Plantar Pressure Gradient Angles to Evaluate Risk of Diabetic Foot Ulcer

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Abstract. Diabetic foot ulcers remain one of the most serious complications of diabetes mellitus. Peak pressure gradient (PPG) has demonstrated to contribute to the development of diabetic foot ulcers. This study used the time-varying directions of instantaneous PPG angle to evaluate the risk of diabetic foot ulcers. A total of 14 participants were studied, including 7 diabetics and 7 non-diabetic controls. The peak plantar pressure (PPP), PPG, and PPG angle at the great toe were calculated from plantar pressures obtained by the F-scan plantar pressure measurement system during walking. The results showed that the PPP and PPG in the diabetics were significantly higher than in the controls, but the PPG angle in the diabetics was significantly lower than in the controls. This study provides evidence that the diabetics are associated with higher PPP and PPG and lower PPG angle as compared to non-diabetics. The proposed PPG angle may improve our understanding of the influence of PPG on the risk for diabetic foot ulcers.

Keywords: diabetic foot ulcers, peak pressure gradient, plantar pressure.

1 Introduction

Diabetes mellitus (DM) is the seventh leading cause of death by disease in the United States [1]. The one of most serious complications of DM is the diabetic foot ulcers [2]. DM causes not only a reduced or loss of protective sensation in the foot, but also changes in the soft tissues of the foot as well as the dryness of the skin, that can lead to excessive formation of callus. These changes affect ambulatory function that may lead to a high peak plantar pressure (PPP) in diabetics. The repetitive high PPP insults to the plantar surface of the diabetic foot have been shown to be associated with the development of foot ulcers. However, Lavery and colleagues [3] suggested that the plantar pressure alone is not adequate to predict the development of skin breakdown and other factors should be explored.

Mueller and colleagues [4] introduced the peak pressure gradient (PPG) to further quantify the changes of plantar pressure distributions in diabetics. The high PPG may contribute to the skin breakdown because they cause large shearing stresses within the

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plantar soft tissues [4]. Although the introduction of the PPG concept has provided a new assessment to understand the development of diabetic foot ulcers, the quantification of the PPG patterns require further investigation and classification [5]. For example, the current definition of the PPG does not quantify the time-varying directions of instantaneous PPG angle (PPG angle), which may be used to estimate the plantar shear directions.

Shear stresses may be an important factor in locating where the skin breakdown occurs in diabetics [6]. The measurement devices of the plantar shear stress are currently being used only in the research environments due to a large size of the sensors [7-9]. However, the PPP and PPG measurements, based on the thin sensors of the plantar pressure mapping device, are easier to obtain in the clinical settings [4, 10, 11]. The PPG may be used to estimate the shear stress for predicting potential trauma to the plantar soft tissues [11, 12]. We postulate that the PPG angle may provide additional information to quantify the PPG patterns. Theoretically, the PPG angle may increase at the distraction of the pressure in concert (Fig. 1a), and decrease at the concentration of the pressure in indentation (Fig. 1b). The purpose of this study was to develop a new method to quantify time-varying directions of instantaneous PPG as defined as the PPG angle in this study in diabetics with peripheral neuropathy.

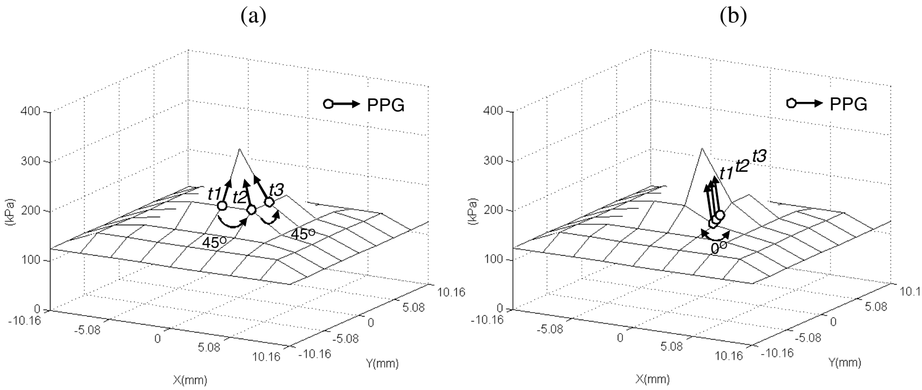

Fig. 1. The time-varying directions of peak plantar gradient (PPG). (a) Distraction pattern: the angles of the time 1 to time 2 is 45° (*t1-t2*), and time 2 to time 3 is 45° (*t2-t3*). (b) Concentration pattern: the angles of the time 1 to time 2 is 0° (*t1-t2*), and time 2 to time 3 is 0° (*t2-t3*). Although the PPG values in (a) and (b) are close, the average of the changes in angles, PPG angles, are very different (45° v.s. 0°).

2 Methods

2.1 Participants

Fourteen volunteers were recruited, including 7 type 2 diabetics (3 males) and 7 non-diabetic healthy controls (4 males). Subjects with gross foot deformities (except minor toe clawing) and prior foot amputations/major surgeries were excluded for a more homogeneous population. The demographic data of the control group were: age 23.1±3.4 years, weight 60.8±14.0 kg, height 1.66±0.12 m, body mass index (BMI) 21.9±3.7 kg/ m2. The demographic data of the diabetic group were: age 44.7±11.9 years, weight 85.3±19.9 kg, height 1.68±0.08 m, BMI 30.1±6.9 kg/m2. The fasting blood glucose level and duration of diabetes were 143.3±61.0 mg/dL and 7.3±7.6 years. All diabetics had peripheral neuropathy as confirmed by inability to sense a 5.07 Semmes-Weinstein monofilament on at least four locations of the plantar foot. This study was approved by an institutional review board. The research protocol was explained to the volunteers who signed an informed consent form.

2.2 Plantar Pressure Measurements

The F-scan system (Tekscan, Boston, MA, USA) was used to collect the plantar pressures data during walking at a self-selected pace in standardized shoes (Fig. 2) [13-15]. Each F-scan in-shoe sensor contains 960 sensing pixels. The size of each pixel is 5.08 x 5.08 mm. A sensor was placed between the subject's sock and the insole of the shoe. All subjects wore ambulatory shoes with a 1-inch heel (Altrex, Teaneck, NJ). The shoe was worn with its standard insert and a thin cotton sock. Subjects wore the sensor inside the shoe for 3-5 min walking before calibration for adequate sensor acclimatization [13, 14]. The sensor was calibrated according to the manufacturer's guidelines. Subjects were allowed to walk at their chosen walking speed, and data were collected at 200 Hz during two walking trials immediately after calibration.

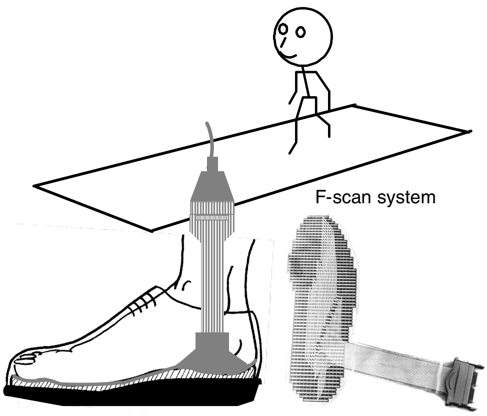

Fig. 2. The F-scan system was used to collect the plantar pressures data during walking at a self-selected pace in standardized shoes

2.3 Data Analysis and Statistics

ASCII files with data from the three middle steps were processed by Matlab codes to determine the PPP and PPG in the 1st toe regions at risk for diabetic foot ulcers [16, 17]. The pressure was determined in a defined area [a 3x3 box of F-Scan sensels

(231.3 mm2)] around the nodes (spacing equal to half the length of the sensor) which were generated using the bicubic polynomial spline function. A pressure data on the plantar surface of the foot may be characterized by the PPP and PPG. The PPP is defined as equation (1)

$$PPP = max\ (p) \tag{1}$$

where p is the pressure distribution on the plantar region surface. The PPG was calculated by determining the greatest difference in pressure from one node (half sensel apart) to the next according to rows, columns, and by diagonal (Fig. 3) [4]. The PPG at the PPP locations can be calculated as equation (2)

$$PPG = max\ \left(\frac{\partial p}{\partial r} \bigg| \left(x_p, y_p \right) \right) \tag{2}$$

where $(\partial p / \partial r) \mid (x_p, y_p)$ (space rate of change of pressure on the plantar surface) is the directional derivative of pressure p at the node of the plantar region (x_p, y_p) on the plantar surface in any direction given by the vector $\vec{r}$. Each node accompanies eight pressure gradients in eight directions. The time-varying directions of the PPGs (PPG angle) (Fig. 3) was the average of the changes in angles as equation (3).

$$PPG\ angle = \frac{1}{N-1} \sum_{i=1}^{N-1} (\alpha_{i+1} - \alpha_i) \tag{3}$$

where N is the time over the half of the peak pressure gradient, where α is the angle of the PPG direction in the time of i.

The differences in the PPP, PPG, and PPG angle between diabetics and controls were examined using the Student t test [18, 19]. The values were presented as the mean ± standard deviation. The level of the significance was set at 0.05.

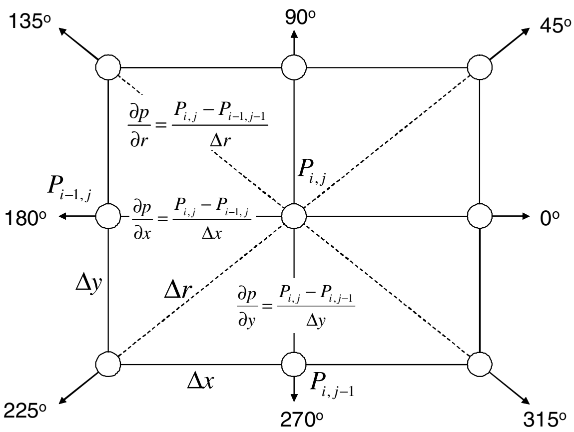

Fig. 3. Calculation of the Peak pressure gradient (PPG) and the time-varying directions of the PPGs (PPG angle)

3 Results and Discussion

The PPP value at the 1st toe was significantly greater in the diabetics (566.2±234.8 kPa) as compared to the controls (313.9±104.2 kPa, p<.05, Fig. 4A). The PPG value at the 1st toe was significantly greater in the diabetic group (128.9±53.8 kPa/mm) as compared to the control group (51.5±16.5 kPa/mm, p<.05, Fig. 4B). The PPG angle at the 1st toe was significantly smaller in the diabetic group (14.6 o±19.0o) as compared to the control group (48.1 o±32.4o, p<.05, Fig. 4C).

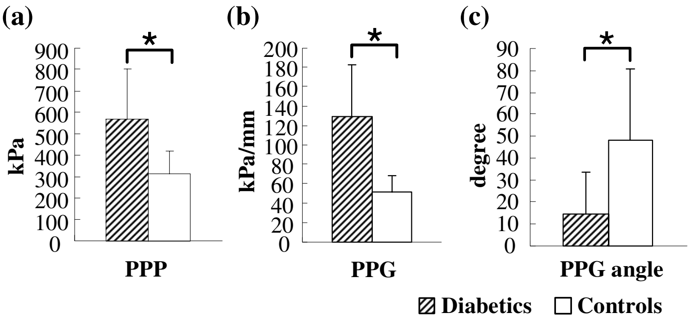

Fig. 4. The comparison of peak plantar pressure (PPP), peak pressure gradient (PPG), and peak pressure gradient angles (PPG angle) in the controls and diabetics; * indicates $p < .05$

The results support our hypotheses that the plantar pressure has higher values in the PPP and PPG in of diabetics during the shoes walking, but smaller values in the PPG angle. The proposed new variable, PPG angle, were able to further define the PPG patterns in diabetics and could provide additional insight into the mechanism of the influences of PPG on the development of diabetic foot ulcers.

The mean PPP were 165% at the 1^{st} toe of the diabetics than controls in this study. These results are consistent with the literature. Zheng et al. [20] demonstrated that the Young's modulus (elasticity) of plantar tissues of the diabetic foot increased at the 1^{st} toe. Perry and colleagues [6] also indicated that the diabetes-associated stiffening of the plantar soft tissues that the pad of the 1^{st} toe may cause this abnormal PPP. Our results support that the 1^{st} toe is higher stiffness and risk for foot ulceration during the walking [21].

The mean PPG were 214% in the 1^{st} toe in the diabetics than in the controls. The increase in PPG at the 1^{st} toe in diabetics may be attributed to a significant limitation of motion at the metatarsophalangeal joints. The exact pathogenesis of the limited joint mobility in diabetics is unclear, but is thought to be related to the progressive stiffening of the collagen-containing tissues due to accumulation of advanced glycation end products (AGEs) [22]. The diabetic foot with limited motion at the metatarsophalangeal joints significantly reduce shock absorbing ability and may cause an abnormal plantar pressure distribution [23]. Fernando el al. [24] showed that the limited joint mobility may be a major factor in causing abnormally high PPP and contribute to the foot ulceration. The authors also proved that the abnormal plantar foot pressures alone did not predict the location of foot ulcers. Our results of the PPP and PPG in the diabetic and control groups support the principle of assessing both the PPP and PPG to predict diabetic foot ulcers.

As expected, the mean PPG angle was at the 1st toe in the diabetics than in the controls in this study. Ahmed et al. [25] reported that the most common sites of diabetic foot ulcers was in the planter surface of the 1st toe. About 33% of diabetics develop callus at the 1st toe. Plantar callus is associated with the high vertical and shear forces in diabetics. When callus is removed, plantar pressures are reduced by 32.1% in diabetics [26]. This finding indicates that callus may act as a foreign body elevating the plantar pressures. As high shear stresses are associated with foot ulcers [27], the high PPG angle in diabetics may be negatively related with shear stresses. This may imply the use of foot pressure mapping system to measure PPP and PPG (PPG angle) should be promoted in clinical settings due to its ease of use. Further studies need to establish the relationship between PPG angle and shear stresses. Calluses are generally not harmful, but may sometimes lead to the changes in PPG angles that may aggravate the risk for foot ulcerations.

4 Conclusions

This study provides evidence that diabetics are associated with higher PPP and PPG and lower PPG angle compared to non-diabetics. The proposed PPG angle may improve our understanding of the influence of PPG on the risk of diabetic foot ulcers. Such knowledge may contribute to the prevention of diabetic foot ulcers.

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