Of falls and fractals: My career with my mentor, colleague and friend, Professor James L. Fozard

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W.D. Kearns. Of falls and fractals: My career with my mentor, colleague and friend, Professor James L. Fozard. Gerontechnology 2010; 9(3):388-396; doi:10.4017/gt.2010.09.03.010.00 Falls are expensive and often life-changing events. In 2000 there were 2.6 M non-fatal falls that cost the US economy in excess of $19 B. Fall prediction is an inexact science due in part to the lack of real-time or even near real-time longitudinal monitoring and assessment technologies which can track conditions preceding a fall. Current fall prediction methodologies assess gait and balance parameters at perhaps one or two points in time and attempt to infer future risk. A system for elders that is analogous to the 'black box' flight recorder used in commercial aviation could potentially enhance our knowledge of how fall risks increase over time and what interventions may be successful. This paper describes a system which relies on miniature transponders and fractal mathematics to determine the tortuosity of elders' paths as they traverse open areas within assisted living facilities. It provides background for the development of the concept, especially as it was influenced by earlier research by Professor James L. Fozard. Preliminary data are presented indicating an association between inter-day path variability and the likelihood of falls in elders residing in an assisted living facility.

Keywords: wandering, dementia falls, electronic tracking

Falls are expensive adverse events for adults over the age of 65, costing the US economy over $19 billion in 2000 and estimates are that it will increase to $55 billion by 2020[1]. Using data from Medicare records, the estimated direct cost of the 10,300 falls resulting in death in the 2000s was approximately $176 million while the 2.6 million non-fatal falls cost $19 billion, with almost two thirds going for hospitalization[1]. Data from other studies[2,3] indicate that approximately a third of all adults over age 65 will experience a fall and that the average cost for a fall including nursing home, emergency room and home health care services is approximately $20,000 per incident[4]. The human toll in pain and suffering by the faller and the costs in time and effort by family and informal caregivers are also significant. Hip fractures and traumatic brain injuries resulting from falls are associated with very high mortality rates[1].

Causes and risk factors

The causes of falls and the increased risk for falls are the result of complex interactions among multiple personal and environmental factors including cognitive factors such as the fear of falling[5,6], and age-related changes in the sensory, physiological, and musculoskeletal systems or medical conditions such as peripheral neuropathy. Stevens' review[1,p294] emphasized the frequent research finding that among community-dwelling older adults, the risk of falling is 3 to 4 times higher in people with muscle weakness or gait and balance disorders. A third of documented falls among the elderly are attributed to environmental factors resulting in accidental falls; the remaining two thirds are attributed to personal factors. Stevens[1] cites the need for improved and more frequent use of gait and balance screening, better medication management (fewer psychoactive medications) and the reduction or elimination of home environmental hazards such as poor lighting, unsecured rugs, and of the need for support rails or other assistive hardware in bathrooms and stairways.

Gait, balance and falls

Standardized assessments of gait and balance (SGB) measure the body's natural ability to maintain equilibrium under standardized challenges. They are time and labor intensive, expensive to administer and summarize the person's status at one point in time. Accordingly, they may not adequately predict transient changes in gait and balance induced by alterations in medications (especially those with psychoactive properties) or short-term infections.

SGB assessments include stride length, step length, support base, step time, swing time, stance time, single support time, double support time and average velocity measures. Measurements outside a laboratory can be performed by a trained professional using a portable gait mat and recording device. Assessment of static balance includes measures of body sway recorded when a person is standing on one or two legs with eyes closed or open; similarly dynamic balance assessments are made while a person is walking or performing an additional task such as talking on a cell phone. Condron et al.[7] found that the addition of a secondary task, counting backwards by threes, distinguished a group of 20 elderly persons with a history of falls in the prior 12 months from a group of age peers with no falls. The reported sensitivity and specificity of classifying subjects into the two groups were both 0.8.

A review by Rubenstein and Josephson[8] elucidates the multiple factors contributing to falls, which limits the predictive power of any one measure. Hill et al.'s research[9] helps define the temporal bounds beyond which standardized gait, balance and muscle strength measures would predict fall incidence. Their subjects were 100 community-dwelling women with an average age of 74 years carefully screened to eliminate those with histories of falls, use of canes or other mobility aids, visual or balance problems, and medications or diseases that could increase fall probability. At 12 month follow-up 49% had fallen at least once and 23% more than once with the majority occurring in or around the home. Fear of falling was the one significant predictor (OR=2.42) of subsequent falls. Hill's extremely rigid screening to eliminate more frail participants may have reduced the relationship between SGB and muscle strength measures and subsequent falls. In our current research program, we study individuals more frail than Hill's subjects.

Recently researchers[10,11] have used fractal analytic techniques to reveal new information about gait and balance variability leading to improved fall prediction. A straightforward analysis of variability can sometimes predict fall risk – for instance, Hausdorff et al.[3] found a relationship between increased stride time variability and increased fall risk in community dwelling elders. Stride time variability also negatively correlated (-0.47) with participants' Mini Mental State Exam scores, a measure used to assist in diagnosing dementia. However, a fractal scaling index of stride times can sometimes detect subtle changes in gait dynamics that variability cannot. For example, Herman et al.[11] found that while gait variability was not correlated with risk of falls for adults with walking difficulties (not associated with any known disability or chronic condition), fractal scaling index was.

Some gait and balance measures such as decreased stride length, increased double support time and reduced walking, which are adaptive strategies to increase stability, are indirect predictors of falls. Reduced stride length has been found to be a poor fall predictor, but a good indicator of fear of falling [6]. Conversely, increased variability in stride to stride length, stride to stride walking speed and double support time is associated with increased fall risk[6]. Step width, conversely, appears associated with fear of falling and falls risk. Probably the best single predictor of falls seems to be stride-to-stride walking speed variability, however, other falls researchers have found that impaired cognitive functioning in dementia, and dementia related wandering are predictive of falls[12].

Gait and manual response time

The links between within-person variability in gait and cognitive deficits extends earlier findings on variability in manual movements and age. It is a truism in gerontology that inter-individual differences increase with age in almost every function which has been studied—reflecting different patterns of experience and interactions with the environment; identical twins are more alike at age 1 than at age 80. The more controversial issue is whether intra-individual differences in functions increase with age as well. In the area of response latencies for making decisions in both continuous (tracking, walking) and discrete tasks (retrieving information from memory, selective and shared attention), the answer would appear to be "yes". In the 1970s, a group of scientists consisting of Jim Fozard, Nancy Waugh, John Thomas and later Leonard Poon, examined the issue of increasing intra-individual variability as part of a highly productive research program known as 'Mental Performance and Aging'[13]. In their researches, they discovered the average time required to retrieve information from sensory, primary, secondary (episodic), and tertiary memory were differentially affected by age. A common feature of their research design was to control for the quality of memory; in addition to examining averages they calculated distributions of latencies by age group, and found relatively longer latencies in successively older cohorts. Fozard and colleagues discovered the distribution of latencies below the median appeared to be very similar across age groups; however, those above the median had higher variability across age. In subsequent work these investigators studied the time required to recall responses to lists of paired associates (ace-boy; cat-dog….) as a function of how well the list was memorized. They found the time to name the response member of the pair that had been correctly recited on previous trials was much longer in older subjects who had mastered fewer of the pairs than was the case for younger subjects who memorized more pairs in the same number of trials. They also found that proactive inhibition played a much greater part in both recall and recognition of items in older age, complementing work by their contemporaries, which investigated age differences in selective and shared attention tasks. The results clearly showed it was harder for older persons to ignore irrelevant stimuli, and therefore they were more influenced by false cueing of target stimuli. A smaller body of research found similar age-related problems occurred in continuous movement tasks (upper limb). So when Fozard and I began looking at movement patterns in frail older persons in 2007, it was only natural that we would focus on intra-individual differences in the spatial (and temporal) dimensions of movement associated with cognitive decline, and on changes in cognitive function associated with medication changes and changes in health. The seminal work by Hausdorff[14] and others showing greater variability in gait as evidenced in simple walking tasks of old people paralleled earlier findings concerning response latencies and studies of attention in the elderly.

The second line of research that is relevant to our present work is the growing body of work showing that walking and quality of gait which are seemingly automatic in young age require additional cognitive effort in older age[15]. Most of the additional processing involves evaluating environmental information gained through the visual system. Fozard has documented this development in his review of the literature on age-related changes in vision in the first three odd numbered editions of the Birren & Schaie 'Handbook of the Psychology of Aging'[16]. Research on age differences in sensory memory reported by Cerella, Poon and Fozard[17] reinforced Fozard's impressions concerning the importance of this body of research; in these studies a group of six or seven letters is presented for periods of 30-200 milliseconds, and the subject reports as many as possible. Since the total time the display is available to the subject is the display time plus the positive afterimage, the advantage of the latter is eliminated by presenting a masking stimulus coincident with the end of the presentation. For all presentation durations, older subjects got fewer letters correct than younger ones. Persons with dementia from a similar study performed in Britain[18] never achieved more that 1-1.5 letters showing both extreme slowness in assimilating information and likely more response inhibition[19].

Automated assessment of movement

The measures of directional variability and movement velocity we have evaluated against SGB measures are derived from research by Kearns et al.[20], and Kearns, Nams and Fozard[21] summarized below. A number of methodologies have been used to track persons' movements within buildings. Hayes and colleagues[22] employed inexpensive passive infrared (PIR) and electromechanical sensors to determine the presence of persons within rooms and were able to detect evidence of cognitive decline which could improve fall risk prediction. However, PIR cannot differentiate individuals by infrared emissions alone, nor can electromechanical sensors on doors, etc. although sophisticated algorithms[23] have been developed which improve correct identification. PIR and electromechanical sensors together can provide adequate zone level coverage but not individual level tracking, which may suffice for the limited case of an individual alone in a building but is entirely insufficient for tracking large numbers of persons simultaneously[24]. Smart house technologies have used floor pressure sensors to measure gait[25] and may employ radio frequency identification devices (RFID) to differentiate individuals in congregate settings[26]. RFID allows the differentiation of unlimited numbers of individuals by assigning a unique identifier to each RFID device attached to an individual or their clothing and records the location of the RFID as it passes by sensors positioned at fixed locations. Ultrawideband is a variant of RFID that allows not only the identification but the vector of a transponder to be known, allowing theoretically hundreds of individuals to be tracked at once.

SGB measures' limited ability to predict future falls has been shown by Hill et al. to be due in part to their being obtained at a single point in time[9]. We contend that continuous monitoring of free movement variability and velocity in close temporal proximity to falls may extend understanding of events leading to a fall in much the same manner that the introduction of the 'black box' flight recorder has resulted in improvements in airline safety. For this reason, we automatically assess free movement variability over months.

Preliminary study

The movement tracking system (MTS) described in this paper was initially developed to quantify wandering behavior associated with dementia. The concept was originally introduced by Kearns and Moore at the federal Agency for Healthcare Research and Quality National Conference on Health Information Technology in April 2006 where it was cited as the most innovative use of Health Information Technology and displayed in Washington, D.C. for Health Information Technology week. The technical evaluation of the system was recently reported by Kearns et al.[20,27] which showed it was capable of differentiating elders with cognitive disabilities from normal elders based only on their free movements[21]. The results relevant to the present discussion are summarized below.

Subjects

Fourteen assisted living facility (ALF) residents completed the 30-day protocol; all but 2 of the 14 participants were female. The mean age was 82.2 (SD=9.92) and the median was 86.5 years, residents ranged from 63 to 93 years of age. One participant was fully ambulatory, 8 used wheelchairs and 5 used a rolling walker. Information was not gathered on past fall history or visual or balance problems in this investigation. One subject volunteered to continue wearing the tag for an extended interval beyond the 30 days of recording to provide information on elder tolerance for wearing the tag.

Apparatus and procedure

The MTS was a Ubisense Inc. Ultra Wideband radio research pack using wrist worn 'compact tag' transponders measuring 38x39x16.5 mm and weighing 25 g, and four wall-mounted sensors. A Belkin Inc. Power of Ethernet 100 BaseT switch and 7 shielded category 5e network cables transferred data to a Dell Inspiron model 1501 notebook computer. Ubisense 2.0 software[20,27] on the computer was used to process and store sensor data. Tags sent signals to four Ubisense 2.0 sensors installed at each corner of an approximately rectangular (25.6 meters by 9.3 meters) common space that interconnected two dormitory wings with an exterior exit and a dining room where all subjects dined; the space contained sofas, tables, comfortable chairs and a television set. Tags were attached by ALF staff by a comfortable wristband after medications and the morning meal and surrendered before retiring. The tags transmitted x, y, and z coordinates in meters once every 0.43 seconds when in motion relative to an origin in one corner of the room. Following 30 days of data collection, the Mini Mental State Exam[28] was administered to each participant.

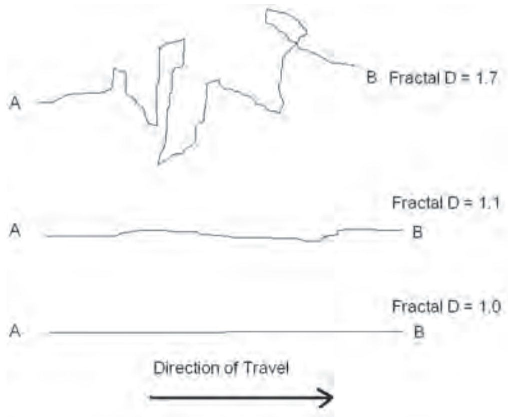

Figure 1. Three hypothetical Fractal D values for walking elders

Results

After software filtering to remove errant data 854,336 location data points were available for analysis. Location data points were consolidated into paths using the following algorithm: the beginning and ending of a path was defined by tags that did not change position for 60 s. Each participant's path data were blindly analyzed for tortuosity using the Mean Fractal D estimator program[29]. Fractal D (tortuosity) ranges in value from a minimum of 1, when the line is perfectly straight, to maximum of 2 when the line is so tortuous as to completely cover a plane. Thus, a person that is wandering aimlessly (a random walk) would have a tortuous path and a Fractal D approaching 2.0 (*Figure 1*).

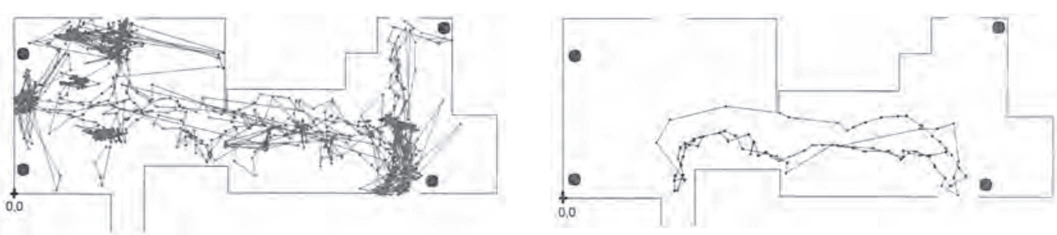

Figure 2. Two hours of raw location data from two subjects recorded at 9 a.m. at the first assisted living facility site. Subject #10 (left panel) demonstrated a highly variable path and a mean Fractal D of 1.62 and an MMSE of 21 and suffered a hip fracture after wearing the tag for 80 days. Subject #12 (right panel) followed relatively straighter paths and had a mean Fractal D of only 1.24 and an MMSE of 25. Ovals denote sensor locations

The median number of data points per participant was 43,397, and ranged from 3,727 to 230,241 reflecting large individual differences in both time spent in range of the MTS and differences in their total amount of movement (*Figure 2*). When consolidated into paths they ranged in number from 141 to 1,030 with an average of 530.2 per person. The mean MMSE score was 20.4 (SD=4.91) and the median was 20.5. A Pearson product-moment correlation coefficient computed between each subject's average Fractal D and their MMSE score was statistically significant (r=-0.047, p<0.05), supporting the primary hypothesis that persons with lower cognitive functioning had more tortuous walking paths.

A serendipitous finding in the study came from the data of two participants who experienced falls during the observation period. We examined the day to day variability in their Fractal D scores prior to their falls. The results show that in comparison to similar persons who did not experience a fall, the variability in the daily Fractal D's for the fallers increased considerably (*Figure 3*). Although there is significant between-subject variability in day to day Fractal D, the day to day pattern within a particular participant is generally quite consistent. It was this finding

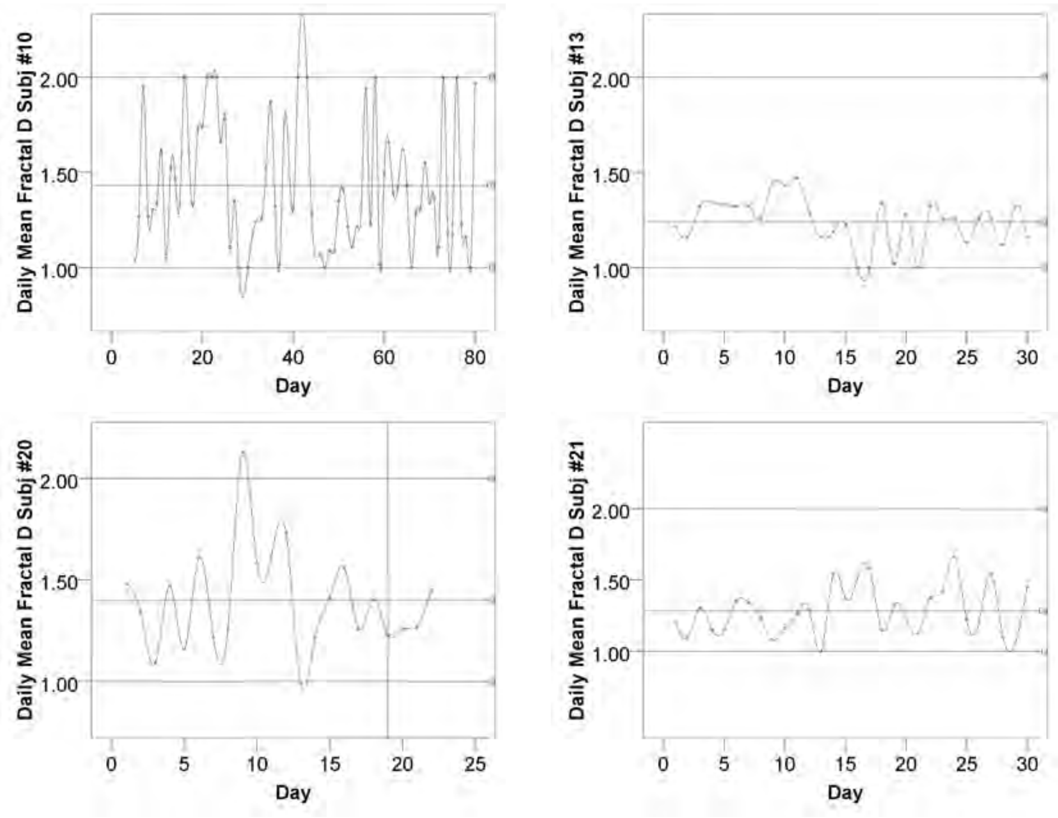

Figure 3. Top: Daily Fractal D variability for the same two subjects from ALF site #1 using all data (the left panel represents 80 days, the right panel 30 days). Subject #10 (top left) wore the tag for 80 days at which time she suffered a hip fracture. Top right: Subject #12 had less variable daily Fractal D measures and wore the tag for 30 days with no falls. Lag 1 autocorrelations for subject #10 and #12 were .07 (p=.54) and .35 (p<.05), respectively, with no other lags significant suggesting that subject #10's movements represented a random process. The high level of day to day variability in subject #10 suggests it may be predictive of her subsequent fall.
Bottom: Daily Fractal D for subject #20 residing at a second ALF research site who fell after 18 days of wearing the tag. The vertical bar in each graph denotes the point in time the fall took place. Bottom right: Daily Fractal D for subject #21 at the second ALF site who wore the tag for 30 days with no falls

that led us to our current funded research examining changes in Fractal D preceding a fall.

Discussion

We have found in our researches that Fractal D tortuosity is relatively insensitive to either distance travelled or velocity, both of which failed to differentiate participants' MMSE. The MTS correlates negatively and significantly with subjects' MMSE scores independent of the subject's method of locomotion (wheelchair vs. walker vs. unassisted ambulation), suggesting Fractal D is sensitive to the underlying cognitive functions directing locomotion and MTS may permit quantification of cognitive contributions to fall risk even in individuals who cannot stand and can generate no SGB data. Since Fractal D can be assessed in less ambulatory individuals, it is highly relevant to the eventual development of fall prediction models in frail elderly. A practical advantage of MTS is that the 'path' is the unit of analysis and the MTS need only be located in areas routinely traversed by subjects, such as atriums, and not the entire ALF thereby reducing implementation costs. There are drawbacks to the MTS method; radio reflections introduce tracking inaccuracies, however, the technology underlying MTS has matured significantly through the introduction of three new versions and errors have decreased significantly. Furthermore, Fractal D is insensitive to small-scale random variations. UWB RFID systems must be precisely calibrated (often requiring laser rangefinders) in order to ensure accurate data, and the cost of the systems (approximately $7,000) limits their availability to researchers.

Realization of an automated MTS to dynamically update Fractal D requires software development and implementation of several components. The first component calculates Fractal D in realtime for each subject when a path is generated. The second component generates local reports of Fractal D levels for each participant for the benefit of ALF administrators interested in assessing fall risk. A third component is the secure transfer of the information to offsite databases and electronic health records systems. In its final realization, we anticipate the MTS will be able to collect, analyze and distribute fall risk information automatically.

Conclusion

Jim Fozard's enthusiasm for our work comes in part from his longstanding interest in the possibilities of manipulating the environment to improve our adaptation to aging. This interest was described in a series of papers written with colleagues Popkin and Fisk[30,31] and fully developed and published in numerous articles in Gerontechnology. His starting point was human factors and ergonomics; he was active in developing the Technical Group on Aging and edited the first special issue on aging of the journal Human Factors[31]. There is a difference between Gerontechnology and the excellent body of work showing the complex interplay between environment and people as related to aging. Unquestionably the towering figure in this work is Powell Lawton[32]. Lawton argued that greater individual competence helped overcome challenges resulting from environmental press. The optimum state for an individual existed when competence was just high enough for environmental press to be stimulating but not overwhelming. As noted by Lawton in the Proceedings of the Second International Conference on Gerontechnology[33], we move beyond the limitations imposed by environmental press when we identify environmental interventions according to goals such as prevention, compensation, enhancement of quality of life, etc. Our current research employs unobtrusive location-aware technology to both identify and, in future, work automatically signal interventions for motor problems.

While I have characterized myself as the recipient of Jim's mentoring, I have learned that in gerontechnology, mentoring is necessarily a reciprocal process involving many people[34]. When I volunteered to co-teach a seminar on environmental interventions and aging introduced by Professor Jim Fozard at the University of South Florida, I took the opportunity to introduce him to the multitudes of possibilities inherent in networked technologies used in various classes of communication systems[35,36]. This novel exposure opened his eyes to the prospects of expanded service coordination and delivery available through computer networks. I, in return, have received a broad education in human factors and aging from one of the true masters in the field.

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