*Journals of Gerontology: MEDICAL SCIENCES*
*Cite journal as: J Gerontol A Biol Sci Med Sci. 2013 July;68(7):820–827*
doi:10.1093/gerona/gls255


*Advance Access publication December 18, 2012*

# Independent Domains of Gait in Older Adults and Associated Motor and Nonmotor Attributes: Validation of a Factor Analysis Approach

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***Background.*** Gait is an important predictor of survival in older adults. Gait characteristics help to identify markers of incipient pathology, inform diagnostic algorithms and disease progression, and measure efficacy of interventions. However, there is no clear framework to guide selection of gait characteristics. This study developed and validated a model of gait in older adults based on a strong theoretical paradigm.

***Methods.*** One hundred and eighty-nine older adults with a mean (*SD*) age of 69.5 (7.6) years were assessed for 16 spatiotemporal gait variables using a 7-m instrumented walkway (GAITRite) while walking for 2 minutes. Principal components analysis and factor analysis "varimax" procedure were used to derive a model that was validated using a multimethod approach: replication of previous work; association of gait domains with motor, cognitive, and behavioral attributes; and discriminatory properties of gait domains using age as a criterion.

***Results.*** Five factors emerged from the principal components analysis: pace (22.5%), rhythm (19.3%), variability (15.1%), asymmetry (14.5%), and postural control (8.0%), explaining 79.5% of gait variance in total. Age, executive function, power of attention, balance self-efficacy, and physical fatigue were independently and selectively associated with 4 gait domains, explaining up to 40.1% of total variance. Median age discriminated pace, variability, and postural control domains.

***Conclusions.*** This study supports a 5-factor model of gait in older adults with domains that preferentially select for motor, cognitive, and behavioral attributes. Future research is required to validate the model. If successful, it will facilitate hypothesis-driven research to explain underlying gait mechanisms, identify contributory features to gait disturbance, and examine the effect of intervention.

***Key Words:*** Older adults—Gait—Factor analysis—Model.

*Received August 15, 2012; Accepted November 25, 2012*

*Decision Editor: Stephen Kritchevsky, PhD*

SAFE and effective gait is a hallmark of independence across the life span. Gait performance is a predictor for survival (1), cognitive decline (2), falls status (3), and quality of life (4) and is considered a maker of global health. Public health recommendations include a minimum daily step count for the protective effect walking has on overall health status (5). Despite its apparent simplicity, walking is a complex act that becomes more challenging with age. Although gait is mostly automatic when walking in predictable environments, cognitive control is required to maintain performance under more complex conditions and to mitigate the effects of age and pathology (6).

A broad range of characteristics is used to describe gait performance. Gait speed is preeminent and applied widely as an evaluative, a discriminatory, and a predictive measure across the life span because of its robust clinimetric properties (7). However, gait is multidimensional and cannot be captured by one characteristic. Other measures also play a significant role. For example, gait variability (stride-to-stride fluctuations of gait) is a more sensitive predictor of falls than gait speed (8) and discriminates (ahead of gait speed) for detection of presymptomatic carriers of the LRRK2-G2019S mutation as a precursor of Parkinson's disease, possibly due to incipient change in subcortical and spinal networks (9). Stride time variability has also been suggested as a marker of serum 25-hydroxyvitamin D insufficiency in older adults (10). Step width and step width variability reflect the postural control of gait, although interpretation is challenging because some variability is required to respond flexibly to the changing demands of terrain and trajectory (11).

Covariance among gait characteristics is high, suggesting redundancy and the need to identify key variables without

compromising selectivity. One approach is to group characteristics into domains of gait, which has been attempted previously. An early classification derived two broad domains of gait from variability measures: gait patterning and dynamic balance control (12). A more recent factor analysis of eight gait variables identified three independent domains: rhythm, pace, and variability (2), which were subsequently shown to have discriminative properties. The pace factor discriminated nonamnestic mild cognitive impairment from normal cognition, whereas the rhythm and variability factors discerned amnestic mild cognitive impairment from normal cognition (13). Hollman and colleagues (14) subjected 23 gait variables to factor analysis and yielded a five-factor model that included rhythm, phases of the gait cycle, variability, pace, and base of support.

Domains provide a useful schema to explain the contribution of underlying cognitive and other nonmotor features to gait disturbance. Attention and executive function are positively correlated with gait speed in older adults with and without cognitive impairment (13), and imaging work reports a preferential involvement of cortical and subcortical areas to gait characteristics. Rosano and colleagues (15) reported an association between gait speed and reduction in grey matter volumes in a widely distributed network of cortical regions, including the dorsolateral prefrontral cortex, whereas step width was associated with smaller pallidum and parietal cortex.

However, the rationale for the number and type of gait characteristics included in a model of gait is not always clear, limiting interpretation. Also, gait characteristics do not consistently load onto identical domains. For example, stride length has been represented as a marker for both rhythmicity (16) and pace domains of gait (13), creating ambiguity. Development of a framework for gait will facilitate hypothesis-driven research to explain underlying gait mechanisms, identify contributory features to gait disturbance, and examine the effect of intervention.

This study builds on earlier work and conducts a factor analysis based on a strong theoretical paradigm to classify domains of gait in older adults. Our aim was to develop a model of gait in older adults and validate the model using a multimethod approach that included replication of previous work; association of gait domains with motor, cognitive, and behavioral attributes; and discriminatory properties of gait domains using age as a criterion.

## Methods

### *Participants*

Older adults were recruited from research active general practices via a regional primary care research network, from local hospital trusts via advertising and via the Public Engagement Team based at the Institute for Ageing and Health at Newcastle University. Inclusion criteria were as follows: (a) aged 60 years and older; (b) able to walk independently without a walking aid; (c) no significant cognitive impairment, mood disorder, or movement disorder; and (d) language skills sufficient to comply with testing. Exclusion criteria were as follows: (a) cognitive impairment based on Mini-Mental Status Examination score of less than 24 (17) or dementia as defined by *Diagnostic and Statistical Manual of Mental Disorders*, 4th edition (DSM IV) (18); (b) significant vascular comorbidity (ie, stroke disease); and (c) unable to consent. The study was approved by the Newcastle and North Tyneside Research Ethics Committee and informed consent was obtained from all participants. All testing took place at the Clinical Ageing Research Unit, Newcastle University.

### *Outcome Measures*

*Demographic and clinical variables.*—Participants were assessed for demographic and clinical variables that included age, gender, body mass index, the National Adult Reading Test (19), which is a general measure of intelligence, and self-reported comorbidities, medication, and falls status.

*Motor variables.*—Motor variables included balance (single leg stance) and timed chair stand, which is a proxy for muscle strength.

*Cognitive variables.*—Cognition was assessed with (a) the Mini-Mental Status Examination (17); (b) the power of attention (a composite measure of the mean of simple reaction time, choice reaction time, and digit vigilance time from the Cognitive Drug Research battery [20]); (c) pattern recognition memory and spatial recognition memory (21); and (d) executive function using the one touch stockings of Cambridge. These last three tests were from the Cambridge Neuropsychological Automated Testing Battery (21).

*Behavioral measures.*—These include balance self-efficacy, measured by the Activities-Specific Balance Confidence (ABC) scale (22); depression, assessed using the Geriatric Depression Scale (23); and physical fatigue from the Multidimensional Fatigue Inventory (24).

### *Quantitative Gait Evaluation*

Individual footfall data was captured over a 7-m long instrumented walkway using embedded pressure sensors (GAITRite, CIR Systems Inc.), for which reliability and validity has been established (25). Gait was measured during a 2-minute continuous walk around a 25-m circuit and the mat was positioned along one side of the circuit allowing data to be sampled intermittently as each participant walked at their preferred speed repeatedly over the mat. Continuous gait was evaluated to capture steady-state locomotion and avoid acceleration and deceleration. Approximately, five passes over the mat were made from which gait characteristics were determined. Gait characteristics were expressed as (a) mean spatiotemporal

characteristics, (b) gait dynamics (step-to-step variability calculated from left- and right-step standard deviation [*SD*] from a minimum of 40 steps per participant [26]), and (c) asymmetry (coordination of lower limbs). Data were collected at 240 Hz and analyzed using proprietary software. Data for individual steps for each condition was extracted from the Gaitrite database using Microsoft Access 2007. Detailed description of the method of calculating gait characteristics is reported in detail elsewhere (26).

### *Gait Characteristics for Factor Analysis*

The rationale for selection of gait characteristics into the factor analysis was based on our earlier work examining discrete aspects of gait and their predictors in healthy older adults and people with pathology (27,28); research examining the reliability of gait characteristics and methodological issues (26,29); and consideration of previous factor analyses and relevant literature (30–32). A key requirement of the model was its putative application for a broad range of gait pathologies. Data considerations were as follows:

1. Inclusion of a sufficient number of gait characteristics to ensure that the model accurately represents the underlying construct (gait) while avoiding duplication and redundancy in the model (eg, step length but not stride length).
2. The use of step rather than stride characteristics (step variability measures are more reliable [26]).
3. Preservation of original measurement units (eg, step time rather than cadence).
4. Inclusion of measures for step asymmetry because of their diagnostic and predictive utility (33).
5. Use of *SD* rather than coefficient of variation (defined as mean/*SD* × 100) because it provides clarity for interpretation (29).

### *Data Analysis*

Data analysis consisted of two main phases: the factor analysis and model validation. Prior to factor analysis gait, data were inspected for distribution and associations among gait variables examined with Pearson's correlation coefficients. Temporal gait variability characteristics were log transformed and step asymmetry data were square root transformed to improve normality of distribution.

*Factor analysis.*—A principal component analysis was conducted to identify which combination of characteristics best capture gait. Varimax rotation was used to derive orthogonal factor scores, with the minimum eigenvalue for extraction set at 1. Scree plots, factor loadings, item loadings, and cross-loadings were examined. Items that met a minimum loading of 0.5 were considered relevant.

*Model validation.*—A multimethod approach was taken to validate the model of gait, which emerged from the factor analysis. First, we replicated an earlier factor analysis (2) using our data and using the coefficient of variation rather than *SD* for gait dynamics. Second, we used hierarchical regression analysis to identify associations between gait domains and explanatory characteristics. A single gait characteristic was selected from each domain and used as a dependent variable. Characteristics were selected because they produced the strongest communality for the factor they represent or because they are commonly used to describe gait (eg, step velocity, step time). Based on previous predictive models (2,13,27) and bivariate analysis, we selected 11 predictor variables to represent cognitive, motor, behavioral, and clinical domains. Age was entered first, followed by the second block, which included motor variables, such as single leg stance and timed chair stand. The third block consisted of behavioral outcomes, such as balance self-efficacy, physical fatigue, and depression, and the fourth block comprised cognitive variables, such as global cognition (Mini-Mental State Examination), spatial recognition memory (% correct), pattern recognition memory (mean correct latency), executive function (one touch stockings of Cambridge—problems solved on first choice), and power of attention. Last, we carried out a criterion analysis to discriminate gait domains. Age was selected because of its profound effect on gait performance and dichotomized for median age. Gait characteristics from each domain were then compared using independent *t* tests.

Residuals and collinearity diagnostics were examined and assumptions met for testing. Standardized beta coefficients and part squared correlations were used to evaluate the relative contribution of each predictor to the variance of dependent measures. Preliminary analysis showed a difference in strength but not direction of association between explanatory variables and gait characteristics for gender, and gender was therefore not included in hierarchical analysis. The alpha level was set at 0.05. Statistical Package for the Social Sciences (SPSS) for Windows (V 17) was used to analyze the data.

## Results

One hundred and eighty-nine healthy community-dwelling older adults with an average age of 69.5 years and Mini-Mental Status Examination score of 29 were recruited to the study. Four female participants (2.1%), reported at least one fall within 6 months. Gait, motor, and cognitive scores were comparable to referent values and overall indicate a high functioning group. Depression scores were low and balance self-efficacy scores high. Fatigue scores were highest for the general fatigue domain (Tables 1 and 2).

### *Principal Component Analysis*

Sixteen gait variables were included in the principal component analysis, which yielded five orthogonal factors

Table 1. Subject, Clinical Characteristics, and Gait Outcomes in Participants ($n$ = 189)

| Characteristic | Mean | *SD* | Range |
|---|---|---|---|
| Personal characteristics | | | |
| Men/women (79:110) | | | |
| Age | 69.5 | 7.6 | 48–89 |
| MMSE | 29.3 | 1.0 | 26–30 |
| BMI | 2.8 | 5.8 | 0–58 |
| NART | 116.9 | 7.6 | 91–131 |
| Behavioral characteristics | | | |
| ABC scale (0–100) | 91.7 | 10.8 | 26.5–100 |
| Geriatric depression scale (0–100) | 1.1 | 1.8 | 0–14 |
| MFI—General fatigue subscale (0–20) | 8.5 | 3.7 | 4–20 |
| MFI—Physical fatigue subscale (0–20) | 8.2 | 3.6 | 4–20 |
| MFI—Reduced activity subscale (0–20) | 7.4 | 3.4 | 4–20 |
| MFI—Reduced motivation subscale (0–20) | 6.4 | 2.7 | 4–20 |
| MFI—Mental fatigue subscale (0–20) | 7.5 | 3.2 | 4–20 |
| Motor characteristics | | | |
| Right leg stance (s) | 15.6 | 12.5 | 0–30 |
| Left leg stance (s) | 14.6 | 12.0 | 0–30 |
| Timed chair stand (s) | 12.3 | 4.0 | 0–36.5 |
| Cognitive characteristics | | | |
| One touch stocking problems solved first choice ($n$ = 176) | 15.8 | 3.2 | 1–20 |
| One touch stocking mean latency ($n$ = 176) | 17045.3 | 10470.4 | 5272.6–75635.0 |
| Spatial recognition memory % correct ($n$ = 179) | 81.2 | 9.5 | 55–100 |
| Spatial recognition memory mean correct latency ($n$ = 179) | 22.05.3 | 554.0 | 1200.6–3961.1 |
| Pattern recognition memory % correct ($n$ = 179) | 87.5 | 10.3 | 41.6–100 |
| Pattern recognition memory mean correct latency ($n$ = 179) | 2187.2 | 548.5 | 1276.5–4233.4 |
| Power of attention ($n$ = 173) | 1309.3 | 154.1 | 1046.5–1830.0 |

*Notes:* MMSE = Mini-Mental State Examination; BMI = body mass index; NART = National Adult Reading Test; MFI = Multidimensional Fatigue Inventory.

Table 2. Gait Characteristics for All Participants ($n$ = 189)

| Characteristic | Mean | *SD* | Range |
|---|---|---|---|
| Mean spatiotemporal characteristics | | | |
| Step velocity (m/s) | 1.26 | 0.194 | 0.59–1.86 |
| Step length (m) | 0.670 | 0.083 | 0.41–0.89 |
| Step width (m) | 0.089 | 0.024 | 0.02–0.16 |
| Step time (ms) | 537 | 47 | 440–696 |
| Step swing time (ms) | 386 | 30 | 313–467 |
| Step stance time (ms) | 688 | 72 | 533–970 |
| Variability characteristics (*SD*) | | | |
| Step velocity (m/s) | 0.053 | 0.012 | 0.03–0.09 |
| Step length (m) | 0.019 | 0.005 | 0.01–0.04 |
| Step width (m) | 0.022 | 0.005 | 0.01–0.04 |
| Step time (ms) | 16.4 | 5.8 | 7.55–48.9 |
| Step swing time (ms) | 15.2 | 5.5 | 7.96–50.7 |
| Step stance time (ms) | 19.8 | 8.0 | 8.09–68.4 |
| Asymmetry characteristics | | | |
| Step length (m) | 0.020 | 0.017 | 0.00–0.09 |
| Step time (ms) | 11.3 | 11.4 | 0.08–70.5 |
| Step stance (ms) | 8.9 | 9.3 | 0.06–59.3 |
| Step swing time (ms) | 8.9 | 9.4 | 0.04–54.6 |

accounting for 79.5% of total variance in test scores. We described the factors as rhythm, pace, asymmetry, variability, and postural control. There were no cross-loadings, and all item loadings were greater than 0.5 other than step width variability, which loaded onto the variability domain with a loading of 0.476 (Table 3).

### *Model Validation*

*Replication of previous model.*—Between-factor loadings were highly comparable when our data were applied to Verghese's model (13) using the same eight gait characteristics (Table 4). Regression models were significant for gait domains other than variability (analysis of variance $p$ = .07), with predictors explaining from 11.1% (variability) to 41% (pace) of variance.

*Association between gait domains and explanatory characteristics.*—There were significant associations between cognitive, motor, and clinical attributes for pace, asymmetry, rhythm, and postural control but not for the variability domain. Balance self-efficacy was the strongest variable for two domains (pace and asymmetry), with higher ABC scores denoting a more rapid and less asymmetrical gait. Faster times for attention tasks and timed chair stand (a proxy for muscle strength) were also associated with a faster gait (pace). Older age and higher scores for executive function (greater number of problems solved on first choice) predicted greater step length asymmetry (postural control) and higher scores for fatigue were associated with step time (rhythm; Table 5).

*Discriminant analysis.*—Using median age (69 years) as a criterion standard, significant differences were found

Table 3. Item Loadings for the Five-Factor Rotated Solution and Communalities (Varimax Rotation)

| Item | Pace | Rhythm | Asymmetry | Variability | Postural Control |
|---|---|---|---|---|---|
| Pace | | | | | |
| Step velocity (m/s) | **–0.866** | –0.355 | –0.178 | 0.019 | –0.117 |
| Step length (m) | **–0.915** | 0.184 | –0.120 | 0.015 | –.043 |
| Step time variability (ms) | **0.711** | 0.347 | 0.150 | 0.483 | 0.093 |
| Step swing time variability (ms) | **0.618** | 0.390 | 0.244 | 0.386 | 0.135 |
| Step stance time variability (ms) | **0.749** | 0.302 | 0.098 | 0.461 | 0.059 |
| Rhythm | | | | | |
| Step time (ms) | 0.303 | **0.906** | 0.191 | 0.027 | 0.143 |
| Step swing time (ms) | –0.078 | **0.912** | 0.114 | –0.007 | –0.004 |
| Step stance time (ms) | 0.426 | **0.807** | 0.202 | 0.037 | 0.189 |
| Asymmetry | | | | | |
| Step time asymmetry (ms) | 0.155 | 0.178 | **0.670** | –0.044 | 0.247 |
| Step swing asymmetry (ms) | 0.105 | 0.114 | **0.934** | 0.062 | –0.016 |
| Step stance asymmetry (ms) | 0.133 | 0.099 | **0.916** | 0.058 | –0.036 |
| Variability (*SD*) | | | | | |
| Step velocity variability (m/s) | 0.148 | –0.215 | –0.054 | **0.879** | –0.026 |
| Step length variability (m) | 0.181 | 0.118 | 0.117 | **0.799** | 0.257 |
| Step width variability (m) | –0.426 | 0.368 | –0.037 | **0.476** | –0.013 |
| Postural control | | | | | |
| Step width (m) | 0.063 | 0.023 | –0.001 | 0.275 | **0.656** |
| Step length asymmetry (m) | 0.081 | 0.129 | 0.105 | –0.070 | **0.788** |
| %Variance | **22.5** | **19.3** | **15.1** | **14.5** | **8.0** |

*Note:* Relevant item loadings in bold.

Table 4. Replication of Verghese and Colleagues' (13) Factor Analysis

| | Pace | Rhythm | Variability |
|---|---|---|---|
| Stride velocity (m/s) | **0.808** | –0.412 | –0.357 |
| Stride length (m) | **0.860** | 0.149 | –0.410 |
| Stride time (ms) | –0.256 | **0.956** | 0.140 |
| Double support time (ms) | **–0.667** | **0.614** | 0.226 |
| Stride swing time (ms) | 0.211 | **0.915** | 0.024 |
| Stride stance time (ms) | –0.434 | **0.867** | 0.175 |
| Stride length variability (m/CV) | –0.249 | 0.099 | **0.837** |
| Stride swing variability (m/s CV) | –0.259 | .139 | **.828** |

*Note:* Relevant item loadings in bold.

for three of the five gait domain characteristics: pace (step velocity), variability (step velocity variability), and postural control (step length asymmetry). Age did not discriminate for rhythm (step time) or asymmetry (swing time asymmetry) domains (Table 6).

## Discussion

This study examined a model of gait and its correlates in healthy older adults who were predominantly nonfallers and who presented with moderate to high levels of cognitive and motor function and age-normative gait characteristics. We confirmed the presence of independent gait domains, some of which are associated with selected cognitive and motor characteristics. This suggests that gait is not a unitary concept. Different neural mechanisms are involved, depending on which domain is measured. Importantly, these domains are discrete for this cohort who presented with high functioning gait. Results from our related analysis (34) indicate that when the model is applied to pathological gait, the domains are even more discrete and the associations with independent characteristics stronger.

A principle guide for our selection of gait characteristics to be entered into the factor analysis was to aim for comprehensive coverage but importantly to avoid duplication. This resulted in subtle but critical differences with previous models. Our loadings and domains were similar to Verghese's model (13), but because we entered a greater number of (independent) gait characteristics, two further domains emerged: asymmetry and postural control. We argue that both are required for a comprehensive assessment of gait. Intact postural control is key to effective gait and may be a biomarker for early neurodegenerative disease (35), and asymmetry is a primary feature of some pathological gait disorders such as parkinsonian and hemiparetic gait (36). We also identified similar domains to Hollman's (14) model that identified rhythm, phases, variability, pace, and base of support domains. Key differences are fewer gait characteristics in our analysis (16 compared with 23) and inclusion of asymmetry characteristics.

The factor analysis yielded some unexpected results. We expected all variability characteristics to load onto the variability domain in keeping with earlier models. Instead, variability of temporal gait characteristics loaded onto the pace domain, whereas step velocity and step length variability comprised the variability domain, which explained 13.9% of total variance. Cross-loadings for variability (*SD*) and mean characteristics are to some degree inevitable because of their statistical relationship, which persisted even after we had log transformed the data. The effect was

Table 5. Summary of Hierarchical Regression Analyses Predicting Key Gait Variables Identified From Factor Analysis

| Gait Domain (gait characteristic) | | $R^2$ ($R^2$ Δ) | Significant Predictors | β* | Partial Correlations | ANOVA *p* |
|---|---|---|---|---|---|---|
| Pace (step velocity), m/s | Step 1 | 0.054 | Balance self-efficacy | 0.300* | 0.508 | (<.001) |
| | Step 2 | 0.249 (0.194) | | −0.160^ | −0.421 | |
| | Step 3 | 0.361 (0.112) | Timed chair stand | −0.195^ | −0.385 | |
| | Step 4 | **0.401** (0.039) | Power of attention | | | |
| Rhythm (step time), ms | Step 1 | 0.002 | Physical fatigue | 0.183 | 0.115 | (.003) |
| | Step 2 | 0.082 (0.080) | | | | |
| | Step 3 | 0.137 (0.055) | | | | |
| | Step 4 | **0.167** (0.030) | | | | |
| Variability (step velocity variability), m/s; *SD* | Step 1 | 0.037 | — | — | — | (.066) |
| | Step 2 | 0.063 (0.026) | | | | |
| | Step 3 | 0.069 (0.006) | | | | |
| | Step 4 | **0.113** (0.044) | | | | |
| Asymmetry (step swing time asymmetry), ms | Step 1 | 0.022 | Balance self-efficacy | −0.425* | −0.351 | (<.001) |
| | Step 2 | 0.025 (0.003) | | | | |
| | Step 3 | 0.186 (0.160) | | | | |
| | Step 4 | **0.204** (0.018) | | | | |
| Postural control (step length asymmetry), m | Step 1 | 0.059 | Age | 0.213 | 0.191 | (.005) |
| | Step 2 | 0.080 (0.020) | Executive function | 0.211 | 0.198 | |
| | Step 3 | 0.128 (0.024) | | | | |
| | Step 4 | **0.209** (0.053) | | | | |

*Notes:* ANOVA = analysis of variance.

Step 1= age; Step 2 = age, single leg stance, timed chair stand; Step 3 = age, single leg stance, timed chair stand, balance self-efficacy, physical fatigue, depression; and Step 4 = age, single leg stance, timed chair stand, balance self-efficacy, physical fatigue, depression, spatial recognition memory, pattern recognition memory, executive function, power of attention.

Model $R^2$ reported in bold font.

Standardized β* = $p < .001$, β^ = $p < .01$, β^ = $p < .005$ ($p = .055$ for physical activity and pattern recognition memory).

Table 6. Characteristics of Participants by Age

| | Age ≤ 69 (*n* = 101) | Age > 69 (*n* = 88) | |
|---|---|---|---|
| Gait domain (Gait characteristic) | Mean (*SD*) | Mean (*SD*) | Significance |
| Pace (Step velocity), m/s | 1.30 (0.16) | 1.21 (0.21) | 0.002 |
| Rhythm (Step time), ms | 532.4 (47.4) | 542.7 (47.7) | 0.141 |
| Variability (Step velocity variability), m/s, *SD* | 0.050 (0.001) | 0.056 (0.013) | 0.003 |
| Asymmetry (Step swing asymmetry), ms | 8.04 (7.37) | 9.9 (11.2) | 0.304 |
| Postural control (Step length asymmetry), m | 0.017(0.015) | 0.024 (0.019) | 0.017 |

greater for temporal rather than spatial characteristics, and we therefore chose to retain the natural measurement units. Differences in our findings compared with earlier work may be due to the inclusion of different gait characteristics (we included five variability characteristics compared with two in Verghese's model (13) and eight in Hollman's model (14), and the use of *SD* rather than coefficient of variation). When we limited gait variability characteristics to those used in Verghese's model and reported coefficient of variation rather than *SD*, our results are almost identical. Similar to Verghese, we did not convincingly identify predictors for the variability domain, suggesting that gait variability underpins gait in a subtle and complex way. However, the discriminatory and predictive properties of gait variability over and above gait speed for certain pathologies (8) and its ability to predict disability in older adults support its utility. A second unexpected finding was the loading for step width variability, which was just less than 0.5, but which may become more prominent when gait pathology is present (34). Concerns regarding the unstable clinimetric properties of step width and step width variability have been reported elsewhere (11),and novel analysis of mediolateral sway from accelerometry data may provide a more robust approach to measurement of postural control, which is a key feature of gait (37).

The model was tested against cognitive, behavioral, and motor correlates to help identify independent substrates. Results show limited associations, possibly reflecting the high functioning status of the group across the spectrum of tests. The importance of balance self-efficacy supports earlier findings in older adults (27) and in people with Parkinson's disease, where falls efficacy was identified as the most significant predictor of gait speed (28,38). Attention was significantly associated with gait speed (pace domain) as reported elsewhere in normal aging (39) and supported by imaging studies that report an association between gait speed and gray matter volumes in basal ganglia and cortico-striato-thalamic connections (40). Spatial recognition memory and pattern recognition memory tasks did not preferentially select for the rhythm and pace domains

despite earlier work that reports the role of memory tasks in discriminating amnestic over nonamnestic gait dysfunction (13), also supported by imaging studies that identify hippocampal involvement in gait (16). This is likely to reflect our choice of memory tests that were specific to pattern and spatial memory recall and not commonly used memory tests, which are more global in nature. A limitation of this study is that we did not incorporate a test of visuomotor function given the critical role of vision to gait control.

Gait characteristics representing three of the five domains were significantly different when age was used as a criterion to discriminate gait performance. This finding suggests that pace, variability, and postural control are more sensitive to age than rhythm or asymmetry. This may reflect "higher order" cognitive gait control and the impact of declining executive function on gait rather than rhythm, which is a rudimentary feature of gait mediated by brainstem and spinal cord networks. Asymmetry is likely to become evident when unilateral pathology is present, rather than as a direct consequence of aging.

In conclusion, this study presents a model to guide assessment of gait. Although gait speed (pace domain) represents overall performance, it does not allow inferences to be made about underlying pathophysiology and contributing mechanisms, a limitation this model aims to address. The model provides a comprehensive but flexible approach to assessment. Selection of gait characteristics (and thereby domains) will depend on the gait pathology; for example, step asymmetry may be useful to detect pathology with a unilateral onset, whereas gait speed may be more sensitive to cognitive decline.

Caution is required before the model can be accepted, given the differences between the model and earlier work. The model must be validated for populations such as the frail elderly and for pathological gait. Preliminary data analysis from an incident cohort of Parkinson's disease suggests consistent domains with slightly stronger loadings and clearer factor determination. If the model is robust, it will provide a strong foundation for selection of gait characteristics to pursue hypothesis-driven research to identify underlying gait mechanisms in aging and pathology, contributory features to gait disturbance, and to examine the effect of intervention.

### Funding

The research was supported by the National Institute for Health Research (NIHR) Newcastle Biomedical Research Centre based at Newcastle upon Tyne Hospitals National Health Service (NHS) Foundation Trust and Newcastle University.

### Acknowledgments

The views expressed are those of the authors and not necessarily those of the NHS, the National Institute for Health Research (NIHR), or the Department of Health. We would like to acknowledge Mrs. Dadirayi Mhiripiri for her assistance with data collection.

### References

1. Studenski S, Perera S, Patel K, et al. Gait speed and survival in older adults. *JAMA*. 2011;305:50–58.
2. Verghese J, Wang C, Lipton RB, Holtzer R, Xue X. Quantitative gait dysfunction and risk of cognitive decline and dementia. *J Neurol Neurosurg Psychiatr*. 2007;78:929–935.
3. Beauchet O, Annweiler C, Dubost V, et al. Stops walking when talking: a predictor of falls in older adults? *Eur J Neurol*. 2009;16:786–795.
4. Hirvensalo M, Rantanen T, Heikkinen E. Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. *JAGS*. 2000;48:493–498.
5. Tudor-Locke C, Bassett DJ. How Many Steps/Day Are Enough? Preliminary Pedometer Indices for Public Health. *Sports Med.* 2004;34:1–8.
6. Holtzer R, Verghese J, Xue X, Lipton RB. Cognitive processes related to gait velocity: results from the Einstein Aging Study. *Neuropsychology*. 2006;20:215–223.
7. Wade D. *Measurement in neurological rehabilitation.* Oxford, UK: Oxford University Press; 1992.
8. Hausdorff J. Gait dynamics, fractals and falls: finding meaning in the stride-to-stride fluctuations of human walking. *Human Move Sci.* 2007;26:557–589.
9. Mirelman A, Gurevich T, Giladi N, Bar-Shira A, Orr-Urtreger A, Hausdorff JM. Gait alterations in healthy carriers of the LRRK2 G2019S mutation. *Ann Neurol*. 2011;69:193–197.
10. Beauchet O, Annweiler C, Verghese J, Fantino B, Herrmann FR, Allali G. Biology of gait control: vitamin D involvement. *Neurology*. 2011;76:1617–1622.
11. Brach JS, Berlin JE, VanSwearingen JM, Newman AB, Studenski SA. Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. *J Neuroeng Rehabil*. 2005;2:21.
12. Gabell A, Nayak US. The effect of age on variability in gait. *J Gerontol*. 1984;39:662–666.
13. Verghese J, Robbins T, Holtzer R, et al. Gait dysfunction in mild cognitive impairment syndromes. *J Am Geriatr Soc.* 2008;56:1244–1251.
14. Hollman JH, McDade EM, Petersen RC. Normative spatiotemporal gait parameters in older adults. *Gait Posture*. 2011;34:111–118.
15. Rosano C, Aizenstein H, Brach J, Longenberger A, Studenski S, Newman AB. Special article: gait measures indicate underlying focal gray matter atrophy in the brain of older adults. *J Gerontol A Biol Sci Med Sci*. 2008;63:1380–1388.
16. Zimmerman ME, Lipton RB, Pan JW, Hetherington HP, Verghese J. MRI- and MRS-derived hippocampal correlates of quantitative locomotor function in older adults. *Brain Res*. 2009;1291:73–81.
17. Folstein M, Folstein S, McHugh P. Mini-mental state. A practical method for grading the congitive state of patients for the clinician. *J Psychiatr Res*. 1975;12:189–198.
18. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition - Text Revision (IV-TR).* 4th ed. (text revised). Washington DC: American Psychiatric Association; 2000.
19. Nelson HE, O'Connell A. Dementia: the estimation of premorbid intelligence levels using the New Adult Reading Test. *Cortex*. 1978;14:234–244.
20. Taylor JP, Rowan EN, Lett D, O'Brien JT, McKeith IG, Burn DJ. Poor attentional function predicts cognitive decline in patients with non-demented Parkinson's disease independent of motor phenotype. *J Neurol Neurosurg Psychiatr*. 2008;79:1318–1323.
21. Cambridge-Cognition-Limited. *CANTABeclipse™: Test Administration Guide Manual*. 5th ed. Cambridge, UK; 2012.
22. Myers AM, Fletcher PC, Myers AH, Sherk W. Discriminative and evaluative properties of the activities-specific balance confidence (ABC) scale. *J Gerontol A Biol Sci Med Sci*. 1998;53:M287–M294.
23. Schrag A, Barone P, Brown RG, et al. Depression rating scales in Parkinson's disease: critique and recommendations. *Mov Disord*. 2007;22:1077–1092.
24. Smets EM, Garssen B, Bonke B, De Haes JC. The Multidimensional Fatigue Inventory (MFI) psychometric qualities of an instrument to assess fatigue. *J Psychosom Res*. 1995;39:315–325.

25. Bilney B, Morris M, Webster K. Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. *Gait Posture*. 2003;17:68–74.
26. Galna B, Lord S, Rochester L. Is gait variability reliable in older adults and in Parkinson's disease? Towards an optimal testing protocol. *Gait Posture*. 2012. doi:10.1016/j.gaitpost.2012.09.025
27. Lord SE, Weatherall M, Rochester L. Community ambulation in older adults: which internal characteristics are important? *Arch Phys Med Rehabil*. 2010;91:378–383.
28. Rochester L, Nieuwboer A, Baker K, et al. Walking speed during single and dual tasks in Parkinson's disease: which characteristics are important? *Mov Disord*. 2008;23:2312–2318.
29. Lord S, Howe T, Greenland J, Simpson L, Rochester L. Gait variability in older adults: a structured review of testing protocol and clinimetric properties. *Gait Posture*. 2011;34:443–450.
30. Brach JS, Perera S, Studenski S, Katz M, Hall C, Verghese J. Meaningful change in measures of gait variability in older adults. *Gait Posture*. 2010;31:175–179.
31. Hollman JH, Childs KB, McNeil ML, Mueller AC, Quilter CM, Youdas JW. Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals. *Gait Posture*. 2010; 32:23–28.
32. Paterson KL, Hill KD, Lythgo ND, Maschette W. The reliability of spatiotemporal gait data for young and older women during continuous overground walking. *Arch Phys Med Rehabil*. 2008; 89:2360–2365.
33. Baltadjieva R, Giladi N, Gruendinger L, Peretz C, Hausdorff J. Marked alterations in the gait timing and rhythmicity of patients with de novo Parkinson's disease. *Euro J Neurosci.* 2006;24:1815–1820.
34. Lord S, Galna B, Burn D, Wesnes K, Rochester L. Attention rather than spatial memory predicts distinct characteristics of Parkinson's disease. *Mov Disord*. 2011;26:S392–S424.
35. Mancini M, Horak FB, Zampieri C, Carlson-Kuhta P, Nutt JG, Chiari L. Trunk accelerometry reveals postural instability in untreated Parkinson's disease. *Parkinsonism Relat Disord*. 2011;17:557–562.
36. Patterson KK, Parafianowicz I, Danells CJ, et al. Gait asymmetry in community-ambulating stroke survivors. *Arch Phys Med Rehabil*. 2008;89:304–310.
37. Nutt JG, Horak FB, Bloem BR. Milestones in gait, balance, and falling. *Mov Disord*. 2011;26:1166–1174.
38. Maki BE. Gait changes in older adults: predictors of falls or indicators of fear. *J Am Geriatr Soc*. 1997;45:313–320.
39. Inzitari M, Newman AB, Yaffe K, et al. Gait speed predicts decline in attention and psychomotor speed in older adults: the health aging and body composition study. *Neuroepidemiology*. 2007;29:156–162.
40. Rosano C, Brach J, Longstreth Jr WT, Newman AB. Quantitative measures of gait characteristics indicate prevalence of underlying subclinical structural brain abnormalities in high-functioning older adults. *Neuroepidemiology*. 2006;26:52–60.