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Novel dynamic peak and distribution plantar pressure measures on diabetic patients during walking

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ABSTRACT

Diabetic peripheral neuropathy (DPN) is a common complication leading to foot ulceration and amputation. Several kinematic, kinetic and plantar pressure measures have been proposed for DPN detection, however findings have been inconsistent. In this work, we present new shape features that capture variations in the plantar pressure using shape and entropy measures to the study of patients with retinopathy, DPN and nephropathy, and a control diabetic group with no complications. The change in the peak plantar pressure (PPP) position with each step for both feet was represented as a convex polygon, asymmetry index, area of the convex polygon, 2nd wavelet moment (WM2) and sample entropy (SamEn). WM2 and the SamEn were more sensitive in capturing variations due to presence of complications than the area and asymmetry measures. WM2 of the left heel (median: 1st IQ, 3rd IQ): 8.27 (4.6,14.8) and left forefoot: 9.2 (2.4,16) were significantly lower for the DPN group compared to the control (CONT) group (heel 11.9 (5.0,16.4); forefoot: 10.3 (4.4,21.3), $p < 0.05$). SamEn for the DPN group was significantly lower in the right foot compared to the left foot (1.3 (1.26, 1.37) and 1.33 (1.26,1.4), $p < 0.01$) compared to CONT (right foot: 1.37 (1.24,1.45) and left foot: 1.34 (1.25,1.42), $P < 0.05$). These new shape and regularity features have shown promising results in detecting diabetic peripheral neuropathy and warrant further investigation.

1. Introduction

Diabetic peripheral neuropathy (DPN) is the most common complication of diabetes mellitus (DM), affecting as many as 60% of patients, and is considered as the greatest source of morbidity and mortality in diabetic patients. DPN is characterized by damage to the peripheral nervous system resulting in reduced peripheral sensation, hence compromising the proprioceptive feedback control of human locomotion. It manifests in several forms, including sensory, focal or multifocal neuropathy and is diagnosed using a monofilament test, nerve conduction, ankle and knee reflex testing and vibration perception threshold [1]. However, there continues to be a gap in accurate/reliable measures for the quantification of the effect of diabetic complications on the foot during gait. Previous studies have used kinematics, kinetics and plantar pressure to determine foot health as well as EMG to study gait variations [2] but inconsistent results of these conventional methods render them not useful for systematically diagnosing gait abnormalities associated with DPN nor for the prediction of diabetic foot ulceration [3–5]. Several studies have reported reduced peak power and moment at the ankle joint, while others reported no changes [6]. Furthermore, the peak plantar pressure (PPP), which is currently the primary quantitative gait measure used for plantar ulcer prediction may not be predictive of ulcer recurrence and amputation [7]. Several studies have also highlighted that foot ulcers do not necessarily occur at peak pressure sites but may occur at sites that experience normal plantar pressure [7]. This finding was substantiated by reports that PPP was not significantly different between DPN patients and diabetes mellitus patients with no neuropathy at the heel region,

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although it was significantly higher for DPN patients at the forefoot [8,9]. A single point measure of PPP as currently applied in clinical assessment is also known to vary in association with gait speed and several other factors, which makes it a poor indicator, particularly considering that currently there is no specific clinically adopted threshold for PPP that predicts the development of foot ulceration [7]. Therefore, dynamic measures of PPP may provide better and more accurate information on pathophysiological changes associated with DPN and risk of plantar ulceration.

Patients with DPN are more likely to present with diabetic associated comorbidities [10]. The most often diagnosed complications of diabetes are nephropathy, foot problems and retinopathy. These complications have been shown to have some common causes but the effect of diabetic complications and their interaction with DPN on gait and plantar pressure variation has not been fully studied. A number of studies have investigated gait alterations associated with retinopathy and autonomic neuropathy [11]. Those typically looked at balance, falls and gait instability. Therefore, measuring variables that further characterize altered gait in diabetes may be relevant to predict the risk of ulceration before the presentation of clinically detectable neuropathy [4]. Nephropathy may have an effect on gait due to the associated uremia, which affects the peripheral sensory, motor and autonomic nervous systems [12,13]. Investigation of the variations (dynamics) of the plantar pressure location and distribution across the plantar surface of the foot (rather than a single measure of magnitude) correlated to diabetic patients characterized by the presence of different comorbidities and combinations of these may shed light on the role of gait alterations on plantar pressure and hence risk of ulceration in patients with T2DM.

Shape analysis such as SamEn has previously been successfully used to monitor the dynamics in several biological systems including gait [14]. Fourier descriptors and wavelets have also been successfully applied to two-dimensional shape analysis. The continuous wavelet transform (CWT) is a signal and image-processing tool that has been extensively applied in many different fields including neuroscience, finance and astronomy. Due to its ability to detect singularities, CWT is a powerful tool for image segmentation and feature extraction [15]. The continuous-point method derived from CWT has also been useful for clinical diagnostics of a wide range of morphological deformities in clinical practice including craniostenosis and brachiocephaly [16]. Previous research has investigated changes in plantar pressure distribution in DPN during standing and walking including pedobarographic statistical parameter mapping (pSPM) [7,17,18]. The pSPM illustrates the distribution of the plantar pressure during gait. The proposed shape features of the current study extend pSPM by providing numeric results that are normalized and useful as a clinical descriptors of PPP variation during walking and highlight PPP variability as a function of walking by simple convex hull representations that indicate the complexity of PPP variability across the plantar surface of the foot.

2. Methods

2.1. Subjects

Type 2 Diabetes Mellitus (T2DM) patients were enrolled in this study. Plantar pressure (PP) data was collected from 211 T2DM patients (136 females and 75 males) at Sheikh Khalifa Medical Center (SKMC) and Mafraq Hospital in Abu Dhabi, United Arab Emirates between July 2014 and May 2015. The study was approved by the Institutional Ethics Committee of SKMC and Mafraq Hospital (REC-04062014 and R292 respectively). Each volunteer agreed to take part in this study after a briefing session, upon which each signed an informed consent form that had been approved by the ethics committees. Diagnosis of T2DM was based on the patients' medical records. The presence of diabetic associated complications was confirmed by a qualified physician, based on the criteria outlined by the World Health Organization (WHO) consultation group report [19].

Three types of diabetic complications were considered: 1) peripheral neuropathy, 2) retinopathy, and 3) nephropathy. The patients were categorized into 8 groups: 1) ALL-C group which included patients with retinopathy, nephropathy and peripheral neuropathy, 2) RNp: which included patients with retinopathy and nephropathy, 3) DPNNp: patients with peripheral neuropathy and nephropathy, 4) RDPN: patients with retinopathy and neuropathy, 5) DPN: patients with peripheral neuropathy, 6) R: patient with retinopathy, 7) Np: patients with nephropathy, and 8) a control group (CONT), which included patients with none of the three complications. Peripheral neuropathy was diagnosed using a monofilament test and response to ankle and knee reflex testing [20]. Retinopathy was defined as either white or red lesions or both present in the retina according to WHO criteria [21]. The presence of nephropathy was determined by urine albumin level higher than 20 μg/min for microalbuminuria and higher than 200 μg/min for macroalbuminuria or if the estimated glomerular filtration rate (eGFR) was less than 60 mL/min/1.73 m^2.

2.2. Data collection and processing

Patients walked twice with their normal speed on the Tekscan multisensory portable gait assessment system (Walkway from Tekscan Inc., MA). Each trial contained 2–3 step cycles. The Tekscan walkway captured the spatial distribution of the plantar pressure for each step with a frame rate of 30 frames per second. The normalized (x,y) position of the PPP in the heel and forefoot regions for each foot and step taken as shown in Fig. 1 was extracted from the data using a purpose written Matlab code (Mathworks Inc., MA). To account for differences in the size of the feet across patients and for left and right foot variations, position normalization was carried out. Two convex polygons representing the variation in the PPP (x,y) position of the heel and forefoot regions were constructed for each foot using the built-in "convexhull" function and three shape features computed. These were the area of the convex polygon (*A*), the Asymmetry Index (*AI*), which was defined as the ratio between the longest distance

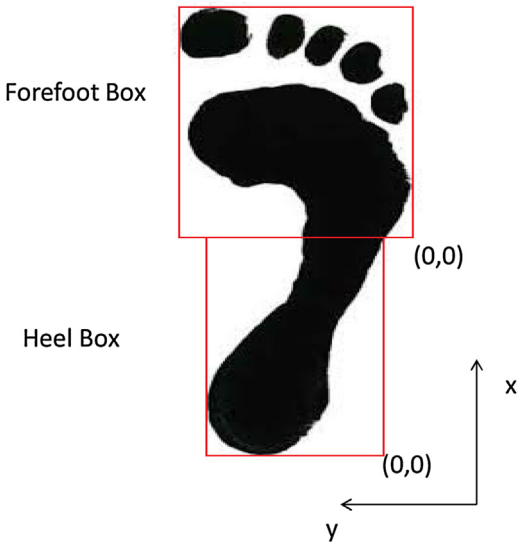

Fig. 1. Forefoot and heel boxes of the foot. In each box, the PPP normalized x and y positions from the origin of the box were determined.