Published in final edited form as:

Top Stroke Rehabil. 2019 May ; 26(4): 255–260. doi:10.1080/10749357.2019.1591038.

Relationships between Gait Variability and Ambulatory Activity Post Stroke

Lisa A. Zukowski^{1,2}, Jody A. Feld³, Carol A. Giuliani^{1,3}, and Prudence Plummer^{1,3}

¹Division of Physical Therapy, Department of Allied Health Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC

²Department of Physical Therapy, High Point University, High Point, NC

³Human Movement Science Curriculum, University of North Carolina at Chapel Hill, Chapel Hill, NC

Abstract

Background: Fall risk and balance confidence are related to gait variability and ambulatory activity post-stroke, yet whether a relationship exists between gait variability and ambulatory activity is unknown. Knowing if gait variability measured under naturalistic conditions is related to ambulatory activity could explain more about the relationship between falls and walking activity post-stroke.

Objectives: To examine relationships between spontaneous, daily ambulatory activity and gait variability during single- and dual-task walking, in low- and high-distraction settings in adults post-stroke.

Methods: Sixteen community-dwelling adults post-stroke participated in a cross-sectional study. Spatiotemporal gait parameters were recorded during single- and cognitive-motor dual-task walking in low- and high-distraction settings. Coefficient of variation was calculated for stride length and stride duration. Average walking bout duration, maximum walking bout duration, and total number of steps per day were captured using an activity monitor. Correlations between ambulatory activity measures and gait variability were examined.

Results: In the high-distraction setting, single-task stride duration variability was negatively related to all three ambulatory activity measures, but the strongest relationship was a negative correlation between dual-task stride duration variability and average walking duration. In the low-distraction setting, single-task stride duration variability was negatively related to maximum walking duration. None of the other variability measures were related to ambulatory activity.

Conclusions: The finding that stride duration variability in a high-distraction environment, with or without an additional cognitive task, is related to ambulatory activity in community-dwelling stroke survivors suggests that assessments incorporating attentional demands of real-world walking may be useful additions to clinical practice.

Corresponding Author: Lisa A. Zukowski, PhD, High Point University, Department of Physical Therapy, One University Parkway, Drawer 67, High Point, NC 27262, lzukowsk@highpoint.edu, Phone: (336)841-9581.

Disclosure statement

The authors report no conflicts of interest.

Keywords

Stroke; Gait; Ambulatory activity; Dual-task; Cognition; Variability

Introduction

Individuals post-stroke report low levels of ambulatory activity in the home and community settings.^{1,2} Low ambulatory activity has been linked to depression and a subsequent reduction in quality of life.¹⁻³ Individuals with low ambulatory activity six weeks post-stroke have also been unlikely to resume their pre-stroke community activities a year later, increasing risk of secondary cardiovascular issues and having another stroke.^{1,4,5} Therefore, increasing ambulatory activity levels post-stroke throughout recovery is important to maximize quality of life and minimize public health burden.

A number of factors have been associated with post-stroke ambulatory activity, including walking ability and balance confidence,^{1,6-9} but so far, no single factor can adequately predict amount of ambulatory activity.^{9,10} Gait speed is a common measure of walking ability that is related to post-stroke ambulatory activity.¹ However, many community-dwelling stroke survivors remain highly inactive despite recovery of functional walking speed.¹¹ Walking ability together with balance self-efficacy may better predict post-stroke ambulatory activity levels than walking ability alone.⁷⁻⁹ The mediating effect of self-efficacy on the relationship between walking ability and ambulatory activity post-stroke may be explained by an increased risk of falling.^{2,12,13} Fall-related disability, or resultant decrease in balance confidence after falls that do not result in injury, can further reduce already low levels of ambulatory activity post-stroke.^{2,3} Reinforcing this idea, individuals post-stroke at higher risk of falling have been shown to avoid walking activities at a higher rate than those at lower risk of falling.⁶ However, including measures of both walking ability and balance confidence in a predictive model still does not fully explain variance in ambulatory activity.⁹ Gait variability, a measure of walking ability with a known association with fall risk and balance confidence,¹⁴⁻¹⁶ may be a strong single predictor of ambulatory activity.

Gait variability is often quantified in terms of stride length and stride duration variability, both of which have been related to fall risk¹⁴ and balance confidence^{15,16} post-stroke. Specifically, increased step length variability predicted increased fall rates (multivariate Poisson regression rate ratio 1.4; 95% CI 1.2 to 1.7; $p=0.001$)¹⁴ in community-dwelling individuals post-stroke after discharge from inpatient rehabilitation. More recently, Schinkel-Ivy et al.^{15,16} observed that individuals post-stroke with more variable temporal step characteristics had lower confidence in their balance, leading them to suggest that greater step duration variability may be associated with more reactive, and thus, less efficient balance control. The relationship between gait variability to fall risk and balance confidence suggests that gait variability may be a strong predictor of ambulatory activity, but the relationship between gait variability and ambulatory activity post-stroke is currently unknown.

Finally, traditional clinical measures of walking ability may not be strong predictors of everyday ambulatory activity because they fail to adequately replicate real-world walking demands. Gait parameters may need to be assessed under more naturalistic conditions to be able to predict ambulatory activity in the community. The ecological validity of walking assessments can be increased by adding a cognitive task (dual-task walking) or assessing walking outside the clinic/lab environment. The purpose of this study was to examine the relationship between everyday ambulatory activity and gait variability in more ecologically-valid walking conditions. We hypothesized that gait variability measured in a high-distraction environment (especially in dual-task conditions) would be more robustly related to amount of everyday ambulation than gait variability measured in a low-distraction environment and single-task conditions.

Methods

The cross-sectional study sample comprised 16 community-dwelling stroke survivors (49.9 ± 14.0 years of age, 15.6 ± 10.5 months post-stroke) who were a subset of participants in an ongoing larger study for which the inclusion criteria were: stroke onset within three years, able to walk at least 50 meters with or without an assistive device, and able to follow a 3-step command. Exclusion criteria were pre-existing neurological impairments, uncorrected visual or hearing impairments, orthopedic conditions affecting gait, and more than one fall in the previous year. The study was approved by the Institutional Review Board and all participants provided written informed consent. The manuscript conforms to the STROBE Guidelines.

Participants completed cognitive and walking tasks in single- and dual-task conditions and in two different environments: quiet hallway (low distraction) and hospital lobby (high distraction). The hospital lobby was used for the high-distraction environment because it is noisy, heavily furnished, and has frequent, unpredictable pedestrian traffic.

The cognitive task used for the dual-task paradigm was the auditory Stroop task,¹⁷ administered using DirectRT (Empirisoft, New York, NY). In this task, participants heard the word “high” or “low” spoken in a high-pitched or a low-pitched voice and were instructed to indicate the pitch of the word by saying “high” or “low” as quickly and accurately as possible. Thus, participants had to inhibit their habitual response of repeating the word they heard and identify the pitch of the voice. Inhibition of attention is relevant for everyday community mobility,¹⁸ especially in busy environments, making this a highly suitable task for the current research objectives. A wireless headset (A-00006, Logitech, Newark, CA) was used with DirectRT to present the auditory stimuli and record the participants’ responses and reaction times. Participants completed at least two practice blocks of 30 trials each while seated to ensure task familiarization before testing. Single-task performance of the Stroop task in each environment was recorded while sitting.

The gait task in each environment required participants to walk continuously for 60 m (turning after 30 m) at their self-selected speed. Participants with slower gait speed walked only 30 m to minimize fatigue. There was an average of 37 strides per walking trial. Gait performance was recorded with five wireless, tri-axial accelerometers (100 Hz, LEGSys™,

Biosensics, Cambridge, MA) that were affixed to each shin, each thigh, and the low back. The LEGSys™ algorithm utilized to calculate spatiotemporal gait parameters has been validated in clinical populations.^{19,20}

Testing order was the same in each environment and was as follows: (1) cognitive single-task, (2) gait single-task, (3) dual-task, and (4) gait single-task. The first gait single-task served as an orientation/familiarization to the environment and pathway. Only the second gait single-task was used for analysis. Environment order was counterbalanced across participants. The testing was conducted in a single session. Between testing in the two environments, participants completed the Activities-specific Balance Confidence (ABC) Scale, a validated measure of balance confidence.²¹

Spontaneous, daily ambulatory activity was recorded for each participant over 2 consecutive days using an unobtrusive, single wireless, tri-axial accelerometer (40 Hz, PAMSys™, Biosensics, Cambridge, MA) worn on the midline chest in a pouch pinned to the inside of the clothing. The PAMSys™ software algorithms used to compute ambulatory activity have been validated in clinical populations.^{22–24}

For each gait trial for each participant, the mean value and standard deviation for stride length and stride duration were computed using the LEGSys™ algorithm. These values were then used to calculate the coefficient of variation (CV, %) of stride length and stride duration. For each cognitive trial, mean reaction time and accuracy of responses were calculated. The ambulatory activity variables, extracted using PAMSys™ software were: average walking bout duration (average duration (seconds) across all discrete episodes of walking over 2-day period), maximum walking bout duration (longest duration (seconds) of discrete episodes of walking over 2-day period), and average number of steps per day.

For descriptive purposes, the effect of task and environment on gait and cognitive performance were examined using Task (single-task, dual-task) x Environment (low-distraction, high-distraction) repeated measures ANOVAs. The relationships between each of the three ambulatory activity measures and CV of stride length and stride duration in each gait condition were examined using Spearman's rho (r_s) correlation coefficients. Significance was set a priori at $\alpha = 0.05$, and all statistical analyses were performed using SPSS (Version 24, IBM Corp., Armonk, NY).

Results

Participant characteristics are summarized in Table 1, and the mean values for all performance indicators are presented in Table 2. Maximum walking duration and steps per day were not normally distributed. The median duration of the longest walking bout was 267.4 s (IQR: 133.5–547.8 s), and the median number of steps per day was 1923.8 (IQR: 666.5 to 3019.8). The average duration of all walking bouts was 59.1 s (SD: 22.5 s, range: 25.9–94.7 s). The Task x Environment ANOVA showed that there was a significant main effect of Task on gait speed ($F(1,15)=12.52$, $p<0.01$, $\eta_p^2=0.46$) and accuracy of responses ($F(1,15)=8.70$, $p=0.01$, $\eta_p^2=0.37$), indicating that participants walked faster and responded more accurately during single-task conditions than during dual-task trials. This effect was

not different between environments. Gait variability and reaction time did not significantly differ between environments or tasks (Table 2).

In the high-distraction environment, there were significant negative correlations between single-task stride duration variability and all three ambulatory activity measures: maximum walking bout duration ($r_s = -0.61$, $p = 0.01$), average walking bout duration ($r_s = -0.51$, $p = 0.04$), and number of steps per day ($r_s = -0.51$, $p = 0.05$) (Table 3, Figure 1b), where individuals with higher stride duration variability exhibited shorter durations of the longest walking bout, shorter average walking bouts, and fewer steps per day. Also in the high-distraction environment, dual-task stride duration variability was negatively related to average walking bout duration ($r_s = -0.67$, $p < 0.01$) (Table 3). In contrast, in the low-distraction environment, single-task stride duration variability was significantly related only to maximum walking bout duration ($r_s = -0.50$, $p = 0.05$), and the relationships between dual-task stride duration variability and ambulatory activity measures were weak ($r_s = -0.29$) and not significant (Table 3, Figure 1a and 1c). Stride length variability had no significant correlations with ambulatory activity (Table 3).

A post-hoc, secondary exploration examined the relationship between balance confidence (ABC score) and each of the three ambulatory activity measures using Spearman's rho (r_s) correlation coefficients. Balance confidence was positively related to maximum walking bout duration ($r_s = 0.57$, $p = 0.02$) and number of steps per day ($r_s = 0.65$, $p < 0.01$) but was not significantly related to average walking duration ($r_s = 0.22$, $p > 0.05$).

Discussion

The purpose of this study was to identify relationships between post-stroke ambulatory activity and gait variability, and to explore whether relationships were differentially impacted by level of distraction and cognitive load. Consistent with our hypothesis, we found that gait variability in the low-distraction environment did not relate to any measure of ambulatory activity, with the exception of a fairly weak correlation ($r_s = -0.50$) between single-task stride duration variability and maximum walking bout duration. Conversely, as expected, gait variability in the high distraction environment was significantly associated with all measures of ambulatory activity. Single-task gait variability was significantly associated with all three measures of ambulatory activity; however, the strongest association was between dual-task stride duration variability and average walking bout duration, in partial support of our overall hypothesis.

Our findings may suggest that temporal stride variability in the high-distraction environment could be a good proxy for estimating how active an individual post-stroke will be in everyday life. The higher stride duration variability observed in less active individuals could be due to poorer self-efficacy for balance.^{9,15,16} Individuals with poor balance confidence tend to focus more on their travel path while walking and less on potential obstacles in their path,²⁵ limiting their ability to anticipate necessary path adjustments to avoid pedestrians or obstacles. Therefore, gait variability may have been increased by the need to make more sudden, larger amplitude adjustments in stepping. Alternatively, people with poor balance confidence may have simply been more hesitant and inconsistent in their gait.

Stride duration CV in the high-distraction environment may encapsulate the moderating relationship between balance confidence, walking ability and ambulatory activity found by French et al.⁹ Indeed, the effect sizes for the relationships between single-task stride duration CV in the high-distraction environment and maximum walking bout duration ($r_s^2=0.37$) and dual-task stride duration CV in the high-distraction environment and average walking bout duration ($r_s^2=0.45$) are equivalent to or better than the previously reported mediating effect of self-efficacy on the relationship between gait speed and ambulatory activity ($R^2=0.38$).⁹ The effect sizes for the relationships between stride duration CV and ambulatory activity are generally stronger than for those between balance self-efficacy and maximum walking bout duration ($r_s^2=0.32$) and number of steps per day ($r_s^2=0.42$) in this study, demonstrating that stride duration CV may represent more than just balance confidence and therefore could be a strong predictor of ambulatory activity post-stroke. However, the capacity of stride duration CV to predict ambulatory post-stroke should be explored with a larger sample size before drawing conclusions.

The finding that gait variability in a high-distraction environment is associated with ambulatory activity could be explained by the high attentional demands of walking post-stroke in a real-world environment,²⁶ even without an additional cognitive load. Walking in a high-distraction environment may mirror the confidence needed and difficulty associated with everyday walking. The relationship between single-task stride duration CV in the high-distraction environment to all three measures of ambulatory activity is of interest, despite some of the significant relationships being weaker ($r_s>-0.52$), because it may signify that single-task stride duration CV could be a well-rounded predictor of ambulatory activity. Single-task stride duration CV was related to total number of steps taken each day, which is the ambulatory activity measure typically studied in post-stroke literature,^{1,7,9,27} and to the longest and average bout durations each day, which may both relate to an individual's endurance or even reflect independence post-stroke.²⁸

Relative to single-task stride duration CV, a stronger association between dual-task stride duration CV in the high-distraction environment and average walking bout duration was observed. The moderately strong relationship between these two variables could reflect that balance confidence influences endurance or independence post-stroke. Previous research shows that in addition to counting daily step activity post-stroke, quantifying walking bout durations is important because shorter walking bouts of 30–90 seconds are primarily associated with performing daily essential activities, such as walking to the bathroom, and may not be sufficiently intense to result in motor or cardiovascular improvements over time.²⁸ Dual-task stride duration CV in a high-distraction environment could be an important predictor of walking intensity post-stroke and therefore of ambulatory activity in the home and community, even if it were a less consistent predictor of certain measures of ambulatory activity than single-task stride duration CV. Again though, the predictive capacity of this variable will need to be determined with a larger sample size.

The less consistent relationship between dual-task stride duration CV and ambulatory activity may be the result of a greater disparity in the ability to perform a cognitive task while walking, relative to walking without an additional cognitive load post-stroke. This disparity in dual-tasking ability is demonstrated in Figure 1, with greater between-subject

variability during dual- relative to single-task walking in each environment but especially in the high-distraction environment. Although some data points appear to be outliers driving the relationships in Figure 1, all data points represent real performances and therefore should remain in the analysis.

In contrast to stride duration CV, no relationship was observed between stride length CV and ambulatory activity. This was surprising because stride length CV has been shown to be related to fall risk in individuals post-stroke, and individuals post-stroke at higher risk of falling typically avoid walking activities more than those at a lower risk of falling.^{6,14} We may not have observed a significant relationship between stride length CV and ambulatory activity because we excluded individuals who were at higher risk of falling, defined as more than one fall in the last year. However, the average balance confidence score ($68.3\% \pm 19.3$) would suggest that our participant sample was at higher risk of falling, scoring closer to the average range for individuals post-stroke who experience multiple falls ($61.4\% \pm 11.7$) than for those who experience one or no falls ($84.9\% \pm 12.3$).²⁹ Thus alternatively, we may not have observed a significant relationship between these two variables because although individuals post-stroke at a higher risk of falling may avoid certain walking activities that seem especially likely to result in falls, they may select to participate in other walking activities that seem safer.

The absence of significant Task and Environment effects for stride duration variability may be due to the fact that participants' gait variability did not change in a uniform manner across testing conditions, resulting in large between-subject variability for both environments and task conditions (Table 2). However, the mean value and between-subject variability for stride duration CV during single-task walking in the low-distraction environment ($4.61\% \pm 1.81$) in this study are similar to reported values for a study sample comprised of community-dwelling individuals post-stroke and age-matched healthy older adults during single-task walking on a self-paced treadmill ($4.72\% \pm 2.12$).³⁰ Thus, even with a larger number of participants, the small observed effects would probably still not reach statistical significance.

A study limitation is the relatively small sample that precluded a regression analysis between gait variability and ambulatory activity. Based on the correlation coefficients observed in this study, we determined that a sample size of 45–50 would be necessary to sufficiently power a regression analysis to examine the ability of stride duration variability in a high-distraction environment to predict measures of everyday ambulatory activity after stroke. Nonetheless, this study is important because it provided the first exploration of the relationship between gait variability and ambulatory activity, and how this relationship is affected by environmental distractions and cognitive load. Now that the relationship between stride duration CV in a high-distraction environment and ambulatory activity has been identified, future research should utilize a larger sample to explore the capacity of stride duration CV to predict ambulatory activity. Although stride duration CV is a single variable that may be just as good as or better than gait speed and balance self-efficacy in predicting ambulatory activity, gait variability is not as easy to measure in a clinic. Future research should also explore methods of reproducing more real-world environments in the clinic and a gait

variability surrogate that can be measured with a stopwatch and other tools readily available to clinicians.

This study provides evidence that stride duration variability is associated with ambulatory activity for community-dwelling individuals post-stroke when measured during walking in a high-distraction environment. The relationship between gait variability and ambulatory activity is the most consistent when stride duration variability is measured during walking without an additional cognitive load in a high-distraction environment, but the relationship is the strongest between dual-task gait variability in the high-distraction environment and average walking bout duration. Stride duration variability measured in a traditional low-distraction setting is not associated with ambulatory activity. Assessments that incorporate attentional demands of real-world walking may be useful additions to clinical practice.

Funding

This study was funded in part by the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) (1R21HD076157-01A1).

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Figure 1.

Relationships between the total number of steps taken each day and stride duration CV during: (a) single-task walking in the low-distraction environment, (b) single-task walking in the high-distraction environment, (c) dual-task walking in the low-distraction environment, and (d) dual-task walking in the high-distraction environment. The gray symbols represent individual values measured in the low-distraction environment, the black symbols represent individual values measured in the high-distraction environment, the triangles represent individual values measured during single-task walking, and the circles represent individual values measured during dual-task walking.

Table 1.

Demographic characteristics, cognitive assessment, and balance confidence of participants (n=16). Values are Mean $\pm$ SD unless otherwise indicated.

Age (years)	49.9 $\pm$ 14.0
Gender	8 males, 8 females
Time Post-Stroke (months)	15.6 $\pm$ 10.5
Type of Stroke	6 hemorrhagic, 9 ischemic, 1 uncertain
Side of Hemiplegia	8 right, 8 left
Montreal Cognitive Assessment (max. 30)	24.9 $\pm$ 2.7
Activities-Specific Balance Confidence Scale (max. 100)	68.3 $\pm$ 19.3

Table 2.

Gait and cognitive performances in each condition. Values are Mean±SD.

	Low Distraction		High Distraction		Task x Environment	
	Single-Task	Dual-Task	Single-Task	Dual-Task	p	η_p^2
Gait Performance						
Gait Speed (m/s)	0.83±0.36	0.76±0.35	0.80±0.33	0.76±0.31	0.152	0.132
Stride Duration CV (%)	4.61±1.81	4.76±2.25	5.38±2.37	5.40±2.81	0.893	0.001
Stride Length CV (%)	6.41±4.21	6.98±2.63	6.76±2.77	6.40±2.04	0.356	0.057
Cognitive Performance						
Accuracy (%)	94.0±8.9	88.5±12.8	93.2±10.2	85.0±18.5	0.528	0.027
Reaction Time (ms)	1180±221	1268±251	1260±269	1238±254	0.105	0.166

Table 3.

Spearman's correlation coefficients between measures of ambulatory activity and stride variability (n=16).

		Maximum Walking Bout Duration (s)	Average Walking Bout Duration (s)	Total Number of Steps Taken Each Day
Stride Duration CV (%)				
Low Distraction				
Single-Task	Correlation	-0.503[*]	-0.397	-0.462
Dual-Task	Correlation	-0.279	-0.294	-0.076
High Distraction				
Single-Task	Correlation	-0.612[*]	-0.512[*]	-0.506[*]
Dual-Task	Correlation	-0.459	-0.671^{**}	-0.265
Stride Length CV (%)				
Low Distraction				
Single-Task	Correlation	-0.312	-0.226	-0.041
Dual-Task	Correlation	-0.338	-0.282	-0.079
High Distraction				
Single-Task	Correlation	-0.450	-0.424	-0.268
Dual-Task	Correlation	0.109	0.012	0.385

^{*} Denotes a significance at the $\alpha=0.05$ level

^{**} Denotes a significance at the $\alpha=0.01$ level