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Gait Coordination Impairment is Associated with Mobility in Older Adults

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Abstract

Background—Impairments to body systems contribute to mobility limitations. The objective of this study was to determine whether impaired gait coordination, as measured by the Phase Coordination Index (PCI), is significantly associated with mobility limitations in older adults, even after adjusting for other gait features.

Methods—We conducted a cross-sectional analysis of performance-based measures of mobility in older adults (N = 164) 77 – 101 years of age, participants in the population-based MOBILIZE Boston Study. Mobility outcomes included the Short Physical Performance Battery (SPPB) and each of its three components. Multivariable linear regression models, adjusting for age and gender,

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were used to examine the associations of PCI and the coefficients of variation of stride length, width and time, stance time, and step width with each outcome.

Results—PCI accounted for more variance in SPPB score ($R^2 = 0.21$), gait speed ($R^2 = 0.17$), chair rise score ($R^2 = 0.10$), and balance score ($R^2 = 0.09$) than any of the other gait measures. Impaired gait coordination was significantly associated with performance on the SPPB and each of its component tasks, even after accounting for gait measures previously linked to mobility tasks (all $P < 0.05$). In multivariable linear regression modeling PCI accounted for an additional 9% of the variance in SPPB score ($P < 0.001$), after accounting for the other gait variables, age, and gender.

Conclusions—This study shows that impaired gait coordination is associated with poorer mobility performance in older adults, independent of other gait variables previously linked to mobility tasks.

Keywords

aging; coordination; gait; mobility

1. Introduction

Mobility is classified by the World Health Organization as an activity that consists of moving by changing body position or location and may include activities such as walking and climbing stairs (Organization, 2001). Mobility limitations decrease participation in activities of daily living and can lead to loss of independence. These limitations contribute to falls (Hausdorff, Rios, & Edelberg, 2001), disability, hospitalization and even death in older adults (Vermeulen, Neyens, van Rossum, Spreeuwenberg, & de Witte, 2011). Mobility limitations affect over 15 million older adults and are expected to lead to a \$42 billion increase in annual healthcare costs by the year 2040 (Hardy, Kang, Studenski, & Degenholtz, 2011).

A number of body system impairments have been identified as risk factors for mobility limitations. These include cognitive (Montero-Odasso, Verghese, Beauchet, & Hausdorff, 2012) and peripheral neuromuscular (e.g., reduced leg strength, trunk endurance, and range of motion) impairments (Bean et al., 2013). Alterations in gait characteristics that have been identified as risk factors for mobility limitations include measures of the amplitude (e.g., length, width) and the variability in the duration of spatial-temporal properties such as strides, steps and stance (Brach, Studenski, Perera, VanSwearingen, & Newman, 2008; Brach, Studenski, Perera, VanSwearingen, & Newman, 2007; Hausdorff et al., 2001). The identification of new contributors to mobility limitations in older adults are needed to identify those at risk for mobility limitations and to improve rehabilitative outcomes, as currently known factors account for less than 50% of the variance in measures of mobility (Bean et al., 2013).

Another class of body movement measures is the timing of one body segment in relation to another, termed coordination (Kelso, 1995). Impairments in the coordination of the left-right stepping pattern during the gait cycle have not been well studied with respect to mobility

limitations in older adults. The Phase Coordination Index (PCI) provides a means of evaluating gait coordination that combines the variability and asymmetry of the left-right step timing during locomotion. Prior research has shown that PCI distinguishes older from young adults even when gait speed and stride time variability do not (Plotnik, Giladi, & Hausdorff, 2007). Poorer gait coordination (i.e., higher PCI values) has also been found post-stroke (Meijer et al., 2011), and in patients with Parkinson's disease with (vs. without) freezing gait (Peterson, Plotnik, Hausdorff, & Earhart, 2012). The relationship of PCI to standard measures of mobility performance in older adults is not well established.

We view gait coordination, as measured by PCI, as a novel and potentially important gait impairment. Thus, while the association of standard mobility measures with gait impairment measures (i.e., gait variability) is known, the relative strength of association of PCI with mobility performance has not been evaluated. Therefore, we conducted a study of PCI and other gait impairment measures and their relationship with standard measures of mobility within the Maintenance of Balance, Independent Living, Intellect and Zest in the Elderly (MOBILIZE) of Boston study (MBS), a population-based study of older adults. The Short Physical Performance Battery (SPPB) is a measure of mobility performance that has been shown to be predictive of disability, nursing home admission, and mortality (Guralnik et al., 2000; Guralnik et al., 1994). The aim of this study was to examine the association of gait coordination with mobility performance in older adults. We hypothesized that, after adjusting for age and gender, PCI would be significantly associated with SPPB scores.

2. Methods

2.1. Participants

Community dwelling older adults aged 77 – 101 years were recruited for the current follow-up assessment wave of the MBS. Details of the original design, recruitment and assessment for the MOBILIZE Boston Study have been previously published (Leveille et al., 2008). When the MBS began in 2005 to 2008, participants were recruited door to door in Boston and 5 surrounding communities. Eligibility criteria included age 70 years or older, ability to speak and understand English, ability walk 20 feet without personal assistance, sufficient vision to read written material, and the expectation of living in the area for at least the subsequent 2 years. Exclusion criteria were a Mini-Mental State Exam score of less than 18, severe language, visual or hearing deficits, or having a terminal disease. Interested spouses and domestic partners of participants were allowed to join the study if they were aged 65 or older and met other eligibility criteria. All participants completed a new written informed consent form for the current follow-up that was approved by the Hebrew Senior Life Institutional Review Board.

2.2. Measures

2.2.1. Gait analysis—Participants were instructed to walk at their usual pace across a 16 foot long GAITRite Electronic Walkway (Menz, Latt, Tiedemann, Mun San Kwan, & Lord, 2004)^a. The participants performed 2 walking trials that consisted of 3 passes each across the gait walkway and an additional 3 feet on either end of the walkway. Variables calculated from gait walkway data were the mean gait speed, PCI and the coefficient of variation (CV =

SD/Mean) of the: 1) stride time; 2) stride length; 3) stride width; 4) step width; and 5) stance time; expressed as percentages. Participants who completed a total of 6 passes across the walkway and with a sufficient number of strides to determine at least 15 data values for each gait variable were included in the analysis (N = 164; 120 female).

Data from the first 15 strides for each participant were used to calculate each gait variable. The stride time, length and width, step time, width and stance time data time series were determined by the GAITRite software. The speed of individual strides was calculated as the stride distance divided by the stride time. The 15 stride speeds were then averaged to determine the mean gait speed for each participant. The PCI (as described below) and the CV (SD/Mean) of stride time, length and width, the step width and stance time were calculated using custom written MATLAB software^b. Inferential statistical analysis was conducted using IBM SPSS software (version 22)^c using a Type I error rate of 0.05.

PCI was determined from the first 15 gait phase (ϕ) values for each participant. The gait phase (ϕ) for individual strides is determined by dividing step times by stride times and multiplying by 360° . Gait coordination that is perfectly symmetrical would have step times that are one half of stride times and gait phase values of $\phi = 180^\circ$. PCI was calculated as previously recommended (Plotnik et al., 2007) using the absolute deviation of the gait phase from 180° (ϕ_{ABS}) and the coefficient of variation of gait phase ($CV \phi = SD \phi / Mean \phi$). Increments in PCI values indicate increments in the variability of ϕ and/or the deviation of ϕ from symmetrical coordination (180°). As mean gait phase values fell within a narrow range we used standard linear, rather than circular, statistics for analysis.

2.2.2. Short Physical Performance Battery—Participants performed the SPPB, which consists of usual walking speed, standing balance, and a five-repetition chair stand test (Guralnik et al., 1994). Scores from each component are scored between 0–4 which when summed creates a total score ranging from 0 to 12, with higher scores indicating better performance. SPPB score was calculated in the standard manner, including scores for gait speed, balance and chair rise time (Guralnik et al., 1994).

2.2.3. Gait speed—The gait speed score included in the total SPPB score was determined by having participants walk at their usual pace across a 4-meter course. The faster of two trials was used to determine the gait score according to the following criterion: a score of 0 was assigned to participants who could not perform the task; 1 for task completion in greater than 5.7 seconds; 2 for completion between 4.1 and 5.7 seconds; 3 for completion between 3.2 and 4.09 seconds; 4 for completion in less than 3.2 seconds.

2.2.4. Repeated chair stands—While seated in a chair participants were instructed to stand and sit 5 times as quickly as they were able with their arms crossed. The chair stand score was determined according to the following criterion: a score of 0 was assigned to participants who could not perform the task; 1 for task completion in greater than 16.7 seconds; 2 for completion between 13.7 and 16.69 seconds; 3 for completion between 11.2 and 13.59 seconds; or 4 for completion in less than 11.2 seconds. In linear regression modelling of individual SPPB component tasks chair rise score, rather than time, was used

for analysis so data for participants who were unable to perform the chair rise test could be included.

2.2.5. Standing balance—Balance was assessed with three 10-second stands: standing with the feet touching side-by-side, semi-tandem stand with the side of one heel touching the side of the big toe of the other foot, and full tandem (heel to toe) stand. If a participant was unable to perform one of these stands for 10 seconds they were not requested to perform the subsequent more challenging standing tests. Balance score was determined by the following criterion: 0 = side-by-side balance time of 0 – 9 seconds or unable to perform; 1 = side-by-side stand time of 10 seconds and < 10 seconds for semi-tandem stand; 2 = semi-tandem stand time of 10 seconds and full tandem stand time 0 – 2 seconds; 3 = semi-tandem stand time of 10 seconds and tandem stand for 3 – 9 seconds; 4 = full tandem stand for 10 seconds.

2.3. Demographic and health characteristics

Demographic characteristics included age, gender, and race. Body mass index was calculated as measured weight in kilograms divided by height in squared meters.

2.4. Comorbidity

Participants were asked if a physician had told them that they had heart disease (myocardial infarction, atrial fibrillation, pacemaker, angina, or congestive heart failure), high blood pressure, high cholesterol, diabetes, an ulcer, kidney disease, liver disease, anemia, cancer, depression, osteoarthritis, spinal stenosis, rheumatoid arthritis, gout, asthma, stroke, Parkinson's disease, Multiple Sclerosis, an eye disease, or Alzheimer's disease.

2.5. Statistical analyses

First, descriptive statistics were calculated for participant characteristics using means and standard deviations for normally distributed data. Second the covariance of the corresponding gait variables was evaluated using Pearson correlation analysis. Third, multivariable linear regression models were constructed with each mobility performance outcome measure as a separate dependent variable. Initially, the associations of each individual gait variable with the outcome were examined within separate age and gender adjusted models for each outcome. Fourth, to evaluate, the relative contribution of PCI for each outcome we estimated multivariable models constructed using manual backward elimination ($P < 0.05$) with all 5 gait impairment measures other than PCI and compared this to a model constructed using the same manual backward elimination process with PCI included.

All models were adjusted for age and gender. Evaluation of the assumption of normality of residuals was confirmed by inspection. Changes in the total variance (R^2) attending addition or subtraction of independent variables from models were obtained in order to evaluate the relative contribution of PCI over and above existing gait parameters. Lastly, adjustment for the burden of illness might be conceived as an over adjustment since impairments may be the manifestation of chronic illnesses. Thus, as part of a sensitivity analysis, all final models were evaluated with the addition of number of chronic conditions as an adjustment variable

in order to observe if this adjustment meaningfully altered the primary relationships focused upon within the aims of the study.

3. Results

Descriptive statistics for each variable examined are presented in Table 1. Participants had a mean (standard deviation) age of 86 (4.70) years and 73% (n=120) were female. Participants had a median of 5 chronic conditions (range: 0–13). All gait variables had Pearson correlation coefficients < 0.40 , with the exceptions of the correlations between: a) the CV of stride length and step width ($r = 0.76$); and b) PCI and the CV of stride time ($r = 0.41$). For this reason, either the CV of stride length or the CV of step width, but not both, were included in the construction of regression models. Both PCI and the CV of stride time were used in regression models as the variance inflation factor for each was < 1.2 .

In linear regression models, after adjusting for age and gender, each gait variable except the CV of stance time was significantly associated with SPPB score, gait speed, and chair rise score (Figure 1). Only PCI and the CV of step width were significantly associated with balance score. Compared to the other gait variables, PCI had the strongest association with SPPB score ($R^2 = 0.21$), gait speed ($R^2 = 0.17$), chair rise score ($R^2 = 0.10$), and balance score ($R^2 = 0.09$).

Table 2 presents the multivariable regression models predicting SPPB score. The CV of stride time, width and step width were statistically significant predictors (model $P < 0.001$, $R^2 = 0.18$). In the model constructed including PCI with the other five gait variables the statistically significant predictors of SPPB were PCI, the CV of stride width and the CV of stride time (model $P < 0.001$, $R^2 = 0.27$). This model showed that including PCI in the regression increased the variance accounted for by 9%. The model including PCI and the other five gait variables accounted for only 6% more of the variance in SPPB score than PCI alone (27% vs. 21%). In the model including PCI, only the CV of stride time and width and PCI were significant in the model. In the multivariable model constructed adjusting for number of chronic conditions without PCI, statistically significant predictors of SPPB were the CV of step width, stride width and stride time ($P < 0.001$, model $R^2 = 0.16$). In the model constructed including PCI the statistically significant predictors were PCI, CV stride width and stride time ($P < 0.001$, $R^2 = 0.23$). These models showed that adjusting for the number of chronic conditions led to only a slight decrease in variance accounted both with and without PCI.

4. Discussion

The first major finding of our study was that PCI was significantly associated with SPPB score and each of its component tasks, as we hypothesized. The second major finding was that PCI accounted for more of the variance in each mobility measure than any of the other gait variables. PCI alone accounted for more of the variance in SPPB score than the multivariable model constructed from all the other gait variables. PCI was also shown to be a significant predictor of SPPB score even when adjusting for the number of chronic

conditions. These results are the first to show that gait coordination impairment is an important factor associated with mobility performance.

It is well established in the motor control literature that the relative timing of movements is more tightly controlled than absolute movement time or amplitude. In Generalized Motor Program theory (Schmidt, 1975) relative timing constitutes an 'invariant' movement characteristic that defines motor programs. From the Dynamic Systems Theory perspective (Kelso, 1995), coordination is the movement characteristic that is organized into stable patterns (termed an 'order parameter'). Nonetheless, the coordination of the left-right stepping pattern during the gait cycle in older adults has not been well studied. Failure to maintain low levels of coordination variability and/or symmetry may reflect a breakdown in the ability to properly organize motor output such as gait. Consistent with this, in the present study the ability to regulate gait coordination (as measured by PCI) was found to be the gait variable most strongly associated with each outcome variable.

The identification of coordination impairments as contributors to mobility limitations may have implications for rehabilitation. Prior research has shown that coordination can be improved with training (Jirsa, Fink, Foo, & Kelso, 2000). Further research is needed to determine if interventions that improve coordination will decrease mobility limitations, leading to reduced fall risk and disability in daily activities. Improved coordination might also allow older adults to compensate for other body system impairments in strength, speed, and range of motion that are risk factors for mobility limitations (Bean, Kiely, LaRose, & Leveille, 2008; Bean et al., 2013).

A limitation of the study was that the calculation of gait variables was limited to 15 stride values per participant. Increasing the number of strides assessed can increase the reliability of gait measures (Brach, Perera, Studenski, & Newman, 2008). The study design intentionally limited the walking distance (and indirectly the number of strides to be performed) due to the mobility limitations in the target population. Also, the present study was a secondary data analysis and could not alter the gait measurement procedures. However, even a 4 meter walk has been shown to have fair to good test-retest reliability (Brach, Perera, et al., 2008).

5. Conclusions

In summary, the ability to maintain proper coordination of the left-right stepping pattern during gait appears to be an important part of mobility for older adults, above and beyond traditional gait measures. Future longitudinal research is needed to examine gait coordination impairment as a risk factor for the development of mobility limitations.

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Figure 1.

Representation of the total model R^2 values from 24 separate, age and gender adjusted, linear regression models of each separate gait variable with corresponding mobility outcomes (Short Physical Performance Battery score, gait speed, chair rise score, balance score). All P -values < 0.05 denoted by *. PCI = Phase Coordination Index; CV = coefficient of variation. SPPB = Short Physical Performance Battery.

Table 1 Descriptive statistics^{*} for MOBILIZE Boston participants (N=164).

Variable	Mean $\pm$ SD	Min	Max
Age (years)	85.62 $\pm$ 4.70	77	101
% Female	73		
BMI (kg/m ²)	26.70 $\pm$ 4.61	18	43
# chronic conditions	5.27 $\pm$ 2.47	0	13
SPPB score	7.91 $\pm$ 2.47	1	12
Gait speed (m/s)	0.78 $\pm$ 0.19	0.36	1.20
Chair rise score	1.97 $\pm$ 1.38	0	4
Balance score	2.74 $\pm$ 1.16	0	4
PCI	6.97 $\pm$ 2.45	2.47	15.09
Stride length CV (%)	5.08 $\pm$ 2.59	1.74	17.48
Stride time CV (%)	3.60 $\pm$ 1.44	1.01	10.22
Stance time CV (%)	4.26 $\pm$ 1.53	1.66	9.46
Step width CV (%)	6.50 $\pm$ 2.89	2.27	20.35
Stride width CV (%)	15.81 $\pm$ 8.59	3.04	51.40

^{*} Mean $\pm$ SD unless otherwise indicated.

Abbreviations: BMI, body mass index; CV, coefficient of variation; Max, maximum; Min, minimum; PCI, Phase Coordination Index; SD, standard deviation; SPPB, Short Physical Performance Battery.

Table 2

Multivariable models evaluating the association between gait characteristics and scores on the SPPB and its component tasks, adjusted for age and gender.

Model 1 ($R^2 = 0.18$) $P < 0.001$				
Outcome: SPPB score	Variables	Estimate	SE	P
	Stride time CV	-0.460	0.122	< 0.001
	Step width CV	-0.191	0.064	0.003
	Stride width CV	0.048	0.021	0.025
Model 2 ($R^2 = 0.27$) $P < 0.001$				
		Estimate	SE	P
	Stride time CV	-0.253	0.124	0.043
	Step width CV	-0.105	0.063	0.100
	Stride width CV	0.042	0.020	0.036
	PCI	-0.346	0.078	< 0.001
Model 1 ($R^2 = 0.33$) $P < 0.001$				
Outcome: Gait speed	Variables	Estimate	SE	P
	Stride time CV	-3.981	0.867	< 0.001
	Step width CV	-1.813	0.454	< 0.001
	Stride width CV	0.718	0.150	< 0.001
Model 2 ($R^2 = 0.37$) $P < 0.001$				
		Estimate	SE	P
	Stride time CV	-2.998	0.914	0.001
	Step width CV	-1.404	0.467	0.003
	Stride width CV	0.693	0.147	< 0.001
	PCI	-1.643	0.572	0.005
Model 1 ($R^2 = 0.04$) $P = 0.007$				
Outcome: Chair rise score	Variables	Estimate	SE	P
	Stride time CV	-0.199	0.073	0.007
Model 2 ($R^2 = 0.11$) $P < 0.001$				
	Variables	Estimate	SE	P
	Stride time CV	-0.091	0.077	0.242
	PCI	-0.159	0.046	0.001
Model 1 ($R^2 = 0.03$) $P = 0.017$				
Outcome: Balance score	Variables	Estimate	SE	P
	Step width CV	-0.078	0.032	0.017
Model 2 ($R^2 = 0.09$) $P < 0.001$				
	Variables	Estimate	SE	P

Outcome Balance score	Variables	Model 1 ($R^2 = 0.03$) $P = 0.017$		
		Estimate	SE	P
	Step width CV	-0.040	0.033	0.232
	PCI	-0.126	0.038	0.001

N = 164 in all models. Abbreviations: CV, coefficient of variation; PCI, Phase Coordination Index; SE, standard error; SPPB, Short Physical Performance Battery.

* Each Model 1 is for the regression of gait variables on mobility performance outcomes without PCI. Each Model 2 is for the regression of gait variables including PCI in the model.