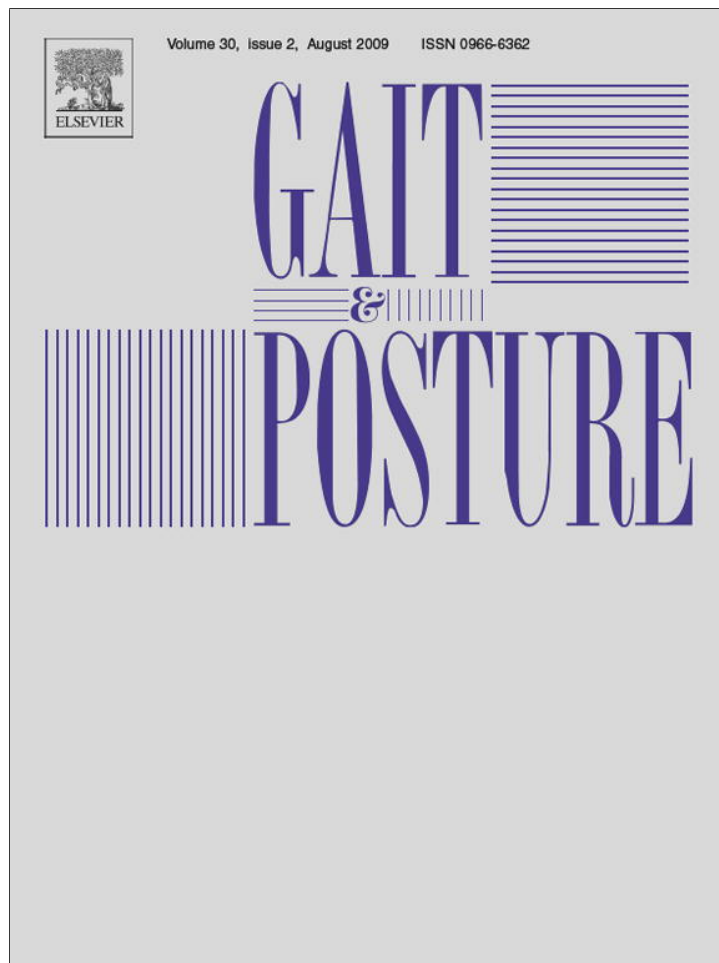


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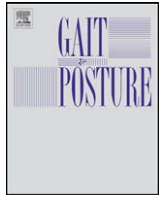
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Short communication

Characteristics of functional gait among people with and without peripheral neuropathy

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ABSTRACT

It is advantageous from a rehabilitation standpoint to determine physiological factors associated with functional gait. These factors may be fundamentally different in those with peripheral neuropathy (PN) compared to age-matched healthy individuals. The purpose of this investigation was to examine associations between functional gait and measures of leg strength, standing balance, and locomotor kinematics in people with and without PN.

Methods: Individuals with PN and age-matched controls were assessed for functional gait by the 6-min walk and timed up-and-go tests. Leg strength was measured as isokinetic peak torque of the knee extensors. Standing balance was assessed by center-of-pressure sway velocity and area during quiet stance. Locomotor kinematics from treadmill walking were used to compute stride duration variability and local instability (i.e., finite-time Lyapunov exponents), which estimate kinematic divergence caused by small-scale perturbations.

Results: Leg strength and locomotor kinematics – in particular local instability – correlated with functional gait performance in controls. Conversely, reduced functional gait performance in the PN group was primarily mediated by impaired standing balance control.

Discussion: Locomotor kinematics predicts functional gait, and the magnitude of variability and local instability should be calculated to fully evaluate locomotor system health. The observation that different factors associated with functional gait between groups speaks to the uniqueness of the PN-related movement disorder. Functional gait-related rehabilitation programs for PN patients should be tailored toward this uniqueness.

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1. Introduction

Determination of factors associated with functional gait – as assessed by field-tests such as the timed up-and-go [1] – is pertinent to rehabilitative intervention design. For example, leg strength predicts functional gait in older adults [2] and consequently, strength training is commonly emphasized for this population.

In addition to leg strength, properties of locomotor kinematics may also predict functional gait. Stride duration variability (SDvar) is one possible factor that increases with aging [3] and pathology [4]. However, SDvar provides little indication of the *moment-to-moment* control of locomotion. To this end, researchers have quantified “local instability” (λ_{MAX}) [5,6]. This analysis assumes that “small-scale” perturbations continuously disturb the loco-

motor system when walking. λ_{MAX} estimates the *rate* of kinematic divergence caused by these perturbations. Both pathological [6] and fall-prone populations [7] demonstrate increased λ_{MAX} values. Due to its time-dependent properties, λ_{MAX} may more sensitively predict functional gait as compared to SDvar.

Determining factors associated with functional gait are particularly important in movement-disordered populations. Peripheral neuropathy (PN) refers to the deterioration of peripheral sensory nerves [8]. Related loss of somatosensation reduces independence and increases falls [9]. Yet, individuals with PN exhibit minimal strength decline [10] and walk with “normal” SDvar and λ_{MAX} at preferred speed [5]. In contrast, PN severely impairs standing balance (i.e., postural sway) [10]. Therefore, factors associated with functional gait in this population may be fundamentally different compared to their healthy counterparts.

The purpose of this study was to determine factors associated with functional gait in individuals with PN and controls. We hypothesized that λ_{MAX} would more strongly associate with

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functional gait compared to SDvar, and different factors would underlie functional gait in those with PN compared to controls.

2. Methods

2.1. Participants and protocol

Twelve individuals with PN and twelve controls gave informed consent. Neurologist-diagnosed PN was confirmed using a 5.07 gauge Semmes-Weinstein monofilament (North Coast Medical, Inc.) to assess plantar pressure detection thresholds at the heel, mid-sole, first/fifth metatarsal bases, and hallux [11]. The number of sites with intact sensation was summed. Inclusion criteria for the PN and control groups were ≤ 3 and 5 sites, respectively. Exclusion criteria were foot ulceration, any other movement disorder, uncontrolled disease, or inability to walk 6-min unassisted.

Functional gait, leg strength and standing balance were assessed on visit one. Kinematic properties of treadmill walking were assessed on visit two.

2.2. Functional gait

The 6-min walk (distance) and timed up-and-go (seconds) represented functional gait and were administered using standard procedures [1,12].

2.3. Leg strength

Knee extensor peak torque (KEPT) was measured at 60°/s with a dynamometer (Biodesx Medical, Shirley, NY) [11]. Following warm-up, five maximal knee extension movements were completed with 10-s rest between trials. Peak torque from the three best trials was averaged.

2.4. Standing balance

Standing balance was assessed with a force platform (AMTI, Watertown, MA). Participants completed three 30-s trials with normal stance and eyes-closed. Center-of-pressure was sampled (500 Hz). Average velocity (VEL) and area of a confidence ellipse enclosing 95% of the center-of-pressure trajectory (AREA) were calculated [13].

2.5. Locomotor kinematics

Average 6-min walk speed determined treadmill speed. After familiarization, 3-min trials were completed. Two-dimensional sagittal-plane joint motions were acquired (60 Hz) using motion analysis (Motion Analysis Corp, Santa Rosa, CA). Reflective markers were placed on the right ASIS, greater trochanter, lateral femoral condyle, lateral malleolus, and 5th metatarsal head. Hip, knee, and ankle joint angle time-series were computed.

SDvar, defined as the standard deviation from the mean stride duration over thirty consecutive strides, was quantified. Time-series were low-pass filtered (6 Hz) and stride durations were computed by determining times between consecutive maximum knee angles [14].

λ_{MAX} was quantified by computing finite-time Lyapunov exponents from 100 consecutive strides. Rosenstein et al. [15] and Dingwell and Cusumano [5] algorithms were employed. Each time-series was reconstructed into a five-dimensional state-space. Distances between all possible pairs of nearest neighbor trajectories were tracked as the system moved forward in time, averaged, and graphed on a logarithmic scale normalized to average stride duration. Rate of divergence was estimated by the slope of a least-squares line fitted to the produced curve from 0 to 1 strides. λ_{MAX} was computed by averaging hip, knee, and ankle joint values.

2.6. Data analysis

Analyses were performed using Statistix software (V1.0, Boston, MA). Potential differences in group characteristics, functional gait (6-min walk, timed up-and-go), and predictor variables (AREA, VEL, KEPT, SDvar, λ_{MAX}) were examined with Student's *t*-tests. Relationships between predictor variables and functional gait were examined with Pearson correlations. The impact of predictor variables on group differences in functional gait was explored using least-squares models. Significance level was $p < .05$.

3. Results

3.1. Group characteristics

Groups demonstrated similar age, height, and body mass. Average diagnosed PN duration was 5 ± 5 years. Average PN group plantar pressure detection threshold scores were $2.1 \pm .3$ sites (out of five) with intact sensation (Table 1).

Table 1

Group demographics and the effects of PN on functional gait and select predictor variables related to leg strength, standing balance, and locomotor kinematics.

	Group (mean \pm SEM)		p value
	Controls	PN	
Participant demographics			
Age (years)	68 \pm 10	66 \pm 11	.65
Height (cm)	169 \pm 6	172 \pm 11	.32
Body mass (kg)	78 \pm 20	84 \pm 18	.45
PN duration (years)	–	5 \pm 5	–
Plantar pressure detection (# of intact sites)	5 \pm 0	2 \pm 1	.001
Functional gait			
6-Min walk (m)	530 \pm 25	391 \pm 27	.01
Timed up-and-go (seconds)	7.1 \pm .5	9.5 \pm .6	.02
Strength			
KEPT (N m)	146 \pm 14	121 \pm 17	.25
Standing balance			
VEL (cm/s)	2.4 \pm .2	3.0 \pm .4	.25
AREA (cm ²)	3.8 \pm .4	11.8 \pm 2.4	.01
Locomotor kinematics			
SDvar (ms)	19.9 \pm 1.6	27.2 \pm 1.9	.01
λ_{MAX}^a	2.92 \pm .12	3.08 \pm .09	.33

Abbreviations: PN—peripheral neuropathy, KEPT—knee extensor peak torque, AREA—center of pressure area, VEL—center of pressure average velocity SDvar—stride duration variability, λ_{MAX} —local instability.

^a Denotes units = $\{(\ln\{dj(i)\})/\text{stride}\} \times 100$.

3.2. Effects of PN

The PN group exhibited reduced functional gait as indicated by decreased 6-min walk distance ($p = .01$) and increased timed up-and-go time ($p = .02$) (Table 1).

The PN group demonstrated greater ($p < .01$) AREA during standing balance and SDvar during treadmill walking. No group differences were observed in KEPT, or λ_{MAX} during treadmill walking (Table 1).

3.3. Relationships between predictor variables and functional gait

In controls, predictor variables of leg strength and locomotor kinematics, *but not standing balance*, significantly correlated with functional gait. Specifically, smaller KEPT and larger λ_{MAX} values associated with shorter 6-min walk distance and longer timed up-and-go time. Greater SDvar also associated with longer timed up-and-go time (Table 2, Fig. 1).

Table 2

Correlations (*R*, *p*) between functional gait and measures of leg strength, standing balance, and locomotor kinematics.

	6-Min walk		Timed up-and-go	
	Controls	PN	Controls	PN
Leg strength				
KEPT	.63, .04	.21, .51	–.67, .02	–.15, .63
Standing balance				
AREA	–.37, .24	–.78, .003	.22, .48	.62, .03
VEL	–.02, .94	–.49, .10	.27, .39	.23, .47
Locomotor kinematics				
SDvar	–.51, .09	.18, .58	.75, .005	–.29, .36
λ_{MAX}	–.71, .01	.28, .37	.76, .004	–.38, .22

Significant correlations have been presented in bold. When examining positive and negative correlations, it is of note that *walking further* in the 6-min walk indicates increased performance, where as completing the timed up-and-go in *less* time indicates increased performance. Abbreviations: PN—peripheral neuropathy, KEPT—knee extensor peak torque, AREA—center of pressure area, VEL—center of pressure average velocity SDvar—stride duration variability, λ_{MAX} —local instability.

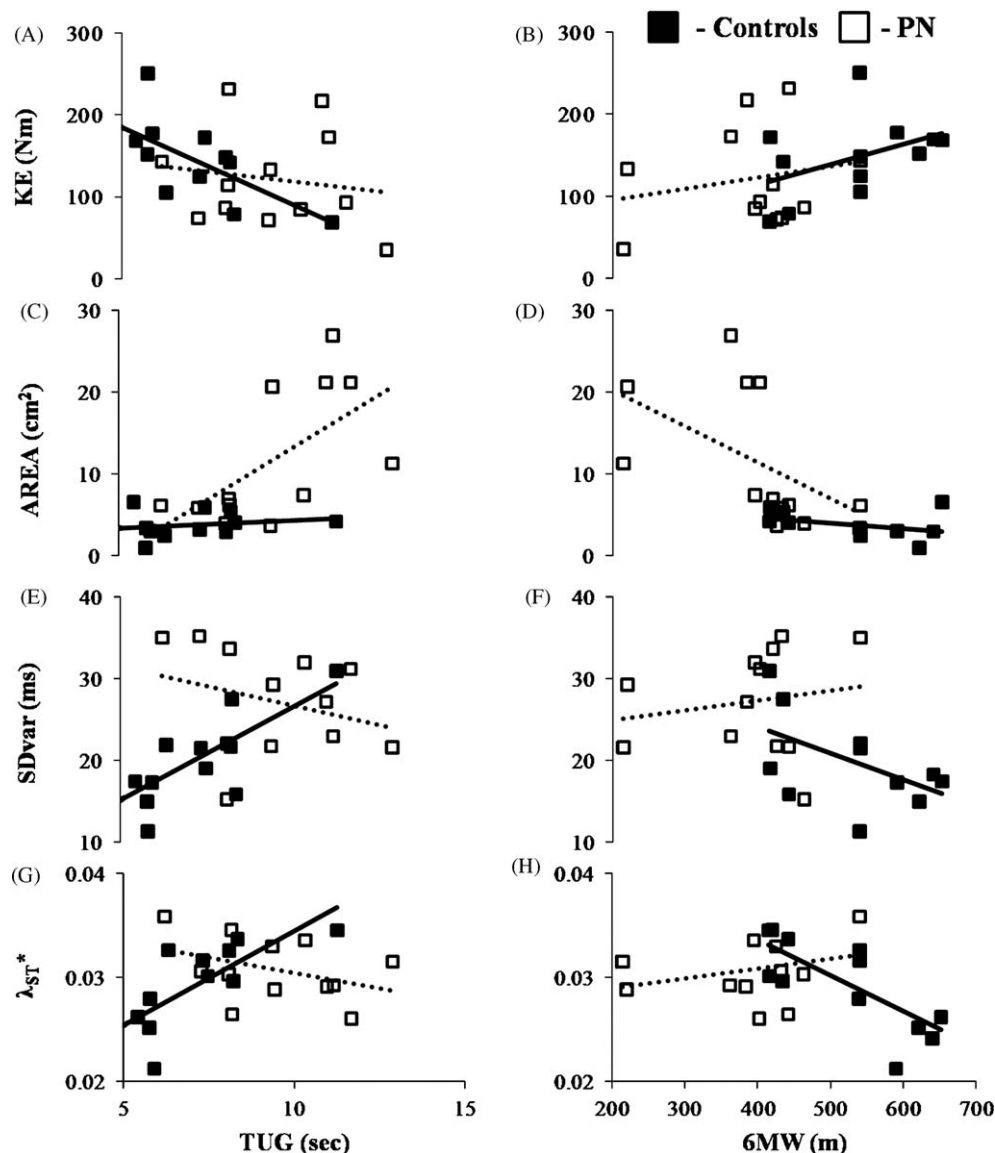


Fig. 1. Relationships between selected predictor variables and functional gait performance. The timed up-and-go (A–D) and the 6-min walk (E–H) have been plotted against leg strength (knee extensor peak torque, KEPT), standing balance (center of pressure area, AREA), and select kinematic properties of treadmill walking (stride duration variability, SDvar; local instability, λ_{MAX}). Presented predictor variables were chosen based on significant Pearson product correlation in at least one group (see Table 2). Solid (controls) and dashed (PN) lines were placed using the method of least squares. It is of note that completing the timed up-and-go in *less* time and covering *more* distance in the 6-min walk indicates better performance.

Within the PN group, no measure of leg strength or locomotor kinematics significantly correlated to functional gait. Instead, only standing balance AREA associated with shorter 6-min walk distance and longer timed up-and-go time (Table 2, Fig. 1).

Observations that (1) PN decreased functional gait, (2) PN altered specific predictor variables, and (3) different predictor variables correlated to functional gait in each group, prompted further analysis to determine the influence of each predictor variable on group differences in functional gait. Group differences in functional gait were ameliorated (6-min walk, $p = .78$; timed up-and-go, $p = .76$) when AREA was included as a covariate. Group differences in functional gait persisted, however, when KEPT, VEL, SDvar, or λ_{MAX} were included.

4. Discussion

This investigation examined predictors of functional gait in people with and without PN. Two main results were observed.

First, in controls, increased SDvar and λ_{MAX} associated with reduced functional gait performance. This supports the notion that greater values reflect locomotor system impairment [3,4,6,7]. Moreover, close relationships between λ_{MAX} and both functional gait field-tests highlight the value of assessing *moment-to-moment* properties of locomotor kinematics. Second, healthy controls with greater leg strength demonstrated increased functional gait performance. However, although individuals with PN demonstrated similar leg strength, this factor was *not* related to functional gait within this group. Instead, only standing balance AREA predicted functional gait. These observations suggest that leg strength is an important factor for functional gait, *provided that one has adequate standing balance control*.

In conclusion, relationships between functional gait and local instability indicated the importance of assessing this locomotor kinematic property. The negative impact of PN on functional gait highlights the need for exercise intervention with this population.

The effectiveness of such programs might be augmented by training designed to improve standing balance.

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Conflict of interest

The authors have no conflict of interests to be declared.

References

- [1] Podsiadlo D, Richardson S. The timed up & go: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 1991;39:142–8.
- [2] Mistic MM, Rosengren KS, Woods JA, Evans EM. Muscle quality, aerobic fitness and fat mass predict lower-extremity physical function in community-dwelling older adults. *Gerontology* 2007;53:260–6.
- [3] Grabiner PC, Biswas ST, Grabiner MD. Age-related changes in spatial and temporal gait variables. *Arch Phys Med Rehabil* 2001;82:31–5.
- [4] Dingwell JB, Cavanagh PR. Increased variability of continuous overground walking in neuropathic patients is only indirectly related to sensory loss. *Gait Posture* 2001;14:1–10.
- [5] Dingwell JB, Cusumano JP. Nonlinear time series analysis of normal and pathological human walking. *Chaos* 2000;10:848–63.
- [6] Manor B, Wolenski P, Li L. Faster walking speeds increase local instability among people with peripheral neuropathy. *J Biomech* 2008;41:2787–92.
- [7] Lockhart TE, Liu J. Differentiating fall-prone and healthy adults using local dynamic stability. *Ergonomics* 2008;51:1860–72.
- [8] Boulton AJ, Malik RA, Arezzo JC, Sosenko JM. Diabetic somatic neuropathies. *Diabetes Care* 2004;27:1458–86.
- [9] Cavanagh PR, Derr JA, Ulbrecht JS, Maser RE, Orchard TJ. Problems with gait and posture in neuropathic patients with insulin-dependent diabetes mellitus. *Diabet Med* 1992;9:469–74.
- [10] Menz HB, Lord SR, St. George R, Fitzpatrick RC. Walking stability and sensorimotor function in older people with diabetic peripheral neuropathy. *Arch Phys Med Rehabil* 2004;85:245–52.
- [11] Manor B, Doherty A, Li L. The reliability of physical performance measures in peripheral neuropathy. *Gait Posture* 2008;28:343–6.
- [12] Brooks D, Solway S, Gibbons WJ. ATS statement on six-minute walk test. *Am J Respir Crit Care Med* 2003;166:1287.
- [13] Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng* 1996;43:956–66.
- [14] Li L, Haddad JM, Hamill J. Stability and variability may respond differently to changes in walking speed. *Hum Mov Sci* 2005;24:257–67.
- [15] Rosenstein MT, Collins JJ, DeLuca CJ. A practical method for calculating largest lyapunov exponents from small data sets. *Phys D Nonlinear Phenom* 1993;65:117–34.