Tortuosity in Movement Paths Is Related to Cognitive Impairment

Wireless Fractal Estimation in Assisted Living Facility Residents

W. D. Kearns[1]; V. O. Nams[2]; J. L. Fozard[3]
[1]Department of Aging and Mental Health, Louis de la Parte Florida Mental Health Institute, College of Behavioral and Community Sciences, University of South Florida, Tampa, FL, USA;
[2]Department of environmental Sciences, Nova Scotia Agricultural College, Truro, Nova Scotia, Canada;
[3]School of Aging Studies, College of Behavioral and Community Sciences, University of South Florida, Tampa, FL, USA

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Summary
Background: Using traditional assessment procedures, prior research demonstrated that deficiencies in gait and balance occur in the later stages of dementia.
Objective: We tested the hypothesis that an automated system capable of detecting path tortuosity (irregular movement) in elders would show that greater tortuosity was associated with greater cognitive impairment, potentially allowing early detection of dementia over time as tortuosity levels slowly increased.
Methods: An ultra-wideband sensor network using wireless transponders measured daytime locomotion to an accuracy of 20 cm in 14 elderly residents in an assisted living facility (ALF) as they traversed a shared living area while performing daily activities such as going to a dining area, conversing and watching television. Transponder location was updated at 0.4 sec intervals while in motion and revealed large individual differences in activity patterns.
Results: Fractal dimension (Fractal D), a measure of movement path tortuosity (directed vs. irregular or apparently aimless locomotion) was significantly and negatively correlated with cognitive status as measured by the Mini Mental State Examination administered to each participant at the study's end.
Conclusions: Previous studies of locomotion in laboratory settings that have demonstrated gait variability increases with poor cognitive status have necessarily controlled various components of gait. The present results demonstrate that directional changes and other locomotion components can be studied by monitoring free movements in normal living settings over time. Implications for assessment and management of dementia-related wandering are discussed.

Correspondence to:
William D. Kearns, PhD
Department of Aging and Mental Health
MHC 1436
Louis de la Parte Florida Mental Health Institute
College of Behavioral and Community Sciences
University of South Florida
13301 N. Bruce B. Downs Blvd.
Tampa, Florida 33612
USA
E-mail: kearns@fmhi.usf.edu

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1. Introduction

Gait and balance disturbances related to impaired cognitive functioning and falls have been studied on prescribed courses using devices such as gait mats and accelerometers [1–5]. Most of the published research on the consequences on gait and balance resulting from cognitive deficits utilize brief, structured assessments that require ambulatory subjects to traverse a designated path under various challenges – cognitive deficits identified by independent psychological assessments, and/or those imposed by the task itself, e.g., dual tasking, walking speed, path complexity, etc. One major result of this work is the identification of variability in the temporal components of the stride to stride movements. Giladi et al. [6], Verghese et al. [7] and Hausdorff et al. [8] have applied fractal analytic techniques to standard gait assessments to unveil new gait variability information. Giladi et al. [6] have found that increased stride time variability correlated negatively (–.47) with participants' MMSE scores, and also predicted increased fall risk in community-dwelling elders. Temporal variability may reflect deficiencies in memory and cognition needed to navigate one's environment, directly influencing dementia-related wandering [9]. The expression of wandering's spatial component has been defined as the difference in length of successive strides or the number of times a step falls outside a specified path [10].

The present investigation relates cognitive functioning to the natural variability of movement paths unconstrained by a contrived test environment; we directly assess natural path variability generated in routine activities in normal living environments using a technology that also measures rate and quantity of movement. Quantifying the temporal and spatial components of wandering behavior, defined as repetitive or random variations in unconstrained voluntary movements [11], has remained a challenging task because these components can be expressed over large areas. Wandering is manifested in goal-directed (e.g., going from bedroom to bathroom), and aimless movements [12] and occurs in approximately 60% of dementia patients. The importance of the spatial component in detecting preclinical cognitive decline has been underscored in a longitudinal study that identified three cognitive functions which changed in the years prior to dementia diagnosis: visuospatial, global, and verbal and working memory [13] declined at three, two, and one year prior to diagnosis, respectively. In a study of five years of clinical records of symptoms identified in patients with preclinical dementia, gait disturbances were the earliest predictor, followed by cognitive complaints [14].

A behavioral rating scale [15] has been used to successfully classify different wandering patterns in open field situations using trained observers; however it is obtrusive, requires vigilant observers, and necessarily restricts the range over which observations may be gathered. Algase and colleagues [16] have attempted to automate data collection and extend the scope of observations by comparing the effectiveness of four accelerometer devices to measure wandering while simultaneously categorizing behavior using observers; the best device accounted for about 69% of the variance in observer-defined wandering. The devices tested did not provide participant vector data, however, so no information regarding the directional characteristics of the paths generated was gathered.

One goal of the present study was to test an automated movement assessment system which yields duration and vector information comparable or exceeding those derivable from accelerometry and gait mats, with the eventual aim of detecting long-term changes in natural movement variability possibly indicative of cognitive decline [17–19]. Kearns and colleagues [20] have demonstrated that ultra-wideband (UWB) radio transponders can accurately track persons inside buildings to within 20 cm under laboratory conditions, suggesting that naturally occurring wandering behavior in ALFs and other settings could be similarly quantified. Because wandering involves directional changes in successive movement patterns at various spatial scales [4], fractal analytic techniques, similar to those employed to study gait variability in the temporal domain [21] should in theory successfully characterize movement variability in the spatial domain.

Fractal analysis of spatial data measures geometrical aspects of shapes at various spatial scales and has been used extensively with lower animals to study various aspects of movement such as searching [22], navigation [23], dispersal [24] and orientation [25], with a range of animals from birds [26] to mammals [27] to fish [28] to insects [29]. Fractal dimension (Fractal D) is the continuous analog of geometrical dimensions [30]. For lines, Fractal D ranges from a minimum of 1 for a straight line, to maximum of 2 when the line is so tortuous as to completely cover the plane. Wandering involves a relatively tortuous path and thus should have a high Fractal D. The measured value of Fractal D depends in part on the spatial scale used [31] to evaluate the movement path; a person walking down a corridor but turning every now and then to investigate something would have a low Fractal D at large spatial scales and a high Fractal D at small spatial scales. Thus it is important to choose an appropriate range of spatial scales for estimating Fractal D.

We should clarify some potential confusion. The term fractal has been used in different ways: it has been used for both the concept of self-similarity and for the actual estimate calculated [32]. If a curve is self-similar (i.e. a constant Fractal D at all spatial scales), then it is said to be fractal. Thus movement paths typically are not fractal. We use the term fractal for the actual estimate.

The principal hypothesis tested in this study was that path tortuosity measured by Fractal D would be negatively correlated with a standard metric of cognitive functioning, the Mini Mental State Exam (MMSE) [33], obtained from elderly ALF residents. Persons whose paths contain more random components (irregular turns) resulting in higher Fractal D values, were predicted to have lower MMSE scores than persons taking more direct paths. A second purpose of the study was to obtain descriptive data on the diurnal variability of elders' movements, particularly as they related to MMSE scores.

2. Methods

2.1 Subjects

Fourteen (12 female) of 17 ALF resident volunteers completed the protocol. Their mean and median ages were 82.2 (SD = 9.92) and 86.5 years, respectively. One participant was fully ambulatory, eight used wheelchairs and five used a rolling walker. ALF client records identified six participants with a diagnosis of dementia and one with a diagnosis of Parkinson's disease (▶Table 1). The client record did not specify duration or severity of the diagnosis of dementia or other diseases. It did indicate whether assistance with any of seven activities (ADL) or instrumental activities of daily living (IADL) was required at the most recent review. The activities reported included ambulation, bathing, dressing, toileting, eating, grooming and transferring. The mean number of the seven activities requiring assistance was 5.4 (SD = 1.78); the median number was 6. The MMSE scores and Fractal D scores are presented in ▶Table 1 and will be discussed in the Results section.

2.2 Apparatus

The data collection system was a Ubisense, Inc. ultra-wideband radio research pack with 14 compact tag wrist-worn transponders measuring 38 mm × 39 mm × 16.5 mm with a weight of 25 g, and four wall-mounted sensors. Full compact tag transponder specifications may be found at http://www.ubisense.net/media/pdf/UbisensCompact%20Tag%20EN%20V1.0.pdf. A Belkin, Inc. Power of Ethernet 100 BaseT switch and seven shielded category 5e network cables comprised the sensor network which transferred data to a Dell Inspiron model 1501 notebook computer. Ubisense 2.0 software on the computer was used to process and store sensor data.

2.3 Procedure

Following University of South Florida IRB approval, prospective research participants and their caregivers were recruited by one investigator (JLF) and informed that the intent of the study was to examine movement patterns of elderly persons, and that to participate they would be required to wear a small tag during their waking hours for a period of 30 days. Informed consent and proxy consent were obtained under the supervision of JLF at the assisted living facility to ensure prospective participants potentially having cognitive impairment could still participate. Participants were informed the tag was safe and would emit very weak radio waves (about 1/10th that of a common cellular telephone) and that they could discontinue the study at any time they desired. By design, a second investigator (WDK) was blind to the identity, age, gender, mobility aids used and diagnosis of dementia of the participant.

2.4 Description of Monitored Area and Sensor Installation

Four Ubisense 2.0 sensors were installed at each corner of an approximately rectangular (25.6 meters by 9.3 meters) common space that interconnected two dormitory wings, an exterior exit and a dining room where all subjects ate their meals. The monitored space served two major functions: it was the conduit between the dormitory wings and dining room or exterior door and it served as a gathering place for recreational activities with sofas, tables, comfortable chairs and a television set. The locations of the sensors and the entrances to the monitored space are shown in ►Figure 1. As shown in Figure 1 and discussed in the results, there were large individual differences in the amount of participant activity in the monitored space.

2.5 Experimental Protocol

Tags were attached after the participants' morning meal and medications and surrendered before retiring. When in motion, the tags transmitted x, y, and z coordinates in centimeters once every 0.43 seconds relative to an origin set in one corner of the room. Following 30 days of data collection, a trained gerontology graduate student blind to the study's purpose administered the Mini Mental State Exam [33] to each participant. An independent measure of participant wandering behavior, the Revised Algase Wandering Scale – Community Version (RAWS-CV) [34], was also completed by ALF staff members who interacted with the participants daily and were well acquainted with their behaviors during the study interval. ALF staff members were blind to the MMSE and Fractal D measures.

2.6 Data Reduction and Calculation of Fractal D

Approximately 1.4 million data points were generated by all participants completing the protocol. Some readings, especially those from locations very close to corners and walls, may be less accurate than those from the more open areas due to radio reflections [35]. Accordingly, radio reflections generating clearly impossible data (for example indicating a participant had passed through a solid wall) were rejected by software filters. Similarly, observations determined to occur outside the monitored area regardless of their accuracy, were rejected, leaving 854,336 data points. The rule defining a path was: 1) a tag that did not change for 60 sec or more was stationary; 2) the first datum recorded thereafter (in response to movement) started a new path; 3) successive data points were accrued until the tag was again stationary for another 60 sec.

Fractal D was estimated using the FractalMean estimator (an extension of the divider estimator) using the program Fractal [36]. Visual inspection of the slope of the Fractal D output from the "Fractal" program for the first 10 participants (done with no knowledge of the MMSE scores) clearly indicated the greatest variability across subjects occurred in spatial scales ranging from 2 to 7; therefore these spatial scales were used in all subsequent analyses. Fractal D was estimated for each path generated by each participant and then averaged to produce a single score for each individual.

2.7 Statistical Analyses Used

The major hypothesis, and the one for which the study was powered, was that there would be a negative association of Fractal D with MMSE scores and this was assessed with a Pearson product moment correlation coefficient and a one-tailed test of significance, as the direction of the association was predicted. A set of secondary exploratory analyses were also conducted. The first determined whether MMSE and Fractal D scores differed significantly by means of locomotion (wheelchair vs. walker/independent locomotion) and each was evaluated by a t-test (two-tailed) of that measure's values for each type of locomotion. The second explored the relationship of cognitive impairment to ability to perform activities of daily living and was evaluated using a Pearson product moment correlation coefficient and a two-tailed test of significance of MMSE and ADL scores. An exploratory diurnal variability analysis examined if hourly mean cumulative distance traveled across 30 days would differ by degree of cognitive impairment, using a mixed model (groups (2) × time (13)) analysis of variance in which the groups' variable was whether a participant's MMSE score fell above or below the median MMSE, and the within-subjects variable was the mean distance travelled during each of the 13 hours of daily recordings. The last analysis explored the relationship of MMSE scores to the recorded diagnosis of dementia using a two-tailed t-test. Finally, descriptive statistics describing the relationship of Fractal D values and the MMSE scores to the observer's judgment of wandering (yes/no) on the RAWS-CV validation item were compiled.

3. Results

All participants but one were administered the MMSE after completing the protocol. One participant died before the test could be administered but had an MMSE administered within two months of the start of the study, and this measure was used as a proxy; the scores appear in ►Table 1. MMSE scores did not differ reliably by method of ambulation (wheelchair vs.

Table 1 Participant characteristics and data

Participant #	Age	Dementia diagnosis	ADLs need asst.	MMSE	Fractal D	Number of trails	Number of sightings	Cumulative distance (in meters)	Rate of travel (m/sec)	Wanderer (Yes/No)
1†	91	Y	7	8	1.68	464	69,557	23,315.9	.30	Y
2	63	N	6	14	1.59	1,029	142,945	43,324.7	.37	Y
3	64	Y	1	19	1.84	521	230,241	91,384.3	.58	Y
4†	93	N	2	19	1.27	373	33,341	15,148.5	.55	Y
5*	73	Y	6	20	1.30	398	23,457	11,476.1	.61	N
6†	92	N	6	20	1.44	430	42,858	15,653.5	.43	Y
7†	84	Y	6	20	1.54	456	43,937	10,853.1	.17	Y
8	88	N	7	21	1.19	141	3,727	3,151.8	.65	Y
9	88	Y	5	21	1.79	793	111,592	47,728.6	.42	Y
10†	88	Y	5	21	1.62	940	35,026	11,817.6	.29	Y
11*	75	N	6	24	1.35	813	49,026	23,521.2	.60	N
12†	79	N	6	25	1.26	313	14,403	8,325.6	.48	N
13†	86	N	6	25	1.24	557	32,808	14,633.7	.37	Y
14†	88	N	7	28	1.41	189	19,301	8,499.9	.51	N

* male, † wheelchair user

walker-ambulatory; t = – .33 df = 12, p = 0.74). The Pearson product moment correlation coefficient between MMSE scores and participants' ADL levels was also not significant (r = .06, n = 14 p = 0.84).

The median number of location data points (sightings) obtained per participant was 43,397, with a range of 3727 to 230,241 reflecting large individual differences in both time spent by the participants in the monitored area and their rate of travel. The numbers of paths per participant also varied considerably from 141 to 1029 with a mean of 530.2 and an SD of 269.6.

A Pearson product moment correlation coefficient computed between MMSE and Fractal D measures to evaluate the principal hypothesis that more variable walking paths would predict lower MMSE scores, was statistically significant (r = – .47 n = 14, p = .046), supporting the study's primary hypothesis (▶Table 1). Fractal D did not differ by means of ambulation (wheelchair vs. walker-ambulatory; t = .66 df = 12, p = 0.52). A graphic presentation of two subjects' location data which differed considerably on Fractal D values appears in ▶Figure 1.

Participants classified as wanderers by ALF staff using the RAWS-CV are identified in ▶Table 1; an entry of "Y" means that the rater responded "yes" to the validation item "Is this person (the one being rated) a wanderer?". The descriptive statistics reveal all seven participants with Fractal D scores above the median for the sample and two with scores below it were rated as wanderers using the RAWS-CV. Only one of four participants having MMSE scores at or above 24 was classified a wanderer. These early findings suggest some overlap between the Fractal D measures and subjective observations made by untrained observers who are familiar with the day-to-day movements of the participants.

The relationship between MMSE scores and the recorded diagnosis of dementia was not statistically significant (t = – 1.52 df = 12, p = .155 (two-tailed)) which may be a function of the small sample size. Three individuals with no diagnosis of dementia in their client record were found to have MMSE scores below 21.

3.1 Diurnal Variability Analysis

The cumulative distance traveled for participants above and below the median MMSE value of 20.5 by hour of the day was calculated. A two-way (high vs. low MMSE) by time (13-hour) mixed model analysis of variance was performed on these data to evaluate the effects of MMSE level on activity levels at each hour of the day. Neither the F test for MMSE status (F = 1.1, MS = 45438744, df = 1, 12 p = 0.31), or time (F = 1.7, MS = 13343711, df = 12, 144 p = 0.07) were significant although the analysis of the time factor was suggestive of a weak trend; neither was the groups' x time interaction significant (F = 0.33, MS = 2618257, df = 12, 144 p = 0.98).

4. Discussion

The study evaluated the principal hypothesis that movement path tortuosity would be greater in elderly ALF residents with lower measures of cognitive functioning. A wireless tracking technology gathered data across 30 days from 14 ALF residents moving in a common space measuring approximately 9 by 25 m. A fractal mathematic index of path tortuosity (Fractal D) blindly calculated from these data predicted participants' MMSE scores obtained at the end of the study, accounting for 22% of the variance in the total MMSE score. The relationship between ALF client record diagnosis of dementia and the observed MMSE was not statistically significant. This may be due to the fact that low MMSE scores were underrepresented in our sample; only two subjects in the present investigation had MMSE scores below 19. Some studies in the literature have reported weaker relationships between MMSE scores and the presence of a dementia diagnosis in community-dwelling elders with lower educational levels [37, 38].

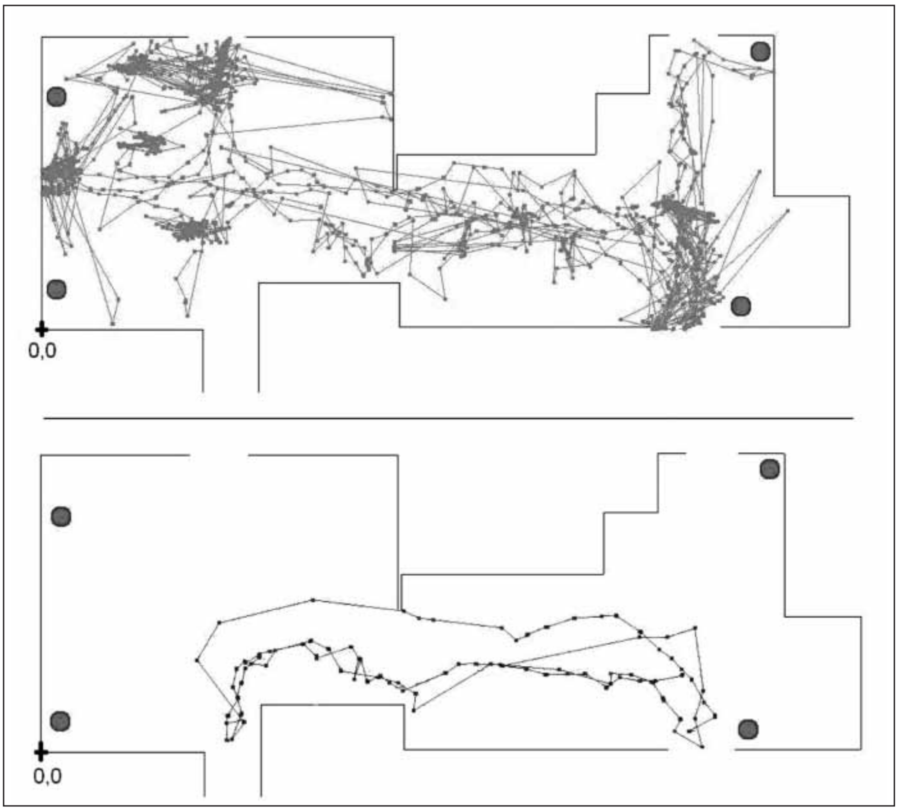

Fig. 1 Raw location data for two participants for two hours recorded beginning at 9 a.m. Upper panel: Participant #10 has highly variable paths resulting in a mean Fractal D of 1.62. Lower panel: Participant #12 followed relatively straighter paths and had a mean Fractal D of 1.24. Participant #10 had the 4th highest mean Fractal D value of any subject and suffered a hip fracture from a fall which occurred after the study's completion. Ovals denote the locations of sensors in the room, 0.0 indicates reference coordinates, breaks on left represent entrances to dormitory wings, break on upper right indicates exit door, break on lower right indicates entry to dining area.

There was limited evidence that Fractal D scores corresponded to human judgments of wandering behavior. All participants with Fractal D scores above the sample median were classified by the RAWS-CV as wanderers by ALF staff familiar with participants' daily movement patterns.

Our findings of increased spatial variability and lower MMSE scores are consistent with earlier results [39, 40] which demonstrate increased temporal variability in gait and balance in persons with dementia under controlled conditions. However, we present an approach for characterizing changes in gait related to cognitive decline through vector information obtained from freely moving individuals in their home environments thus minimally intruding on normal routines and behavior. The present approach successfully predicted MMSE values irrespective of type of ambulation (ambulatory, walker, or wheelchair) precisely because it measures path tortuosity over large spatial scales (2–7); one would expect different types of ambulation to affect movement at smaller spatial scales. The small number of subjects in the current investigation precludes an analysis of the potential confounding effects of age and disease status on the observed relationship of Fractal D and MMSE measures, issues which should be evaluated in a larger study.

The ability to differentiate subjects on path tortuosity independent of means of locomotion (wheelchair vs. walker/ambulatory) suggests Fractal D is sensitive to cognitive functions which direct locomotion, and can potentially allow quantification of wandering and assessment of its relative contribution to the risk of events such as falls even if the individual can generate no balance and gait data due to being wheelchair-bound and unable to stand. To the extent Fractal D can be assessed in less ambulatory individuals it may be relevant to the eventual development of fall prediction models in frail elderly.

Psychometric research on persons clinically diagnosed with dementia indicates that long-term preclinical changes in spatial abilities occur 3–5 years before diagnosis. The approach presented may yield a relatively simple and inexpensive way of charting changes in movement which may be predictive of a later diagnosis of dementia. Currently formal gait and balance assessments, as well as the short length of the present study, do not allow an assessment of longitudinal changes in movement, however the technology used in the current study is well adapted to long-term continuous recording.

Our research fits within the *movement ecology paradigm* [41], a transactional analysis linking three features of an individual – internal state, navigational capacity and motion capacity – to features in their external environment. Briefly, each change in an individual's location, called the "movement path", brings about a change in the person-environment dynamic that may change the three components of the moving person. In the present study, the internal state, or "why move", could be defined by the goals of traversing the common space for meals, getting to a sleeping area, or for recreational purposes. Navigational capacity, or "where to move", was compared in persons with or without a diagnosis of dementia and by differences in cognitive ability. Motion capacity, or "how to move", applies to persons who either walk independently or with the aid of a walker or a wheelchair. The present research extends the movement ecology paradigm to human studies of gait and mental status. Specifically the present research evaluates the impact of cognitive deficits on navigational capacity, reflected in the tortuosity of the movement paths. Gait and balance research referenced earlier more directly addresses motion capacity, or "how to move", since the "why" and "where" were determined by the research protocol.

The drawbacks to the method we employed for tracking movement, including the technology's high cost, and the difficulty involved in initially setting up the system (which requires highly precise sensor placement) will diminish as the technology matures and becomes more widespread. Unlike active infrared systems which provide gross positioning information at a low cost but can be installed easily in many places [42] and which have yielded promising data on Parkinson's disease, the technology we employ provides highly specific placement information for passages through which persons routinely traverse and need not be installed in an entire assisted living facility, which may facilitate its use in future studies. Furthermore the device can monitor several hundred individuals simultaneously, allowing for significant economies of scale. Ultra-wideband radio as a technology has improved markedly in the past five years; however radio reflections continue to introduce problems for accurate tracking of individuals [35]. UWB systems must be precisely calibrated (often requiring laser rangefinders) in order to ensure accurate data, and the cost of the systems (approximately US$ 7000 at the time of this writing) limit their availability to researchers. However, this instrumentation shows some promise possibly as an early detection system for dementia or for assessing risk of future falls related to the dementing process. Our results indicate that coupling UWB with Fractal D spatial analytic technique described 22% of the variance in MMSE scores; future research will be aimed at clarifying the nature of this relationship.

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References

1. Spirduso WW. Balance and posture. In: Spirduso W, Francis K, MacRae P, editors. Physical dimensions of aging. Champaign, Ill: Human Kinetics; 2005.
2. Fozard JL. Sensory and Cognitive Changes with Age. In: Schaie KW, editor. Mobility and transportation in the elderly. New York: Springer; 2000. pp 1–44.
3. Evans WJ. Effects of Exercise on Body Composition and Functional Capacity of the Elderly. In: Schaie KW, editor. Mobility and transportation in the elderly. New York: Springer; 2000. pp 71–90.
4. Allali G, Kressig RW, Assal F, Herrmann FR, Dubost V, Beauchet O. Changes in gait while backward counting in demented older adults with frontal lobe dysfunction. Gait & Post 2007; 26: 572–576.
5. Verghese J, Lipton RB, Hall CB, Kuslansky G, Katz MJ, Buschke H. Abnormality of gait as a predictor of non-Alzheimer's dementia. NEJM 2002; 347: 1761–1768.
6. Giladi N, Herman T, Reider-Groswasser II, Gurevich T, Hausdorff J. Clinical characteristics of elderly patients with a cautious gait of unknown origin. J Neurol 2005; 252: 300–306.
7. Verghese J, Holtzer R, Lipton RB, Wang C. Quantitative gait markers and incident fall risk in older adults. J Gerontol A Biol Sci Med Sci 2009; 64A (8): 896–901.
8. Hausdorff J, Rios D, Edelberg H. Gait variability and fall risk in community-living older adults: A 1-year prospective study. Arch Phys Med and Rehabil 2001; 82 (8): 1050–1056.
9. Luis CA, Brown LM. Neuropsychological correlates of wanderers. In: Nelson AL, Algase DL, editors. Evidence-based protocols for managing wandering behaviors. New York: Springer; 2007. pp 65–74.
10. Merory JR, Wittwer JE, Rowe CC, Webster KE. Quantitative gait analysis in patients with dementia with Lewy bodies and Alzheimer's disease. Gait & Post 2007; 26: 414–419.
11. Algase D. Assessment of wandering behaviors. In: Nelson AL, Algase DL, editors. Evidence-based protocols for managing wandering behavior. New York: Springer; 2007. pp 75–120.
12. Algase DL, Moore DH, Vandeweerd C, Gavin-Dreschnack DJ. Mapping the maze of terms and definitions in dementia-related wandering. Aging & Ment Hlth 2007; 11: 686–698.
13. Johnson DK, Storandt M, Morris JC, Galvin JE. Longitudinal study of the transition from healthy aging to Alzheimer disease. Arch Neurol 2009; 66 (10): 1254–1259.
14. Ramakers Ihgb, Visser PJ, Aalten P, Boesten JHM, Metsemakers JFM, Jolles J, et al. Symptoms of preclinical dementia in general practice up to five years before dementia diagnosis. Demen and Ger Cog Disord 2007; 24: 300–306.
15. Nelson AL, Algase DL. Appendix B. Measurement Tools for Wandering. Revised Algase Wandering Scale-Community Version. In: Nelson AL, Algase DL, editors. Evidence-based protocols for managing wandering behavior. New York: Springer; 2007. pp 385–397.
16. Algase DL, Beattie ER, Leitsch SA, Beel-Bates CA. Biomechanical activity devices to index wandering behavior in dementia. Am J Alz Dis & Oth Demen 2003; 18: 85–92.
17. Teicher M. Actigraphy and Motion Analysis: New Tools for Psychiatry. Harv Rev Psychiat 1995; 3: 18–35.
18. Teicher M, McGreenery CE, Ohashi K. Actigraph assessment of rest activity disturbances in psychiatric disorders. Psychosomatic Medicine: Proceedings of the 18th World Congress on Psychosomatic Medicine, held in Kobe, Japan, August 21–26, 2005. 1287: 32–37.
19. Verghese J, Wang C, Lipton RB, Holtzer R, Xue X. Quantitative gait dysfunction and risk of cognitive decline and dementia. J Neurol, Neurosurg & Psych 2007; 78: 929–935.
20. Kearns WD, Algase DL, Moore DH, Ahmed S. Ultra wideband radio: A novel method for measuring wandering in persons with dementia. Gerontech 2008; 7: 48–57.
21. Hausdorff JM. Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. Hum Mvt Sci 2007; 26: 555–589.
22. Bascompte J, Vilà C. Fractals and search paths in mammals. Landscape Ecol 1997; 12: 213–221.
23. Caldwell IR, Nams VO. A compass without a map: Tortuosity and orientation of eastern painted turtles (*Chrysemys picta picta*) released in unfamiliar territory. Can J Zool 2006; 84: 1129–1137.
24. Doerr VAJ, Doerr ED. Fractal analysis can explain individual variation in dispersal search paths. Ecology 2004; 85: 1428–1438.
25. Nams VO. Detecting oriented movement of animals. Anim Behav 2006; 72: 1197–1203.
26. Desrochers A, Fortin MJ. Understanding avian responses to forest boundaries: a case study with chickadee winter flocks. Oikos 2000; 91: 376–384.
27. Mårell A, Ball JP, Hofgaard A. Foraging and movement paths of female reindeer: Insights from fractal analysis, correlated random walks, and Lévy flights. Can J Zool 2002; 80: 854–865.
28. Coughlin DJ, Strickler JR, Sanderson B. Swimming and search behaviour in clownfish, *Amphiprion perideraion*, larvae. Anim Behav 1992; 44: 427–440.
29. Fourcassie V, Coughlin D, Traniello JFA. Fractal analysis of search behavior in ants. Naturwissenschaften 1992; 79: 87–89.
30. Mandelbrot B. How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science 1967; 156: 636–638.
31. Nams VO. Using animal movement paths to measure response to spatial scale. Oecologia 2005; 143: 179–188.
32. Nams VO, Bourgeois M. Fractal dimension measures habitat use at different spatial scales: an example with marten. Can J Zool 2004; 82: 1738–1747.
33. Crum RM, Anthony JC, Bassett SS, Folstein MF. Population-based norms for the Mini-Mental State Examination by age and educational level. JAMA 1993; 269: 2386–2391.

34. Algase D, Yao L, Beel-Bates C, Song J. Theoretical Models of Wandering. In: Nelson A, Algase DL, editors. Evidence-Based Protocols for Managing Wandering Behaviors. New York: Springer Publishing Company; 2007.
35. Kearns WD, Algase D, Moore DH, Ahmed S. Ultra wideband radio: A novel method for measuring wandering in persons with dementia. Gerontech 2008; 7: 48–57.
36. Nams VO. Improving accuracy and precision in estimating fractal dimension of animal movement paths. Acta Biotheoretica 2006; 54: 1–11.
37. Maeker E, Bombois S, Pardessus V, Tiberghien F, Dipompeo C, Thevenon A, et al. Cognitive disorders and falls: experience of the Lille multidisciplinary falls service. Revue Neurologique 2005; 161: 419–426.
38. Scazufca M, Almeida OP, Vallada HP, Tasse WA, Menezes PR. Limitations of the Mini-Mental State Examination for screening dementia in a community with low socioeconomic status: results from the Sao Paulo Ageing & Health Study. Eur Arch Psychiatry Clin Neurosci 2009; 259: 8–15.
39. Sheridan PL, Hausdorff JM. The role of higher-level cognitive function in gait: executive dysfunction contributes to fall risk in Alzheimer's disease. Dem & Ger Cog Dis 2007; 24: 125–137.
40. Verghese J, Derby C, Katz MJ, Lipton RB. High risk neurological gait syndrome and vascular dementia. J Neur Trans 2007; 114: 1249–1252.
41. Nathan R, Getz WM, Revilla E, Holyoak M, Kadmon R, Saltz D, et al. A movement ecology paradigm for unifying organismal movement research. Proceedings of the National Academy of Sciences 2008; 105 (49): 19052–19059.
42. Pavel M, Hayes T, Tsay I, Erdogmus D, Paul A, Larimer N, Jimison H. Continuous assessment of gait velocity in Parkinson's disease from unobtrusive measurements. Proceedings of the 3rd International IEEE Conference on Neural Engineering. CNE '07. Kohala Coast, Hawaii, USA, 2007. pp 700–703.