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Gait efficiency on an uneven surface is associated with falls and injury in older subjects with a spectrum of lower limb neuromuscular function: a prospective study

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Abstract

Objective—To determine which gait measures on smooth and uneven surfaces predict falls and fall-related injuries in older subjects with diabetic peripheral neuropathy (DPN).

Design—Twenty-seven subjects (12 women) with a spectrum of peripheral nerve function ranging from normal to moderately severe DPN walked on smooth and uneven surfaces, with gait parameters determined by optoelectronic kinematic techniques. Falls and injuries were then determined prospectively over the following year.

Results—Seventeen subjects (62.9%) fell and 12 (44.4%) sustained a fall-related injury. As compared to non-fallers, the subject group reporting any fall, as well as the subject group reporting fall-related injury, demonstrated decreased speed, greater step width (SW), shorter step length (SL) and greater step-width-to-step-length ratio (SW:SL) on both surfaces. Uneven surface SW:SL was the strongest predictor of falls (pseudo- $R^2 = 0.65$; $p = .012$) and remained so with inclusion of other relevant variables into the model. Post-hoc analysis comparing injured with non-injured fallers showed no difference in any gait parameter.

Conclusion—SW:SL on an uneven surface is the strongest predictor of falls and injuries in older subjects with a spectrum of peripheral neurologic function. Given the relationship between SW:SL and efficiency, older neuropathic patients at increased fall risk appear to sacrifice efficiency for stability on uneven surfaces.

Keywords

Accidental Falls; Injury; Gait; Diabetic Neuropathy

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INTRODUCTION

Walking for exercise has been shown to reduce the occurrence of coronary events¹ and cognitive decline² in older women, decrease mortality in men,³ and reduce obesity and new cases of Type 2 diabetes mellitus.⁴ In those already with diabetes, walking improves metabolic regulation and decreases mortality.^{5,6} Therefore, routine walking for exercise prolongs life and reduces the frequency of age-related complications.

However Type 2 diabetes mellitus, which affects about 26 million people in the United States,⁷ is commonly associated with diabetic peripheral neuropathy (DPN). DPN is a potent source of postural instability and falls. More specifically, older patients with DPN demonstrate shorter unipedal stance times⁸ and irregular gait patterns as compared to their counterparts without DPN. These gait abnormalities include slower and less efficient walking and greater fluctuations in step time, length, and width as compared to healthy older subjects.^{9–11} Additionally, a large proportion of falls in older people with DPN occur due to surface irregularities.¹² Falls resulting in injury commonly lead to declining health and function, and even non-injurious falls lead to a loss of confidence and reductions in physical activity.¹³ As a result it is difficult, if not hazardous, for older people with DPN to acquire the health benefits associated with walking for exercise due their increased fall risk.

Few studies have used laboratory-based gait measures to prospectively predict falls and/or fall-related injury. Among these, Hausdorff et al. found that increased step time variability during a six minute walk predicted falls during one year of follow-up,¹⁴ and Maki et al. concluded that gait speed variability was the best predictor of falls in a cohort of older subjects.¹⁵ Importantly, none of these studies used fall-related injury as an outcome. In prior work involving older subjects with PN, we found that step time variability on an uneven surface was increased in those who sustained a fall-related injury; however, only six subjects were injured and there were no gait parameter differences between subjects who fell and those who did not.¹²

In the present study, we evaluated the ability of gait measures on smooth and uneven surfaces to predict falls and fall-related injuries in a cohort of older subjects with a spectrum of peripheral neurologic function. After baseline clinical and gait evaluations, we prospectively monitored the number of falls and fall-related injuries that occurred in the following year. We then compared gait measures in those who fell and/or sustained a fall-related injury with those who did not. We hypothesized that the baseline gait characteristics of subjects who fell and/or were injured would be slower, more variable, and less efficient (as demonstrated by an increased step-width-to-step-length ratio; SW:SL)¹⁶ than subjects who did not fall, and that these differences would be accentuated on the uneven surface.

METHODS

Subjects

Twenty-seven subjects participated in the study, 16 subjects with varying degrees of DPN and 11 without. (Table 1) Subjects were recruited from the University of Michigan Orthotics and Prosthetics Clinic, Endocrinology Clinic, and the Older Americans Independence Center

Human Subjects Core. Written informed consent was obtained from all subjects after review from the Institutional Review Board. Eligible subjects were between the ages of 50 and 85 years, weighed < 136 kg (as required for harness support system during gait evaluation), had not fallen within the month prior to participation, and were free of central neurologic disease, vestibular disorders, symptomatic coronary artery disease, plantar skin sores or joint replacement within the previous year, symptomatic postural hypotension, severe musculoskeletal deformity (e.g., amputation or Charcot changes), lower extremity or back pain that limited standing to <10 minutes, were able to walk 1 block or more, and had greater than anti-gravity ankle strength (> grade 3/5 by manual muscle testing). Subjects with DPN had a history of type 2 diabetes mellitus confirmed by review of records and the ongoing use of oral hypoglycemic agents or insulin. The presence of DPN was confirmed by: (a) symptoms (subject reported altered sensation in the distal lower limbs); (b) signs (Michigan Diabetes Neuropathy Score; MDNS >10;¹⁷ and (c) bilaterally abnormal fibular motor nerve conduction studies (recording over the extensor digitorum brevis, defined as amplitude <2.0 mV, latency >6.2 ms, and/or conduction velocity <41.0 m/s, using Nicolet Viking 4). Subjects without DPN had no history of diabetes mellitus, no symptoms or signs of DPN (MDNS <10),¹⁸ and normal fibular nerve conduction studies. Subjects were excluded if they reported a fall within 1 month of testing.

Subject Preparation

Subjects were fitted in a safety harness that housed a cable fastened to an overhead track. The cable was secured high enough to catch subjects should they experience an accidental fall. Subjects wore flat-soled, standard athletic shoes. Kinematic data was collected through two optoelectronic markers (infrared-emitted diodes) positioned 5 cm apart on an aluminum strip (10 cm × 1.5 cm) that was bent at a 90 degree angle and inserted under the laces of each shoe at the midline. The top marker was located anterior to the center of the malleoli. The subjects also wore a waist marker positioned on a belt at the level of the umbilicus. (Figure 1)

Walkway Set-up and Collection of Gait Data

The smooth surface was constructed of flat, linoleum tile. The uneven surface was created with wooden prisms (H = 1.5 cm, W = 3.5 cm, L = 6–16 cm) randomly dispersed at a density of approximately 26 pieces/m² and then covered with dark industrial carpeting. The blocks of wood were located within the mid 6.5 m section of carpet and were not changed between trials. For trials on both the smooth and uneven surfaces, subjects were instructed to walk down the runway at their own pace, as if they were “walking to mail a letter.” Subjects completed 10 trials on each walkway, with the first 2 used for accommodation and the last 8 for data collection. The subjects ambulated down the walkway toward an optoelectronic camera system (Optotrak 3020, Northern Digital Corp., Waterloo, Ontario) which recorded marker positions at 100 Hz. To detect heel strike and toe off, each subject wore rearfoot and forefoot foot switches in each shoe (force sensing resistors made by FlexiForce, Tekscan Inc., South Boston, MA). These sensors were connected to the data acquisition hardware. A custom C++ program operating in conjunction with the Optotrak Application Programming Interface was then used to track the timing of heel strike and toe off for each step. Once the heel strike and toe off information were known, then the timing of double support was

known and SW and SL information was taken from the kinematic marker data in the manner of Thies et al.¹⁹ Step time was the interval between heel strikes for successive steps and its standard deviation was used as the measure of step time variability. Kinematic data were quantified by using a custom algorithm written in MATLAB. Gait speed was determined by taking the time derivative of the waist marker during the comfortable gait speed interval. To find this interval, the data taken when the waist velocity was less than 85% of the maximum velocity for that trial was eliminated to account for the time when a subject was accelerating or decelerating.

Recording falls and fall-related injuries—Falls and fall-related injuries were recorded through one year of follow-up using methods described by Tinetti et al.²⁰ Twenty-six calendars (each spanning a two-week period) were provided to each of the 27 subjects so that data could be collected prospectively for each subject for one year. Subjects assessed themselves daily, and if a fall or fall-related injury occurred, they checked a box on the calendar and recorded a description of the circumstances. Subjects returned the calendars every two weeks, and in the few cases where a subject did not return a calendar the study coordinator contacted the subject to determine the occurrence of a fall or fall-related injury during the missed time period. Falls were identified as unintentional changes in body posture that resulted in the subject coming to rest on the ground or other lower level that was not a consequence of a physical blow or loss of consciousness. Fall-related injuries were defined as per prior protocols with major injuries defined as an Abbreviated Injury Scale Score greater than two,²¹ and minor injuries defined as abrasions, bruises, and lacerations that did not require sutures but interfered with the subject's activities of daily living for at least 24 hours.²²

Statistical Analyses

Descriptive statistics were generated for each of the relevant gait measures on smooth and uneven surfaces, and inspected for normality. Standard t-tests were used to identify between group differences in mean gait measures between subjects who fell and those who did not, and subjects who sustained a fall-related injury and those who did not fall. Receiver operator characteristics (ROC) curves were generated to evaluate the combined sensitivity and specificity characteristics of the best gait measure predictors on the smooth and uneven surfaces. Logistic regression was used to determine if significant gait parameters remained independent predictors of falls in the presence of other relevant variables such as age, gender and neuropathy severity. No more than two variables were introduced into the models simultaneously given the subject number of 27. The gait variable with the greatest effect size (differences in fall-related group means/means of standard deviations), was entered first and then the gait variable with the 2nd greatest effect size was entered next to determine the independence of the two gait measures. Finally, the demographic and neuropathy-related variables with the greatest effect sizes were entered with the one optimal gait measure predictor. ROC and multivariate analyses were not performed for the no fall vs. injury group as the number of subjects (17) was insufficient.

RESULTS

Subjects

Twenty-seven subjects participated in laboratory gait analysis and prospective fall recording. (Table 1.a.) Technical concerns caused loss of gait data for one subject on the uneven surface. No subjects dropped out of the study during the year-long follow-up.

Falls

Of the 27 subjects, 17 reported a fall and 10 did not in the year following baseline evaluation. (Table 1.b.)

Univariate analyses—There were significant fall group differences in STV on the smooth surface ($p = .027$) and a similar trend on the uneven surface ($p = .073$). However, in contrast to the hypotheses, subjects who fell showed *decreased* STV on both surfaces rather than the hypothesized increases. Subjects who fell walked at a significantly slower speed, with greater SW, shorter SL, and greater SW:SL on both surfaces as compared to those who did not fall. Fall group differences in gait parameters as determined by effect size were greatest for SW:SL on the uneven surface. (Table 2)

Multivariate analyses: SW:SL on the uneven surface demonstrated the greatest effect size and was entered into a logistic regression model first. The resulting odds ratio was 1.53 (95% confidence 1.10, 2.14) with pseudo- $r^2 = 0.65$ and p value of 0.012. When age, gender, comorbidities, and all other gait parameters demonstrating significant univariate fall group differences were introduced into the model, SW:SL on the uneven surface remained significant while the other variables did not. The lone exception was the MDNS score, a measure of DPN severity, which demonstrated a trend toward significance ($p = .071$) while SW:SL uneven also showed a trend toward significance ($p = 0.068$). The pseudo- r^2 for this two-variable models was 0.81.

Receiver operator characteristics (ROC) curve evaluation: ROC curves for accidental fall demonstrated that for the smooth surface the area under the curve (AUC) was .85 (95% confidence interval, .70, 1.00), while that for the uneven surface was .92 (95% confidence interval, .81, 1.00). Optimal sensitivity and specificity for the even surface were 94% and 60% (SW:SL = .26), and 100% and 70% (SW:SL = .27) for the uneven surface, suggesting that the latter had greater discriminative capability in this cohort.

Fall-Related Injuries

Of the 27 subjects, 12 were injured and 10 did not fall, indicating that 5 subjects fell without injury.

Univariate analyses—There no significant injury/no-fall group differences in STV on either surface. Injured subjects demonstrated a significantly slower speed, shorter SL, and greater SW:SL on both surfaces as compared to no fall subjects. (Table 3) Injured subjects also showed increased SW on the uneven surface, but not on the smooth surface. SW:SL on

the uneven surface demonstrated the greatest effect size of the variables demonstrating significant fall/injury group differences.

Post-hoc analyses—In post-hoc analyses, groups with and without DPN were evaluated separately. The one DPN subject who did not report a fall demonstrated a decreased SW:SL as compared with the 15 who did fall ($.23$ vs $.36 \pm .05$, respectively). Similarly, the two subjects without DPN who reported a fall demonstrated increased SW:SL as compared to those who did not fall ($.29 \pm .01$ vs $.25 \pm .05$, respectively). Lastly, subjects who fell without injury ($n = 5$) were compared to those who fell with injury ($n = 12$). No group differences in gait measures on either surface were identified (all p values > 0.3).

DISCUSSION

This study found that prior to falling or being injured from a fall older subjects with varying degrees of peripheral neurologic function walked with slower speed, shorter SL, and greater SW and SW:SL than non-fallers. Moreover, fallers and subjects injured from a fall altered their speed, SW, SL, and SW:SL to a greater degree than non-fallers on the uneven surface as compared to the smooth surface. SW:SL on the uneven surface remained a significant predictor of falls in the presence of age, gender, and other relevant gait parameters. Given this, we can conclude that SW:SL on the uneven surface was the strongest gait measure predictor of falls and fall-related injury.

Few works have prospectively assessed gait parameters on different surfaces as predictors of falls and fall-related injuries, and none have evaluated the relationship between SW and SL. Taylor et al. examined whether gait parameters measured while walking with and without a competing mental task predicted falls in a cohort of cognitively impaired older subjects. Although prospective fallers demonstrated significant differences in gait, the addition of a cognitive challenge did not alter gait measures so as to allow more sensitive identification of fallers.²³ This stands in contrast to our findings in which a physical challenge for patients with peripheral neurologic disease, the uneven surface, did identify fallers more effectively than the condition without challenge. This finding is consistent with other accepted diagnostic medical tests that demonstrate improved sensitivity by stressing the physiologic system in question, such as the glucose tolerance and cardiac stress test, both of which are superior to fasting glucose and resting electrocardiography.

Of interest, the data with reference to STV showed that subjects who fell demonstrated decreased STV on the even surface and a trend toward the same on the uneven surface. This stands in contrast with other work finding that increased STV is associated with falls.^{12,14} This finding may be reconciled by the fact that the reported work includes a large proportion of subjects with DPN, while the other study did not. Prior analyses of older DPN subjects showed that increased STV on an irregular surface is associated with reduced extremes in lateral foot placement, and therefore less chaotic frontal plane control.¹¹ In addition, analyses of dynamic walking models concluded that gait variability could not be easily used to predict fall risk whereas “neuronal noise,” as is likely present in older patients with DPN, clearly did increase fall risk.²⁴ Regardless, STV was of no significance in this population in the presence of SW:SL on the uneven surface.

To our knowledge, this is the first study to examine SW:SL on different surfaces as a predictor of falls and fall-related injuries. SW:SL is a measure of efficiency with the most efficient individuals walking with a SW:SL of 0.13, suggesting that an efficient SL is approximately eight times greater than SW.¹⁶ In the reported work, fallers and injured subjects demonstrated an increased SW:SL on both surfaces, but differences from non-fallers were more marked on the uneven surface. An increased SW:SL provides several advantages for maintaining frontal plane control. Greater SW creates a larger base of support and makes it easier to maintain the center of mass within the migrating base of support. A shorter SL minimizes the time in swing phase during which the subject is required to control the center of mass while on one foot. Finally, a larger SW:SL decreases the chance of a foot collision or a crossover step, both of which are destabilizing events.^{19, 25} It is also possible that the increased SW was related to uneven surface-related decrease in walking speed, given other research which found that distal afferent function is more important to postural equilibrium during slow walking than fast walking.²⁶ Those who fell or were injured made more extreme SW and SL changes on the uneven surface as compared to the smooth surface, indicating a sense of instability when presented with this physical challenge. The strength of the ratio in identifying subjects who fell, as compared to either SW or SL in isolation, suggests that subjects at increased fall risk use different strategies on uneven surfaces, with varying degrees of increases in SW and/or decreases in SL. Overall, it appears that older neuropathic subjects at increased fall risk used a conservative strategy on the uneven surface, one that sacrificed speed and efficiency for stability. In contrast, subject who did not fall did not change their strategy and maintained their usual efficiency.

There may be some application of the findings to clinical care. An older patient who provides history confirming slowing of gait speed on uneven surfaces may deserve a dedicated lower limb neuromuscular examination, and hip strengthening therapy recommended for patients with distal afferent impairment and/or proximal weakness.^{8,27} Given that none of the subjects fell during uneven surface testing, patients with known lower limb neuromuscular disease may be counseled to try increasing SW and decreasing SL when encountering hazardous irregular surfaces. The work also suggests that appropriate challenge, or perturbation, during gait testing in the clinic or laboratory may improve diagnostic precision with reference to the identification of patients at increased risk for fall and fall-related injury.

The strengths of this study include the careful screening of subjects, the thorough evaluation of peripheral nerve function, the inclusion of a population with DPN, a common disorder that markedly increases risk of falls and fall-related injury, the testing protocol, which included a physically challenging environment, and the study's prospective nature over one year with no subject drop out. Moreover, given the relatively small total number of subjects, a large number of falls and injuries were recorded, consistent with the group's neuromuscular status. The study also had limitations. Chief among these is the small sample size. Not only is sampling bias likely, but there were insufficient numbers to reasonably use multivariate techniques with more than two variables. Additionally, the prospective nature of the study and frequent contact between the study coordinator and subjects may have led to the over-reporting of falls or related events.

In conclusion, SW:SL on an uneven surface was the strongest predictor of falls and fall-related injuries in the high risk older population studied. The data suggest that older diabetic subjects at increased fall risk sacrifice speed and efficiency for stability on uneven surfaces. Efficacy of interventions in this population, such as hip and trunk strengthening, may be judged by the ability to walk more quickly or efficiently on standardized uneven surfaces.

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Abbreviations

DPN	Diabetic peripheral neuropathy
SL	Step length
STV	Step time variability
SW	Step width
SW	SL = Step-width-to-step-length ratio

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Figure 1. Experimental set-up for uneven surface gait analysis. V = Velocity marker; SW = Step Width; SL = Step Length

Table 1a

Demographic and neuromuscular characteristics of all subjects, and those with and without DPN

	All Subjects (n = 27)	(+) DPN (n = 16)	(-) DPN (n = 11)
Gender (women/men)	16 women/11 men	11 women/5 men	5 women/6 men
Age (years)	69.2 ± 8.4	70.8 ± 8.8	66.8 ± 7.8
Body Mass Index	30.3 ± 6.3	31.9 ± 5.3	28.0 ± 7.2
Michigan Diabetes Neuropathy Score	8.9 ± 8.0	14.6 ± 5.1	1.6 ± 1.12*
Fibular Motor Amplitude (mV)	3.2 ± 2.5	1.9 ± 2.2 mV	5.2 ± 1.6*
Fibular Motor Conduction Velocity (m/sec)	40.8 ± 5.6	36.8 ± 3.7	45.2 ± 3.7*

* Denotes p value < .01

Table 1b

Demographic and neuromuscular characteristics of subjects who did and did not fall

	(+) Fall (n = 17)	(-) Fall (n = 10)
Gender (women/men)	11 women/6 men	5 women/5 men
Age (years)	72.5 ± 7.6	63.5 ± 6.9*
Body Mass Index	31.6 ± 5.3	28.1 ± 7.5
Michigan Diabetes Neuropathy Score	13.3 ± 6.6	1.4 ± 2.9*
Fibular Motor Amplitude (mV)	1.9 ± 2.2 mV	5.4 ± 1.5*
Fibular Motor Conduction Velocity (m/sec)	38.1 ± 4.7	44.4 ± 4.7*

* Denotes p value < .01

Table 2

Fall group differences in gait measures on smooth and uneven surfaces. Note that effect size is greatest for the SW:SL on the uneven surface.

	Smooth Surface				Uneven Surface			
	(+) Fall (n = 17)	(-) Fall (n = 10)	p	E.S.*	(+) Fall (n = 17)	(-) Fall (n = 10)	p	E.S.*
Speed (m/sec)	1.23 ± .15	1.37 ± .17	.036	0.9	1.15 ± .17	1.34 ± .15	.007	1.2
Step Width (cm)	20.3 ± 2.7	17.4 ± 3.6	.029	0.9	20.2 ± 2.6	16.9 ± 3.5	.009	1.1
Step Length (cm)	62.9 ± 7.5	68.9 ± 6.9	.049	0.8	58.6 ± 7.4	67.7 ± 7.3	.005	1.2
SW:SL [†]	.33 ± .05	.25 ± .05	.002	1.6	.35 ± .05	.25 ± .05	<.001	2.0
Step Time Variability	.025 ± .012	.047 ± .036	.027	0.9	.039 ± .014	.055 ± .031	0.073	0.7

* E.S. = Effect Size

[†] SW:SL = Step-Width-to-Step-Length Ratio

Table 3

Injury group differences in gait measures on smooth and uneven surfaces. Note that effects size is greatest for the SW:SL on the uneven surface.

	Smooth Surface				Uneven Surface			
	(+) Injury (n = 12)	(-) Fall (n = 10)	p	E.S.*	(+) Injury (n = 11)	(-) Fall (n = 10)	p	E.S.*
Speed (m/sec)	1.21 ± .14	1.37 ± .17	.019	1.1	1.13 ± .16	1.34 ± .15	.007	1.4
Step Width (cm)	20.1 ± 2.6	17.4 ± 3.6	.058	0.9	20.1 ± 2.7	16.9 ± 3.5	.029	1.0
Step Length (cm)	61.8 ± 6.5	68.9 ± 6.9	.021	1.1	57.5 ± 6.4	67.7 ± 7.3	.003	1.5
SW:SL [†]	.33 ± .04	.25 ± .05	.001	1.8	.35 ± .04	.25 ± .05	<.001	2.2
Step Time Variability	.025 ± .012	.048 ± .037	.059	0.9	.040 ± .013	.056 ± .031	.135	0.7

* E.S. = Effect Size

[†] Step-Width-to-Step-Length Ratio