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Gait Variability and the Risk of Incident Mobility Disability in Community-Dwelling Older Adults

Jennifer S. Brach, Stephanie A. Studenski, Subashan Perera, Jessie M. VanSwearingen, and Anne B. Newman

Department of Physical Therapy, Division of Geriatric Medicine, Department of Epidemiology, University of Pittsburgh, Pennsylvania.

Background. Gait speed is a strong predictor of incident walking disability. The objective was to determine if gait variability adds to the prediction of incident mobility disability independent of gait speed.

Methods. Participants included 379 older adults (mean age = 79 years; 78% Caucasian, and 40% men) in the Cardiovascular Health Study at the Pittsburgh site. All could ambulate independently and reported no difficulty walking a half mile. Gait characteristics were determined from a 4-meter computerized walkway. For each gait parameter, variability was defined as the standard deviation from the individual steps from two passes. Incident walking disability was obtained by phone interview every 6 months for 54 months and was defined as new difficulty walking a half mile or inability to walk a half mile.

Results. Of the 379 participants, 222 (58.6%) developed incident mobility disability. In unadjusted Cox proportional hazards models gait speed, mean step length, mean stance time, and stance time variability were associated with incident mobility disability. After adjusting for gait speed, demographics, chronic conditions, prescription medications, health status, and physical activity level, only stance time variability remained an important indicator of disability. In the adjusted model, an increase in stance time variability of 0.01 seconds was associated with a 13% higher incidence of mobility disability (hazard ratio 1.13, 95% confidence interval, 1.01–1.27).

Conclusions. Stance time variability is an independent predictor of future mobility disability. Future efforts are needed to determine whether interventions that decrease stance time variability will also delay mobility disability.

IN community-dwelling older persons, gait speed is a strong predictor of future mobility disability (1–3). Gait characteristics other than speed, such as step length, step width, and stance time, may help to better identify older persons at risk for mobility disability. However, gait characteristics such as step length and stance time tend to be highly related to gait speed (4,5) and would probably not add to the prediction of future mobility disability.

Fluctuations in gait characteristics from one step to the next, or gait variability, have recently gained much attention (6–10). Gait variability is related to future falls (6,7), but the association between gait variability and future mobility disability has yet to be determined. Variability of gait characteristics, specifically stride time and swing time, has been shown to be predictive of future falls when gait speed failed to distinguish between community-dwelling older persons who had fallen and those who had not fallen (8). Step width variability is related to fall history only in those older individuals walking at a near normal walking speed, $\geq$1.0 m/s (10). Gait variability appears to provide unique information regarding fall status not provided by speed alone.

The objective of the present study was to determine if measures of gait variability add to the prediction of incident mobility disability above and beyond the contribution of gait speed in a cohort of community-dwelling older persons who reported no difficulty walking a half mile at baseline. We hypothesize that gait variability will add to the identification of incident mobility disability above that of gait speed alone.

Methods

Study Population

Participants were recruited from the Pittsburgh site of the Cardiovascular Health Study (CHS). CHS is a population-based, ongoing longitudinal multicenter study of coronary heart disease and stroke risk in community-dwelling older adults 65 years old and older (11,12). At the initiation of the CHS in 1989–1990, individuals were identified from the Health Care Financing Administration sampling frame. Individuals who were 65 years old or older, noninstitutionalized, expected to remain in the area for 3 years, and able to give informed consent were included in the study. Individuals who were wheelchair-bound in the home or who were receiving hospice care, radiation therapy, or chemotherapy for cancer were excluded (11,12). In 1989–1990 an original cohort of 5201 predominately Caucasian (i.e., > 95% Caucasian) men and women were enrolled, and in 1992–1993 a cohort of 687 African Americans was added.

Participants in the current study included men and women who attended the tenth clinic visit in 1998–1999 at the Pittsburgh site, who could walk without the assistance of another person, who did not use an assistive device for ambulation, who could follow directions to complete the gait assessment, who did not have a history of stroke or Parkinson's disease, and who were free of mobility disability by self-report (Figure 1).

Incident Mobility Disability

Mobility disability was assessed by telephone contact at 12 months and every 6 months after that for 54 months.

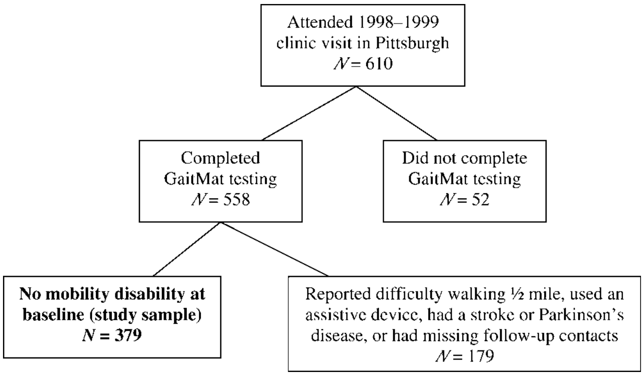

Figure 1. Determination of study sample.

Mobility disability was assessed by interview based on self-reported change in ability to walk one-half mile. Participants were asked ''Have you had a change in your ability to walk a half mile, about 5 or 6 blocks?'' Individuals who reported having a change in their ability to walk a half mile were asked a follow-up question to determine how their walking ability changed. Response categories were less difficulty walking, new onset of difficulty walking, more difficulty walking, and can no longer walk. Individuals who reported a new onset of difficulty walking, more difficulty walking, or no longer able to walk were classified as having incident mobility disability. The few individuals who reported an improvement in their walking following a report of no difficulty walking were classified as having no difficulty walking a half mile.

Gait Characteristics

The GaitMat II (E.Q., Inc., Chalfont, PA) system was used for the gait analysis (13). The GaitMat II consists of a 4-meter-long walkway on which the individual walks and a computer system that controls the GaitMat II and analyzes the data. In addition to the 4-meter-long walkway, there are initial and final 1-meter inactive sections of the walkway to allow for acceleration and deceleration of the participant. The GaitMat II is an automated gait analysis system based on the opening and closing of pressure sensitive switches that are represented on the computer screen as footprints when the participant walks on the walkway. After two practice passes, each participant completed two passes at their self-selected walking speed for data collection.

We were primarily interested in gait speed and variability of step length, step width, and stance time. Step length and width represent spatial characteristics in two different planes. Stance time was selected as the temporal gait characteristic. Step length, step width, and stance time were also specifically selected because they have been studied by other investigators (6–8,14). Gait speed was determined by dividing the distance traversed by the time between the first and last step (e.g., switch closure). Step length was determined as the distance between two consecutive footprints, measured from the heel of one footprint to the heel of the next footprint. Step width was determined as the distance between the outermost borders of two consecutive footprints. Stance time was determined as the time one foot was in contact with the floor (i.e., from initial foot-to-floor contact until final foot-to-floor contact). The mean step length, stance time, and step width for each individual were determined from all of the steps (right and left) from a single person recorded from the two passes. Likewise, the standard deviations of step length, step width, and stance time determined from all of the right and left steps recorded over two passes, approximately 10–12 steps, were calculated for each person and used as measures of variability.

Potential Confounders

During the 1998–1999 clinic visit, data were collected on a large number of potential confounders. Factors that have been previously shown to be related to mobility disability were selected for inclusion in the analyses. The selected variables include demographics, health-related factors, cognitive–psychosocial factors, and physical function/physical activity.

The demographic factors included age, sex, and race. The health-related factors included general health status, physician-diagnosed chronic conditions, number of prescription medications, body mass index, ankle–arm index, visual impairment, hearing impairment, and self-reported history of a fall in the past 12 months. General health status was self-reported as excellent, very good, good, or fair/poor. Chronic conditions included the following seven self-reported conditions: arthritis, cancer, heart disease, congestive heart failure, claudication, and diabetes mellitus. The presence of heart disease and congestive heart failure were confirmed by medical records. Body mass index was based on measured height and weight. Visual impairment was coded as present if the participant reported inability to see to drive, to watch television, or to recognize someone across a room with or without glasses, and hearing impairment was coded as present if the participant reported inability to hear well enough to use the phone, listen to the radio, or carry on a conversation in a crowded room, with or without a hearing aid.

The cognitive–psychosocial factors included cognitive status, as assessed by the modified Mini-Mental State Examination (3MS) and the modified Center for Epidemiologic Studies Depression Scale (CES-D) (15–17). The 3MS, a global measure of cognition including attention, memory, and language, incorporates four added test items, and is scored on a 0–100 scale (15). A validated 10-item version of the CES-D was used as a measure of mood. Scores range from 0 to 30, with a score of $\geq$10 on this modified scale indicating significant depressive symptoms (17).

The physical function/physical activity factors included self-reported difficulty with activities of daily living (ADL) and instrumental activities of daily living (IADL) and self-reported number of blocks walked in the past week (18). The ADL assessed were bathing, dressing, eating, using the toilet, walking around the home, or getting out of a bed or chair, and the IADL were heavy housework, light housework, shopping for personal items, preparing own meals, paying bills or managing money, or using the telephone. For all potential confounders the amount of missing data was $\leq$5%.

Statistical Analyses

Differences in baseline characteristics between individuals who developed walking disability and those who did not report walking disability were described and tested using the chi-square test for proportions and Student *t* tests for means. The association between mean gait characteristics, variability of gait characteristics, and gait speed were examined using Pearson product-moment correlation coefficients (19).

Longitudinal analyses were conducted using the first occurrence of incident self-reported difficulty walking a half mile (mobility disability) as the endpoint. First, a series of Cox proportional hazard regression models were fitted for time to incidence of mobility disability with each mean gait characteristic (step length, step width, and stance time) as the primary factor of interest (20). The initial models examined the unadjusted association between each of the gait characteristics (step length, step width, and stance time) and incident mobility disability. Subsequent models adjusted for gait speed (2nd models), age, gender, and race (3rd models), and confounders related to mobility disability in bivariate analyses, i.e., chronic conditions, number of prescription medications, health status, physical activity, and cognitive status (4th models). Participants in whom mobility disability was not observed by the end of study period, who were lost to follow-up, or who died prior to developing mobility disability were included as right-censored observations.

A second series of Cox proportional hazard regression models were fitted for time to incidence of mobility disability with each gait variability characteristic (step length variability, step width variability, and stance time variability) as the primary factor of interest (20). Subsequent models were adjusted for gait speed (2nd models), age, gender, and race (3rd models), and potential confounders (4th models) as described above. Because the association between step width variability and fall history has been shown to be u-shaped (10), when examining the association between gait variability and incident mobility disability, the measures of gait variability were examined both as continuous and as categorical (split at quartiles) to test for nonlinear effects. The findings for the continuous and categorical variables were consistent, so we assumed that the association was approximately linear. Hazard ratios (HR), 95% confidence intervals, and *p* values are reported. Outcomes were ascertained at defined follow-up time points (every 6 months), thus several events could be recorded as occurring at the same time; therefore, this was accounted for in the SAS software (SAS Institute, Inc., Cary, NC) with the TIES=EXACT option of PHREG. The EXACT method assumes that there is a true but unknown ordering for the event times (20). The sensitivity of the findings was assessed using discrete survival analysis. The results of the discrete survival analyses were similar to those of the Cox proportional hazard regression models.

To determine if the association between gait variability and incident mobility disability was stronger in individuals walking at a near normal walking speed than in individuals who walk slowly, an interaction between gait speed and the gait variability characteristic was added to the models. Analyses were also repeated stratifying the sample by a gait speed of 1.0 m/s. All analyses were performed using SAS software.

Results

Table 1 provides the baseline characteristics of the entire study cohort and the cohort stratified by the presence of incident mobility disability. As a whole, the cohort was fairly high functioning with only 8% reporting any difficulty with ADL and 16% reporting difficulty with IADL and walking at a mean gait speed of 1.07 m/s. Of the 379 participants, 222 (58.6%) developed incident mobility disability. Of the 33 who died during follow-up, 16 (48.5%) had mobility disability before death. When comparing those individuals who were excluded from the analyses because they reported difficulty walking a half mile at baseline (prevalent mobility disability) to those individuals included in the analyses, the biggest differences between the groups were in gait speed (0.91 m/s and 1.07 m/s, respectively) and stance time variability (0.045 s and 0.035 s, respectively).

Several characteristics were associated ($p < .05$) with incident mobility disability in unadjusted, bivariate analyses (Table 1). Individuals who developed mobility disability during the follow-up time period were older, reported poorer health status, had a greater number of chronic conditions, took more prescription medications, and were less physically active than individuals who did not develop mobility disability. Compared to individuals who did not develop mobility disability, individuals who developed mobility disability walked slower, took shorter steps, and had a greater variability of stance time.

The mean gait characteristics of step length and stance time were strongly related to gait speed ($r = .90, p < .0001$ and $r = -.78, p < .0001$, respectively) whereas mean step width was weakly associated with gait speed ($r = -.34, p < .0001$). Gait variability characteristics were also related to gait speed but to a much lesser degree than the mean gait characteristics (step length variability $r = -.18, p < .0001$; stance time variability $r = -.58, p < .0001$; step width variability $r = .24, p < .0001$).

Table 2 provides the results for the series of proportional hazard models. Only models in which the association between the gait characteristic and mobility disability was represented by $p < .25$ are presented. In the unadjusted models for gait characteristics, mean step length and mean stance time were each associated with the outcome. When the models were adjusted for gait speed, the associations of mean step length and mean stance time to mobility disability were attenuated.

Of the measures of gait variability, only stance time variability was associated with incident mobility disability. Stance time variability remained an important indicator of incident mobility disability even after adjusting for gait speed, age, gender, race, chronic conditions, prescription medications, health status, and physical activity level (Table 2). In the fully adjusted model, greater stance time variability of 0.01 seconds (i.e., approximately half a standard deviation increase) was associated with a 13% higher incidence of mobility disability. The interactions between gait speed and gait variability were not significant, and the results were not different when the sample was stratified by gait speed.

Discussion

In this prospective cohort study of community-dwelling older persons, we found that variability in stance time during

Table 1. Mean (*SD*) Baseline Characteristics of 379 Participants Stratified by Subsequent Mobility Disability Status Over 54 Months

Baseline Characteristics	Total Cohort (*N* = 379)	Incident Mobility Disability Yes (*N* = 222)	No (*N* = 157)	*p**
Demographics				
Age	79.1 ± 4.2	79.4 ± 4.3	78.6 ± 3.9	.07
Caucasian, *n* (%)	296 (78)	174 (78.4)	122 (77.1)	.68
Male, *n* (%)	154 (40.6)	85 (38.3)	69 (40.0)	.27
Health-related				
Health status, *n* (%)				
Excellent	23 (6.1)	9 (4.1)	14 (8.9)	.02
Very good	108 (28.5)	55 (24.8)	53 (33.8)	
Good	200 (52.9)	124 (55.9)	76 (48.4)	
Fair/Poor	48 (12.7)	34 (15.3)	14 (8.9)	
Chronic conditions	0.73 ± 0.87	0.91 ± 0.97	.49 ± .63	<.0001
Chronic conditions, *n* (%)				
0	175 (48.1)	85 (40.5)	90 (58.4)	<.0001
1	130 (35.7)	77 (36.7)	53 (34.4)	
≥2	59 (16.2)	48 (22.9)	11 (7.1)	
Prescription medications	2.8 ± 2.4	3.2 ± 2.6	2.3 ± 1.9	.0004
Ankle–arm index	1.04 ± 0.19	1.03 ± 0.19	1.05 ± 0.18	.47
Body mass index (kg/m^2)	25.6 ± 4.1	25.7 ± 4.1	25.5 ± 4.0	.69
Visual impairment, *n* (%)	100 (29.8)	63 (32.3)	35 (27.3)	.23
Hearing impairment, *n* (%)	47 (12.8)	28 (13.0)	19 (12.5)	.88
Fallen in past year, *n* (%)	63 (16.7)	43 (19.5)	20 (12.8)	.09
Cognitive-Psychosocial				
Score on 3MS (0–100)	93.1 ± 7.7	93.0 ± 6.7	93.3 ± 8.8	.71
Depressed (CES-D ≥10), *n* (%)	44 (11.6)	30 (13.6)	14 (8.9)	.16
Physical Function/Physical Activity				
ADL difficulty, *n* (%)	32 (8.4)	22 (9.9)	10 (6.4)	.22
IADL difficulty, *n* (%)	50 (13.2)	33 (14.9)	17 (10.8)	.25
Blocks walked	40.9 ± 53.8	34.9 ± 52.1	49.1 ± 55.1	.01
Mean gait characteristics				
Gait speed, m/s	1.07 (.20)	1.04 (.19)	1.11 (.20)	.003
Step length, m	.58 (.09)	.57 (.08)	.60 (.09)	.003
Step width, m	.21 (.04)	.21 (.05)	.21 (.04)	.78
Stance time, s	.72 (.08)	.72 (.08)	.71 (.08)	.13
Gait variability (*SD*)				
Step length, m	.03 (.01)	.034 (.015)	.033 (.012)	.21
Step width, m	.04 (.02)	.036 (.017)	.036 (.014)	.59
Stance time, s	.03 (.02)	.036 (.017)	.032 (.013)	.05

Notes: *Comparison between those with and without incident mobility disability.

SD = standard deviation; 3MS = modified Mini-Mental State Examination; CES-D = Center for Epidemiologic Studies Depression Scale; ADL = activities of daily living; IADL = instrumental activities of daily living.

a self-selected walking speed task was independently associated with the risk of developing difficulty walking a half mile. After adjusting for gait speed and several potential confounding factors, stance time variability still added to the prediction of mobility disability. Because stance time variability provides additional information above and beyond that of gait speed, it is worth the additional time and effort to measure stance time variability. To our knowledge, this is the first prospective study to link gait variability to an outcome other than falls.

We examined variability of three gait characteristics—step length, step width, and stance time—which have been shown in previous research to be related to fall history and future falling (6–8). In a cross-sectional study examining the association between falls and gait variability, stance time, swing time, and stride time variability were increased in individuals who had fallen compared to those who had not fallen in the past year (8). In prospective studies of gait variability and future falls, stride time, swing time, stride length, and double support time variability were all predictive of future falls (6,7). Of the three gait characteristics we examined (step length variability, stance time variability, and step width variability), only stance time variability was related to incident mobility disability after adjusting for gait speed and confounding factors.

One potential explanation for this finding is that individual gait characteristics may be related to different outcomes. Stride width and double support time are believed to represent balance control (21). Increases in the variability of stride width or double support time may indicate a lack of

Table 2. Hazard Ratios for Incident Mobility Disability Associated with Gait Characteristics

	Model 1		Model 2		Model 3		Model 4	
Gait Characteristics	HR (95% CI)	*p*	HR (95% CI)	*p*	HR (95% CI)	*p*	HR (95% CI)	*p*
Mean								
Step length, m	.97 (.95 to .98)	<.0001	1.01 (.98 to1.04)	.56	—	—	—	—
Step width, m	1.02 (.99 to 1.05)	.27			—	—	—	—
Stance time, s	1.04 (1.02 to 1.06)	<.001	1.01 (.99 to 1.04)	.23	1.02 (.99 to 1.05)	.13	1.03 (0.99 to 1.06)	.11
Gait variability*								
Step length, m	1.09 (1.00 to 1.18)	.07	1.07 (.98 to 1.18)	.11	1.07 (.98 to 1.17)	.14	1.07 (.97 to 1.19)	.18
Step width, m	1.00 (.92 to 1.08)	.92	—	—	—	—	—	—
Stance time, s	1.26 (1.15 to 1.37)	<.0001	1.15 (1.04 to 1.27)	.007	1.13 (1.02 to 1.25)	.02	1.13 (1.01 to 1.27)	.03

Notes: Model 1 was unadjusted; Model 2 was adjusted for gait speed; Model 3 was adjusted for gait speed, age, gender, and race; Model 4 was adjusted for gait speed, age, gender, race, chronic conditions, medications, health status, physical activity, and cognitive status. Data were progressed to the next model if the *p* value for the gait characteristic was ≤.25.

*HR values are for a .01-unit increase.

HR = hazard ratio; CI = confidence interval.

compensation for instability. Therefore, step width and double support variability would more likely be related to instability or falls. We did not see an association between step width variability and mobility disability in our study. Our sample was quite functional at baseline (with a mean gait speed = 1.07 m/s and no difficulty walking a half mile). We would expect that individuals with impaired balance as indicated by extreme step width variability would report difficulty walking a half mile and thus would have been excluded from our analyses of incident mobility disability.

Previous investigators have suggested that step length and stance time are related to the automatic stepping mechanism (21). Therefore, a higher degree of variability in step length or stance time variability could possibly indicate a disruption of the automatic stepping mechanism or that the person is ''thinking about taking each step.'' If this were the case, why wouldn't step length variability also be related to mobility disability? Perhaps individuals who are ''thinking'' about walking (a goal-directed movement) are more likely to focus on step length than on the timing of each step. Goal-directed movements involve a relationship among speed, accuracy, and amplitude (22,23). Improving accuracy in stepping amplitude (consistent length steps) requires a trade-off in the consistency of the timing of the steps.

Increases in stance time variability may precede increases in step length variability. Spatial characteristics of walking, which can be directed by visual cues, are likely to be a more obvious strategy for the walker then is monitoring temporal aspects of gait. Thus, perhaps the focus of the older walker is on consistency of step length and not on consistent stance time. However, as the ability to walk continues to decline, step length variability might also increase.

In previous research we found a nonlinear association between step width variability and history of falls (10). In the current project, a nonlinear association between step width variability and incident mobility disability was not apparent. A likely explanation is a problem of spectrum bias with step width variability. The majority of individuals with minimal step width variability (i.e., those likely to have fallen in the past year) were excluded from the current analyses because at baseline they had reported difficulty walking a half mile. This finding supports the theory that individuals with poor balance, represented by extreme step width variability, are likely to report difficulty walking a half mile.

Mean step length and stance time were related to incident mobility disability. However, when adjusted for gait speed, the associations were no longer significant. This finding is best explained by the strong correlations between gait speed, step length, and stance time (in this study the correlations were .90 and −.78, respectively). Therefore, step length and stance time do not provide additional information regarding the risk for future mobility disability beyond that provided by gait speed. Stance time variability was related to incident mobility even after adjusting for gait speed, thus suggesting that stance time variability provides different information than gait speed. Likewise, Frenkel-Toledo and colleagues (24) have shown that, in both healthy controls and patients with Parkinson's disease, swing time variability was not related to gait speed but stride time variability was related to gait speed, thus supporting the current findings that some measures of gait variability provide information about walking that is different than that provided by measures of gait speed. Swing time and stance time are both temporal measures of gait. Both swing time and stance time may represent the automatic stepping mechanism which is thought to be responsible for the regularity of stepping during gait (21).

When including both gait speed and specific gait characteristics in a model, it is important to recognize that a high correlation between the predictor variables can cause colinearity problems. The correlations between gait speed and gait variability characteristics were −.58 to .24. The gold standard criterion for determining whether colinearity occurs in our analysis was to check whether the regression coefficient estimate (i.e., HRs in a Cox model) and its standard error for one predictor is relatively stable (i.e., no large fluctuations or change of sign or direction) when the other predictor is added to the model. With the addition of gait speed, HR for step length variability changed from 1.09 to only 1.07, and that for stance time variability changed from 1.26 to only 1.15. (The standard errors of these remained relatively stable as well.) These changes are not sufficiently large to be indicative of any colinearity problems. In contrast, we acknowledge that mean gait characteristics are highly correlated with gait speed, and the correlations may be sufficiently strong to cause some colinearity problems. HR estimates changed direction

(0.97–1.01) and p values changed noticeably ($< .0001$ to .56 and $< .001$ to .23).

When interpreting the results a few factors need to be taken into consideration. First, the sample is not representative of all community-dwelling older persons. The sample was selected to be a relatively healthy sample with good mobility at baseline so that we could examine the outcome of incident mobility disability. Second, the measure of gait variability was based on a limited number of steps (10–12). Naturally, the number of data points or steps used in calculation of gait variability plays an important role in the consistency of the measure, with longer walks giving more stable estimates. Owings and Grabiner (25) have demonstrated that hundreds of steps are needed to achieve a reliable estimate of gait variability. However, the difference in their methodology (gait variability was measured while participants walked on a treadmill) makes it difficult to generalize the findings to measures of gait variability collected from over ground walking. In addition, the primary outcome, mobility disability, was based on self-report and not on an actual test of walking ability, which may have underestimated the amount of mobility disability in the study. The reliability and validity of this particular self-reported outcome has yet to be established; however, the measure is similar to measures of disability that have been used in other studies (1,3), and the questionnaire has face validity. In addition, gait speed has been shown to be a strong predictor of mobility disability (1,3), and in the current study gait speed was strongly related to the mobility disability outcome, thus adding to the validity of the outcome.

In this study we were able to study gait variability and the outcome of mobility while controlling for gait speed and a number of potential confounding factors in a relatively large sample of community-dwelling older persons. We were also able to follow our participants for an extended period of time, 54 months, with biannual phone contacts. We determined that stance time variability provides additional information above and beyond gait speed in predicting future mobility disability. Stance time variability may be a very early indicator of preclinical mobility disability. Future efforts are needed to determine whether interventions that decrease stance time variability will also delay or prevent mobility disability.

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Correspondence

Address correspondence to Jennifer S. Brach, PhD, PT, Department of Physical Therapy, University of Pittsburgh, 6035 Forbes Tower, Pittsburgh, PA 15260. E-mail: jbrach@pitt.edu

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