Diabetic Peripheral Neuropathy Compromises Balance During Daily Activities

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PATHOPHYSIOLOGY/COMPLICATIONS

OBJECTIVE

Patients with diabetes with peripheral neuropathy have a well-recognized increased risk of falls that may result in hospitalization. Therefore this study aimed to assess balance during the dynamic daily activities of walking on level ground and stair negotiation, where falls are most likely to occur.

RESEARCH DESIGN AND METHODS

Gait analysis during level walking and stair negotiation was performed in 22 patients with diabetic neuropathy (DPN), 39 patients with diabetes without neuropathy (D), and 28 nondiabetic control subjects (C) using a motion analysis system and embedded force plates in a staircase and level walkway. Balance was assessed by measuring the separation between the body center of mass and center of pressure during level walking, stair ascent, and stair descent.

RESULTS

DPN patients demonstrated greater ($P < 0.05$) maximum and range of separations of their center of mass from their center of pressure in the medial-lateral plane during stair descent, stair ascent, and level walking compared with the C group, as well as increased ($P < 0.05$) mean separation during level walking and stair ascent. The same group also demonstrated greater ($P < 0.05$) maximum anterior separations (toward the staircase) during stair ascent. No differences were observed in D patients.

CONCLUSIONS

Greater separations of the center of mass from the center of pressure present a greater challenge to balance. Therefore, the higher medial-lateral separations found in patients with DPN will require greater muscular demands to control upright posture. This may contribute to explaining why patients with DPN are more likely to fall, with the higher separations placing them at a higher risk of experiencing a sideways fall than nondiabetic control subjects.

Patients with diabetic peripheral neuropathy (DPN) have an altered gait strategy (1–3) and a fivefold increased risk of falling (4–6). Falling is a major health risk in many developed countries; for example, in the general U.K. population, over a quarter of accidents that required hospital treatment were the result of a fall (7). A fall is preceded by loss of balance, which may be recoverable in some individuals, but requires rapid responses and a high level of strength from the lower-limb muscles (8,9). Nevertheless, the more likely an individual is to lose balance, the more likely they will at some point experience a fall. Therefore, quantifying balance control

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during every day gait activities may be considered one of the closest proxies for the risk of falling.

Measures of “balance” in patients with diabetes and DPN have been mostly limited to postural sway during quiet standing, showing greater deviations in the center of pressure and increased postural sway (4). Postural movements during both quiet standing and walking have demonstrated greater variability in patients with DPN (3,10,11), which suggests an inherent difficulty in regulating their movements resulting in a need for more frequent adjustments to balance, which in itself could be destabilizing.

Previous studies have focused on the deviation in the center of pressure as a measure for the movement of the body via where the force is applied to the ground. A few studies have quantified postural sway directly by measuring movement of the body center of mass or accelerations of body regions (10). The use of center-of-pressure position alone as a measure of balance during quiet standing may provide some useful insights; however, measurements combining body movement together with the center of pressure are more appropriate for exposing underlying balance impairments (12). A person is most stable when their center of mass is directly above their center of pressure, as is the case during quiet standing. Separation of the body center of mass from the center of pressure is proportional to horizontal acceleration (13) and consequentially related to the muscular demands required to remain upright. Therefore, measurement of separation between the center of mass and center of pressure provides a superior measure, as it accounts for both postural movements (via the center of mass) and foot placements (via the center of pressure). Given the implicit relationship between increased separations of the center of mass from the center of pressure and the increase in muscular effort required to maintain upright posture, higher separations between the two represent greater challenges to balance (14,15). While a number of previous studies in other populations have used this measure (15,16), it has only been applied in a patient population with diabetes during quiet standing (17), where balance is relatively unchallenged and the risk of falling is low.

During walking activities, when an individual transfers their weight from one limb to another there are brief periods of large separation between the center of mass and the center of pressure. High levels of muscular strength are required to maintain balance during these periods. These large separations between the center of mass and center of pressure experienced during the single stance periods of dynamic gait activities may be a contributing factor toward understanding why the risk of falling during gait activities is much greater than during quiet standing. Few studies, however, have attempted to address the issue of balance during walking in patients with diabetes, and none have addressed the much more physically challenging activities of stair ascent and descent, during which the risk of falling is known to be very high (7). We therefore investigated a more “dynamic” measure of balance during stair ascent, stair descent, and level walking—three activities with the highest risk of fall-related injury (7)—with the hypothesis that individuals with peripheral neuropathy would display greater separations between their center of mass and center of pressure (i.e., poorer balance), thereby contributing to explaining why they are at high risk of falls.

RESEARCH DESIGN AND METHODS

Participants

After receiving ethics approval from all relevant bodies, 89 participants were recruited to take part. Participants all gave their informed written consent before being allocated to one of three groups based on defined criteria: patients with diabetes and moderate-severe peripheral neuropathy (DPN) (*n* = 22), patients with diabetes but no peripheral neuropathy (D) (*n* = 39), and healthy control subjects without diabetes and without peripheral neuropathy (C) (*n* = 28).

Clinical Assessment

All participants underwent a clinical assessment: presence of peripheral neuropathy was assessed using a modified Neuropathy Disability Score (mNDS) and the vibration perception threshold (VPT). The mNDS is a semiquantitative composite score derived from the assessment of perception of temperature, vibration, and pain and Achilles tendon reflex (18). In addition, VPT, a quantitative assessment of vibration perception, was performed using a neurosthesiometer (Horwell, Nottingham, U.K.) (19). Patients were defined as having moderate-to-severe neuropathy and classed as DPN if in either one or both of their feet they displayed either an mNDS score of $\geq$6 or a VPT of $\geq$25 V (or both). Patients were deemed to have no neuropathy and were grouped as D if in both feet they displayed scores for the mNDS of $\leq$5 and for the VPT of $\leq$24. All nondiabetic control subjects were confirmed to have no peripheral neuropathy (mNDS $<$6 and VPT $<$25 V). A random blood glucose reading was also taken from the nondiabetic control subjects to confirm the absence of diabetes. Major exclusion criteria included the following: an inability to walk independently of assistance, presence of any lower-limb amputation, significant foot deformity (e.g., Charcot), open foot ulcers, history of cerebral injury and poor visual acuity (less than 6/18 of any etiology), and a BMI $>$35 kg/m^2. Where possible, duration of diabetes and the most recent HbA$_{1c}$ readings for patients with diabetes were ascertained using hospital records.

Gait Analysis

Participants were invited to a gait laboratory with a bespoke seven-step instrumented staircase for assessing stair ascent and descent and a level 8-m walkway for assessing “normal” level walking. Participants were provided with standardized footwear with a neutral foot bed (MedSurg; Darco, Raisting, Germany) to ensure no influence on gait from different styles of shoe while also ensuring that the patients with diabetes walked with appropriate footwear. Three-dimensional motion data were recorded in the gait laboratory using a 10-camera motion-capture system (Vicon, Oxford, U.K.) positioned around the test areas. With use of a Helen-Hayes–based full-body model, 56 reflective markers were placed at key anatomical positions on the participants to track movement of all body segments. For elimination of movement artifacts in the markers from loose clothing, participants were given close-fitting shorts and tops to wear, and wherever possible markers were placed directly onto the skin. Force data were collected simultaneously with the motion data using three embedded force platforms (Kistler, Winterthur, Switzerland) in the level walkway and four embedded force platforms (Kistler) in the middle four steps of the staircase. For safety, a full-body harness was worn by all participants during gait analysis on the staircase.

Stair testing (ascent and descent) and level walking were assessed on two separate occasions to allow movement of the camera-based motion analysis system around the staircase or the level walkway. During stair ascent and descent, participants were asked to start at the top/bottom of the staircase close enough to the edge of the step to be ready to take their first step. They were then instructed to ascend/descend the staircase at a speed they felt most comfortable (i.e., their self-selected speed), not using the handrails unless they felt unable to complete the task without them. For walking on a level surface, participants were instructed to start behind a mark on the level walkway and, when instructed, walk to the other end of the walkway at the speed they felt most comfortable. During level walking, the start mark was moved incrementally forward or backward to achieve "clean" (without the foot overlapping the edges) foot contacts with the force plates without the participants aiming to step on them. During stair ascent and descent, the force plates formed the entirety of the center of the four middle steps so that clean foot contacts with the force plates occurred without aid. Stair ascent and descent and level walking tasks were repeated until the achievement of at least three trials for each gait task with clean foot contacts with the force plates.

During the session when level walking was assessed, data for quiet standing was also collected to compare against the walking activities and to provide a reference for comparison with previous studies that have solely investigated quiet standing. Participants were asked to stand comfortably with their feet side-by-side (approximately shoulder width apart) and with one foot placed on each force plate. Motion and force data were then collected for two separate 30-s long trials: during both, participants were asked to stand comfortably still with their arms down by their sides and facing straight ahead. During the first trial, they were asked to perform this task with their eyes open, and during the second trial they performed this task with their eyes closed.

Dynamic Sway and Postural Sway

Motion data collected during gait analysis were processed, and Dempster segment parameter model (20) was used to calculate mass distribution for each body segment, thereby allowing calculation of an accurate entire-body center-of-mass position throughout the trials. Ground-reaction force data from the force plates were assessed to calculate the center of pressure (the point from which the resultant ground reaction force originates) during periods when a foot was in contact with the ground. When two feet were simultaneously on two separate force plates, data from the individual force plates were combined using an equation described by Winter (13) to yield a weighted average position for the center of pressure. This enabled the separation between the position of the center of mass and the position of the center of pressure to be calculated throughout the trials in both the medial-lateral and anterior-posterior planes (Fig. 1). We have termed these separations between the center of mass and center of pressure "dynamic sway" during the gait activities of level walking, stair ascent, and stair descent and "postural sway" during quiet standing. The maximum sway (in the medial-lateral plane and separately for the anterior-posterior plane) and the range of sway (difference between maximum left and maximum right sway in the medial-lateral plane and difference between anterior maximum and posterior maximum in anterior-posterior plane) were measured to quantify extremes in dynamic sway and postural sway. Typical levels of sway throughout the trial were quantified by the mean sway in each plane. For quantification of the within-participant reproducibility of the main variable (separations between the center of mass and center of pressure), the coefficient of variation for the range of medial-lateral dynamic sway was calculated for all groups across the three gait tasks (results of which are presented in Supplementary Table 1). The reproducibility of this variable will reflect both inherent biological variability (associated with group and task) and methodological (equipment) variability.

Statistical Analysis

Variables were calculated for each trial before an average across the trials of each activity was calculated per participant to give a single result per person for each activity. Between-group differences for all variables were tested using a one-way ANOVA and followed up using Tukey post hoc tests with respect to the control group. The level of agreement

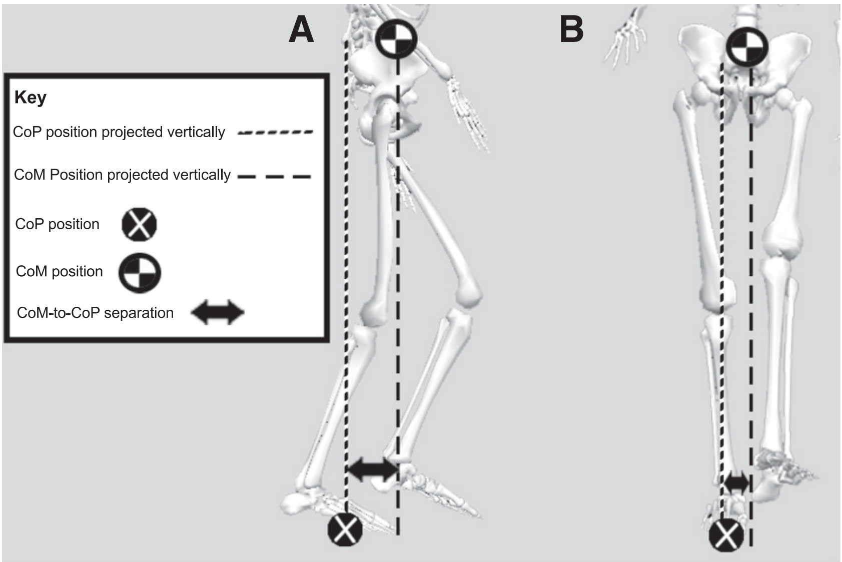

Figure 1—Graphic illustration of the measurement of center-of-mass to center-of-pressure separation in the anterior-posterior (*A*) and medial-lateral (*B*) planes. The center-of-mass location is projected downward, and the center-of-pressure position is projected upwards. Horizontal arrows show the center-of-mass (CoM) to center-of-pressure (CoP) separation.

between the maximum dynamic sway (chosen as one of the key variables showing significant differences across the gait tasks) and three other variables—VPT, stance width, and maximum medial-lateral postural sway during quiet standing with eyes open—was tested using Pearson correlations.

RESULTS

Clinical Assessment and Demographics

There was a higher proportion of male participants in all three groups compared with female participants (Table 1). There were no significant differences between the groups with regard to age or height, but the DPN group was significantly ($P < 0.05$) heavier and had a higher BMI (Table 1). The D group displayed no significant differences from the C group for either neuropathy test. The DPN group as expected displayed significantly higher scores for both neuropathy tests compared with the C group ($P < 0.05$) (Table 1).

Duration since diagnosis of diabetes and HbA_{1c} readings were ascertained for 38 of the 61 participants with diabetes (D, 26 of 39; and DPN, 12 of 22 participants). There were no significant differences shown between the D and DPN groups for duration since diabetes diagnosis or HbA_{1c} readings (Table 1).

Dynamic Sway

During both stair ascent and descent, the DPN group demonstrated significantly ($P < 0.05$) greater maximum and range of center-of-mass to center-of-pressure separation in the medial-lateral plane compared with the C group (Table 2). During level walking, the DPN group again showed significantly ($P < 0.05$) greater maximum and range of medial-lateral center-of-mass to center-of-pressure separation but also a significant ($P < 0.05$) increase in the mean medial-lateral center-of-mass to center-of-pressure separation relative to the C group (Table 2). In the anterior-posterior plane during both stair ascent and descent, there was an increased range of separation in the DPN group relative to the C group ($P < 0.05$) (Table 2). During stair ascent, the DPN group also showed increased maximum anterior separation relative to the C group, and during stair descent the DPN group showed a decreased maximum posterior separation and mean separation relative to the C group ($P < 0.05$) (Table 2). During level walking, the DPN group displayed a lower mean separation than the C group ($P < 0.05$) (Table 2). No significant differences were observed between the D and C groups for any variable during any gait task in either medial-lateral or anterior-posterior plane.

Gait Parameters

Gait velocities were significantly lower in the DPN group compared with the control group during stair ascent, stair descent, and level walking ($P < 0.05$) (Table 2), with no significant difference displayed between the D and C groups during stair ascent or descent, but a reduction in gait velocity was observed in the D group relative to the C group during level walking ($P < 0.05$) (Table 2). During stair descent and level walking, there were significant increases in step width in the DPN group relative to the C group during stair descent and level walking ($P < 0.05$) (Table 2) but no significant change during stair ascent. Step length was calculated only for level walking, as during stair ascent and descent, step length is constrained by the depth of the step. Step length during level walking was significantly lower in both D and DPN groups relative to the C group ($P < 0.05$) (Table 2).

Postural Sway During Quiet Standing

During quiet standing in the eyes-open condition, the DPN group displayed significantly greater mean and range of anterior-posterior separation relative to the C group and a greater mean medial-lateral separation (Table 2). During the eyes-closed condition, the DPN group demonstrated increased mean and range in separations relative to the C group in both medial-lateral and anterior-posterior planes (Table 2). The D group demonstrated greater maximum separations in both medial-lateral and anterior-posterior planes relative to the C group in both eyes-open and eyes-closed conditions (Table 2) but no significant changes in mean or range of separations.

Correlations

Positive correlations were found between the VPT and maximum medial-lateral dynamic sway during stair ascent, stair descent, and level walking ($P < 0.05$) (Fig. 2*A*–*C*). Positive correlations were found between stance width and maximum medial-lateral dynamic sway during all three gait activities of stair ascent, stair descent, and level walking ($P < 0.05$) (Fig. 2*D*–*F*). During stair descent, maximum medial-lateral postural sway was only weakly correlated with maximum medial-lateral dynamic sway ($P < 0.05$; $r = 0.27$), but no significant associations were present between these variables for stair ascent and level walking ($P > 0.05$; $r = 0.23$, and $r = 0.21$, respectively).

Table 1—Clinical measurements and demographics

	C	D	DPN
n	28	39	22
Male:female ratio	15:13	20:19	15:7
Age (years)	53 (18)	56 (13)	57 (9)
Body mass (kg)	75 (13)	78 (12)	93 (22)**
Height (m)	1.71 (0.09)	1.67 (0.10)	1.74 (0.10)
BMI (kg/m^2)	26 (4)	28 (4)	31 (6)**
mNDS (score/10)	1 (1)	2 (2)	7 (3)**
VPT (volts)	8 (5)	10 (5)	30 (9)**
Duration (years)‡		22 (13)	25 (16)
HbA_{1c} (% [mmol/mol])‡		8.2 [66] (3.7 [17])	9.2 [77] (4.3 [24])

Data are means (SD) unless otherwise indicated. **Significant ($P < 0.01$) difference from the control group. ‡Results are only available for a sample of the entire group, for $n = 26$ in the D group and $n = 12$ in the DPN group.

CONCLUSIONS

For the first time, we have shown that balance is markedly impaired in patients with DPN during the gait activities of level ground walking, stair ascent, and stair descent. This balance impairment in patients with DPN was predominantly

Table 2—Dynamic sway and postural sway (center-of-mass to center-of-pressure separation)

Activity	Means C	Means D	Means DPN
Level walking			
Medial/lateral (cm)			
Max	7.8 (1.9)	7.7 (1.7)	10 (2.6)**
Range	13 (2.8)	12.8 (2.4)	16.6 (4.5)**
Mean	5.1 (1.1)	4.8 (0.9)	6.1 (1.4)**
Anterior/posterior (cm)			
Anterior max	23.3 (2.8)	22.3 (2.7)	22.6 (3.2)
Posterior max	31.2 (3.5)	29.4 (4.1)	28.5 (4.4)
Range	54.6 (5.2)	51.7 (6)	51.1 (7)
Mean	12 (1.1)	11 (1.6)	10.8 (2.2)*
Gait velocity (m/s)	1.41 (0.2)	1.28 (0.17)*	1.19 (0.17)**
Stance width (cm)	11.3 (2.1)	10.9 (2.4)	14.3 (3.5)**
Step length (cm)	72.5 (7.4)	67.4 (6.1)*	65.4 (10.9)**
Stair ascent			
Medial/lateral (cm)			
Max	10.4 (2.7)	10.1 (2.3)	13.2 (1.9)**
Range	17.5 (4.2)	17.7 (3.8)	23.1 (4.2)**
Mean	5.3 (1.4)	4.9 (1.1)	6.1 (1.4)
Anterior/posterior (cm)			
Anterior max	13 (2.9)	14.6 (3.2)	16.5 (3.6)**
Posterior max	13.5 (2.6)	13.7 (2.2)	13.1 (2.9)
Range	26.5 (2.9)	28.4 (3.1)	29.6 (3.9)**
Mean	5.1 (0.5)	5.3 (0.7)	5.3 (0.7)
Gait velocity (m/s)	0.48 (0.1)	0.44 (0.1)	0.39 (0.1)**
Stance width (cm)	13.2 (8.1)	11 (2.8)	14.4 (2.2)
Stair descent			
Medial/lateral (cm)			
Max	12.4 (2.7)	12.5 (2.5)	15.6 (3.2)**
Range	21.8 (4.4)	22.3 (4.3)	28.2 (5.2)**
Mean	6.4 (1.2)	6 (1.2)	7.1 (1.3)
Anterior/posterior (cm)			
Anterior max	10.6 (1.9)	10.8 (1.8)	10.7 (2)
Posterior max	18.6 (3.1)	17.4 (2.2)	16.7 (2.1)*
Range	29.2 (2.5)	28.3 (2.3)	27.4 (2.4)*
Mean	4.9 (0.6)	4.7 (0.5)	4.4 (0.6)*
Gait velocity (m/s)	0.53 (0.1)	0.47 (0.1)	0.42 (0.1)**
Stance width (cm)	15.1 (2.2)	14.9 (2.6)	17.3 (2.7)*
Quiet standing (eyes open)			
Medial/lateral (cm)			
Max	1.2 (0.65)	0.74 (0.46)**	1.07 (0.48)
Range	0.54 (0.25)	0.66 (0.54)	0.75 (0.33)
Mean	0.07 (0.04)	0.08 (0.03)	0.1 (0.05)*
Anterior/posterior (cm)			
Anterior max	1.35 (1.4)	1.15 (1.16)	1.21 (1.22)
Posterior max	−0.32 (1.09)	0.15 (1.39)	0.45 (1.13)
Range	1.03 (0.6)	1.29 (0.62)	1.66 (0.66)**
Mean	0.14 (0.08)	0.16 (0.05)	0.21 (0.07)**
Quiet standing (eyes closed)			
Medial/lateral (cm)			
Max	1.2 (0.62)	0.82 (0.45)*	1.18 (0.65)
Range	0.58 (0.24)	0.77 (0.46)	0.92 (0.61)*
Mean	0.08 (0.04)	0.09 (0.03)	0.13 (0.09)*
Anterior/posterior (cm)			
Anterior max	1.55 (1.22)	1.37 (1.17)	1.54 (1.26)
Posterior max	−0.13 (1.16)	0.26 (1.32)	0.72 (1.18)
Range	1.42 (0.58)	1.63 (0.6)	2.26 (0.98)**
Mean	0.18 (0.08)	0.21 (0.06)	0.29 (0.11)**

Data are means (SD). *Significant ($P < 0.05$) difference from the control group. **Significant ($P < 0.01$) difference from the control group.

in the medial-lateral plane and was greatest during stair descent.

During the gait tasks, we found no significant balance impairments in patients with diabetes without DPN, clearly emphasizing that the link between diabetes and instability is a symptom of peripheral neuropathy. This was further reinforced via a significant positive correlation between one of the key variables—maximum medial-lateral dynamic sway—and the extent of peripheral neuropathy (VPT score) (Fig. 2*A*–*C*).

Impairments to balance in patients with DPN were found mainly in the medial-lateral plane, with increased maximum and range of dynamic sway observed in this plane during all three gait activities. During stair ascent, there was an indication of impaired anterior-posterior balance by the increased maximum dynamic sway in the anterior direction (Table 2). However, no increase in posterior dynamic sway (away from the staircase) was observed, suggesting that individuals preferred to lean slightly toward the stairs, potentially falling toward the stairs rather than away if a fall were to occur. During stair descent, the DPN group displayed the opposite behavior, with a decrease in dynamic sway toward the staircase (Table 2). This may be a response to the decreased haptic feedback and proprioception common to patients with DPN, as a greater reliance is placed on visual stimuli for accurate foot placement, which posterior dynamic sway would occlude. During level walking, decreased dynamic sway in the anterior-posterior plane in patients with DPN compared with the C group (Table 2) is likely the result of the shorter step length (Table 2). Shortening step length is a common strategy in populations known to be at heightened risk of falling, as this maintains a closer control of the center of mass above the center of pressure, thereby reducing muscular demands and decreasing the risk of falling (21,22).

The potential increase in fall risk due to increased dynamic sway and the associated increase in muscular effort to maintain balance is of particular concern when combined with marked muscular deficiencies that are present in patients with DPN (23). Our findings of increased maximum and range of dynamic sway in patients with DPN

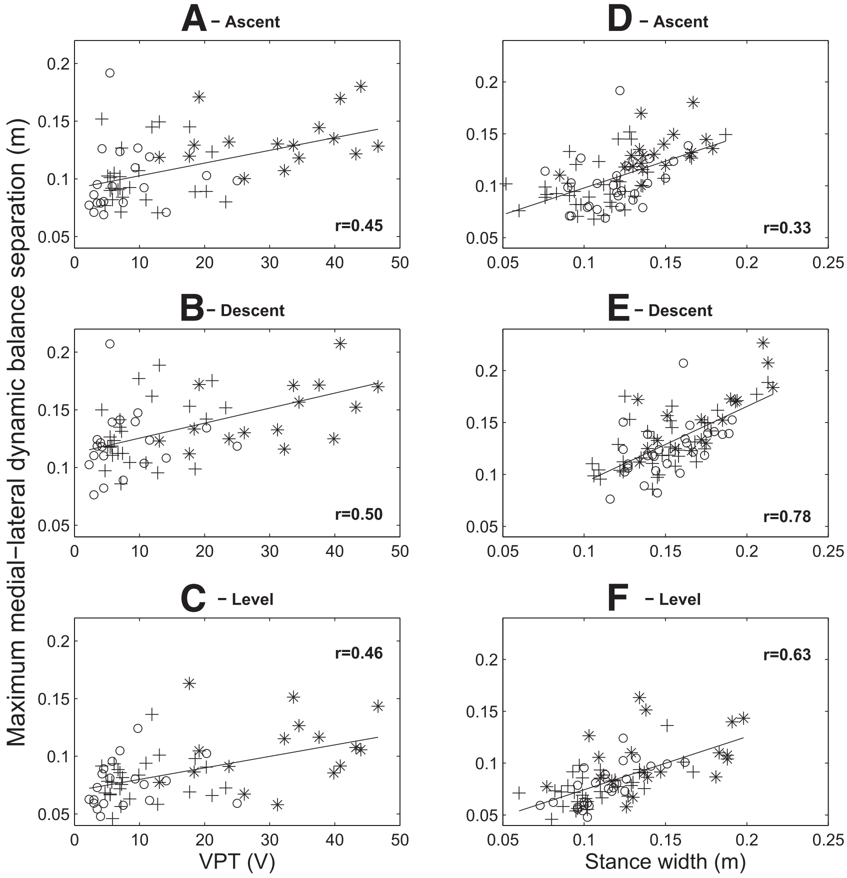

Figure 2—Correlation results. *A–C*: Maximum medial-lateral dynamic sway plotted as a function of VPT score. *D–F*: Maximum medial-lateral dynamic sway plotted as a function of stance width. Values are individual participant data points, with group indicated as follows: *DPN group, +D group, ○C group.

highlight the extremes of dynamic sway that are occurring during these gait activities. These extremes in dynamic sway show the momentary points when a loss of balance becomes most likely, as the center of mass is at the furthest point from the center of pressure and the muscular demands to maintain balance are highest. Therefore, the larger "extremes" (maximum sway) shown by patients with DPN suggest they are more vulnerable to a fall during these activities. Mean dynamic sway represents a general level of the magnitude of separation throughout the activities and was significantly higher in the medial-lateral plane in the patients with DPN compared with the C group during level walking alone, indicating a consistently poorer ability to control sway in patients with DPN during this activity.

The magnitude of dynamic sway observed in the current study varies between gait activities. Stair descent is widely recognized as an activity where the risk of falling is highest (7,24,25), and in agreement with these reports, we found the largest magnitudes of dynamic sway in all three participant groups during this activity, particularly in patients with DPN. As the difficulty of the gait task decreases, we found the magnitude of the dynamic sway also reduces, as did the extent of difference between the groups, with level walking demonstrating the smallest levels of dynamic sway throughout the groups and yielding the smallest differences between the groups (Table 2).

Our findings have demonstrated an increased stance width in patients with DPN during stair descent and level walking (Table 2). Normally considered a compensatory mechanism, during dynamic gait activities an increased stance width increases separation between the center of mass and center of pressure (sway) during periods of single-limb support when moving away from the supporting limb. Correlations between stance width and maximum medial-lateral dynamic sway showed strong positive correlations during stair descent and level walking (r = 0.78 and r = 0.63, respectively) (Fig. 2*E* and *F*) and a weak positive correlation (r = 0.33) (Fig. 2*D*) during stair ascent. This calls into question the effectiveness of patients with DPN adopting a wider stance as a compensation for instability. Although during double-limb support, when two feet are in contact with the ground, this will create a much better support system, during activities with single-limb support periods (i.e., all types of walking activity) we suggest these participants are temporarily increasing their level of instability. The DPN population investigated also demonstrated a significantly higher body mass than the other two groups (Table 1), a common finding among populations with neuropathy, who also tend to be less active. Although differences in BMI were observed between the groups, fat mass distribution would be symmetrical and would therefore not impact upon the body center of mass position in the medial-lateral plane. Increased abdominal fat mass may slightly shift the center of mass anteriorly; however, fat mass distribution may not differ in a consistent way between groups. During dynamic gait activities, the position of the center of mass and center of pressure are in constant flux (due to the movement of the limbs), making this unlikely to affect our measurements in the anterior-posterior direction.

This study also demonstrated a greater level of postural sway in patients with DPN during quiet standing both with eyes open and eyes closed (Table 2). Due to the stable nature of quiet standing compared with gait, it is perhaps unsurprising that the magnitudes of postural sway were considerably smaller than those of dynamic sway during the gait activities: none of the groups displayed maximum postural sway values >1.6 cm in either plane (Table 2), as opposed to maximum excursions during the gait activities in some cases exceeding 30 cm (Table 2). These small excursions during quiet standing are in agreement with the findings of Corriveau et al. (17) in elderly patients with DPN and can be explained by the stable nature of quiet standing. When comparing maximum medial-lateral postural sway during quiet standing with eyes open to maximum medial-lateral dynamic sway during the three gait activities, we found a significant but poor correlation only during stair descent ($P < 0.05$, $r = 0.27$) and no significant relationship during stair ascent or level walking. This suggests that while the control mechanisms of balance during gait activities and quiet standing are related, postural sway during quiet standing does not provide a very accurate representation of balance when considered in relation to falls, which predominantly occur during gait activities (7,25,26).

Limitations

Duration since diagnosis of diabetes and HbA_{1c} readings were obtained for participants with records at the local hospital; as described in the RESULTS, this demographic information was available for just over 50% of the D and DPN groups.

Our sample population included a slight bias toward a higher number of male participants within all three groups, but particularly within the DPN group. While the distribution of the center of mass may differ slightly between males and females, the male-to-female ratios across the three cohort groups were relatively similar, albeit somewhat higher within the DPN group (C, 54%; D, 51%; DPN, 68%).

Summary

We have shown marked impairments in dynamic sway during gait activities in patients with DPN, which become more evident with increasing gait task complexity. Impaired balance in patients with DPN may also be linked to a compensatory mechanism (increased stance width) that is used because of perceived instability but may actually increase the risk of falling.

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References

1. Katoulis EC, Ebdon-Parry M, Lanshammar H, Vileikyte L, Kulkarni J, Boulton AJ. Gait abnormalities in diabetic neuropathy. Diabetes Care 1997 20:1904–1907
2. Allet L, Armand S, Golay A, Monnin D, de Bie RA, de Bruin ED. Gait characteristics of diabetic patients: a systematic review. Diabetes Metab Res Rev 2008;24:173–191
3. 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;85:245–252
4. Bonnet CT, Ray C. Peripheral neuropathy may not be the only fundamental reason explaining increased sway in diabetic individuals. Clin Biomech (Bristol, Avon) 2011;26:699–706
5. Richardson JK, Hurvitz EA. Peripheral neuropathy: a true risk factor for falls. J Gerontol A Biol Sci Med Sci 1995;50:M211–M215
6. Tilling LM, Darawil K, Britton M. Falls as a complication of diabetes mellitus in older people. J Diabetes Complications 2006;20:158–162
7. Report of the home and leisure accident surveillance system: 2000, 2001 and 2002 data [Internet], 2003. Available from http://www.hassandlass.org.uk. Accessed 3 July 2014
8. Pijnappels M, Reeves ND, Maganaris CN, van Dieën JH. Tripping without falling; lower limb strength, a limitation for balance recovery and a target for training in the elderly. J Electromyogr Kinesiol 2008;18:188–196
9. Pijnappels M, van der Burg PJCE, Reeves ND, van Dieën JH. Identification of elderly fallers by muscle strength measures. Eur J Appl Physiol 2008;102:585–592
10. Turcot K, Allet L, Golay A, Hoffmeyer P, Armand S. Investigation of standing balance in diabetic patients with and without peripheral neuropathy using accelerometers. Clin Biomech (Bristol, Avon) 2009;24:716–721
11. Morrison S, Colberg SR, Parson HK, Vinik AI. Relation between risk of falling and postural sway complexity in diabetes. Gait Posture 2012;35:662–668
12. Benvenuti F, Mecacci R, Gineprari I, et al. Kinematic characteristics of standing disequilibrium: reliability and validity of a posturographic protocol. Arch Phys Med Rehabil 1999;80:278–287
13. Winter DA. Human balance and posture control during standing and walking. Gait Posture 1995;3:193–214
14. Zachazewski JE, Riley PO, Krebs DE. Biomechanical analysis of body mass transfer during stair ascent and descent of healthy subjects. J Rehabil Res Dev 1993;30:412–422
15. Lee H-J, Chou L-S. Balance control during stair negotiation in older adults. J Biomech 2007;40:2530–2536
16. Mian OS, Narici MV, Minetti AE, Baltzopoulos V. Centre of mass motion during stair negotiation in young and older men. Gait Posture 2007;26:463–469
17. Corriveau H, Prince F, Hebert R, et al. Evaluation of postural stability in elderly with diabetic neuropathy. Diabetes Care 2000;23:1187–1191
18. Boulton AJM. Management of diabetic peripheral neuropathy. Clin Diabetes 2005;23:9–15
19. Boulton AJ, Malik RA, Arezzo JC, Sosenko JM. Diabetic somatic neuropathies. Diabetes Care 2004;27:1458–1486
20. Dempster WT. Space requirements of the seated operator: geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs [Internet], 1955. Available from http://books.google.co.uk/books/about/Space_Requirements_of_the_Seated_Operato.html?id=Ks1pAAAAMAAJ&redir_esc=y. Accessed 20 July 2014
21. Bhatt T, Wening JD, Pai Y-C. Influence of gait speed on stability: recovery from anterior slips and compensatory stepping. Gait Posture 2005;21:146–156
22. Espy DD, Yang F, Bhatt T, Pai Y-C. Independent influence of gait speed and step length on stability and fall risk. Gait Posture 2010;32:378–382
23. Andreassen CS, Jakobsen J, Andersen H. Muscle weakness: a progressive late complication in diabetic distal symmetric polyneuropathy. Diabetes 2006;55:806–812
24. Startzell JK, Owens DA, Mulfinger LM, Cavanagh PR. Stair negotiation in older people: a review. J Am Geriatr Soc 2000;48:567–580
25. Svanström L. Falls on stairs: an epidemiological accident study. Scand J Soc Med 1974;2:113–120
26. Pauls JL. Safety standards, requirements, and litigation in relation to building use and safety, especially safety from falls involving stairs. Saf Sci 1991;14:125–154