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Sensorimotor Factors Affecting Gait Variability in Older People—A Population-Based Study

Michele L. Callisaya,[1] Leigh Blizzard,[1] Jennifer L. McGinley,[2,3] Michael D. Schmidt,[1,4] and Velandai K. Srikanth[1,5]

[1]Menzies Research Institute, Tasmania, Australia.
[2]Murdoch Children's Research Institute, Victoria, Australia.
[3]School of Physiotherapy, University of Melbourne, Victoria, Australia.
[4]Department of Kinesiology, University of Georgia, Athens.
[5]Stroke and Ageing Research Group, Southern Clinical School, Department of Medicine, Monash Medical Centre, Victoria, Australia.

Address correspondence to Michele L. Callisaya, BSc, Menzies Research Institute, Private Bay 23, Tasmania, Australia. Email: michelec@utas.edu.au

Background. Intra-individual gait variability predicts falls and disability in older people. Knowledge of factors that contribute to gait variability may lead to interventions aimed at reducing decline in mobility and falls risk. The aim of this population-based study was to examine whether poorer performance on a range of sensorimotor measures was associated with greater gait variability.

Methods. Individuals aged 60–86 years ($n = 412$) were randomly selected from the Southern Tasmanian electoral roll. Spatial (step length and step width) and temporal (step time and double support time [DST]) gait measures were recorded with a *GAITRite* walkway. Variability for each gait measure was the standard deviation of measurements recorded during six walks. Sensorimotor measures included visual contrast sensitivity, lower limb proprioception, quadriceps strength, reaction time, and body sway (eyes open and closed). Regression analysis was used to determine the relationships between sensorimotor measures and gait variability.

Results. Greater sway on a foam mat (eyes closed) was associated with greater variability in all gait measures ($p < .05$). Slower reaction time was associated with greater variability in both temporal gait measures ($p < .05$), whereas poorer proprioception was only associated with greater DST variability ($p = .01$) and weaker quadriceps strength with greater step time variability. Other sensorimotor factors were not independently associated with gait variability.

Conclusions. Body sway, reaction time, quadriceps strength, and proprioception are likely factors that may explain gait variability in the general older population. Further research is warranted to determine causality of these associations and whether intervention programs addressing these factors may reduce gait variability in older people.

Key Words: Gait variability—Sensorimotor—Older adults—Population based.

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THE prevalence of walking problems is reported to be as high as 35% in older adults (1). The inability to walk safely may lead to falls, hospitalization, and loss of independence (2). Gait variability, the intra-individual fluctuation in a gait measure (such as step time variability) from one step to the next, may be a more sensitive predictor of falls risk and mobility impairment than averaged measures such as mean step time (3–5). Gait variability in step width, step length, step time, and double support time (DST) increases with advancing age (6). Although cerebral disease has been linked to gait variability (7,8), little is known about the contribution of clinically identifiable sensorimotor abilities.

Sensorimotor functions such as muscle strength, balance, reaction time, vision, and proprioception decline with advancing age (9), and it is possible that these functions may play a role in determining gait variability. A better understanding of modifiable sensorimotor factors that predict increased gait variability could be of use in designing intervention programs to reduce gait variability and possibly falls risk. Few studies have been conducted to examine these relationships (4,10–13). In these, poorer strength, balance, and processing speed are reported to be associated with greater stride and stance time variability (4,10,13), poorer strength and processing speed with greater step length variability (12,13), and poorer balance and paradoxically better vibration sense with increased step width variability (11,13). Although informative, these studies are limited by the use of small convenience-based samples (4,10–12), the use of only univariable analyses (4,12), and the inclusion of only individual sensorimotor measures (11). Gait variability is highly likely to be determined by many factors (10), and therefore, it is appropriate to explore the combined effects

of such factors and minimize the possibility of confounding by extraneous factors such as age and body size. Furthermore, there has been only one population-based study examining this topic (13) but with several limitations. This study relied on self-reported, ranked, or indirect measurements of sensorimotor factors, with potential consequent measurement bias or imprecision of estimates. In addition, measures of balance were not included, despite others suggesting that step width and DST variability might represent balance control during gait (14).

In a population-based sample of older people, we aimed to study whether a range of sensorimotor abilities were independently associated with several measures of temporal and spatial gait variability. We hypothesized that poorer performance in these sensorimotor measures would be associated with greater gait variability.

Methods

The study sample consisted of participants aged 60–86 years (n = 412) randomly selected from the Southern Tasmanian electoral roll. Recruitment procedures have been detailed previously (15). Participants were included if they were able to walk without the use of a gait aid and excluded if they lived in a nursing home, were unable to follow simple commands in English, or had any contraindications to magnetic resonance imaging, as this was part of the larger study. The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study, and written consent was obtained from all participants. All physical measurements were performed during the same visit.

Gait Analysis

Temporal (step time and DST) and spatial (step length and step width) gait variables were measured at preferred speed using a 4.6-m computerized mat with embedded pressure sensors (GAITRite system; CIR Systems, Clifton, NJ). Step width was calculated as the perpendicular distance from heel center of one footprint to the line of progression formed by two footprints of the opposite foot. These variables were selected as they have been examined in previous studies of falls risk (5,16,17) and represent both temporal and spatial measures and in both the frontal and the sagittal planes. Participants performed six walks starting and finishing 2 m before and after the mat to allow for acceleration and deceleration. As in previous studies, the standard deviation of the mean of all steps recorded in six walks was used to represent variability of each measure (3–5,13,18).

Sensorimotor Factors

Sensorimotor function was assessed using the short form of the Physiological Profile Assessment (PPA), which has been described previously (19). The PPA is a validated battery of the following sensorimotor measurements (20): (a) visual contrast sensitivity (VCS; dB), (b) lower limb proprioception (degrees), (c) maximal isometric quadriceps strength (kilogram), (d) simple reaction time (millisecond), (e) postural sway (millimeters) using a sway meter that measures displacement of the body while standing on foam with eyes open (SEO) and standing on foam with eyes closed (SEC). Poorer performance is indicated by lower scores of VCS and quadriceps strength, higher scores of proprioception, longer reaction time, and greater displacement in body sway. The reliability of the items on the PPA ranges from moderate to excellent (20).

Other Measurements

Height (centimeters), weight (kilograms), and self-reported history of lower limb arthritis, stroke, Parkinson's disease, dementia, hypertension, diabetes mellitus, and falls (in the preceding 12 months) were recorded using a standardized questionnaire to characterize the study population. Mood was measured using the Geriatric Depression scale (short version) (21) and functional dependence using the Lawton's Instrumental Activities of Daily Living scale (brief version) (22). Executive function and cognitive speed were measured using the Victoria Stroop test (23) and the Digit-Symbol coding subtest of the Wechsler Adult Intelligence scale—Third Edition (24). Nonresponders also completed a brief phone interview providing their medical history and history of falls in the previous 12 months to estimate potential nonresponse bias.

Data Analysis

As there were no differences between left and right gait variability measures ($p > .05$), we used the average of the measures of the two sides in further analyses. Spearman correlations were first used to estimate the relationships between variables. Multivariable linear regression was used to model the effect of each sensorimotor factor on individual gait variability measures first adjusting for age, sex, height, and weight. We further adjusted the models for gait speed because it has been postulated that speed may affect variability (25). In the final models for each sensorimotor factor, additional adjustment was made for other sensorimotor factors and relevant covariates. Statistical interaction between covariates was assessed by including the product of those covariates as terms in the regression. Two women were excluded from analysis, one because of influential extreme high values in step time, step width, and DST variability and the other because she was unable to complete testing due to significant cognitive disability. Analyses were conducted using STATA version 9.0 (StataCorp, College Station, TX).

Table 1. Sample Characteristics (n = 410)

Characteristic	
Age, *M* (*SD*)	72.0 (7.0)
Height (cm), *M* (*SD*)	167.0 (9.0)
Weight (kg), *M* (*SD*)	77.9 (15.1)
Medical history, *n* (%)	
Hypertension	202 (49.3)
Diabetes	50 (12.2)
Stroke	34 (8.3)
Parkinson's disease	2 (0.5)
Dementia	2 (0.5)
Arthritis	181 (44.4)
Self-reported falls in previous 12 months	68 (16.6)
Other	
Geriatric Depression scale (short version), *M* (*SD*)	2.05 (2.32)
Independent in activities of daily living (%)	97.5
Gait characteristics, *M* (*SD*)	
Speed (cm/s)	113.90 (20.90)
Step time (s)	0.55 (0.05)
Step length (cm)	61.73 (9.09)
DST (s)	0.25 (0.06)
Step width (cm)	9.99 (2.94)
Variability gait characteristics, *M* (*SD*)	
Step time variability (ms)	21.77 (10.67)
DST variability (ms)	20.40 (7.76)
Step length variability (cm)	2.72 (0.92)
Step width variability (cm)	2.12 (0.69)
Sensorimotor variables, *M* (*SD*)	
Visual contrast sensitivity (dB)	20.69 (2.17)
Reaction time (ms)	232.13 (41.77)
Proprioception (degrees)	1.56 (1.23)
Quadriceps strength (kg)	32.03 (11.97)
Sway eyes open (mm)	21.15 (12.98)
Sway eyes closed (mm)	48.17 (43.53)

Note: DST variability = double support time.

Results

The sample response proportion was 51% (412/804). Nonresponders were older (p = .01) and were more likely to report hypertension (p = .03) but did not differ from responders with respect to sex or other medical history.

Demographic, medical, and gait characteristics are summarized in Table 1. The mean age of the sample was 72 (*SD* 7.0) years, with 42.9% being women. The mean walking speed was 113.9 cm/s, with a mean of 27.3 (*SD* 5.4) steps recorded per person.

Correlation coefficients are provided in Table 2. Poorer performance in VCS, proprioception, SEO, and SEC were associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in all measures except step width. Poorer quadriceps strength was associated with greater variability in temporal but not spatial variability measures. Associations between the gait variability measures ranged from 0.15 to 0.51.

The associations between sensorimotor factors and each of the gait variability measures adjusted for covariates are summarized as regression coefficients in Table 3. After adjusting for age, sex, height, and weight (Model 1), poorer performance on all sensorimotor measures was associated with greater step time variability. Poorer performance in reaction time, proprioception, and SEC were associated with greater DST variability. Greater sway (eyes open and closed) and slower reaction time were associated with greater step length variability. Only greater displacement in SEC was associated with greater step width variability. After the addition of gait speed (Model 2), there was a marked reduction in the magnitude of the association between sensorimotor factors and temporal variability measures (range of reduction in coefficients 24%–100%), such that the majority of the associations were no longer significant. Gait speed was not included in the final model (Table 4) for temporal gait measures because, based on these results and on physiological grounds, we could not exclude the possibility that gait speed was an intermediate in the relationship between sensorimotor factors and temporal gait variability. Adjustment for gait speed only modestly reduced the strength of the associations of sensorimotor factors with spatial variability measures (range of reduction in coefficients 0%–34%) and hence was retained in the final models.

As a number of sensorimotor factors are thought to contribute to postural control in standing (26), we initially examined the associations between sensorimotor factors and

Table 2. Spearman Correlations Between Sensorimotor and Gait Variables (n = 410)

	Age	Gait Speed	Step Time Variability (ms)	DST Variability (ms)	Step Length Variability (cm)	Step Width Variability (cm)
Age (y)	—	–0.37*	0.27*	0.27*	0.22*	0.17**
Gait speed (cm/s)	—	—	–0.59*	–0.53*	–0.20*	–0.05
Visual contrast sensitivity (dB)	–0.43*	0.22*	–0.22*	–0.18*	–0.15**	–0.13**
Reaction time (ms)	0.17**	–0.35*	0.18*	0.21*	0.11***	–0.00
Proprioception (degrees)	0.12***	0.09	0.15**	0.18*	0.13**	0.12***
Quadriceps strength (kg)	–0.33*	0.37*	–0.18*	–0.18*	–0.00	–0.02
Sway eyes open (mm)	0.29*	–0.25*	0.18*	0.13**	0.17**	0.17**
Sway eyes closed (mm)	0.34*	–0.20*	0.28*	0.23*	0.16**	0.21*
Step time variability (ms)	—	—	—	0.51*	0.40*	0.17**
DST variability (ms)	—	—	—	—	0.37*	0.15***
Step length variability (cm)	—	—	—	—	—	0.18**

Notes: DST variability = double support time.
*p < .001; **p < .01; ***p < .05.

Table 3. Associations Between Gait Variability (outcome) Sensorimotor Factors Adjusted for Covariates ($n = 410$)

	Step Time Variability (ms)		DST Variability (ms)		Step Length Variability (cm)		Step Width Variability (cm)	
	Model 1, β (95% CI)	Model 2, β (95% CI)	Model 1, β (95% CI)	Model 2, β (95% CI)	Model 1, β (95% CI)	Model 2, β (95% CI)	Model 1, β (95% CI)	Model 2, β (95% CI)
Visual contrast sensitivity (dB)	−0.344 (−0.641 to −0.048)***	−0.178 (−0.435 to 0.080)	−0.240 (−0.529 to 0.048)	−0.091 (−0.348 to 0.166)	−0.028 (−0.064 to 0.007)	−0.022 (−0.058 to 0.014)	−0.004 (−0.033 to 0.025)	−0.004 (−0.033 to 0.025)
Reaction time (ms)	0.025 (0.010 to 0.040)***	0.001 (−0.012 to 0.016)	0.031 (0.017 to 0.045)*	0.011 (−0.00 to 0.024)	0.003 (0.001 to 0.004)**	0.002 (0.000 to 0.004)***	0.000 (−0.001 to 0.002)	0.000 (−0.001 to 0.002)
Proprioception (degrees)	0.566 (0.038 to 1.090)***	0.350 (−0.090 to 0.791)	0.799 (0.299 to 1.298)**	0.611 (0.177 to 1.045)**	0.023 (−0.037 to 0.083)	0.015 (−0.044 to 0.074)	0.041 (−0.008 to 0.087)	0.041 (−0.007 to 0.090)
Quadriceps strength (kg)	−0.091 (−0.154 to −0.027)**	0.001 (−0.048 to 0.067)	−0.038 (−0.100 to 0.024)	0.054 (−0.029 to 0.112)	−0.002 (−0.009 to 0.006)	0.002 (−0.006 to 0.010)	−0.001 (−0.007 to 0.089)	−0.001 (−0.007 to 0.005)
Sway eyes open (mm)	0.055 (0.007 to 0.103)***	0.001 (−0.040 to 0.043)	0.036 (−0.001 to 0.081)	−0.012 (−0.053 to 0.029)	0.008 (0.002 to 0.013)**	0.006 (0.000 to 0.012)***	0.003 (−0.001 to 0.008)	0.004 (−0.001 to 0.008)
Sway eyes closed (mm)	0.035 (0.020 to 0.050)*	0.021 (0.008 to 0.034)**	0.030 (0.016 to 0.044)*	0.017 (0.005 to 0.030)**	0.003 (0.001 to 0.004)**	0.002 (0.000 to 0.004)***	0.004 (0.002 to 0.006)*	0.004 (0.002 to 0.007)*

Notes: DST variability = double support time.
Model 1—Adjusted for age, sex, height, and weight.
Model 2—Model 1 + gait speed.
*$p < .001$; **$p < .01$; ***$p < .05$.

each gait variability measure without including measures of body sway in the final models. Slower reaction time was associated with greater variability in all measures except step width variability, weaker quadriceps strength was associated with greater step time variability, and poorer proprioception was associated with greater DST variability. When sway measures were added to the final models (Table 4), they remained essentially unchanged except that larger displacement in SEC was associated with greater variability in all measures, and the association between reaction time and step length variability was no longer significant. VCS and SEO were not significantly associated with any of the gait variability measures. There were no significant interactions between any of the covariates. Adjusting for executive function and cognitive speed made no difference to the results except for the association of the reaction time task of the PPA with step time variability, which was largely attenuated by inclusion of these cognitive tasks. Reaction time appeared to be a proxy for central processing speed and mental flexibility in this relationship and was therefore not included in the final model. Adjusting the results for the Geriatric Depression score suggested that poorer mood may be an intermediate in the associations of reaction time and quadriceps strength with step time variability and was therefore also not included in the final model. The strength of the associations between sensorimotor measures and each gait variability measure is also summarized in Table 4 as partial R^2 values from the final multivariable models. The models explained 11%–19% of the variance in gait variability.

Discussion

In this population-based study, we investigated the effect of a range of important sensorimotor functions on several measures of gait variability. Poorer postural sway (eyes closed, standing on a foam mat) was independently associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in temporal measures (step time and DST variability), weaker quadriceps strength was associated with greater step time variability, and poorer proprioception was associated with greater DST variability. These results provide evidence that sensorimotor factors may affect differently on gait variability, albeit with some common effects, thus adding to the theoretical knowledge of mechanisms underlying gait control. They also provide insights into which factors may be potentially modified to improve gait variability and thus possibly reduce the risk of mobility decline and falling in older people.

Postural sway (SEC) was consistently associated with all measures of gait variability and explained the greatest proportion of their variance. In contrast, previous investigators have reported quadriceps strength as the strongest predictor of gait speed (19,27), indicating that gait speed and gait variability may have different underlying mechanisms.

Table 4. Multivariable Associations Between Gait Variability (outcome) and Sensorimotor Factors (n = 410)

Gait Measure	Predictor Variable	β (95% CI)	p Value	Partial R^2
Step time variability (ms)*	Sway eyes closed	0.031 (0.016 to 0.046)	<.001	0.04
	Reaction time	0.015 (0.005 to 0.030)	.042	0.01
	Quadriceps strength	−.071 (−0.134 to −0.007)	.028	0.01
	R^2	0.16		
DST variability (ms)*	Sway eyes closed	0.023 (0.009 to 0.037)	.001	0.02
	Reaction time	0.024 (0.010 to 0.038)	.001	0.02
	Proprioception	0.660 (0.179 to 1.142)	.007	0.01
	R^2	0.19		
Step length variability (cm)*†	Sway eyes closed	0.002 (0.000 to 0.004)	.014	0.01
	R^2	0.14		
Step width variability (cm)*†	Sway eyes closed	0.004 (0.002 to 0.007)	<.001	0.03
	R^2	0.11		

Notes: DST variability = double support time.
The reported R^2 value is for the model adjusted for covariates.
*All models adjusted for age, sex, height, weight, and other significant sensorimotor factors.
†Also adjusted for gait speed.

These reported differences may contribute to the understanding of why measures of gait variability, but not gait speed, are predictors of falls in some populations (4,5). The exact mechanisms underlying the association between SEC and gait variability measures are unknown. SEC is a static test of postural control that measures a participant's ability to maintain the center of gravity within the limits of the base of support when standing on a foam mat with the eyes closed. Poorer performance on such a test may result in difficulty maintaining stability in a more dynamic and complex activity such as walking, where the body is in motion and the center of gravity is outside the base of support for much of the gait cycle (28). The SEC test is also thought to measure the ability of the vestibular system to maintain postural stability after the reduction of proprioceptive and visual input (29). Age- or disease-related decline may result in a less reliable vestibular system that is unable to compensate for reduced sensory information, potentially leading to increased sway (9,30). Altering the timing and length of steps during walking may be an attempt to regain one's balance or alternatively an attempt to stabilize vision when there is poor underlying postural control (31). Interestingly SEO, a condition where both the vision and the vestibular system are available to maintain balance, was not independently associated with gait variability in the final models. This may indicate that some aspects of vision are particularly important to maintain a regular gait pattern in older adults. Alternatively, SEC may simply represent a more complex task where the body is unable to compensate for reduction in two senses (29).

Our findings support the prior suggestion that step width and DST variability represent balance ability while walking (14) but also indicate that step length and step time variability may also represent this concept. This is consistent with other smaller studies that have found that measures of balance are associated with greater step width (11) and temporal variability measures (4,10). However, this is the first study to find postural sway is also associated with step length variability.

Longer reaction time, a measure of processing speed (27), was associated with greater temporal variability but not spatial variability. The body's inability to adequately process incoming sensory and outgoing motor information in a timely manner may lead to inconsistent and inaccurate foot placement. It has previously been suggested that those measures that have a timing component may explain the stronger associations with temporal measures (13). Adjusting our results for cognitive measures reduced the association between reaction time and step time variability by more than one half, suggesting that reaction time might be a proxy for these cognitive measures. Our results are in agreement with most other studies that report tests representing processing speed are associated with temporal variability measures (13,32). Although we could not reproduce a previous finding of an independent association of processing speed with step length variability (13), reaction time was associated with this measure before the addition of SEC. Adjusting for the Geriatric Depression scale reduced the association between reaction time and step time variability by one third, raising the possibility that it may be an intermediate in this association but without excluding a role as a confounder. These results suggest that, in the latter case, exercises to improve reaction time may need to be part of a multifactorial intervention program to reduce step time variability.

Our study is in agreement with others that have reported a relationship between muscle strength and step or stride time variability (4,10). Interestingly, our study also agrees with the study by Brach and colleagues (13) that muscle strength is not associated with step width or step length variability measures. Although muscle strength was assessed differently in their study, these findings add weight to the suggestion that gait variability measures are not homogeneous (13).

The association between poorer proprioception and greater DST variability suggests that proprioceptive feedback is

required to maintain consistent timing in double support phase. Proprioception was also individually associated with step time variability, but when the other sensorimotor variables were added, its effect was no longer significant ($p = .08$).

We hypothesized that poorer performance in all sensorimotor measures would be associated with increased gait variability. However, VCS and SEO were not independent predictors of any of the gait variability measures. In contrast to our study, Brach and colleagues (13) reported that poorer performance on a self-reported test of vision was associated with decreased step width variability. This may have been due to their different method for calculation of step width.

This study adds significantly to knowledge of sensorimotor factors associated with gait variability. It is one of the few studies providing data on both temporal and spatial gait measures and a range of quantitative sensorimotor factors, with careful attention to evaluating the independent contributions of the sensorimotor factors. These factors can potentially be modified or compensated for through exercise programs, education, or provision of a mobility aid and could therefore be targets for interventions aimed at reducing gait variability (33). Being population based, this study also provides results that are more generalizable than those from smaller convenience samples used in the majority of previous studies. However, although there were few differences between responders and nonresponders, the sample is likely to be healthier than the general population as shown by their high levels of independence in activities of daily living. Furthermore, the sensorimotor factors used in this study explained only a small but meaningful amount (34) of the variance in gait variability. It is also possible that other measures of sensorimotor function, such as quadriceps power, joint range of movement, strength of other key muscle groups, or more sensitive measures of vestibular function may have resulted in stronger associations. Further research is needed to determine if the inclusion of these and additional factors such as other cognitive measures or subclinical cerebral changes (13,35,36) are able to explain more of the variance. Another limitation of this study is that small numbers of steps were collected over six trials. This prohibited analysis of long-range correlations in the data and may have affected the reliability of the measures (37). To overcome this, we used a greater number of trials in a large sample. In addition, the number of steps, although small, was in accordance with recommendations (38) and served to avoid participant fatigue. These findings are also limited by their cross-sectional nature and need to be repeated in longitudinal and intervention studies to address causality in relationships.

Summary

Greater postural sway was associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in temporal gait measures. Poorer quadriceps strength was associated with step time variability, and proprioception was associated with greater DST variability. Further research is warranted to determine if inclusion of these factors in intervention programs reduces gait variability, disability, and falls risk in older adults.

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