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Single Sensor Gait Analysis to Detect Diabetic Peripheral Neuropathy: A Proof of Principle Study

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This study explored the potential utility of gait analysis using a single sensor unit (inertial measurement unit [IMU]) as a simple tool to detect peripheral neuropathy in people with diabetes. Seventeen people (14 men) aged 63±9 years (mean±SD) with diabetic peripheral neuropathy performed a 10-m walk test instrumented with an IMU on the lower back. Compared to a reference healthy control data set (matched by gender, age, and body mass index) both spatiotemporal and gait control variables were different between groups, with walking speed, step time, and SDa (gait control parameter) demonstrating good discriminatory power (receiver operating characteristic area under the curve >0.8). These results provide a proof of principle of this relatively simple approach which, when applied in clinical practice, can detect a signal from those with known diabetes peripheral neuropathy. The technology has the potential to be used both routinely in the clinic and for tele-health applications. Further research should focus on investigating its efficacy as an early indicator of or effectiveness of the management of peripheral neuropathy. This could support the development of interventions to prevent complications such as foot ulceration or Charcot's foot.

Keywords: Accelerometry; Diabetes complications; Diabetic neuropathies; Gait

INTRODUCTION

Diabetic peripheral neuropathy (DPN) affects over 50% of people with diabetes mellitus [1]. DPN can lead to reduced independence, lower rates of perceived health and higher mortality rates [1,2] as well as a range of complications including neuropathic ulceration, Charcot's feet, and eventual lower limb amputation. DPN itself often begins years before a formal diagnosis is made [2]. Timely identification of DPN enables the introduction of preventative management, education, and advice measures, which can reduce the rate of the complications of DPN. However, many individuals are not diagnosed with DPN promptly, and hence fail to receive timely intervention [3].

The effect DPN has on gait is highlighted in recent systematic reviews [4,5]. However, whilst the reviews demonstrate temporal-spatial gait parameters are significantly affected by DPN [4], gait analysis does not have sufficiently utility to be used routinely in primary clinical settings. This may be partly due to most objective gait analysis reliant on technology such as pressure mats, specialised treadmills, or laboratories with optical motion capture and force measurement, being time, space and resource intensive and thus a barrier to routine practice [6]. Inertial measurement units (IMUs) are relatively cheap, robust, and easy to use, and also contained within smart phones, opening the possibility for a telehealth application [7]. The data obtained from IMU can be used to estimate temporal-spatial

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gait parameters and provide sensitive data indicative of gait deficits found in various neurological pathologies [7-10]. However, these methodologies have yet to be explored in a primarily DPN pathology.

We propose that gait screening may have the potential to aid in the detection and monitoring of DPN, supporting interventions to prevent complications associated with the diabetic foot, which could increase mobility function and quality of life as indicated by results in other neurological conditions [11,12]. Due to the novelty of the proposed gait assessment mythologies in this area, we set out to test the principle that single, torso-mounted, IMU gait analysis can differentiate those with DPN from age and body mass index (BMI)-reference data in the clinical setting.

METHODS

Participants

People were recruited from the Oxford Centre for Diabetes, Endocrinology & Metabolism (OCDEM) at the Oxford University Hospitals NHS Foundation Trust (Oxford, UK). Inclusion criteria were (1) a clinical diagnosis of DPN (diagnosed on the basis of clinical history and physical examination including tests of light touch and vibration sensation in line with international guidelines [13]); (2) failure of the monofilament test (10 and 75 g); and (3) a score of ≥8 on the Rivermead mobility index and able to walk independently with or without walking aid. Exclusion criteria were (1) a history of amputation or active ulcers (those with previously healed ulcers were eligible); (2) insufficient capacity to consent or uncontrolled psychiatric symptoms; (3) confounding gait factors such as neurological conditions, knee replacements, amputations, or padding; and (4) pregnancy. The study was conducted according to the Declaration of Helsinki and received National Research Ethics Committee approval (NRES: 11/SC/0218).

Reference control data were extracted from a database held by Oxford Brookes University (BIG Database, Oxford, UK). The database consists of data from 2,030 individuals aged between 5 and 80 years with no known pathology affecting gait primarily obtained from visitors to the Science Museum London from April to July 2012 (UREC: 100490). The data base can be interrogated to provide reference data according to desired demographic. Healthy ageing gait performance has been well described in the literature generally resulting in slower gait [14] and reduced gait symmetry [15], with similar results also reported for those with higher subcutaneous thigh fat [16] as well as for DPN [4]. Therefore, based on available demographic data age (REF_{AGE}) and BMI (REF_{BMI}) reference data was extracted from the database, whereby all individuals within 1 standard deviation of age and BMI of the DPN group were included.

Assessment

After obtaining informed consent, demographic data of gender, age, height, weight, shoe size, leg length, time since diabetes diagnosis, Rivermead mobility index, and Barthel index were obtained.

Gait analysis for both groups was performed during a standard 10-m test by attaching an IMU to the lower back that sampled triaxial accelerometer and gyroscope data at a frequency of 100 Hz. Assessment for those with DPN took place at OCDEM in a corridor free from obstacles. Further methodology on how gait parameters were derived has been previously extensively described [8-10,17,18].

Spatiotemporal parameters derived were step time (ms), cadence (steps/min), stride length (m), and walking speed (m/s).

Gait control parameters calculated were beta (deg), SDa (au), SDb (au), ratio (au) [10], and walk ratio (mm/[steps/min]) which have been described as indicators of neuro motor control [19].

Statistical analysis

Group differences were assessed by means of independent samples *t*-test or chi-square statistic. Discriminatory power was further investigated using receiver operating characteristic (ROC) curves, by means of the area under the curve (AUC). Statistical analysis was performed using, compare means, cross tabs, and ROC curve procedures in SPSS version 22 (IBM Co., Armonk, NY, USA).

RESULTS

Descriptive data

Seventeen people (14 men) with DPN and 42 (30 men) controls were included in analysis 63.2±9.2 years (mean±SD). There was no difference in age, gender ratio, height, or BMI between groups ($P>0.05$) (Table 1). DPN was confirmed by none of the participants responding to the 75 or 10 g monofilament test performed by a specialist diabetes podiatrist [20]. Baseline glycosylated hemoglobin was 8.8%±1.0% (73.3±11.5

Table 1. Descriptive data

Demographic	DPN (n=17)	Control (n=42)	Delta[a] (P value)
Age, yr	63±9 (46–81)	61±4 (54–72)	2±2 (0.307)
Sex, male:female	14:3	30:12	X^2 (0.883)
Height, m	1.78±0.9 (1.56–1.91)	1.77±0.9 (1.49–1.93)	0±0 (0.882)
BMI, kg/m^2	33.6±7.6 (24.1–51.7)	31.6±3.9 (25.1–44.6)	2.0±1.9 (0.320)
Time since diagnosis diabetes	24±13 (3–49)	-	-
Barthel index	19±1 (15–20)	-	-
RMI	13±2 (9–15)	-	-

Values are presented as mean±standard deviation (range).
DPN, diabetic peripheral neuropathy; BMI, body mass index; RMI, rivermead mobility index.
[a]Delta (between group difference; DPN–Control) reported with P value of independent samples t-test or for nominal data P value for chi-sqaure statistic reported.

Table 2. Gait assessment data

Gait parameter	DPN	Control	P value[a]	ROC-AUC (95%CI)	ROC P value[b]
Spatiotemporal					
Step time, msec	650±117	543±47	0.002	0.804 (0.657–0.950)	>0.001
Stride length, m	1.33±0.16	1.41±0.17	0.066	0.632 (0.466–0.799)	0.114
Cadence, steps/min	95±16	112±10	0.001	0.797 (0.650–0.944)	>0.001
Walking speed, m/sec	0.85±0.23	1.34±0.18	>0.001	0.975 (0.943–1.000)	>0.001
Control					
Beta	27±10	34±10	0.014	0.735 (0.600–0.870)	0.005
SDa	1.98±0.36	3.91±1.99	>0.001	0.849 (0.748–0.950)	>0.001
SDb	0.56±0.14	0.91±0.56	>0.001	0.667 (0.533–0.800)	0.046
Ratio	3.67±0.94	4.86±2.30	0.044	0.782 (0.649–0.914)	0.001
Walk ratio	7.2±1.1	6.4±1.0	0.012	0.696 (0.551–0.841)	0.019

Values are presented as mean±standard deviation.
DPN, diabetic peripheral neuropathy; ROC-AUC, receiver operating characteristic area under the curve; CI, confidence interval.
[a]Independent samples t-test probability value, coefficient reported, with 95% confidence intervals, [b]Receiver operating characteristic probability value.

mmol/mol) and all patients had evidence of microvascular disease (pre-proliferative retinopathy or urinary microalbuminuria). The majority (eight people) scored 14 on the RMI which indicated little impairment to functional mobility, but not able to run or walk fast without a limp.

Gait analysis

Comparison between DPN and control groups can be found in Table 2, differences were found for all spatiotemporal and control variables except for stride length (P<0.05). Walking speed produced the greatest discriminatory power (AUC=0.975), with good discriminatory power (AUC >0.8) also found for step time and SDa and fair discriminatory power (AUC >0.7) found for cadence, beta, and ratio.

DISCUSSION

This proof of principle study found, for the first time that a single IMU used in the clinical setting during a 10-m walk has the potential to discriminate those with DPN compared to healthy walking.

We intentionally selected those with established DPN in order to determine if we could detect the spatiotemporal gait deficits previously described in this population and found our

results were similar to those reported in recent reviews [4,5]. Interestingly, in our DPN cohort, with minimal functional mobility deficits, walking speed was the most sensitive parameter and average walking speeds in the DPN group was just above the 0.8 m/sec cut-off indicative of frailty in the elderly [21]. Furthermore, this reduction in walking speed can be primarily attributed to temporal rather than spatial changes, as no significant difference were found in stride length compared to control. A previous study, also using a single lower back mounted IMU to measure gait, in those with diabetes but excluding those with DPN, found the reduction in walking speed compared to control was primarily due to spatial gait changes, as they found no significant difference in cadence but a significantly reduced stride length [22]. Whilst, we cannot generalise from this proof of principle study these results are consistent with the results of a recent meta-analysis that gait deficits differ between people with diabetes with and without DPN [5].

Non-linear gait measures may offer further insight into gait dynamics in diabetes than revealed by traditional spatial temporal measurement. Khalaf et al. [23] derived gait entropy from the plantar pressure wave forms during stance and found an entropy was difference between those with DPN and those with diabetes without complication. In the current study we employed a non-linear approached that utilizes the dynamic similarity of the periodic wave forms produced by the centre of mass during walking, that can easily and rapidly be obtained through placing an IMU on the lower back of the participant. Whilst, this is the first time this methodology has been applied in DPN, it has have been previously shown utility in neurological populations in determination of gait control parameters that have shown to be sensitive to subtle gait disturbances in movement disorders [8,9]. The 'ratio' parameter has been found to differentiate those with the Huntington's gene but not displaying symptoms from healthy control walking [9] and in Parkinson's disease SDa was found to account for differences with healthy walking [10]. In the current study, we found SDa had good discriminatory power, with beta and ratio parameters having 'fair' discriminatory power. These the results are encouraging that DPN may present with a characteristic signature and warrant further investigation in those with less severe or pre-symptomatic DPN. In addition these gait measures in combination with assessments of the severity of the neuropathy such as monfiliment, vibration pressure threshold, and biothersiometer techniques may improve our understanding of the functional effects of the pathology and support more efficient diagnosis and monitoring.

Our results demonstrate that a relatively cheap, easy to use single sensor approach can differentiate those with severe DPN over a short-distance walking test when compared to age and BMI matched reference data. Indeed whilst, the potential benefits of large scale gait analysis 'in the field' and reference databases have been proposed, to date no suitable methodology has been established [24]. A simple methodology, such as the one presented, might assist with identification of those at risk and facilitate earlier diagnosis DPN resulting in a more efficient management. Future studies are therefore indicated and should focus more on people at risk off or with mild DPN. Longitudinal studies may provide insights into interindividual changes and define parameters which identify when a person with diabetes has clinically relevant neuropathy and the utility of the technology for clinicians 'in the field' and for telehealth applications.

CONFLICTS OF INTEREST

Oxford Brookes University hold UK, EU, and USA Patent (PCT/GB2009/051767) on the methods used to transpose and integrate data inertial data. Patrick Esser, Johnny Collett, and Helen Dawes are inventors on patent.

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