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One Walk a Year to 1000 Within a Year: Continuous In-home Unobtrusive Gait Assessment of Older Adults

Jeffrey Kaye^{1,2,3,4}, Nora Mattek^{1,2}, Hiroko Dodge^{1,2}, Teresa Buracchio^{2,3}, Daniel Austin^{1,4}, Stuart Hagler^{1,4}, Misha Pavel^{1,4}, and Tamara Hayes^{1,4}

¹Oregon Center for Aging & Technology, Oregon Health & Science University

²Department of Neurology, Oregon Health & Science University

³Neurology Service, Portland Veteran Affairs Medical Center

⁴Department of Biomedical Engineering, Oregon Health & Science University

Abstract

Physical performance measures predict health and function in older populations. Walking speed in particular has consistently predicted morbidity and mortality. However, single brief walking measures may not reflect a person's typical ability. Using a system that unobtrusively and continuously measures walking activity in a person's home we examined walking speed metrics and their relation to function. In 76 persons living independently (mean age, 86) we measured every instance of walking past a line of passive infra-red motion sensors placed strategically in their home during a four-week period surrounding their annual clinical evaluation. Walking speeds and the variance in these measures were calculated and compared to conventional measures of gait, motor function and cognition. Median number of walks per day was 18 ± 15 . Overall mean walking speed was 61 ± 17 cm/sec. Characteristic fast walking speed was 96 cm/sec. Men walked as frequently and fast as women. Those using a walking aid walked significantly slower and with greater variability. Morning speeds were significantly faster than afternoon/evening speeds. In-home walking speeds were significantly associated with several neuropsychological tests as well as tests of motor performance. Unobtrusive home walking assessments are ecologically valid measures of walking function. They provide previously unattainable metrics (periodicity, variability, range of minimum and maximum speeds) of everyday motor function.

Keywords

Gait; Home-based clinical assessment; Technology

Introduction

Physical activity and performance have been considered fundamental to maintaining health as well as predicting salient health outcomes. A wide range of physical performance

Address correspondence to Jeffrey Kaye, MD, Department of Neurology, Oregon Health & Science University, 3181 S.W. Sam Jackson Park Rd., Portland, OR 97239-3098. kaye@ohsu.edu.

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measures have been used to predict health and function especially in older populations¹²³. Among these, aspects of walking such as speed and related metrics (e.g. fast or slow walking, step number, variability) have been of particular interest because they have consistently predicted important outcomes such as self-rated health status⁴, general cognitive function or dementia^{5678910, 11}, as well as both morbidity^{123, 13} and mortality¹⁴¹⁵. In addition, walking speed has also been related to specific cognitive functions¹⁶.

Walking speed is an attractive measure because it is a trait that can quickly summarize or survey the integrity of multiple nervous or body system components, is relatively easy to clinically assess, and is of obvious functional importance in its own right. Current methods for measuring walking speed in the field have generally relied on a stopwatch and observed step counts or the placing of a gait mat or other devices temporarily in the home. Alternatively, research subjects may be asked to come to a physical performance laboratory during an annual visit for these measurements. The limitations of these approaches are that single brief walking measures may not best reflect a person's typical abilities in their home environment. These assessments also may be affected by conscious or unconscious performance biases when the volunteer interprets the instructions to walk for example at a self-selected "usual", "comfortable" or "fast" pace. Further, single, sparsely spaced measures cannot assess within-a-day, day-to-day or other clinically relevant windows of change such as circadian or seasonal variation. To some degree these limitations have been addressed by inferring walking speed by body-worn accelerometers. However, these may vary considerably in their ability to estimate body movement across the full range of possible velocities, depending on the device, its placement, and the measurement algorithm used¹⁷. They also have limited long-term monitoring capability and are unable to determine the location of the walking activity.

An alternative to the current brief, episodic and in-person observational methods of assessing gait is to use a system that continuously and unobtrusively measures walking activity over time in a person's home¹⁸¹⁹. This approach does not require the resident to wear any devices or for an examiner to be present. In this paper we report the use of a passive infrared-based sensing system for continuously assessing walking in the home. We evaluate how the walking metrics obtained with this system relate to conventional or commonly used measures of gait, cognition and functional ability in independently living older adults. In addition, we examine potential new metrics afforded by this approach.

Methods

Subjects

All subjects provided written informed consent to participate. Protocol and consent forms were approved by the Oregon Health and Science University Institutional Review Board. (OHSU IRB #2353). Subjects were recruited from the Portland, Oregon metropolitan area through advertisement and presentations at local retirement communities as part of the ISAAC (Intelligent Systems for Assessing Aging Change) longitudinal cohort study. A total of 265 subjects were enrolled. The subjects lived in a variety of settings from apartments in organized retirement communities to free standing single family homes. Full details of the study enrollment and assessment procedures are provided elsewhere²⁰. In this report we present data for 76 volunteers living alone, thus providing walking data that is unambiguously assigned to the sole resident in these homes.

Home Technology Setup Procedures

Subject's homes were surveyed and the residence floor plan drawn to provide a map of sensors placed strategically about the home. For this report we focus on data only from the sensors comprising a sensor line placed in the ceiling for recording of walking activity. To detect walking motion, four X10 model (MS16A; X10.com) passive infrared motion sensors were fixed sequentially on the ceiling approximately 61cm apart in a confined area such as a hallway or other corridor (see Figure 1).

The field of view of each motion sensor was restricted to ± 4 degrees to facilitate the collection of discrete walking episodes and to ensure that each sensor fired only when someone passed directly below. Speed was estimated if at least three of four sensors in a line fired. The sensor firings were collected via a wireless transceiver connected to a desktop study computer installed in the residence. The computer time-stamped the sensor firings; the data were stored locally and sent via a secure Internet connection to a central database for analysis. The system was then managed remotely using custom management software that supported data viewing, remote software updates, checking of device status and remote computer reboots if needed. Further details of the set-up are provided elsewhere¹⁸¹⁹.

Clinical Assessment Procedures

Subjects were enrolled starting in March 2007. Subjects were clinically assessed at baseline and during annual visits in their home using a standardized battery of tests consisting of physical and neurological examinations including: the MMSE, the Geriatric Depression Scale (GDS) and Functional Activities Questionnaire (FAQ). Health status was further assessed by the modified Cumulative Illness Rating Scale (CIRS). Tests of motor performance included the Tinetti gait and balance scales (balance measured on a scale of 0–26; gait measured on a scale of 0–9 with higher scores indicating better performance)²¹, chair stands, timed 9 m walk at comfortable pace, finger tapping, and the motor section of the Unified Parkinson's Disease Rating Scale (UPDRS). The latter has been used in many longitudinal studies of aging where motor function is assessed^{22–25}. References for the standard scales and methods discussed in this section may be found in our publication²⁰.

Psychometric assessments including the following cognitive domain z-scores were tabulated from 2–3 representative neuropsychological tests for each of five domains as follows: Executive function (Trail Making Test- Part B and Category Fluency Animals and Vegetables); Working memory (Letter-Number Sequencing (WMS-III) and Digit Span Backward (WAIS-R)); Attention/processing speed (Digit Span Forward (WAIS-R), Digit Symbol (WAIS-R) and Trail Making Test- Part A); Memory (Logical Memory II (WMS-R), Visual Reproduction II, and the CERAD Word-List Recall) and Visuospatial function (Picture Completion (WAIS-R) and Block Design (WAIS-R)). Cognitive domain z-scores were calculated using group mean and standard deviations of the raw test scores from all cognitively intact subjects (CDR=0) at study entry into the ISAAC cohort (n=180). The individual subject scores were z-normalized, summed, and averaged for each cognitive domain. A global cognitive score was derived similarly from all 13 tests.

Walking events < 20 cm/s or > 160 cm/s were excluded as outliers (values greater than 2 SD from the mean). Subjects reported via computer when overnight visitors were present. Days with overnight guests and days when staff visited the home were excluded.

Data Analysis

In-home walking activity available for one month centered around the two weeks before and two weeks after each subject's first annual clinical exam was used to compare the conventional clinical measures to the continuous in-home measures. Walking metrics

derived from sensor data included: 1) mean number of walks past the sensor line per day, 2) coefficient of variation (COV) of number of walks per day, 3) mean walking speed (mean of median daily speeds), 4) COV of walking speed, 5) fast walking speed (Median speed of walks > 1 SD above the subject's mean velocity) and 6) slow walking speed (Median speed of walks > 1 SD below the subject's mean velocity). For each subject these measures were summed and averaged for the time period of interest. In-home walking metrics were compared between independent walkers and those who use walking aids. The relationship between the walking metrics and clinical motor measures as well between walking metrics and cognitive measures was examined by running multivariate regression models with each of the six new in-home walking metrics as unique outcome variables and 1) each clinical marker as an independent variable controlling for age, sex and BMI, and 2) each cognitive domain z-score as an independent variable controlling for age, sex, education and GDS. All walking metrics except mean and fast walking speed were log-transformed to normalize their distributions. Mean number of walks per day was also adjusted for mean time (minutes) in the home per day. Statistically significant p-values after Bonferroni adjustment for multiple comparisons are presented. Finally, we investigated the within-subject differences in walking speeds during the morning/early afternoon (6AM to 3PM) versus late afternoon/night (3PM to 6AM) using a paired t-test. All analyses were performed by using SAS version 9.2 software (SAS Institute, Inc, Cary, NC).

Results

Baseline demographic characteristics, clinical motor measures and cognitive test scores of the 76 subjects are given in Table 1. These subjects generated a total of 39,474 walking episodes during their one-month periods for a mean of over 500 walks per subject per month. Participants were older adults (mean age: 86 years), 86% female with 15.5 years of education on average. The volunteers were relatively healthy (mean CIRS: 23; range of possible scores (best-to-worst) = 14 – 70) and free from dementia (mean MMSE: 28).

Median number of walks per day for the one month period was 22 ± 15 . Overall mean in-home walking speed was 61 ± 17 cm/sec. Fast walking speed was 96 cm/sec. Men walked as frequently and as fast as women, even after adjusting for body mass index (BMI). The mean walking speed over one month was not significantly associated with age (age range = 72 – 97). Median number of walks per day was negatively correlated with BMI; participants with higher BMI walked less ($r = -0.26$, $p = 0.04$).

A summary of in-home walking metrics is presented in Table 2 according to use of walking aids (cane, walker) vs. independent walkers. Twenty-six (one-third) subjects self-reported using a cane or walker for most of their walking. Independent walkers walked faster and more frequently with less variability in speed and number of walks per day than those who use an assistive device (all p-values < 0.05). These differences remained significant after adjusting for age, gender and BMI.

Motor measures obtained at the in-person examination were significantly associated with in-home walking metrics after adjusting for age, sex and BMI (Table 3). Stop-watch timed walk, as well as the UPDRS and Tinetti balance assessment were significantly associated ($p < 0.0001$) with in-home walking speed, and were on average faster than the in-home speed. Higher UPDRS score, lower Tinetti gait and balance scores and slower timed walk speeds were strongly associated with increased variability in in-home speeds (all p-values < 0.01). Lower Tinetti scores, as well as slower timed walk speeds, were associated with fewer total number of in-home walks per day, adjusted for time in the home (all p-values < 0.05). A one-point decrease (indicating worse function) in Tinetti Balance score resulted in a 1.6 cm/s decrease in mean in-home walking speed on average, when age, sex and BMI were held

constant. Similarly a one-point increase (indicating worse function) in UPDRS score resulted in a 2.7 cm/s decrease in walking speed.

The relationship of cognitive function to in-home walking metrics showed significant associations after adjusting for age, sex, education and GDS (Table 4). The global cognitive z-score was positively associated with total number of daily walks, mean speed, fast and slow speeds. Attention/processing speed and visuospatial domain z-scores were also strongly associated with in-home mean speed ($p < 0.01$). A one standard deviation increase in the global z-score was associated with a 10.1 cm/s increase in mean in-home walking speed when age, sex, education and GDS were held constant. Similarly, a one standard deviation increase in attention z-score corresponded to a 7.7 cm/s increase in walking speed.

Fifty-three percent of all walking episodes occurred in the morning/early afternoon. Morning/early afternoon speeds were significantly faster than afternoon/evening speeds (mean difference = 4 cm/s, $p < 0.0001$). Variation in walking speeds by hour of the day is presented in the supplementary file.

Discussion

We have demonstrated for the first time a clinically relevant, home-based methodology for assessing walking functions that can be derived entirely without body worn sensors and can be used to assess walking function for very long periods (months to years) of time. Further, this approach provides the capability to generate not only a few isolated exemplars of walking, but an entire population of walking episodes that is automatically time-stamped facilitating analyses based on time of day and life events. Other methods exist for continuous in-home walking assessment. Although direct capture of walking via cameras and video is technically feasible²⁶, independently living adults generally do not wish to have cameras or video installed in their homes for ongoing health surveillance²⁶. Further, our data suggests that awareness of direct observation may itself affect actual performance. Walking speeds in home were typically slower than the stopwatch-derived walking speed. However, this did not mean that subjects were incapable of generating faster gait speeds. We suggest that the population of fast speeds observed in home represent real-life activities such as rushing to the bathroom, answering the telephone or the front door. We can potentially verify this through the additional passive motion sensors located in other areas of the home that detect location-specific activity at a known time. Thus for example, one could show a statistical association of the population of fast walks with movement to the bathroom.

The automated sensor-derived walking measures showed significant associations with conventional episodic measures of walking speed (measured with a stopwatch), overall qualitatively rated gait-related motor function (Tinetti scales), and fine manual motor speed (finger-tapping). In addition, there were similar relationships with the measure of variability in walking speed. Chair stands, often considered a measure of lower extremity functional strength and overall endurance, were not related to any of the automated speed measures. The Tinetti balance scale was strongly associated with sensor-derived walking metrics. These data suggest that the sensor-derived metrics are a valid measure of gait speed and indirectly, balance while walking, but are not strongly influenced by lower extremity strength. This must be considered cautiously since this cohort was relatively healthy and in general did not have significant limitations on mobility. However, a third of the sample did use a cane or assistive device for routine walking and when this group was examined separately they, as would be expected, walked significantly slower and had higher walk-to-walk variability.

Many studies have shown a relationship of cognitive function to walking speed and related motor measures especially in the domains of executive function and attention/processing speed^{7, 27}. We found that sensor-derived walking metrics were also related to similar cognitive measures. In particular, the domains of attention/processing speed and global cognition were significantly associated with sensor-derived mean walking speed and slow and fast speeds. These relationships point to the overall importance of attention, speed of processing and global cognitive function for ambulation. In the Health, Aging and Body Composition study, gait speed predicted decline on attention and processing speed as measured by the Digit Symbol test²⁸. The Three-City Study found that the Trail Making Test A (assessing processing speed) and the Isaacs Set test (a test of verbal fluency), but not the Trail Making Test B (a common executive function measure) were associated with walking speed over time suggesting that attention and processing speed are particularly important for longitudinal outcomes.²⁹ We did not find a relationship between our sensor-derived walking speed and our executive function domain as have some others^{7, 27}. To some degree this may reflect the tests that are used to comprise this domain as there is clearly overlap in attention, speed of processing and executive function measures²⁷.

Of particular interest was the observation of the relationship of the new walking metrics to time of day. People walked significantly faster in the morning compared to the afternoon and evening hours. These within-person time of day differences were similar in magnitude to between-age group differences in gait speed³⁰, as well as to treatment-based differences reported in intervention studies where gait speed is an outcome³¹. This observation suggests the importance of including time of day of assessment in gait analysis. The automated method inherently time stamps all data and allows analysis to be performed across different time epochs without disturbing the volunteer.

A limitation of this report is that in order to relate these new walking measures to a single data point as might be typical in current clinical studies we chose to create a mean walking speed composed of four weeks of data, two weeks before and two weeks after the in-person assessment. There is no “gold standard” for this comparison frame. However, aggregating data constructed from longer term monitoring is likely to reflect activity quite remote from the in-person assessed walking speed, introducing increasing opportunities for the data to be affected by external events (illness, mood changes, medications, etc.) that may affect walking. Another limitation is that this system does not capture walking outside of a residence. However, at least in this older population, we found they spend on average 20.5 hours a day in their homes²⁰.

Future work will explore the longer time series, their trajectories of change, and how they signal or predict functional outcomes of interest. It is anticipated that this continuous data that allows for the automatic derivation of measures of variability may be more sensitive to detecting early changes in motor function indicative of emergent disease or functional disability with aging¹¹. In addition, this approach to measuring walking also lends itself to more efficient trials of interventions where gait is a primary outcome of interest such as rehabilitation for stroke, or drug treatment for multiple sclerosis or Parkinson’s disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

A. The sensor line installed along the ceiling in a residence. Note, light fixtures do not affect the sensor firings. B. A cartoon of a person walking under the sensors and their field of view. C. A scatter plot of a representative volunteer's recordings of all walking events during their one-month period. The stopwatch timed speed, measured at the annual clinical evaluation, is represented by a red star.

Table 1

Participant Demographics, Clinical and Cognitive Variables N=76

Demographics	Mean $\pm$ SD
Age (yrs)	85.9 $\pm$ 4.9
Gender (% Women)	86%
Education (yrs)	15.5 $\pm$ 2.5
Non-white (%)	13%
BMI (kg/m ²)	28.1 $\pm$ 5.1
GDS	1.2 $\pm$ 1.6
FAQ	0.7 $\pm$ 2.1
CIRS	22.6 $\pm$ 3.0
<i>Clinical Motor Measures</i>	
UPDRS	2.6 $\pm$ 3.2
Tinetti Gait (max score: 9)	7.7 $\pm$ 1.8
Tinetti Balance (max score: 26)	20.8 $\pm$ 4.3
Tapping Speed (taps/10 secs)	35.1 $\pm$ 10.1
Chair Stands (secs/5 stands)	9.0 $\pm$ 6.5
Stopwatch Speed (cm/sec)	71.4 $\pm$ 22.9
<i>Psychometric Test Scores</i>	
Mini-Mental State Examination	28.3 $\pm$ 1.7
Logical Memory II (WMS-R)	10.9 $\pm$ 4.2
World-List Recall (CERAD)	6.3 $\pm$ 2.2
Visual Reproduction II (WMS-R)	17.2 $\pm$ 10.8
Digit Span Forward (WAIS-R)	6.8 $\pm$ 1.0
Digit Span Backward (WAIS-R)	4.5 $\pm$ 1.1
Digit-Symbol Written Test	38.2 $\pm$ 11.7
Letter-Number Sequencing (WMS-3)	8.1 $\pm$ 2.7
Category Fluency: Animals	17.1 $\pm$ 5.1
Category Fluency: Vegetables	12.8 $\pm$ 4.6
Trail Making Test, Part A	43.3 $\pm$ 17.9
Trail Making Test, Part B	116.5 $\pm$ 48
Block Design (WAIS-R)	21.3 $\pm$ 7.6
Picture Completion (WAIS-R)	12.7 $\pm$ 3.7

Table 2

Summary of In-home Walking Metrics (four week window) among participants who walk independently and those who use walking aids

Measure	Independent Walkers (n=49)	Walks with Assistance (n=26)	p-value
Number of Walks/Day	24.4 ± 15.4	17.6 ± 14.5	0.03
COV Number of Walks/Day	0.4 ± 0.2	0.6 ± 0.3	0.02
Walking Speed (cm/sec)	65.7 ± 17.1	52.6 ± 13.9	0.001
COV Walking Speed	0.1 ± 0.1	0.2 ± 0.1	0.006
Fast Walking Speed **	97.0 ± 23.9	94.0 ± 21.2	0.59
Slow Walking Speed ***	39.2 ± 12.1	29.3 ± 9.6	0.0002

** Fast Walking Speed= Median speed of walks >1 SD above the subject's mean velocity

*** Slow Walking Speed= Median speed of walks >1 SD below the subject's mean velocity

Table 3

Regression coefficients and 95% confidence intervals for relationships between motor measures (independent) and in-home walking metrics (dependent)

	In-home Walking Metrics					
	Walks per Day	Walks COV	Mean Speed	Speed COV	Slow Speed	Fast Speed
Motor Measures						
UPDRS	-0.05 (-0.10, 0.006)	0.03 (-0.005, 0.06)	-2.72 *** (-4.10, -1.30)	0.08 *** (0.03, 0.12)	-0.05 *** (-0.07, -0.02)	-1 (-2.88, 0.87)
Tinetti Gait	0.09 * (-0.17, -0.0001)	-0.03 (-0.03, 0.08)	2.38 * (-4.65, -0.11)	-0.12 ** (0.04, 0.19)	0.06 ** (-0.10, -0.02)	-0.39 (-2.73, 3.51)
Tinetti Balance	0.04 * (-0.08, -0.004)	-0.01 (-0.01, 0.03)	1.63 *** (-2.59, -0.68)	-0.06 *** (0.02, 0.09)	0.04 *** (-0.05, -0.02)	0.27 (-1.65, 1.10)
Tapping	0.005 (-0.01, 0.02)	-0.007 (-0.02, 0.004)	0.54 * (0.12, 0.95)	-0.02 * (-0.03, -0.003)	0.01 ** (0.003, 0.02)	0.33 (-0.26, 0.93)
Chair Stands	-0.02 (-0.09, 0.05)	0.01 (-0.03, 0.004)	-1.2 (-2.46, 0.06)	-0.003 (-0.04, 0.04)	-0.01 (-0.03, 0.01)	-1.5 (-3.3, 0.20)
Stopwatch Speed	0.008 * (0.002, 0.02)	-0.004 (-0.008, 0.0007)	0.41 *** (0.22, 0.57)	-0.01 *** (-0.02, -0.005)	0.008 *** (0.005, 0.01)	0.22 (-0.03, 0.47)

* p<0.05,

** p<0.01,

p<0.0014 based on the Bonferroni multiple comparison adjustment

Notes: FAQ= Functional Assessment Questionnaire, UPDRS= Parkinson's Scale

All models adjusted for age, sex and BMI; Number of Walks/Day also adjusted for mean time in home each day Walks per Day, Walks COV, Speed COV, Slow Speed were log-transformed to achieve linearity

Table 4

Regression coefficients and 95% confidence intervals for relationships between cognitive measures (independent) and in-home walking metrics (dependent)

	In-home Walking Metrics					
	Walks per Day	Walks COV	Mean Speed	Speed COV	Slow Speed	Fast Speed
Cognitive Measures						
MMSE	-0.04 (-0.14, 0.06)	0.01 (-0.05, 0.08)	1.56 (-0.97, 4.09)	0.01 (-0.08, 0.11)	0.02 (-0.03, 0.07)	1.85 (-1.48, 5.19)
Global Cognitive z-score	-0.42* (-0.84, -0.002)	0.16 (-0.06, 0.38)	10.06** (2.71, 17.41)	0.06 (-0.22, 0.34)	0.17* (0.03, 0.32)	12.24* (2.56, 21.9)
Attention/Processing Speed z-score	-0.25 (-0.59, 0.10)	0.10 (-0.09, 0.28)	7.73** (1.60, 13.86)	0.02 (-0.21, 0.25)	0.13* (0.005, 0.25)	13.92*** (6.0, 21.9)
Executive Function z-score	-0.26 (-0.57, 0.05)	0.15 (-0.01, 0.31)	4.11 (-1.54, 9.77)	0.15 (-0.06, 0.35)	0.09 (-0.02, 0.20)	5.53 (-1.89, 12.95)
Memory z-score	-0.19 (-0.44, 0.07)	0.08 (-0.06, 0.21)	2.77 (-1.80, 7.34)	0.03 (-0.14, 0.20)	0.06 (-0.03, 0.14)	2.82 (-3.16, 8.81)
Working Memory z-score	-0.26* (-0.51, -0.01)	0.10 (-0.03, 0.23)	3.34 (-1.06, 7.74)	0.09 (-0.07, 0.25)	0.03 (-0.06, 0.12)	3.48 (-2.53, 9.49)
Visuospatial z-score	-0.02 (-0.30, 0.25)	0.001 (-0.16, 0.16)	7.13** (1.98, 12.28)	-0.10 (-0.29, 0.09)	0.10 (-0.004, 0.20)	8.77* (2.07, 15.46)

* p<0.05,

** p<0.01,

*** p<0.0012 based on the Bonferroni multiple comparison adjustment

Notes: MMSE=Mini-Mental Status Exam

All models adjusted for age, sex, education and GDS (Geriatric Depression Score);

Number of Walks/Day also adjusted for mean time in home each day

Walks per Day, Walks COV, Speed COV, Slow Speed were log-transformed to achieve linearity