued participation. In the majority, UWB data acquisition was cut-short by a fall, the focal event of the study. Close examination of their data indicated it did not differ significantly from the 49 who completed all 365 days; mean number of observation days for these 20 participants was 204.2 (SD ± 91.6, range 78-348), while the remaining 49 generated data across the 365-day observation interval, hence the data for the 20 participants were included for analysis. From these 69 subjects, 53 were selected according to the protocol described previously in the subjects section of the method.

Results

Principal Findings

The primary investigation concerned the evaluation of the relationship of a measure of path tortuosity (Fractal Dimension) to standardized gait and balance measures and to the likelihood of eventually falling over a one-year observation window. Data collection commenced in February of 2010 following the hiring and training of technical staff and the preparation of data collection software; recruitment proceeded until June of 2010 when 72 individuals had given consent or proxy consent. Fractal D data collection commenced following the consent process as did the assessment of standardized gait and balance. Data collection was completed in 2012. The major results are summarized in the following order: balance, gait, Fractal D and falls, other risk factors, discussion, implications, and practical applications. The material is adapted almost entirely from the publications resulting from this research project.

Balance and gait. Table 2 displays the means, standard deviations and the number of fallers and non-fallers completing each SGB test. Only the stride time coefficient of variability differentiated fallers from non-fallers. Varying numbers of subjects completed the more difficult dynamic balance assessments.

Table 2. Differences between faller and non-faller groups on SGB measures related to Fractal D.

Measure	Fallers	Non-fallers
Static Balance		
Eyes Open Firm Surface t=.71 df=51 p=n.s	2.07 (SD ± 1.01	2.26 (SD ± .96)
Eyes Closed Firm Surface t=.87 df=51 p=n.s	2.0 (SD ± 1.24)	1.7 (SD ± 1.24)
Eyes Open Foam Surface t=.03 df=51 p=n.s.	.39 (SD ± 1.03)	.40 (SD ± .85)
Eyes Closed Foam Surface t=.53 df=51 p=n.s.).	.39, (SD ± 1.03)	.27, SD ± .69
Dynamic Balance Tests		
180 Degree Turn - Number of steps required t=.54 df=35 p=n.s.	6.18 (SD=3.84) n=17	5.65 (SD=1.73) n=20
180 Degree Turn – Duration of turn in seconds t=.52 df=35 p=n.s.	5.79 (SD=2.93) n=17	5.35 (SD=2.18) n=20
TGUG – Duration of Trial in Seconds t=.57 df=29 p=n.s.	19.11 (SD=4.92) n=15	17.09 (SD=4.66) n=16
Stride Time COV Normal Gait t=3.54 df=32 p<.001	.1511 (SD=.028) n=12	.1111 (SD=.032) n=22
Stride Time COV Dual Task t=2.40 df=32 p<.023	.161 (SD=.059) n=12	.119 (SD=.042) n=22

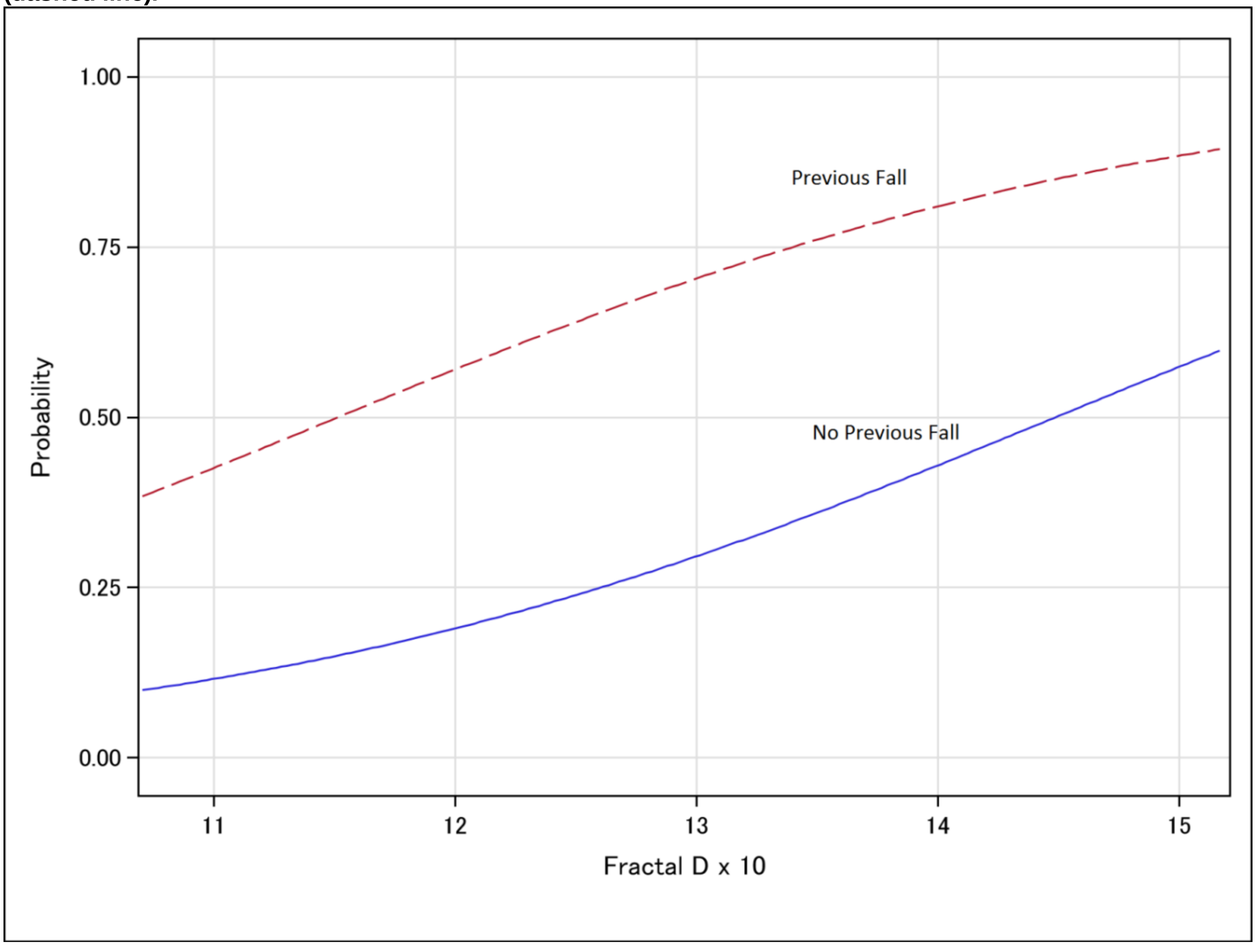
Fractal D, fall history, and psychoactive medications. Preliminary analyses demonstrated that age and gender did not differentiate fallers and non-fallers either when used alone in logistic regressions or when combined with the variables discussed below. Using each participant's fall index date or midpoint index date (for non-fallers), a logistic regression was computed in which four predictors were tested for their ability to differentiate fallers from non-fallers: average Fractal D from movement paths recorded seven days prior to the index date; mean movement path length recorded for the same intervals; one or more recorded falls in the study's baseline year (yes/no); zero versus one or more psychoactive medications prescribed at index event.

Outcomes

Results of the logistic regression revealed odds of falling increased 2.548 (p=.0209; 95% CI 1.152 – 5.635) for every 0.1 increase in Fractal D, while a fall in the prior year increased odds by 7.360 (p=.023; 95% CI 1.760 – 30.785). A non-significant trend for physically longer movement paths to reduce odds of falling (OR=.976 p=.08; 95% CI .949 – 1.003) was observed. Psychoactive medications did not significantly increase odds of falling (OR=.970, p=.889; 95% CI 0.626 – 1.502). The concordance rate for the overall model was 80%. As predicted, mean

Fractal D levels were significantly higher in fallers than non-fallers (1.30 vs. 1.25; t =1.725 df=51 p=.045 [one tailed]). Auxiliary analyses revealed none of the other dimensions of movement differentiated fallers from non-fallers, although a negative relationship of Fractal D with rate of travel (r= -0.54, n=53 p<.001) was similar to that reported earlier.[18] Figure 1 shows the probability of a fall in relation to the average Fractal D in the week prior to the fall conditioned on fall history.

Figure 1. Probability of a fall as a function of the average Fractal D for the seven days preceding a fall for persons with no previous fall (solid line) and persons with a history of one or more falls in the previous year (dashed line).



Changes in Fractal D over time. Possible changes in Fractal D over the total period of time leading up to the fall were evaluated using correlational analyses. The mean Fractal D one week before the fall correlated r=.67 with the Fractal D recorded in the first week of the study and r=.97 with the mean Fractal D in the second (adjacent) week preceding the fall. Neither the first week of the study's recorded mean Fractal D nor the measure recorded two weeks before the fall predicted the future fall.

Relationship of Fractal D to SGB measures. Fractal D was correlated with number of steps (r=.34 n=37 p<.05) and time (r=.47 n=37 p<.01) required to complete the 180 Degree Turn Test, and negatively correlated with the number of degrees rotated (r= -.34 n=37 p<.05), and

(IC3) sway area (r= -.37 n=37 p<.05). Fractal D correlated positively (r=.36 n=37 p<.05) with the time required to complete the Get up and Go Test and positively with Dual-Task Walking Test stride to stride velocity COV (r=.31 n=34 p<.04 [one-tailed]). For the mCTSIB, Fractal D was weakly correlated (r= -.24 n=53 p<.05 [one-tailed] with the number of trials completed) while standing on a foam surface with eyes open. No other measures were related to Fractal D.

ADLs, dementia diagnosis and MMSE. Fallers and non-fallers differed significantly in total ADL's requiring assistance (faller mean=3.91 non-faller=2.50, t=2.605 df=51 p<.05) and ADL's independent (faller mean=2.00 non-faller=3.40, t=2.92 df=51 p<.01) but not in ADL's requiring supervision (faller mean=1.13 non-faller=1.17 t=0.09 df=51 p=n.s.). No significant association was found between falls and dementia diagnosis (Chi-square=.779 df=1 p=ns) or MMSE scores (faller mean=16.8 non-faller mean=19, t=1.14 df=51 p=n.s.); however MMSE scores were negatively correlated with Fractal D (r= -.36 n=53 p<.01), confirming prior observations.[18]

Discussion and Conclusions

Major conclusions. The major finding was that Fractal D, a measure of path tortuosity obtained by telesurveillance technology, is an independent predictor of future falls. Fractal D in combination with a history of one or more falls in the prior year is a strong fall predictor. The failure of psychoactive medications to elevate fall risk was inconsistent with other studies because 51 of 53 participants were taking one or more psychoactive medications.[3, 10, 24] The addition of a continuous dynamic assessment of changes in everyday movement patterns obtained automatically and unobtrusively up to the time of a fall significantly improves fall risk estimation accuracy beyond that provided by other known predictors. In congregate living settings such as nursing homes and ALFs, the costs of the location aware technology are kept relatively low by economies of scale since the infrastructure need not be pervasive; individual tag costs are low, and over 100 residents can be monitored and assessed simultaneously.

While there was a significant difference in Fractal D for fallers and non-fallers, the results don't indicate when group differences emerged. Auxiliary analyses indicated that fallers and non-fallers did not differ significantly at the time of the first week of the study but were significantly different at the time of the fall. This change was not readily predictable from trends in the data nor was it linked to the duration until the fall. For the fallers, the correlation between Fractal D in the seven days immediately preceding the index event with Fractal D in the week prior was 0.97, but was only 0.67 with participants' measures the first week of the study. The results are consistent with our hypothesis that Fractal D delivered by the online monitoring system is more predictive of falls in the near future than in the more distant past. The approach is analogous to the use of an onboard flight recorder by safety engineers to understand events leading up to an aircraft crash.

Cognitive function. Fallers and non-fallers did not differ on MMSE but the negative correlation of MMSE with Fractal D accounting for about 16% of the shared variance reported by Kearns et al. was confirmed.[18, 19] The number of ADLs requiring assistance was significantly higher in our fallers while greater ADL independence distinguished non-fallers, consistent with published findings.[8, 10] Fallers and non-fallers did not differ on static or dynamic balance measures, although fewer successful trials on the foam surface condition is consistent with other studies, as was the eyes open vs. closed difference.[47, 48] The negative correlation of Fractal D with the 180 Degree Turn Test measures indicate that high Fractal D participants make incomplete turns and take longer to do so. Difficulties making a turn even when specifically instructed may reflect navigational errors during normal movements that contribute to increased path tortuosity. We have found Fractal D is inversely related to MMSE geographic orientation item scores[18] indicating spatial confusion.

Gait. Our failure to find that adding a cognitive task increases variability in step lengths, stride times, and stride velocities likely reflects the choice of too easy a cognitive task and a drop in statistical power. Fractal D was significantly correlated with COV and fallers had higher COV than non-fallers, results similar to those of Priest, et al.[49] using similar methodology and instrumentation.

Dispersal of the technology developed for this research program. Five different extensions and adaptations of the technology and measurement systems of the AHRQ-supported research are known to the investigators aside from the development of the patented system described above.

The first adaptation of the location aware technology employed in the present study is was to a sheltered housing rehabilitation program for veterans with traumatic brain injury (TBI) being conducted at the James A. Haley Veterans Hospital.[50] Transponders worn by residents and therapists identify the location of each person in the living area. The location aware technology will enable customized visual and auditory prompts to be triggered as appropriate when individuals reach particular locations (e.g., stoves, the exit to the facility and specific people).

The second adaptation is a study of changes in functional ability in relation to falls. The equipment installed in one of the research sites used in the completed AHRQ-supported project was augmented by the addition of several Ubisense sensors that collectively allow monitoring of patient movements in halls and entrances to sleeping areas where a majority of falls actually occur. This is a year-long study currently in progress.

The third use of our movement tracking system is to validate another movement tracking technology developed specifically to detect falls by installing it in the same public areas of the ALFs employed in the completed AHRQ-supported project. The accuracy of the new technology, developed by Q-track, Inc. in Huntsville, AL and funded under the National Institutes of Health SBIR program, will be compared to that provided by the location aware technology used in the AHRQ-supported study. Dr. Kearns is a consultant to this project via a USF subcontract.

The fourth use involves the use of the customized Fractal Tracker software developed by Craighead.[20] Researchers at the University of Missouri use optical based systems to describe the movements of senior residents in a dedicated cluster of apartments outfitted with a number of movement and activity monitoring sensors.[51, 52] They have successfully used the Fractal Tracker to assess path tortuosity gathered by optical movement sensors (Kinect based) in relation to falls. Preliminary results indicate that residents who fell have higher Fractal D than those who did not. A similar project linking Fractal Dimension to visual recordings of fallers and non-fallers is in the planning stages with researchers at the University of Toronto and Simon Frasier University, British Columbia, CN.

The fifth use is an ongoing research project compares movement path variability in outdoor movement paths by veterans reporting an experience of exposure to situations associated with TBI to those not reporting such exposure. Movement paths are tracked using GPS technology.

Two groups of veterans are being evaluated—veterans living in the community and a group undergoing treatment in the dedicated residential facility for rehabilitation of veterans with TBI described above. Comparison of outdoor movement path variability among the three groups will identify possible differences according to severity of injury. In the group of veteran patients, it will be possible to correlate path variability measured indoors with the Ubisense system to that measured in outdoor movements by the GPS technology.

Summary. With respect to Objective 1, we have determined that the relationship between SGB and subsequent falls is weak, although there is a relationship between some SGB measures and Fractal D. The main reason for this finding was that level of difficulty of most of the SGB assessments were high enough that many of the participants were unable or unwilling to perform them even though were all able to participate in the assessment of movement variability in their daily movements.

With respect to Objective 2 of the original proposal, we have, as predicted, demonstrated that an automatic dynamic quantitative assessment of the variability of everyday movements is an independent predictor of fall risk which, when combined with other known risk factors for falls, can significantly improve the accuracy of fall prediction beyond that possible by other risk factors alone. Because of the large number of residents in most nursing homes and ALFs, we believe the continuous assessment of changes in path tortuosity before a fall may be a useful addition to current procedures used to predict fall risk such as assessment of ADL's, gait and balance, prior fall history, and psychoactive medication use.

With respect to Objective 3, we have created and patented a system of hardware and customized software that provides a reliable and automatic assessment of Fractal D that can be used in ALFs and nursing homes. In addition, information on the direction, duration and speed of movements are automatically assessed. In the commercialization of the patent−owned by the University of South Florida—by Silent Partner (the company licensing the patent), the human tracking function can be combined with other features such as detection of residents exiting or entering the facility or tracking the movements of staff.

The operation of the data collection and processing system was remotely monitored in the present research. Computer and network system failures, battery failures, malfunctioning, lost and unworn transponders were all detected remotely and corrective actions were taken including remedial instructions being sent to the operator of the ALF. The data in the case of the present research was automatically uploaded as a file to a remote site for additional processing; a similar protocol would be employed if the data were being sent via a secure link to an EHR appended to the individual's record. Thus, both the operator of the facility and medical personnel can be apprised of potentially dangerous changes in the movement patterns of residents. All of these features are integrated into the system being commercialized.

All three of the stated goals of the AHRQ grant have been successfully achieved as described in the following list of publications, presentations, and the patent named below.

References

1. Schiller J, Kramarow E, Dey A. *Fall injury episodes among noninstutionalized older adults: United States, 2001-2003.* Hyattsville, MD: National Center for Health Statistics;2007. Advance data from vital and health statistics; no 392.

2. Rizzo JA, Friedkin R, Williams CS, et al. Health care utilization and costs in a Medicare population by fall

status. *Med Care* 1998;36(8):1174-88.

3. Rubenstein L. Falls in older people: epidemiology, risk factors and strategies for prevention. *Age Ageing* 2006;35(Suppl 2):ii37-ii41.

4. Rubenstein L, Josephson K, Robbins A. Falls in the nursing home. *Ann Intern Med* 1994;121(6):442-51.

5. Stevens J, Corso P, Finkelstein E, et al. The costs of fatal and non-fatal falls among older adults. *Inj Prev* 2006;12:290-5.

6. Jensen J, Lundin-Olsson L, Nyberg L, et al. Fall and injury prevention in older people living in residential care facilities. A cluster randomized trial. *Ann Intern Med* 2002;136(10):733-41.

7. Tinetti ME, Doucette JT, Claus EB. The contribution of predisposing and situational risk factors to serious fall injuries. *J Am Geriatr Soc* Nov 1995;43(11):1207-13.

8. Wagner LM, Scott V, Silver M. Current approaches to fall risk assessment in nursing homes. *Geriatr Nurs* 2011;32(4):238-44.

9. Kallin K, Jensen J, Olsson LL, et al. Why the elderly fall in residential care facilities, and suggested remedies. *J Fam Pract* 2004;53(1):41-52.

10. French DD, Werner DC, Campbell RR, et al. A multivariate fall risk assessment model for VHA nursing homes using the minimum data set. *J Am Med Dir Assoc* 2007;8(2):115-22.

11. Hayes TL, Pavel M, Kaye JA. An unobtrusive in-home monitoring system for detection of key motor changes preceding cognitive decline. *Conf Proc IEEE Eng Med Biol Soc* 2004;4:2480-3.

12. Verghese J, Holtzer R, Lipton R, et al. Quantitative gait markers and incident fall risk in older adults. *J Gerontol A Biol Sci Med Sci* 2009;64A(8):896-906.

13. Yogev-Seligmann G, Hausdorff JM, Giladi N. The role of executive function and attention in gait. *Mov Disord* 2008;23(3):329-42; quiz 472.

14. Kearns W, Fozard J, Lamm R. How knowing who, where and when can change health care delivery. In: Rocker C, Ziefle M, eds. *E-health, assistive technologies and applications for assisted living: challenges and solutions*. Hershey, PA: IGI Global; 2011. p. 139-60.

15. Hill K, Schwarz J, Flicker L, et al. Falls among healthy, community-dwelling, older women: a prospective study of frequency, circumstances, consequences and prediction accuracy. *Aust N Z J Public Health* 1999;23(1):41-8.

16. Kearns WD, Fozard JL. Tracking natural human movements identifies differences in cognition and health. In: Augusto J, Huch M, Kameas A, et al., eds. *Handbook of ambient assisted living: technology for healthcare, rehabilitation and well-being*. Amsterdam, NL: IOS Press BV; 2012. p. 331-45.

17. Kearns WD. Of falls and fractals: my career with my mentor, colleague and friend, Professor James L. Fozard. *Gerontechnology* 2010;9(3):388-96.

18. Kearns W, Fozard J, Nams V, et al. Wireless telesurveillance system for detecting dementia. *Gerontechnology* 2011;10(2):90-102.

19. Kearns WD, Nams VO, Fozard JL. Tortuosity in movement paths is related to cognitive impairment. Wireless fractal estimation in assisted living facility residents. *Methods Inf Med* 2010;49(6):592-8.

20. Craighead J. Using fractal dimension to assess robot operator skill in a search task. *J of Intell Robotic Syst* 2011;64(1):97-118.

21. Hausdorff J. Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. *Hum Mov Sci* 2007;26(4):555-89.

22. Hausdorff JM, Balash J, Giladi N. Effects of cognitive challenge on gait variability in patients with Parkinson's disease. *J Geriatr Psychiatry Neurol* 2003;16(1):53-8.

23. Maki BE. Gait changes in older adults: predictors of falls or indicators of fear. *J Am Geriatr Soc* 1997;45(3):313-20.

24. Leipzig RM, Cumming RG, Tinetti ME. Drugs and falls in older people: a systematic review and meta-analysis: I. Psychotropic drugs. *J Am Geriatr Soc* 1999;47(1):30-9.

25. Liu BA, Topper AK, Reeves RA, et al. Falls among older people: relationship to medication use and orthostatic hypotension. *J Am Geriatr Soc* 1995;43(10):1141-5.

26. Ruthazer R, Lipsitz LA. Antidepressants and falls among elderly people in long-term care. *Am J Public Health* 1993;83(5):746-9.

27. Thapa PB, Gideon P, Cost TW, et al. Antidepressants and the risk of falls among nursing home residents. *N Engl J Med* 1998;339(13):875-82.

28. Cumming RG. Epidemiology of medication-related falls and fractures in the elderly. *Drugs Aging* 1998;12(1):43-53.

29. Park-Lee E, Caffrey C, Sengupta M, et al. Residential care facilities: a key sector in the spectrum of long-term care providers in the United States. *NCHS Data Brief* 2011;78:1-8.

30. Kellog International Work Group on the Prevention of Falls by the Elderly. The prevention of falls in later life. A report of the Kellogg International Work Group on the Prevention of Falls by the Elderly. *Dan Med Bull* 1987;34(Suppl 4):1-24.

31. Tromp AM, Smit JH, Deeg DJ, et al. Predictors for falls and fractures in the Longitudinal Aging Study Amsterdam. *J Bone Miner Res* 1998;13(12):1932-9.

32. Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch Phys Med Rehabil* 2001;82(8):1050-6.

33. Algase DL, Son GR, Beattie E, et al. The interrelatedness of wandering and wayfinding in a community sample of persons with dementia. *Dement Geriatr Cogn Disord* 2004;17(3):231-9.

34. Algase DL. Assessment of wandering behaviors. In: Nelson AL, Algase DL, eds. *Evidence-based protocols for managing wandering behaviors*. New York: Springer Publishing Company, LLC; 2007. p. 75-104.

35. Algase DL, Moore DH, Vandeweerd C, et al. Mapping the maze of terms and definitions in dementia-related wandering. *Aging Ment Health* 2007;11(6):686-98.

36. Nams VO. Improving accuracy and precision in estimating fractal dimension of animal movement paths. *Acta Biotheor* 2006;54(1):1-11.

37. Nams VO, Bourgeois M. Fractal dimension measures habitat use at different spatial scales: an example with marten. *Can J Zool* 2004;82:1738-47.

38. Jasiewicz JM, Allum JH, Middleton JW, et al. Gait event detection using linear accelerometers or angular velocity transducers in able-bodied and spinal-cord injured individuals. *Gait Posture* 2006;24(4):502-9.

39. Cutlip RG, Mancinelli C, Huber F, et al. Evaluation of an instrumented walkway for measurement of the kinematic parameters of gait. *Gait Posture* 2000;12(2):134-8.

40. McDonough AL, Batavia M, Chen FC, et al. The validity and reliability of the GAITRite system's measurements: A preliminary evaluation. *Arch Phys Med Rehabil* 2001;82(3):419-25.

41. Crum RM, Anthony JC, Bassett SS, et al. Population-based norms for the Mini-Mental State Examination by age and educational level. *JAMA* 1993;269(18):2386-91.

42. Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction of balance. Suggestion from the field. *Phys Ther* 1986;66(10):1548-50.

43. Podsiadlo D, Richardson S. The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 1991;39(2):142-8.

44. Shumway-Cook A, Brauer S, Woollacott M. Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Phys Ther* 2000;80(9):896-903.

45. Simpson J, Worsfold C, Reilly E, et al. A standard procedure for using TURN180 Testing dynamic postural stability among elderly people. *Physiotherapy* 2002;88(6):342-53.

46. Ebersbach G, Dimitrijevic MR, Poewe W. Influence of concurrent tasks on gait: a dual-task approach. *Percept Mot Skills* 1995;81(1):107-13.

47. Allum JH, Carpenter MG. A speedy solution for balance and gait analysis: angular velocity measured at the centre of body mass. *Curr Opin Neurol* 2005;18(1):15-21.

48. Allum JH, Carpenter MG, Adkin AL. Balance control analysis as a method for screening and identifying balance deficits. *Ann N Y Acad Sci* 2001;942:413-27.

49. Priest AW, Salamon KB, Hollman JH. Age-related differences in dual task walking: a cross sectional study. *J Neuroeng Rehabil* 2008;5:29.

50. Jasiewicz J, Kearns W, Craighead J, et al. Smart rehabilitation for the 21st century: the Tampa Smart Home for veterans with traumatic brain injury. *J Rehabil Res Dev* 2011;48(8):vii-xviii.

51. Stone E, Skubic M. Evaluation of an inexpensive depth camera for in-home gait assessment. *J Ambient Intell Smart Environ* 2011;3(4):349-61.

52. Stone E, Skubic M. Capturing in-home gait parameters using vision-based sensing. *Gerontechnology* 2012;11(2):260.

List of Publications and Products

Patent

University of South Florida. United States Patent, number US7978085-1, issued to Kearns W, Fozard J, and Kostis, E. on July 12, 2011 for the invention of Human and Physical Asset Movement Pattern Analyzer.

Peer-Reviewed Journal Articles and Chapters

1. Kearns WD. Of falls and fractals: My career with my mentor, colleague and friend, Professor James L. Fozard. *Gerontechnology* 2010;9(3):388-96.

2. Kearns WD, Nams VO, Fozard JL. Tortuosity in movement paths is related to cognitive impairment. Wireless fractal estimation in assisted living facility residents. *Methods Inf Med* 2010;49(6):592-98.

3. Kearns WD, Fozard, JL, Lamm RS. How knowing who, when and where about an individual can improve health care. In: Ziefle M and Rocker C, editors. *Human-centered design of e-health technologies: Concepts, methods and applications.* Hershey, PA: IGI Global; 2011. p. 139-60.

4. Kearns WD, Fozard JL, Nams VO, Craighead JD. Wireless telesurveillance system for detecting dementia. *Gerontechnology* 2011;10(2):90-102.

5. Kearns WD, Fozard JL. Tracking natural human movements identifies differences in cognition and health. In: Augusto JC, Huch M, Kameas A, et al, editors. *Handbook of ambient assisted living: Technology for healthcare, rehabilitation and well-being.* Amsterdam, NL: IOS Press; 2012. p. 331-345.

6. Fozard JL, Wahl H-W. Age and cohort effects in gerontechnology: A reconsideration. *Gerontechnology* 2012;11(1):10-21.

7. Kearns WD, Fozard JL, Becker M, et al. Path tortuosity in everyday movements of elderly persons increases fall prediction beyond knowledge of fall history, medication use, and standardized gait and balance assessments. *JAMDA* 2012;13(7):665.e7-685.e13.

Presentations, Including Published Abstracts

1. Fozard JL, Kearns WD (Symposium Conveners). Where and how are you?: Location aware technologies to assess gait and everyday activities. Presenters: A Glascock, A Milhailidis, M Skubic, J Craighead, PC Tuan (Discussant). *Gerontechnology* 2010;9(2):87-90.

2. Kearns WD. Elder path tortuosity covaries with MMSE geographical orientation subscale. *Gerontechnology* 2010;9(2):176-7.

3. Kearns WD, Fozard JL, Nams VO, Craighead J, Jasiewicz, J. High locomotor variability in free movements of assisted living facility residents predicts cognitive impairment. Presentation at GAIT2010; 2010 Feb 26-28; Washington, DC.

4. Kearns W. Of falls and fractals: My career with my mentor, colleague and friend, Professor James L. Fozard. Closing Plenary Speech at the Seventh International Conference on Gerontechnology; 2010 May 26-30; Vancouver, Canada.

5. Kearns W. Evaluation and integration of an automatic fall prediction system. Plenary speech at the 11th Annual Transforming Fall Management Practices Conference; 2010 May 3-6; Clearwater Beach, FL.

6. Kearns WD. Elder path tortuosity covaries with MMSE geographical orientation subscale. Paper presented in symposium entitled "The use of activity monitoring in care for persons with dementia (Willems CG) at the 7th International Conference on Gerontechnology; 2010 May 30; Vancouver, Canada.

7. Craighead J, Kearns WD, Fozard J, Hart Hughes S, Jasiewicz J. Gait up and go. A therapist-friendly iPod-based tool for mobility assessment. Presentation at 2010 Agency for Healthcare Research and Quality Meeting of Contractors and Grantees; 2010 Jun 2-4; Washington, DC.

8. Kearns WD. The role of active location aware technology in a smart house based rehabilitation program for veterans with traumatic brain injury. Invited presentation, Ubisense Worldwide User Conference; 2010 Sep 21-24; Cambridge, England.

9. Kearns W. Location aware technologies: implications for healthcare research and practice. Presentation at USF Polytechnic, Journey through Aging; 2010 Oct 30; Lakeland, FL.

10. Kearns W. Innovative uses of UWRFID in healthcare: how knowing who where and when can improve health services. HIMSS Conference; 2011 Feb 22; Orlando, FL.

11. Kearns WD, Fozard JL. Path tortuosity and fall risk. Presented at the Georgia Institute of Technology Research Institute, 2011 Apr 21, Atlanta, GA.

12. Fozard JL, Kearns WD. Fall risk and movement path variability. Presented at the Georgia Institute of Technology Psychology Department presentation; 2011 Apr 21; Atlanta, GA.

13. Kearns W. Ultra-wideband RTLS tracking in ALF residents links natural movement variability to dementia. Presentation at the US Department of Veterans Affairs national conference "Tracking our Future: VHA and RTLS"; 2011 Jun 1-3; Atlanta, GA.

14. Kearns WD, Fozard JL (Symposium Conveners). The sensitive residence: Predicting health changes using sensor networks. Presenters: C Galambos, T Hayes, WD Kearns, S Sundarrao. *Gerontechnology* 2012;11(2):272-4.

15. Kearns WD, Fozard, JL, Becker M, et al. Something in the way she moves: Falls and fractal dimension. *Gerontechnology* 2012;11(2):272-3.

16. Kearns W. Increased path tortuosity related to falls in assisted living facility residents. Presentation at the 2012 Transforming Fall Management Practices Conference - Wandering and Missing Incidents Consortium: Maximizing Safety and Independence for Persons with Dementia. US Department of Veterans Affairs; 2012; Clearwater Beach, FL.

The following paragraphs summarize the information in the publications and presentations and refer to them by number (e.g., “Publication 2” or “Presentation 2”).

Path tortuosity and cognitive functioning. Impaired cognitive functioning in elderly persons, especially in those with dementia is negatively correlated with path tortuosity. Publications 1, 2 and 4 and Presentations 2, 4, 6, 9-12, demonstrated that the active location aware technology used in the current AHRQ supported research successfully identify differences in everyday movement patterns related to cognitive impairment and the clinical diagnosis of dementia. Specifically, increased movement path tortuosity (irregularity in movement patterns) is negatively correlated with scores on the Mini Mental Status Exam (MMSE), a widely used test for assessing cognitive functioning in the elderly. Publication 4 demonstrated that increased pathway tortuosity better differentiated between demented and non-demented elders than the MMSE. Linking differences in path tortuosity to cognitive functioning created an important conceptual framework for the current research that seeks to demonstrate that increased path tortuosity precedes a fall. Publication 1 summarizes the preliminary data that supported the initial application for the completed AHRQ-supported research project.

Research results supporting the predicted association between elevated path tortuosity and fall risk. Publication 7 and Presentations 5, 6, and 13-15 describe the evidence supporting the association between Fractal D and probability of a fall. Publication 7 also presents the data relating fall risk to SGB and other risk factors for falls. Most of this final report is taken from or adapted from Publication 7.

Rationale for linking changes in path tortuosity to falls. Publications 3-5 elaborate and extend on the rationale for the present research contained in the original grant proposal for the ongoing research. In Publication 3, several chronic conditions of elderly persons were described that are associated with increased difficulties in gait and balance. The paper describes the movement ecology paradigm as a theoretical framework for interpreting changes in path tortuosity. The paradigm is a transactional analysis that links three features of and individual—

internal state (why move), navigational capacity (where to move) and motion capacity (how to move)—to features in the external environment. Each change in a person's location defines a movement path that changes the person-environmental dynamic. Publications 3 and 5 describe several ways in which the automatic movement pattern devices could be used to detect changes in gait, balance and movement patterns by persons living in their homes. Publication 6 describes the relative contributions of cohort and age differences to intrasubject variability particularly in relation to cognition.

Expanding the usefulness of active location aware technology. The first adaptation of the location aware technology employed in the present study was to a sheltered housing rehabilitation program for veterans with traumatic brain injury (TBI) being conducted at the James A. Haley Veterans Hospital. Transponders worn by residents and therapists identify the location of each person in the living area. Customized visual and auditory prompts are triggered as appropriate when individuals reach particular locations (e.g., stoves, washing machines, specific people). This work was described in Presentation 4. Presentation 3 described an effort to improve the quality of the gait and balance assessments used in the ongoing research. A wireless device was created to capture information about the gait and balance assessment in a manner friendlier to the person doing the assessment.