People with diabetic peripheral neuropathy display a decreased stepping accuracy during walking: Potential implications for risk of tripping

Stepping accuracy and toe clearance in people with diabetes

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Conflicts of Interest

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Novelty statement

- Here we examined for the first time, a specific aspect of gait that may lead to an increased risk of tripping during walking, and which may contribute to explaining the increased fall rate in patients with diabetic peripheral neuropathy.
- We showed that patients with diabetic peripheral neuropathy are less accurate at stepping than control participants, and theorised how this may lead to a decreased ability to negotiate around obstacles.

Aims: Patients with diabetic peripheral neuropathy are five times more likely to fall than age-matched controls, however the causes for this have not yet been elucidated. The ability to direct the lower limbs where desired is important when negotiating obstacles, and has been shown to be related to the risk of falling. This study examines the stepping accuracy of people with diabetes and diabetic peripheral neuropathy.

Methods: 14 patients with diabetic peripheral neuropathy (DPN), 12 patients with diabetes but no neuropathy (D) and 10 healthy non-diabetic control participants (C) took part in the study. Accuracy of stepping was measured whilst the participants walked along a walkway consisting of 18 stepping targets.

Results: Patients with diabetes and diabetic peripheral neuropathy were significantly less accurate at stepping on targets than control participants. ($p<0.05$).

Conclusions: Impaired motor control is theorised to be a major factor underlying the changes in stepping accuracy and potentially altered visual gaze behaviour may also play a role. Reduced stepping accuracy may indicate a decreased ability to control the placement of the lower limbs, leading to patients with neuropathy potentially being less able to avoid observed obstacles during walking.

Introduction

Diabetic peripheral neuropathy (DPN) is a common complication of diabetes, characterised by sensory loss in the lower limbs, altered joint-position sensation and impaired muscular function, which can result in alterations to gait [1-3]. Patients with neuropathy are five times more likely to fall than age-matched controls, and approximately 50% of all falls are due to tripping whilst walking [4,5]. It has been suggested that the incidence of trip related falls is determined primarily by the frequency of tripping, and not the ability to recover from a trip [6]. Therefore, the most effective approach to identifying the risk of falling for a particular individual or population is to examine their ability to avoid potential tripping hazards [7,8].

Tripping can occur as a result of observed and unobserved hazards. If a tripping hazard is observed, the person must initiate and co-ordinate a response to avoid it. People with a high risk of falling have been shown to be less accurate and more variable at stepping onto defined targets [9,10]. This reduced ability to move the foot where desired may indicate an impaired control of foot trajectory, which could hinder obstacle avoidance, and ultimately increase the probability of tripping on observed hazards [7]. Causes for a decreased accuracy of stepping are expected to be multi-faceted, with altered motor control and visual gaze strategies expected to be contributory factors. Whilst visual gaze strategy has not to our knowledge been evaluated in people with diabetes, it is known that people with a high risk of falling, such as the elderly population, display differing visual gaze strategies to lower risk groups, altering where and when they look

during walking [9-11]. Previous studies have theorised that visual gaze strategy alters stepping accuracy through taking attention away from the combined positions of the feet and intended targets, but no universal agreement on the exact mechanisms currently exist [9,10].

The aim of this study was to investigate the effects of diabetic peripheral neuropathy on stepping accuracy during level ground walking. Furthermore, this study aimed to provide pilot observations of between-group differences in underlying visual gaze strategies, which may affect stepping accuracy. It was hypothesised that patients with neuropathy would display similar characteristics to other populations at a high risk of falling, displaying a decreased accuracy of stepping.

Patients and methods

Participants

Thirty six participants: 14 patients with diabetic peripheral neuropathy [DPN], 12 patients with diabetes but no neuropathy [D] and 10 healthy non-diabetic control participants [C] matched for age and BMI (Table 1.) gave their written informed consent to participate in this study, which was given ethical approval from the relevant bodies. Major exclusion criteria were open ulcers, use of walking aids, a history of other disorders affecting gait, and a visual acuity <6/18 (of any aetiology, including diabetic retinopathy; identified by performing a Snellen test)[12].

Neuropathy Assessment

The presence and severity of neuropathy was measured using two separate tests: the modified Neuropathy Disability Score (mNDS)[1], and the Vibration Perception Threshold (VPT)[1] using a neurothesiometer (Horwell, Nottingham UK). Patients were deemed to have moderate to severe neuropathy and grouped as DPN if in either one or both of their feet they displayed either an mNDS score of ≥6, or a VPT of ≥25 Volts (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 ≤5 and for the VPT of ≤24 Volts (1)(Table 1.)

Procedure

Preparation

Participants wore tight-fitting clothing (t-shirt and shorts) and therapeutic, open toe shoes with a relatively stiff footbed (Darko MedSurg, Raisting, Germany), as issued by the research team. Sixteen retro-reflective markers were attached to the participant's feet (8 on each foot) on bony prominences of the metatarsals and toes. Three dimensional marker positions were recorded by a ten-camera motion capture system recording at 120Hz (Vicon Nexus, Vicon, Oxford, UK).

Stepping accuracy task

Participants were asked to walk along a 7m long mat with brightly coloured, circular stepping targets (75mm in diameter and positioned flush to the ground) (Fig. 1), until five trials were captured, of which three were used for analysis. Each participant was given the same instructions: "walk at your natural walking speed, stepping on each of the targets as accurately as possible." Kinematic data of foot position, and analogue data of horizontal eye movement were captured from the middle six stepping targets (R4, L4, R5, L5, R6, L6) from a total of eighteen (Fig. 1)[13]. Visual gaze direction was obtained using a head-mounted eye-tracking scanner (ASL 500 mobile gaze tracking system, Bedford, MA, USA) with a sampling frequency of 50Hz, which used corneal and pupil reflections to calculate eye in orbit rotation to an accuracy of one degree.

Data Analysis

Foot stepping accuracy

Stepping accuracy was calculated as the difference between the position of the 2nd metatarsal head with respect to the calibrated centre of the targets, at foot-ground contact. Foot-ground contact was calculated manually as the point at which the trace of the vertical position of the foot reached a fixed minimum height (stance phase). The co-ordinates of the 2nd metatarsal head at foot-ground contact (medio-lateral: *x* and anterior-posterior: *y*) were subtracted from the co-ordinates of the calibrated target positions to calculate the distance of the 2nd metatarsal head from the target. Using the square root of the two squared distances (*x* and *y*), the hypotenuse of the triangle, the absolute distance between the target and the 2nd metatarsal head, was calculated.

Visual acquisition parameters

Data from twelve participants (C: 4; D: 4; and DPN: 4 [216 saccades analyzed in total: 18 saccades per participant]) were used for analysis of visual acquisition. Data were obtained from a sub-sample of the cohort due to a number of issues including the time-consuming nature of these measurements precluding assessment in all participants; non-spherical corneal shape as the result of surgery in some participants, and eyelashes covering the eyes during the tests in other participants. Because of the small cohort of participants, the results are presented as preliminary pilot data.

Two points in the horizontal signal of the eye movement trace were identified: the initial visual acquisition of the target (start of visual acquisition), and the point at which gaze

was subsequently directed away from the target (visual acquisition end). These events were identified using the second derivative of the eye position signal, i.e. the eye acceleration peak at saccade onset. By using the timing of when each individual target was visually acquired, and when gaze was subsequently directed away, four separate variables were obtained: the time between visual acquisition of the target and foot-target contact; the time between the subsequent saccade away from the target with respect to foot-target contact; the time spent looking at the target (fixation duration); and the time taken to transfer gaze between targets.

Statistics

Group differences were tested using a one-way analysis of variance (ANOVA) with a Bonferroni post-hoc test, and all significances reported with respect to the control group. Values are presented as means ± SD; significance was set at $p<0.05$. The level of agreement between stance time during the stepping task and visual gaze cycle time was tested using a Pearson's correlation.

Results

Stepping Accuracy (Fig. 2)

Patients with diabetes (with and without neuropathy; D and DPN groups) were less accurate at stepping, and contacted the ground significantly further away from the centre of the target than the control participants (C:38±31mm, D:60±37mm, DPN:56±36mm; $p<0.05$; power = 0.85).

Visual Acquisition Parameters (Fig. 3)

Markedly different stance times were observed in the cohort providing visual gaze data, compared to those observed for the larger cohort (Table 1; stance time (b)), which was anticipated may impact on the interpretation of visual gaze results presented in absolute time. Visual cycle duration correlated very highly with stance time of these participants ($r = 0.99$; Table 1.). Therefore, the results have been presented as a percentage of the visual gaze cycle, to elucidate the visual gaze strategy independent of differences in stance time.

Patients with neuropathy visually acquired the targets significantly later (C:-87±8%, D:-78±2%, DPN:-67±10%), and remained looking at the targets until significantly later than the control participants (C:0±8%, D:2±8%, DPN:10±13%). The patients with diabetes also looked away from targets significantly later than the control participants, but visually acquired the target at a similar period before foot-target contact. Both the diabetes and diabetic peripheral neuropathy groups spent significantly less time looking

at the target in total (C:87±2%, D:79±4%, DPN:77±8%), and took significantly longer to look between targets ($p<0.05$) compared to the control participants (C:13±2%, D:21±4%, DPN:23±8%) (Fig. 3b).

Discussion

Patients with diabetes and diabetic peripheral neuropathy (DPN) are less accurate at stepping than control participants. This may increase the risk of tripping on observed obstacles. Reduced motor control and altered visual gaze strategies are expected to be a major contributory factor to the decreased stepping accuracy observed in patients with neuropathy.

Patients with neuropathy display a number of functional deficits affecting motor control and gait. The reduced speed and coordination at which movements can be performed in people with diabetic neuropathy are contributed to by a number of factors: reduced joint range of movement, decreased muscle strength, decreased ability to rapidly develop strength and a reduced nerve conduction velocity [14-18]. Furthermore, patients with neuropathy also display a decreased proprioception, which may impair awareness and control of lower limb joint position and orientation during stepping in both normal walking, and when negotiating an obstacle [19-21].

Decreased stepping accuracy in other high fall risk groups has previously been explained by altered visual gaze patterns. Yamada *et al.* identified that the elderly patients' fixation on imminent targets hindered their ability to plan footfall for future targets [9], whilst conversely, Chapman & Hollands concluded that the planning of future movements affected the accuracy of ongoing movements in elderly adults [10]. In the present study we examined visual gaze behaviour in a sub-sample of participants to

provide insight for its potential contribution towards stepping accuracy. These data, however, should be treated with caution due to the small sample size and considered as pilot data to be confirmed by future work. These data showed that patients with neuropathy displayed a more ‘hesitant’ visual gaze strategy, by continuing to look at targets until after foot-target contact, before re-directing gaze to the next target, possibly in an attempt to ensure foot-target contact (Fig. 3)[22]. This contrasts with the ‘confident’ visual gaze strategy observed in the control participants, who re-directed gaze away to the next target immediately upon foot-step contact, indicating a confidence in their ability to step accurately. Patients with diabetic neuropathy also displayed an increased time interval to look between targets. The combination of looking away from the target later, and taking longer to look between targets, may therefore explain why patients with neuropathy are slower to initially visually acquire the target, resulting in a decreased total time spent looking at the target. Bearing in mind the preliminary nature of these visual gaze data, the decreased time available to look at the target during the approach may have hindered co-ordination of an appropriate motor response, contributing to altered swing trajectories of the lower limbs, and ultimately resulting in a reduced stepping accuracy.

Diabetic controls were slightly less accurate at stepping than patients with diabetic neuropathy, and may indicate that diabetic controls displayed some of the altered motor control characteristics of patients with neuropathy before sensory neuropathy is clinically observed, and before this population are aware of their decreased ability to control trajectory of the swinging leg. Bearing in mind the preliminary nature of the

visual gaze data, the reduced stepping accuracy in diabetic controls may potentially be related to a less effective specific aspect of the visual gaze strategy than neuropathy patients. This visual gaze strategy in diabetic controls (looking away from the target sooner after foot-target contact than patients with neuropathy) could potentially be regarded as an ‘over-confident’ strategy that may have adversely affected their stepping accuracy, since this was significantly worse than in healthy controls, and even slightly less accurate than neuropathy patients. The combination of altered motor control of the lower limbs and an ‘over-confident’ visual gaze strategy may potentially explain the poor accuracy of stepping in this diabetic control population. However, although differences in the visual gaze strategy were clearly evident between groups, these data should be treated with caution and considered as preliminary findings due to the small cohorts for this parameter. Impaired motor control is expected to be a major factor in reducing stepping accuracy in patients with diabetes, and particularly neuropathy, which may indicate an impaired ability to avoid any potential upcoming obstacles during walking. An altered visual gaze strategy is a potential explanatory factor for the reduced stepping accuracy that needs to be confirmed by future research.

Whilst the probability of tripping was not directly measured in this study, these gait characteristics may indicate a reduced ability to avoid observed obstacles, posing a particular risk to patients with neuropathy. Future studies should therefore look to examine the actual ability of patients to avoid obstacles when walking. Previous studies in other (non-diabetic) populations have shown that balance can be improved and visual gaze strategy can be altered using such training, which could improve safety [13,23]. An

intervention that aims to modify motor control and visual gaze strategy may improve the ability to observe upcoming obstacles and increase the accuracy of stepping, although this is also an area for further study. Specifically, a resistance exercise training-based element may improve control of the foot and ankle during walking, and improve avoidance of any tripping hazards.

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Conflicts of Interest

The authors certify that they have NO affiliations with or involvement in any organisation or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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Figures

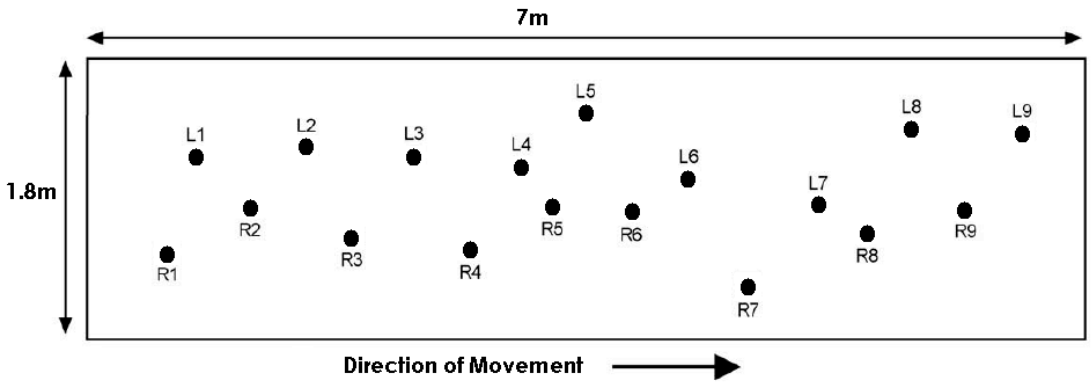

Figure 1. Diagram of the stepping walkway used for the stepping accuracy task. Targets are numbered in order of contact; with 'L' denoting left foot contact (green target) and 'R' denoting right foot contact (red target).

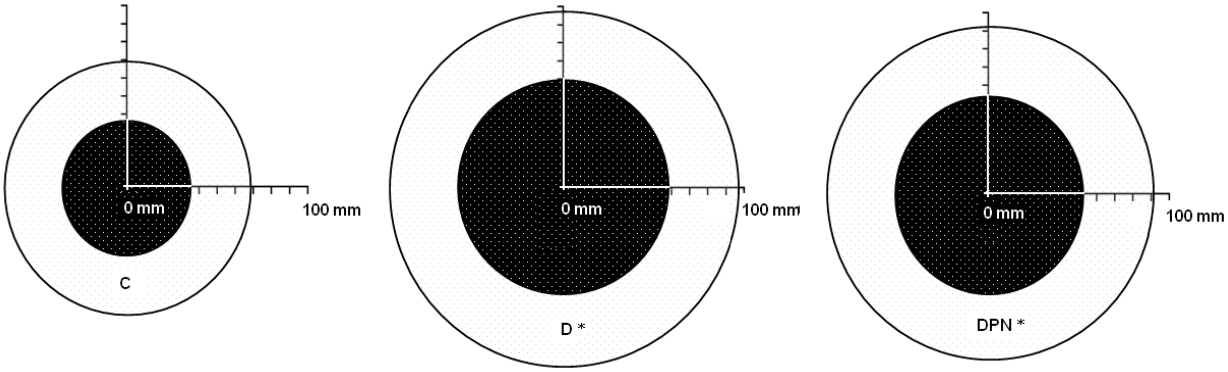

*Figure 2. Group differences in stepping accuracy for controls (C; n=10), patients with diabetes but no neuropathy (D; n=12), and patients with diabetic peripheral neuropathy (DPN; n=14). The black inner circle denotes the mean distance from the centre of the target (0), and the white outer circle denotes the standard deviation. * denotes significantly different group mean accuracy compared to the control group ($p<0.05$).*

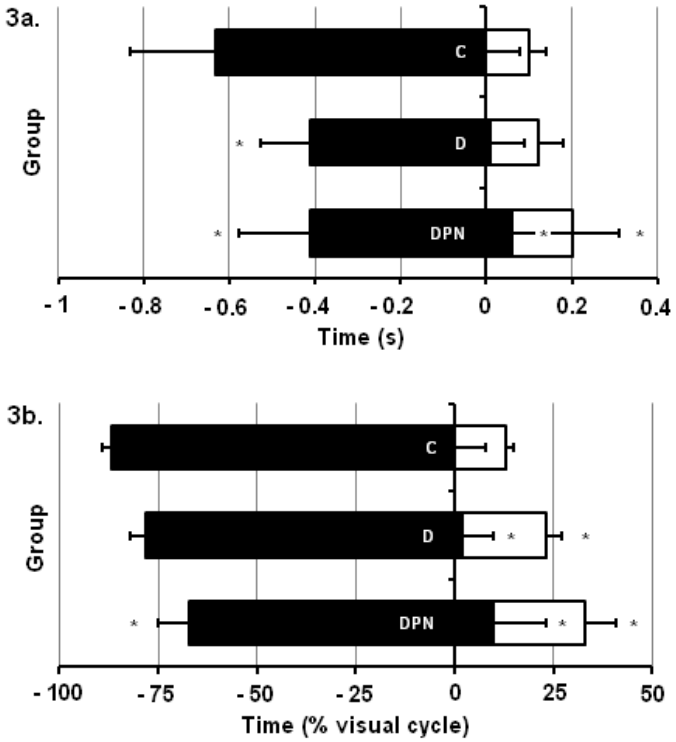

*Figure 3. Target visual acquisition parameters during the stepping task for controls (C; n=4), patients with diabetes but no neuropathy (D; n=4), and patients with diabetic peripheral neuropathy (DPN; n=4). Values are means and standard deviations. 3a displays the results in absolute time and 3b displays the results as a percentage of the entire visual gaze cycle. The black bars denote visual fixation of the target, and the white bars denote the time looking between targets, with the end of the white bar denoting the acquisition of the next target. * denotes significantly different compared to control group ($p<0.05$).*