

Quantitative Gait Markers and Incident Fall Risk in Older Adults

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Background. Identifying quantitative gait markers of falls in older adults may improve diagnostic assessments and suggest novel intervention targets.

Methods. We studied 597 adults aged 70 and older (mean age 80.5 years, 62% women) enrolled in an aging study who received quantitative gait assessments at baseline. Association of speed and six other gait markers (cadence, stride length, swing, double support, stride length variability, and swing time variability) with incident fall rate was studied using generalized estimation equation procedures adjusted for age, sex, education, falls, chronic illnesses, medications, cognition, disability as well as traditional clinical tests of gait and balance.

Results. Over a mean follow-up period of 20 months, 226 (38%) of the 597 participants fell. Mean fall rate was 0.44 per person-year. Slower gait speed (risk ratio [RR] per 10 cm/s decrease 1.069, 95% confidence interval [CI] 1.001–1.142) was associated with higher risk of falls in the fully adjusted models. Among six other markers, worse performance on swing (RR 1.406, 95% CI 1.027–1.926), double-support phase (RR 1.165, 95% CI 1.026–1.321), swing time variability (RR 1.007, 95% CI 1.004–1.010), and stride length variability (RR 1.076, 95% CI 1.030–1.111) predicted fall risk. The associations remained significant even after accounting for cognitive impairment and disability.

Conclusions. Quantitative gait markers are independent predictors of falls in older adults. Gait speed and other markers, especially variability, should be further studied to improve current fall risk assessments and to develop new interventions.

Key Words: Gait—Falls.

ONE third of community-residing adults older than 65 years fall each year (1). Falls result in major adverse outcomes in older adults including injury, institutionalization, and death (2,3). The persistence of high rates of fall in the elderly population despite the availability of many clinical risk assessments (4–6) and the modest success reported with fall intervention trials (5,7) necessitates a better understanding of fall risk factors to develop simple and effective screening tools as well as to identify new intervention targets.

Gait training is a key component of fall prevention interventions (5,7), and gait evaluation is recommended in current fall guidelines (5,8). Yet, uniform clinical gait protocols are lacking and diagnosis of gait abnormalities is highly dependent on examiners' expertise (9,10). Although there are many performance-based mobility tests (5–7,11), they may not be adopted in primary care settings as it takes time and resources to use them accurately (12). Measuring gait speed is suggested as a simple way to assess health and function in older adults (5,6,13). Gait speed has been found to be associated with risk of falls in few studies (14–18), although most studies were limited by small sample size or cross-sectional design (15,16), evaluation of a single sex (17,19), and measurement of limited set of confounders (5,9,18,20).

Gait is a complex motor phenomenon with many other measurable facets besides speed that might identify fall risk. We undertook this study to determine whether and to what extent gait speed and other gait markers are independently associated with risk of falls in a cohort of community-residing adults aged 70 and older. Specifically, we compared the predictive validity of individual gait variables as well as gait domains for fall risk in older adults.

METHODS

Study Population

We undertook a prospective cohort study nested within the Einstein Aging Study (10). The primary aim of the Einstein Aging Study was to identify risk factors for dementia. Study design has been previously reported (10,21). In brief, potential participants (aged 70 and older) identified from Bronx County population lists were contacted by letter explaining the purpose of the study and then by telephone. Participants who gave verbal consent on the telephone were invited for in-person evaluation at our research center. Exclusion criteria included severe audiovisual loss, bed bound due to illness, and institutionalization. The study protocols were approved by the local institutional review board, and

written informed consents were obtained from each participant prior to enrollment. Participants returned at yearly intervals.

Gait

Research assistants conducted quantitative gait studies using a computerized walkway (180 × 35.5 × 0.25 inches) with embedded pressure sensors (GAITRite; CIR Systems, Havertown, PA) at study visits (21,22). Participants were asked to walk on the mat at their “normal pace” for two trials in a quiet well-lit hallway wearing comfortable footwear and without any attached monitors. Start and stop points were marked by white lines on the floor and included 3 feet from the walkway edge for initial acceleration and terminal deceleration. Based on footfalls recorded on the walkway, the software computes gait variables as the mean of two trials. Participants who could ambulate only with walking aids were included, and the GAITRite data were manually edited by research assistants who were blinded to study aims. The GAITRite system is widely used in clinical and research settings, and excellent reliability has been reported in our and other centers (11,21–22).

Falls

Falls were defined as the individual unintentionally coming down on the floor or to a lower level not due to a major intrinsic or extrinsic event (7). Research assistants contacted participants by telephone every 2–3 months in between clinic visits to ascertain any new falls and associated injuries (laceration, fracture, or received emergency care). At baseline and annual follow-up visits, participants were asked about falls in the previous year.

This study began on September 2004 when we started systematically ascertaining falls in our cohort. The first telephone interview was administered in November 2004. Study follow-up ended February 2008. Of the 827 Einstein Aging study participants seen during this 42-month period, 101 had no fall assessments and 79 did not have gait assessments. Thus, 647 participants (78.2%) with gait and fall assessments were eligible. Among these participants, 50 (7.7%) had no follow-up fall assessments. Thus, 597 participants (92.7%) were included in the analysis. Participants who were and were not included were similar in terms of age, sex, and cognitive status. The 597 eligible participants (100%) completed one or more follow-up telephone interviews, and 424 participants (71%) completed 1 year or more follow-up.

Clinical Assessment

Clinical assistants used structured questionnaires to elicit history of medical illnesses, medication use, and depressive symptoms (21,23,24). Presence of depression, diabetes, heart failure, hypertension, angina, myocardial infarction,

strokes, Parkinson’s disease, chronic obstructive lung disease, and arthritis was used to calculate a summary illness index (21,25). We consulted medical records and contacted participants’ family members or physicians to verify or obtain further details. The following seven activities of daily living were assessed based on a disability scale developed for use in community-based cohorts (26): bathing, dressing, grooming, feeding, toileting, walking around home, and getting up from a chair. Participants were asked if they were able to perform an activity unassisted (0 points), unassisted but with difficulty (1 point), or whether they required assistance or were unable to do the activity (2 points). A summary disability score was then computed (range 0–14). Disability was defined as inability or requiring assistance from another person to do any one of these tasks. General cognitive status was assessed by the Blessed Information-Memory-Concentration Test (27). Visual acuity was measured with a Snellen’s chart (<1/200 low acuity). Study clinicians rated gaits as normal or abnormal following visual inspection of walking patterns (10). This clinical rating has high interrater reliability, and gait abnormalities diagnosed by this method have predicted risk for dementia, institutionalization, and death in our cohort (10,24). Unipedal stance time, a sensitive balance test, was recorded as the time participants balanced on one foot without support (maximum 30 seconds; 28). Time taken to get up from a chair five times unassisted was recorded as a test of balance and lower extremity strength (6).

Data Analysis

Baseline characteristics were compared with descriptive statistics, applying nonparametric tests as appropriate. To analyze longitudinal fall data, we used generalized estimating equations (GEEs) with a binomial distribution to model the probability of fall at each follow-up assessment using the log link function (29). GEE method is an extension of generalized linear models for analyzing longitudinal data (30). It can accommodate different follow-up lengths and missing data. It has the advantage that the parameter estimate from GEE analysis is consistent as long as the model for the marginal mean is correctly specified. This method has been used in other fall studies (17,19). Risk ratios (RRs) and 95% confidence intervals (CIs) were estimated from the models.

We selected gait speed (10 cm/s units) and six other markers that have predicted adverse outcomes in our studies (21) as predictors of falls: stride length (10 cm decrease), cadence (10 step decrease), swing phase (10% decrease), double-support phase (10% increase), stride length variability (10% increase), and swing time variability (10% increase). Variability variables are reported as coefficient of variation (100 × standard deviation/mean). We reported performance in other individual measures as 10-unit changes to make our observations clinically intuitive. For instance, the

10 cm/s unit is considered a meaningful change in speed over 1 year in older adults (31). Improvement of similar magnitude in speed and other gait markers have been noted with exercise and pharmacological interventions (31–34).

To identify which marker best predicted falls, we used quasi-likelihood under the independence model criterion, an extension of Akaike information criterion in GEE, as the goodness-of-fit measure to compare best model fit among the five gait markers (35).

All analyses included age, gender, and years of education. The final models also included the following baseline covariates: falls in the year prior to entry, illness index, total medications, disability score, Blessed test score, unipedal stance time, and clinical gait abnormalities (5,9,27,28,36). Univariate associations of these covariates with fall risk were examined using GEE models. The following variables did not influence results in preliminary analyses and were not included in reported models: individual illnesses, specific medications (psychotropics or sedatives), clinical strength and sensory rating, depressive symptoms, low visual acuity, and repeated chair time.

Single gait variables are often highly correlated so that their independent effects on risk for falls may be hard to observe while adjusting for other gait variables. To address this issue, we used factor analysis as a complementary statistical approach. The seven individual gait variables were submitted to principal components analysis using varimax rotation to derive orthogonal statistically independent factors (see Table 2) that were used as predictors in the GEE analysis previously described.

We repeated the aforementioned analysis with injurious falls as the outcomes to corroborate our findings. To account for frail individuals having more falls or recall bias for falls among cognitively impaired participants (37), we conducted sensitivity analyses excluding participants with disability or with cognitive impairment (presence of dementia or Blessed test scores greater than 7; 27).

RESULTS

The 597 eligible participants completed 4478 telephone and in-house follow-up assessments. Falls were reported in 415 interviews (9.2%). The mean number of telephone and in-house follow-up interviews completed during the study period was 7.5 (range 1–18), corresponding to a mean follow-up of 20 months (*SD* 11). The median time to first fall from baseline was 8 months (interquartile range 4–17 months). Falls occurred in 226 participants (38%), of whom 115 fell once and 111 had recurrent falls. The mean fall rate during the study period was 0.44 per person-year. Participants who fell during follow-up were older at baseline (mean age 81.1 vs 80.1 years, $p = .04$) than those who did not fall.

Baseline sample characteristics are presented in Table 1. Average age of the participants was 80.6 years. There were

Table 1. Baseline Variables and Associated Risk for Falls

Variable	Value	Risk Ratio	
		(95% confidence interval)*	<i>p</i> Value
Age, y (mean \pm <i>SD</i>)	80.5 \pm 5.4	1.03 (1.00–1.05)	.02
Female, %	62	1.24 (0.96–1.60)	.10
Education, y (mean \pm <i>SD</i>)	13.9 \pm 3.4	1.02 (0.98–1.05)	.36
Illness index (mean \pm <i>SD</i>)	1.3 \pm 1.1	0.97 (0.89–1.07)	.58
Medication count (mean \pm <i>SD</i>)	5.1 \pm 3.8	1.00 (0.97–1.03)	.85
Fall previous 12 mo, %	33	1.21 (0.93–1.57)	.16
Disability score (mean \pm <i>SD</i>)	0.7 \pm 1.3	1.11 (1.03–1.20)	.009
Blessed test (mean \pm <i>SD</i>), range 0–32	2.2 \pm 2.4	1.01 (0.96–1.06)	.63
GDS [†] (mean \pm <i>SD</i>), range 0–15	2.3 \pm 2.2	1.03 (0.98–1.08)	.31
Visual acuity <1/200, %	26	0.78 (0.57–1.07)	.12
Clinical gait abnormality, %	35	1.43 (1.11–1.83)	.005
Unipedal stance, s (mean \pm <i>SD</i>)	7.0 \pm 8.6	0.99 (0.97–1.00)	.10
Repeated chair rise, s (mean \pm <i>SD</i>)	14.2 \pm 4.8	1.01 (0.98–1.04)	.68

Notes: * Risk ratios are for univariate (unadjusted) associations of clinical variables with fall risk derived using the generalized estimating equation models described in the Methods section.

[†] Geriatric depression scale (24).

227 men (38%) and 370 women (62%). Older age (RR 1.032, $p = .02$) was associated with increased fall risk. Among standard clinical tests done at baseline, gait abnormalities diagnosed by clinicians (RR 1.431, $p = .005$) and disability scores (RR 1.116, $p = .009$) predicted increased fall risk in univariate models.

Gait Speed

The mean gait speed was 92.8 \pm 24.1 cm/s. Slower speed was associated with increased risk of falls (RR per 10 cm/s decrease 1.069, 95% CI 1.001–1.142), even after adjustments for potential confounders and traditional clinical tests of cognition, gait, and balance (Table 3). Clinical gait abnormality and disability scores were not significant in the final models that included gait speed.

Gait speed of less than 70 cm/s is used to define slow gait (13). Participants with gait speed less than 70 (RR 1.540, 95% CI 1.095–2.150) and with speeds between 70 and 100 cm/s (RR 1.276, 95% CI 0.906–1.768) had an increased risk for falling compared with participants with gait speed more than 100 cm/s. The results were not significant when adjusted for additional covariates, although the direction of the associations was similar.

Other Gait Markers

Table 3 shows that among the six other gait markers, worse performance on swing (RR 1.406, 95% CI 1.027–1.926), double-support phase (RR 1.165, 95% CI 1.026–1.321), swing time variability (RR 1.007, 95% CI 1.004–1.010), and stride length variability (RR 1.076, 95% CI 1.030–1.111) predicted fall risk in the final models. All variables remained significant even after statistical corrections for multiple comparisons (data not shown; 38).

Table 2. Factor Loading of Seven Quantitative Variables on Three Independent Gait Factors Rotated and Extracted by Factor Analysis*

Gait Variables	Pace Factor	Variability Factor	Rhythm Factor
Velocity, cm/s	-0.936	-0.090	-0.288
Stride length, cm	-0.738	-0.008	-0.430
Cadence, steps/min	-0.837	-0.036	-0.134
Double-support time, %	0.385	0.092	0.767
Swing time, %	-0.203	0.116	-0.900
Stride length variability, CV	0.180	0.912	-0.095
Swing time variability, CV	-0.071	0.924	0.056
Variance explained, %	33.6	24.5	24.3

Notes: CV = coefficient of variation.

*Higher factor scores denote worse performance.

Model comparisons indicated that stride length variability had the best fit in the final models among the seven gait variables, including speed (35).

Gait Factors

Factor analysis of the seven gait variables resulted in three factors that accounted for 82% variance in gait performance and was similar to the factor structure in our previous study (Table 2). The first factor loaded heavily on speed, cadence, and stride length, and was termed the pace factor. The second factor loaded heavily on double support and swing, and was termed rhythm factor. The final variability factor loaded heavily on the two gait variability variables. In the fully adjusted models, the variability (RR for 1 SD increase 1.067, 95% CI 1.034–1.099) and rhythm factors (RR 1.099, 95% CI 1.001–1.226) were associated with fall rates but not the pace factor (RR 1.120, 95% CI 0.972–1.290).

Sensitivity Analyses

Injuries occurred in 46% of falls. The injurious fall rate was 0.23 per person-year. Women were at higher risk for

injurious falls (RR 1.701, 95% CI 1.234–2.351). In the final model, only increased stride length variability (RR 1.128, 95% CI 1.091–1.170) and swing time variability (RR 1.011, 95% CI 1.008–1.105) predicted injurious falls (Table 3).

The continuous disability score was associated with increased fall risk in univariate models (Table 1) and included as a covariate in final models. We repeated the analyses excluding 29 participants with disability (26). In the remaining 568 nondisabled participants, gait speed predicted fall risk in the initial (RR per 10 cm/s decrease 1.071, 95% CI 1.019–1.131) and final models (RR 1.011, 95% CI 1.001–1.142). Cognitive impairment may result in reduced recall of falls (37). Hence, we repeated the analyses excluding 35 participants with cognitive impairment (Blessed scores >7 or dementia). Gait speed still predicted risk for falls in the initial model (RR 1.082, 95% CI 1.020–1.134) and showed a trend in the final model (RR 1.059, 95% CI 0.991–1.131).

DISCUSSION

In this prospective study of a large well-characterized cohort of community-residing elders, quantitative gait markers were independent and strong predictors of incident falls. Each 10 cm/s decrease in gait speed was associated with a 7% increased risk for falls. Participants with slow gait speed (≤ 70 cm/s) had a 1.5-fold increased risk for falls compared with those with normal speed. The association between gait speed and falls remained robust after accounting for several risk factors that are strongly associated with falls as well as traditional clinical tests of gait and balance (2,5,9). We have observed in our previous study that not all quantitative gait abnormalities have clinical correlates or the subtle clinical signs associated with quantitative gait dysfunction may be underrecognized by clinicians (21).

Table 3. Quantitative Gait Markers and Risk for Falls

Variables	Median (interquartile range)	Unit Change	All Falls (model 1)*		All Falls (model 2)†		Injurious Falls‡	
			Risk Ratio (95% confidence interval)	p Value	Risk Ratio (95% confidence interval)	p Value	Risk Ratio (95% confidence interval)	p Value
Speed	95.10 cm/s (77.70–108.90)	10 cm/s decrease	1.078 (1.025–1.134)	.003	1.069 (1.001–1.142)	.046	1.053 (0.976–1.141)	.249
Cadence	101.80 step/min (93.80–109.10)	10-step decrease	1.085 (0.994–1.184)	.07	1.017 (0.983–1.183)	.11	1.071 (0.950–1.211)	.263
Stride length	112.50 cm (96.88–123.87)	10-cm decrease	1.095 (1.031–1.162)	.003	1.066 (0.984–1.155)	.118	1.001 (0.924–1.131)	.668
Swing phase	36.60% (34.70–38.40)	10% decrease	1.503 (1.132–2.009)	.006	1.406 (1.027–1.926)	.034	0.900 (0.571–1.421)	.644
Double-support phase	26.60% (23.50–30.40)	10% increase	1.207 (1.082–1.347)	<.001	1.165 (1.026–1.321)	.018	1.031 (0.821–1.290)	.794
Stride length variability‡	3.60% (2.48–5.56)	10% increase	1.086 (1.052–1.120)	<.001	1.076 (1.030–1.111)	<.001	1.128 (1.091–1.170)	<.001
Swing time variability‡	5.17% (2.85–7.62)	10% increase	1.007 (1.005–1.009)	<.001	1.007 (1.004–1.010)	<.001	1.011 (1.008–1.015)	<.001

Notes: Risk ratios reported in terms of unit changes in variables (see Methods section).

*Model 1 is adjusted for age, sex, and years of education.

†Model 2 in addition was adjusted for falls in previous year, illness index, medications, disability scores, Blessed test scores, clinical gait abnormalities, and unipedal stance time.

‡Variability reported as coefficient of variation (100 × standard deviation/mean).

Although dependent on availability of equipment, quantitative gait measures can be easily and quickly collected in clinical and research settings without requiring attachment of monitoring devices or extensive training. Gait speed is a simple and quick option for measuring fall risk. Although we measured gait speed using an instrumented walkway, it can be easily measured using a stopwatch. Our analyses also identified gait variables such as swing phase, double-support phase, and gait variability that better predicted falls than speed. Our complementary factor analysis identified three gait domains; of which variability and rhythm domains were associated with increased fall risk. The incremental validity from gait variables reported in this and other studies over traditional risk factors and clinical tests of gait and balance support further exploration of these measures (20,39).

Although gait may be a marker for fall risk factors such as age, illness, or frailty, our results suggest that our gait markers are also directly involved in fall mechanisms. Increased stride length and swing time variability were the most robust predictors of falls, and the only predictors of injurious falls. Stance time variability has been reported to predict incident mobility disability in older adults (40). These results suggest that measures of temporal and spatial gait variability have specific relationships with different mobility outcomes. However, our factor analysis approach also indicates that the variability domain overall has utility in predicting outcomes and providing insights into pathology. Regulation of gait variability is thought to be automated with minimal cognitive input in healthy adults (20,21). Increased gait variability may lead to unstable gait or poor balance (39,41), increasing fall risk. Increased variability of step length was associated with greater burden of subclinical brain vascular abnormalities in high-functioning older adult (42). Neurodegenerative processes may also result in disturbed gait regulation (21). These results suggest that discrete pathological processes may underlie disturbed gait regulation. Our findings have possible therapeutic implications. The individual gait variables identified are potentially modifiable factors. For instance, gait variability and double-support phase were reported to improve with treadmill training or pharmacological interventions (33,34). Slower gait is associated with executive dysfunction and cerebrovascular disease (24,25), which may be amenable to interventions.

Limitations

This nested cohort study was necessarily restricted to participants who received gait and fall assessments since 2004, but participants seen previously were not differentially excluded. We did not study all possible aspects of gait, although most other gait variables can be derived or are highly correlated with our empirically selected measures (20,21,25). Poor recall of falls is linked to cognitive impairment and longer assessment intervals (37). The short intervals and

high interview completion rates help reduce errors in our study. Our contact interval was longer than studies where monthly fall calendars were used but similar or shorter than those using telephone interviews (9,17,19). A more detailed fall collection method was not utilized as falls were not the primary outcome in our parent studies. Hence, it is likely that we may have underestimated effects. However, adjusting for cognitive status or excluding cognitively impaired individuals did not change our results. Gait variability also predicted injurious and recurrent falls, which are less prone to recall bias (37). Previously described single fall risk factors were not significantly associated with falls (Table 1), although the directions of the associations were in the right direction. Many of these risk factors have been examined in smaller samples. Differences in populations, fall and risk factor assessment methods, and definitions used for risk factors may also account for differing results.

The intensity of assessment will depend on the clinical setting (8). Gait speed could be examined as a brief and simple screen to complement current fall risk assessments in primary care settings (5,8). In high-risk patients, in specialty clinics, or in research settings, a more comprehensive gait evaluation including markers such as gait variability may be considered. Quantitative gait markers are independent predictors of falls in older adults and should be further studied to improve current fall risk assessments and tested as intervention targets.

FUNDING

Supported by grants from the National Institute on Aging (grants AG03949, RO1 AG025119, and K23 AG030857).

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Received August 6, 2008

Accepted January 7, 2009

Decision Editor: Luigi Ferrucci, MD, PhD