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Gait Variability Is Associated With Frailty in Community-dwelling Older Adults

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Background. The relationship between frailty and gait characteristics other than velocity has received little attention. Gait variability quantifies the automaticity of gait with greater variability usually indicating an irregular and unstable gait. High gait variability reflects the loss of gait regulation and predicts mobility decline and falls, which may reveal systemic vulnerability. Thus, we hypothesize that high gait variability may be associated with frailty phenotype.

Methods. Cross-sectional study including 100 community-dwelling women and men 75 years and older. Frailty was defined using validated phenotypic criteria and two additional frailty indexes that omit gait velocity criterion were used to verify associations between frailty and quantitative gait parameters. Gait was assessed under usual and fast pace using an electronic walkway.

Results. Frailty phenotype was identified in 20% of the participants and at least one component of frailty was present in 75%. Linear regression models were generated to explore the associations between frailty and gait variability. In the univariate regression model, frailty was associated with higher variability for all the gait parameters of interest. After adjustments, stride time variability under fast gait condition was the most prominent parameter consistently associated with frailty. This association remained significant in two additional frailty indexes that omit gait velocity criterion.

Conclusion. Frailty is associated with low performance in several quantitative gait parameters beyond velocity of which the most prominent is high stride time variability. This finding may help to understand the high risk of falls and mobility decline in people with frailty.

Key Words: Gait—Variability—Frailty—Aged—Disability.

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FRAILTY is now increasingly recognized as a highly prevalent entity, distinct from disability and comorbidity, which increases the vulnerability of older adults to clinically important outcomes including functional decline, falls, and institutionalization (1). As a syndrome, frailty has been operationally defined by Fried et al. using five criteria: slow gait velocity, low physical activity, unintentional weight loss, exhaustion, and muscle weakness (2). The presence of three or more of these criteria has been independently associated with worsening mobility, disability, incident falls, hospitalizations, and mortality (1). Of the five criteria, gait velocity has been reported as one of the strongest to predict adverse outcomes and the most useful for the identification of physical frailty (2,3). Specifically, gait velocity is a robust predictor of future mobility disability, falls and fractures, requirement of a caregiver, hospitalizations, and death (4–6). Because the relationship between frailty and other quantitative gait characteristics has received little research attention, we sought to examine gait characteristics other than velocity that might further our understanding of frailty.

Gait is a complex motor behavior with many measurable facets besides velocity including step length, stride length, step time, stride time, and double support time, among others. Variability of motor movements in humans, including gait variability, is a growing research field because it provides an interesting window for the study of the regulation of the locomotor control (7). Stride-to-stride variability, as measured by the coefficient of variation (CV), is a measure of the reproducibility of limb-coordinated movements from

one stride to the next during steady-state walking. Low stride-to-stride variability reflects automatic processes that require minimal attention and is associated with efficient gait control and gait safety (8). By contrast, high stride time variability has been associated with future falls, Parkinson's disease, and Alzheimer's disease (9,10,11,12). In fact, high stride time variability has been shown to predict future falls in community-dwelling older persons even though gait velocity failed to distinguish between those who had fallen and those who had not (13). Recently, it has been demonstrated that high variability in temporal parameters of gait in relatively healthy older adults is associated with future mobility decline during a 5-year follow-up (9).

High gait variability has been considered a marker of abnormal regulation of gait performance (8,14), which may reflect vulnerability of several systems beyond the locomotor system. Thus, we hypothesize that high gait variability may be associated with the frailty phenotype. A previous study explored gait characteristics in older people transitional to frailty (15); however, the association of quantitative gait characteristics other than velocity, in particular gait variability, with the frailty phenotype has yet to be determined. The aims of this study were (a) to conduct a systematic quantitative gait assessment in community-dwelling older adults stratified by frailty status (ie, frailty, prefrailty, and nonfrailty) (1), and (b) to assess whether gait variability is associated with frailty using three different indexes to identify frailty.

Methods

Study Population

Study participants were recruited from a naturally occurring retirement community (NORC) in London, Ontario, Canada. The Cherryhill NORC is a 13-building apartment complex housing 2,500 older adults (mean age = 79.53 ± 9.53 years) (16) across the spectrum of nonfrail, prefrail, and frail. A convenience sample of older adults residing in the NORC was utilized for this study. All participants were community-living adults and were eligible to participate if they were aged 75 and older, English speaking, and reported being able to ambulate one city block. Exclusion criteria were diagnosis of a terminal illness, life expectancy less than 12 months, pending nursing home placement, hip or knee joint arthroplasty within the preceding 6 months, and diagnosis of dementia. Participants who typically used walking aids were included only if they were able to walk at least 10 m independently without use of the mobility aid. Ethics approval was obtained from the University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects. Informed consent was obtained at enrollment according to protocols approved by the local institutional review board. Data collection occurred between September 2008 and October 2009.

Data Collection

Research staff conducted face-to-face interviews using structured questionnaires to elicit socio-demographic characteristics of age, sex, years of formal education, number of chronic prescribed and over-the-counter medications, and falls in the previous 6 months. A fall was defined as "unintentionally coming to the ground or onto an object" (17–19). Physician diagnosed chronic conditions (diabetes, heart failure, hypertension, angina, myocardial infarction, cancer, previous strokes, osteoarthritis, and lung disease) were ascertained by self-report. The Charlson Comorbidity Index was also administered (20). Functional capacity in basic activities of daily living was evaluated using a disability scale developed for community-based cohorts (21). The summed disability score ranged from 0 to 16, with higher scores representing more disability. A self-report of memory problems, using a 5-point qualitative Likert scale, was elicited by asking participants how their memory was compared with other people their age and how their memory is now compared with the previous 5 years.

Assessment of Frailty Criteria

The five criteria used to identify frailty status of the primary frailty index of interest, the Cardiovascular Health Study (CHS) frailty index were: slow gait velocity, low physical activity, weakness, weight loss, and self-reported exhaustion (1). For the current study, the slow gait velocity criterion was met if the participant walked below one meter per second (1m/sec) at a usual and comfortable pace. Previously, it has been determined that a usual gait velocity below 1m/sec is indicative of adverse health outcomes in older adults (4,5,6,22). The low physical activity criterion was operationalized using the Physical Activity Scale for the Elderly (PASE) (23). PASE scores less than 64 for men and less than 52 for women were used to indicate a positive response of low physical activity. The muscle weakness criterion was met when grip strength in the dominant hand, the average of three readings using a handheld dynamometer (Jamar, Sammons Preston, Bolingbrook, IL), was less than or equal to the cutoff points used in the Cardiovascular Health Study (1). The exhaustion criterion was evaluated using two questions from the Center for Epidemiologic Studies Depression Scale (affirmative answer that everything they did was an effort or they felt they could not get going in the previous 2 months) (24). The weight loss criterion was met if the participant reported they had unintentionally lost more than 10 pounds in the previous 12 months. A total score for the frailty status was then calculated as the sum of positive findings. Individuals were then categorized into one of three frailty categories based on the total frail score as follows: frail, score ≥3; prefrail, score of 1–2; and not frail, score of 0.

The CHS frailty index includes slow gait velocity as a criterion, which is known to be highly correlated with other

quantitative gait parameters. Therefore, to ensure any associations were robust, analyses were repeated using two additional frailty indexes that omit slow gait velocity from their definition criteria of frailty. The second frailty index utilized omits slow gait velocity from the CHS frailty index, providing a sum of four variables (25). In this reduced frailty index, individuals are categorized into one of three frailty categories based on the total score as follows: frail, score 3–4; prefrail, score 1–2; and not frail, score of 0. The third frailty index, The Study of Osteoporotic Fractures (SOF) Index (26), comprises three criteria: unintentional weight loss of 5% or more, weakness, and reduced energy level. The categorization of frailty status in the SOF index is: score 2–3, frail; score of 1, prefrail; and score of 0 as not frail. The criteria within the SOF frailty index were operationalized using the same variable definitions as were used above in the CHS index.

Assessment of Gait and Gait variability

Quantitative gait evaluation utilized a computerized walkway (6 m × 0.5 m × 0.01 m) with embedded pressure sensors (GAITRite; CIR Systems, Havertown, PA). The GAITRite system is reliable tool for gait analysis that has been validated for several gait protocols including gait variability assessment by our center and others (27–30). Three trials were performed for each task of self-selected usual and fast pace; the results from the three trials were then averaged to obtain a single value (8,31). Start and stop points were marked on the floor 1 m from the walkway edge to limit any acceleration and deceleration effects.

The following six quantitative gait variables were assessed: velocity (cm/s), cadence (steps/min), stride time (ms), step width (cm), double support time (ms) and stride length (cm). These six variables were chosen for their previously reported associations with mobility decline, falls, and adverse events (9,13,32). Variability in four gait parameters (stride time, stride length, double support time, and step width) was quantified using the CV, which is the ratio of the standard deviation to the mean multiplied by 100 (CV = [(standard deviation/mean) × 100]). The CV is a standardized measure of variability allowing comparison of gait variables measured in different units, having different means and range of values.

Statistical Analysis

Descriptive statistics of participant characteristics, stratified by frailty level, were evaluated using a one-way analysis of variance (ANOVA) or a Pearson's chi-square test, as appropriate. Evaluation of the crude gait parameter values across the three frailty groups was performed using one-way ANOVA. The presence of an overall statistically significant finding in the ANOVA was followed with post-hoc Tukey analysis to identify significant pairwise associations. Evaluation of the correlation between gait velocity and the other gait parameters evaluated was performed separately for the usual and fast gait conditions.

Initial regression analysis using multivariable linear regression explored the relationship between the five individual criteria of the CHS frailty index (unintentional weight loss, weakness, exhaustion, slow gait velocity, and decreased physical activity) as the independent variable and each gait parameter, as the dependent variable, in separate models.

The main regression analysis with multivariable linear regression was performed to evaluate the association of frailty status with the four different gait variability parameters (stride time variability, stride length variability, double support time variability, and step width variability) in the usual and fast gait conditions. The dependent variable was the measure of gait variability and the independent variable of interest was frailty, modeled as two indicator variables of prefrail and frail referenced to the category of not frail. First, univariate linear regression analyses of frailty status on each of the dependent gait variability parameters were performed. Each of the four measures of gait variability in each test condition (usual or fast pace) was fitted in separate models for a total of eight models. Adjustment for confounding, based on clinical relevance and previous literature, was accomplished by controlling for age, gender, and history of falls. Linear regression diagnostics were performed to evaluate multicollinearity and influential observations. All analyses were performed using SAS version 8.2 (SAS Institute Inc, Cary, NC).

Results

One hundred participants aged 75 and older (mean age 82 ± 5.4, 78% women) were assessed. Characteristics of the study sample, stratified by frailty status using the CHS index, are presented in Table 1. No differences in age, gender, or body mass index were noted across the three frailty groups. Interestingly, 39% of the participants reported having memory problems. The most common frailty criteria were slow gait velocity and exhaustion, with prevalences of 50% and 52%, respectively. Using the CHS index, 20% of the sample was identified as frail and 75% of the participants had at least one frailty component.

Correlations between gait velocity and the other quantitative gait parameters were of a low to moderate magnitude of correlation under both, usual and fast pace conditions. Specifically, under the usual pace test condition, the correlation between gait velocity and the other gait parameters were: stride time ($r = -0.53$, $p < .001$), stride length ($r = -0.48$, $p < .001$), double support time ($r = -0.11$, $p = .27$) and step width ($r = -0.49$, $p < .001$). Under the fast pace test condition, the magnitude of correlation between gait velocity and the other gait parameters was similar: stride time ($r = -0.48$, $p < .001$), stride length ($r = -0.32$, $p < .001$), double support time ($r = 0.12$, $p = .24$), and step width ($r = -0.33$, $p < .001$).

Table 1. Baseline Characteristics of Study Participants in Total Sample and Stratified by Frailty Status

Variable	Total Sample (n = 100)	Stratified by Frailty Status*			p Value
		Not frail (n = 25)	Prefrail (n = 55)	Frail (n = 20)	
Age, mean (*SD*)	82.2 (5.4)	81.0 (6.4)	83.0 (5.2)	82.0 (4.4)	.30
Female, *n* (%)	78 (78%)	18 (72%)	44 (80%)	16 (80%)	.76
Body mass index, mean (*SD*)	26.3 (4.5)	26.8 (4.7)	26.2 (4.5)	26.1 (4.4)	.83
Number of comorbities, mean (*SD*)	3.1 (2.2)	1.6 (1.5)	3.7 (2.2)	3.5 (2.0)	<.001
Number of medications, mean (*SD*)	4.2 (3.2)	3.7 (3.3)	4.3 (3.3)	4.6 (3.0)	.62
Charlson comorbidity index, mean (*SD*)	3.3 (3.1)	1.6 (2.7)	3.7 (3.0)	4.1 (3.1)	.006
Disability score, mean (*SD*)	2.1 (2.7)	0.5 (1.0)	1.9 (2.1)	4.6 (3.9)	<.001
History of falls in previous 6 mo, n (%)	31 (31%)	4 (16%)	18 (33%)	9 (45%)	.001
Self-report of memory problems	39 (39%)	7 (28%)	22 (40%)	10 (50%)	.046
Frailty criteria,* *n* (%)					
Slow gait velocity	50 (50)	0 (0)	31 (56)	19 (95)	<.001
Low physical activity	10 (10)	0 (0)	2 (4)	8 (40)	<.001
Low hand grip	25 (25)	0 (0)	13 (24)	12 (60)	<.001
Unintentional weight loss	5 (5)	0 (0)	1 (2)	4 (20)	<.001
Self-reported exhaustion	52 (52)	0 (0)	32 (58)	20 (100)	<.001

*Frailty status defined as not frail (0 criteria), prefrail (1–2 criteria), and frail (≥ 3 criteria); *SD* = standard deviation.

Quantitative gait characteristics, stratified by frailty status using the CHS index, are presented in Table 2. At the usual pace, overall ANOVA analyses were significant between all six quantitative gait variables and frailty. Statistically significant pairwise associations were found between all frailty groups for gait velocity, stride time and step width. Significant pairwise associations for cadence, stride length, and double support time were between frail and not frail, and prefrail and not frail. There was no statistically significant difference between frail and prefrail. Analysis of the gait variability values at the usual pace revealed significantly increased stride time variability between frail and nonfrail only. Step width variability was significant between prefrail and nonfrail, and frail and nonfrail.

At the fast pace, the six quantitative gait variables were also all significant in the ANOVA analyses. All parameters were significantly different across the three groups for gait variability except for double support time variability. Significant pairwise associations for gait variability parameters were found between frail and nonfrail and prefrail and non frail for stride time variability, stride length variability, and step width variability. Overall, greater differentiation

Table 2. Gait Characteristics at Usual and Fast Pace Stratified by Cardiovascular Health Study Index Frailty Status

	Nonfrail	Prefrail	Frail	ANOVA* p value
Mean quantitative gait characteristics at usual walking pace				
Gait velocity, cm/s	124.15 ± 12.97	95.21 ± 20.73	79.50 ± 19.36	<.001
Stride time, ms	1017.56 ± 56.78	1137.00 ± 111.06	1207.99 ± 138.39	<.001
Cadence, steps/min	118.27 ± 6.68	106.26 ± 9.05	101.22 ± 21.07	<.001
Stride length, cm	126.64 ± 13.85	108.78 ± 18.25	98.65 ± 16.33	<.001
Double support time, s	28.38 ± 3.03	31.74 ± 4.65	34.25 ± 4.77	<.001
Step width, cm	63.74 ± 6.48	55.88 ± 7.65	50.68 ± 7.65	<.001
Mean gait variability (CV) values at usual walking pace				
Stride time variability	2.30 ± 1.10	2.99 ± 1.37	3.78 ± 1.99	.005
Stride length variability	4.01 ± 1.54	5.10 ± 2.79	5.74 ± 2.24	.055
Double support time variability	9.48 ± 4.74	8.79±3.29	10.03 ± 4.77	.451
Step width variability	4.95 ± 1.52	6.59 ± 2.90	6.68 ± 1.67	.016
Mean quantitative gait characteristics at fast walking pace				
Gait velocity, cm/s	155.42 ± 18.60	124.89 ± 26.33	105.69 ± 22.13	<.001
Stride time, ms	901.68 ± 60.12	976.30 ± 109.74	1042.39 ± 116.05	<.001
Cadence, steps/min	133.65 ± 9.32	122.93 ± 14.59	109.98 ± 22.48	<.001
Stride length, cm	140.28 ± 15.85	121.64 ± 20.89	106.56 ± 24.26	<.001
Double support time, s	25.87 ± 3.23	28.28 ± 4.89	32.32 ± 5.83	<.001
Step width, cm	70.68 ± 7.74	61.75 ± 10.26	54.80 ± 11.26	<.001
Mean gait variability (CV) values at fast walking pace				
Stride time variability	1.81 ± 0.71	2.63 ± 1.02	2.91 ± 1.66	.003
Stride length variability	2.93 ± 0.84	4.11 ± 2.02	4.48 ± 1.74	.007
Double support time variability	7.78 ± 3.13	9.30 ± 6.03	9.78 ± 4.47	.388
Step width variability	4.10 ± 1.04	5.72±2.54	5.88 ± 1.76	.005

*One-way ANOVA analysis, statistical significance set at p value less than .05; CV = coefficient of variation, calculated by the formula: $\left[\frac{\text{mean}}{SD}\right]\times 100\%$. ANOVA = analysis of variance.

Table 3. Results of multivariable linear regression of gait variability on Cardiovascular Health Study Index frailty status under usual gait and fast gait speed in eight separate models

			Unadjusted		Adjusted*	
	Model	Frailty Level†	Regression Coefficient‡, (95% CI)	*p* Value	Regression Coefficient‡, (95% CI)	*p* Value
Usual gait						
Stride time variability	1	Prefrail	**0.71 (0.01–1.42)**	**.048**	0.35 (−0.36 to 1.05)	.33
		Frail	**1.51 (0.64–2.37)**	**<.001**	**1.17(0.32–2.02)**	**.008**
Stride length variability	2	Prefrail	1.09 (−0.09 to 2.28)	0.07	0.54 (−0.66 to 1.73)	.38
		Frail	**1.73 (0.28–3.17)**	**.02**	1.18 (−0.27 to 2.63)	.11
Double support time variability	3	Prefrail	-0.69 (−2.64 to 1.25)	.48	−1.34 (−3.34 to 0.66)	.19
		Frail	0.55 (−1.83 to 2.93)	.65	−0.02 (−2.44 to 2.40)	.99
Step width variability	4	Prefrail	**1.64 (0.47–2.80)**	**.007**	1.05 (−0.13 to 2.23)	.08
		Frail	**1.72 (0.30–3.15)**	**.02**	1.10 (−0.33 to 2.53)	.13
Fast gait						
Stride time variability	5	Prefrail	**0.82 (0.28–1.37)**	**.004**	**0.79 (0.22–1.37)**	**.008**
		Frail	**1.10 (0.44–1.77)**	**.001**	**1.10 (0.41–1.80)**	**.002**
Stride length variability	6	Prefrail	**1.18 (0.33–2.03)**	**.007**	**0.96 (0.07–1.85)**	**.03**
		Frail	**1.55 (0.51–2.59)**	**.004**	**1.36 (0.28–2.43)**	**.01**
Double support time variability	7	Prefrail	1.51 (−1.04 to 4.07)	.24	1.74 (−0.96 to 4.44)	.20
		Frail	1.99 (−1.11 to 5.10)	.21	2.25 (−1.01 to 5.52)	.17
Step width variability	8	Prefrail	**1.62 (0.60–2.65)**	**.002**	**1.39 (0.31–2.47)**	**.01**
		Frail	**1.79 (0.53–3.04)**	**.006**	**1.57 (0.25–2.88)**	**.02**

Notes: The dependent variable was the measure of gait variability and the independent variable of interest was frailty, modeled as two indicator variables of prefrail and frail referenced to the category of not frail. CI = confidence interval. Bold values are statistical significant at *p* value level less than .05.

*Adjusted for age, gender, and history of falls in the previous 6 months.

† Nonfrail group is the reference category

‡ Unstandardized regression coefficients.

between the three frailty groups was evident under the fast pace walking condition compared with usual pace.

In the adjusted linear regression of the five individual frailty criteria, each in a separate model, of the CHS index on each of the gait parameters, as the dependent variable, we found that slow gait speed was significantly associated with all quantitative measures of gait at usual and fast pace (data not presented). Interestingly, exhaustion was also independently associated with each of the quantitative gait parameters and stride time variability and stride length variability under both usual and fast pace test conditions. Decreased physical activity was associated with gait velocity (usual and fast pace), stride length (usual and fast pace), step width (usual and fast pace), stride time variability (usual pace), and double support time (fast pace).

The results of the linear regression analysis of the relationship of the CHS frailty index to gait variability parameters are presented in Table 3. In the unadjusted analysis for the usual and fast pace conditions, stride time variability (p = .0008), stride length variability (p = .0198), and step width variability had a significant association to frailty. In the adjusted analyses, usual pace stride time variability (p = .0076) remained significant along with fast pace stride time variability (p = .010), stride length variability (p = .0139), and step width (p = .0199) variability.

On the categorization of frailty status, using the CHS index as the standard, the percentage agreement for the reduced index was 100% for not frail, 84% of people categorized as prefrail with the CHS index were categorized as prefrail with the reduced index, but 76% of people categorized as frail with the CHS index were labeled as prefrail with the reduced index. Agreement with the SOF index was 100% not frail, 76% as prefrail, and 76% as frail. Regression modeling was repeated in the two other frailty indexes; results of the adjusted multivariable regression analysis for the three frailty indexes are summarized in Table 4. Across the three indexes, fast gait stride time variability was significant among people categorized as frail and fast gait step width variability was significant among people categorized as pre frail. Finally, Figure 1 provides a visual representation of the variation in stride time by frailty status, comparing the fluctuations of the stride time in milliseconds between a non frail and a frail participant.

Discussion

This study demonstrated that low performance in several quantitative gait parameters, other than velocity, are associated with the frailty phenotype. Additionally, we have provided preliminary empirical support that high gait variability is associated with frailty status. Based on previous research that indicates that high gait variability is a marker of the loss of the complexity and regulation of gait performance, our results suggest that the regulation of gait is impaired in older adults with frailty (14,33,34).

There is strong evidence that slow gait velocity is a marker of frailty; however, little is known whether other quantitative gait parameters also have an association with the frailty phenotype. Due to the fact that temporospatial quantitative gait parameters and gait variability are highly

Table 4. Multivariable Linear Regression Analysis Results Comparing the Association of Frailty, Defined Using Three Frailty Indexes, On the Outcome of Each Gait Variability Parameters

Gait Parameter	Frailty Level	Cardiovascular Health Study Index	Reduced Frailty Index	Study of Osteoporotic Fractures Index
Usual gait				
Stride time variability	Prefrail	n/s	n/s	n/s
	Frail	1.17 (0.32–2.02) $p = .008$	2.03 (0.58–2.48) $p = .007$	n/s
Stride length variability	Prefrail	n/s	n/s	n/s
	Frail	n/s	n/s	n/s
Double support time variability	Prefrail	n/s	−2.38 (−4.08 to −0.68) $p = .007$	−2.62 (−4.37 to −0.87) $p = .004$
	Frail	n/s	n/s	n/s
Step width variability	Prefrail	n/s	n/s	n/s
	Frail	n/s	n/s	n/s
Fast gait				
Stride time variability	Prefrail	0.79 (0.22–1.37) $p = .008$	n/s	n/s
	Frail	1.10 (0.41–1.80) $p = .002$	1.86 (0.67–3.05) $p = .003$	0.87 (0.20–1.55) $p = .012$
Stride length variability	Prefrail	0.96 (0.07–1.85) $p = .03$	n/s	n/s
	Frail	1.36 (0.28–2.43) $p = .01$	n/s	n/s
Double support time variability	Prefrail	n/s	n/s	n/s
	Frail	n/s	n/s	n/s
Step width variability	Prefrail	1.39 (0.31–2.47) $p = .01$	1.07 (0.12–2.03) $p = .028$	1.14 (0.14–2.13) $p = .025$
	Frail	1.57 (0.25–2.88) $p = .02$	n/s	n/s

Notes: Results for gait variability represent 8eight separate regression models, one for each gait variability parameter. The dependent variable was the measure of gait variability and the independent variable of interest was frailty, modeled as two indicator variables of prefrail and frail referenced to the category of not frail. Regression coefficients and p values for significant associations, $p < .05$, are presented. n/s = not statistically significant at $p < .05$; Regression models adjusted for age, sex, and past history of falls.

correlated with gait velocity, the potential circularity and redundancy of these associations was addressed by repeated analyses on gait variability in two additional frailty indexes that did not include gait velocity as a criterion. The consistency of association between frailty and gait variability in the three frailty models supports the idea that variability in some quantitative gait parameters such as stride time variability at fast pace is associated with frailty independent of gait velocity.

In the unadjusted analysis, a significant association was found between step width variability and frailty but not between double support time variability and frailty. Step width and double support time are believed to represent balance control in older individuals (35,36). Therefore, increases in step width variability may indicate a lack of compensation for instability and may be a marker for future falls.

The associations between high gait variability and frailty is consistent with previous research that demonstrated gait variability is associated with several outcomes related to frailty such as falls, cognitive decline, and mobility decline. For instance, in a cross-sectional study examining the association between falls and gait variability, it was found that stance time variability, swing time variability, and stride time variability were increased in individuals who had fallen compared with those who had not fallen (37). In prospective studies, variability in the gait parameters of stride

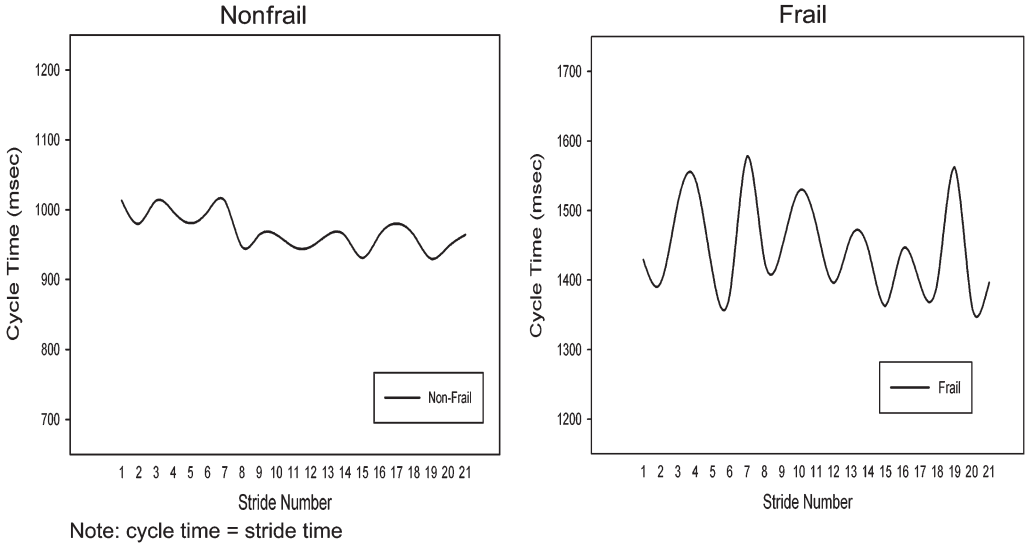

Figure 1. Comparison of stride time fluctuations (milliseconds) between a nonfrail and a frail participant. Note: cycle time = stride time.

time, swing time, stride length, and double support time were all predictive of future falls (13,38). Of interest, after adjusting for potential confounding factors in our study—including history of falls—only stride time variability was associated with frailty under fast pace for all frailty indexes. This may suggest that stride time variability provides unique information concerning gait stability and its regulation in people with frailty.

Previous investigators have suggested that stride length and time are related to the automatic stepping mechanism and are therefore more dependent on central neural control and cognitive functions than musculoskeletal performance (13,14,31,35). Low variability values of stride time while steady-state walking, which reflect the automated rhythmic feature of gait, are indicators of safe gait and are used as a clinical index of gait stability (31,39,40,41). Walking is one of the most repetitive and "hard wired"human movements, the normal fluctuation in stride time variability is usually below 3% among healthy adults (31,42,43). Increased stride time variability has been associated not only with falls but also with cognitive motor neurodegenerative diseases such as Parkinson's and Alzheimer's diseases (40,44,45). In our study, participants with the frailty phenotype had a mean stride time variability of 3.8%. By contrast, individuals belonging to the nonfrail and prefrail group had stride time variability below 3%. Therefore, a higher degree of variability in stride time could possibly indicate a disturbance of the automatic stepping mechanism due to abnormal higher cortical levels of control in gait regulation while steady-state walking. This suggests that higher cerebral functions and cognition may be subtly impaired in the older adults with frailty. Cognitive function was evaluated by self-report in our sample; therefore, occult cognitive dysfunction that might contribute to the high gait variability in the frail group cannot be ruled out. A future study assessing the effect of cognitive and brain function on gait variability in people with frailty is needed to confirm this hypothesis.

Additionally, greater differentiation between the three frailty status groups (ie, frail, prefrail and not frail) on gait variability was most evident under the fast pace walking condition in each frailty index. This is a very interesting finding and consistent with previous studies that found fast walking, being a more demanding task, allows identification of older persons with lower functional level and lower physiological reserve (26,46–48). Usual gait, or walking at a self-selected pace, may not have sufficiently stressed our participants with a lower physiological reserve, and the additional effort needed for fast paced walking allowed differences in fitness and functionality to emerge. It is also possible that the higher demands imposed on the balance control system during fast walking necessitate additional physiological effort; therefore, high gait variability under fast velocity may be indicative of low neuromuscular or cognitive reserve and reflect more vulnerability.

One explanation for the presence of high gait variability in people with frailty is that it may indicate a loss of complexity in the dynamics of the gait pattern. Frailty, as a physiological concept, is understood as a lack of homeostasis with a multisystem reduction in reserve capacity that is close to the threshold for failure (49) and a generalized loss of complexity of several physiological systems (33,34,50). One way to capture this loss of complexity is through the measurement of variability in physiological processes. For instance, an age-related loss of complexity and variability has been described in several physiological processes including cardiovascular control, pulsatile hormone release, electroencephalographic potentials, and gait performance (33). In agreement with this, a recent study, using data from the Women's Health and Aging Study, I and II, has provided empirical evidence that the frailty phenotype has a nonlinear relationship with dysregulation in several physiological systems (51). In this study, the neuromuscular domain was evaluated by assessing upper limb fine motor speed but information on gait performance was not available. Our findings in gait performance and gait variability are complementary with their results and support the theory that an aggregate loss of complexity with aging in physiological systems can be a determinant of frailty.

In addition, it has been demonstrated that less regulation of heart rate, evaluated as heart rate variability, is also associated with frailty phenotype (50). Because gait is a complex motor task that is highly regulated by several systems, we postulate that the increase in gait variability seen in older adults with frailty may reflect a multisystem reduction in physiological reserve capacity. In other words, high gait variability can be seen as a reflection of the inconsistency of the central neuromuscular control system's ability to regulate gait and maintain a steady walking pattern. Under this framework, it is easy to understand that measures of gait variability would be associated with instability, mobility decline, falls, and frailty status. Future research is needed to determine whether a measure of physiological complexity such as gait variability might be useful for screening and/or monitoring of clinical vulnerability in older individuals.

This study is limited by the cross sectional design; although it is clear that associations exist between frailty status and gait variability, we cannot ascertain the temporal order. Another limitation is the convenience sample of participants used in this study and, as a result, the findings may not be generalizable to all community-dwelling older adults. Of note, our study sample included older people with relatively good functionality and few participants reported low physical activity or unintentional weight loss. Therefore, our findings are probably a conservative estimate of the magnitude of association between gait variability and frailty. Finally, there is a possibility that our sample size was not sufficiently powered to show additional associations in the adjusted regression analyses; therefore, reproduction of our findings in a larger sample is warranted. Despite these

limitations, we were able to study gait variability and the association with frailty status while controlling potential confounding factors, including age, gait velocity. and history of falls, in community-dwelling older adults.

In conclusion, frailty is associated with low performance in several quantitative gait parameters beyond velocity and this association was more evident under the fast pace walking condition than the usual pace in each frailty index. The most prominent parameter associated with frailty status is high stride time variability. This association may provide empirical evidence to understand the model of frailty as a syndrome of homeostatic impairment with a lack of complexity and, consequently, increased vulnerability.

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