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Short communication

Spatial relationships between shearing stresses and pressure on the plantar skin surface during gait

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ABSTRACT

Based on the hypothesis that diabetic foot lesions have a mechanical etiology, extensive efforts have sought to establish a relationship between ulcer occurrence and plantar pressure distribution. However, these factors are still not fully understood. The purpose of this study was to simultaneously record shear and pressure distributions in the heel and forefoot and to answer whether: (i) peak pressure and peak shear for anterior–posterior (AP) and medio-lateral (ML) occur at different locations, and if (ii) peak pressure is always centrally located between sites of maximum AP and ML shear stresses. A custom built system was used to collect shear and pressure data simultaneously on 11 subjects using the 2-step method. The peak pressure was found to be 362 kPa $\pm$ 106 in the heel and 527 kPa $\pm$ 123 in the forefoot. In addition, the average peak shear values were higher in the forefoot than in the heel. The greatest shear on the plantar surface of the forefoot occurred in the anterior direction (mean and std. dev.: 37.7 $\pm$ 7.6 kPa), whereas for the heel, peak shear the foot was in the posterior direction (21.2 $\pm$ 5 kPa). The results of this study suggest that the interactions of the shear forces caused greater "spreading" in the forefoot and greater tissue "dragging" in the heel. The results also showed that peak shear stresses do not occur at the same site or time as peak pressure. This may be an important factor in locating where skin breakdown occurs in patients at high-risk for ulceration.

1. Introduction

Diabetic foot ulcers continue to be a burden on the US healthcare system with an annual cost of approximately $6 billion (Frykberg et al., 2006). Based on the hypothesis that diabetic foot lesions have a mechanical etiology, extensive efforts have sought to establish a relationship between ulcer occurrence and plantar pressure distribution (Pataky et al., 2002; Pavicic and Korting, 2006; Pollard and Le Quesne, 1983). In most of the pressure distribution studies peak pressure parameters were chosen as a possible ulcer predictor. However the existing longitudinal studies have yielded only moderate correlations between peak pressure and the occurrence of diabetic foot lesions (Armstrong et al., 1998; Lavery et al., 2003; Veves et al., 1992).

Surprisingly, only one research group has examined whether all plantar ulcers developed in the follow-up period matched the baseline peak pressure sites. Veves et al. (1992) reported that only 38% of the ulcers developed under the peak pressure area. As an outcome, foot pressure has been labeled as a "poor tool" in the prediction of diabetic ulcers and where they would occur (Lavery et al., 2003).

Recently, investigators have examined shear stresses and their distribution under diabetic feet in more detail. One such study (Yavuz et al., 2007, 2009) showed that shearing stresses and peak pressures do not typically occur at the same location. What has not been studied is whether this discrepancy between peak shear locations is due to tissue being "spread" radially as a result of pressure between the foot and ground, or whether it is due to a "dragging" effect where the forward (or backward) motion of the foot causes tissue to become bunched in front of (or behind) the site of maximum pressure.

Therefore the purpose of this study was to simultaneously record shear and pressure distributions in the heel and forefoot and answer the questions whether: (i) peak pressure and peak shear for anterior–posterior (AP) and medio-lateral (ML) occur at different locations, and if (ii) peak pressure is always centrally located between sites of maximum AP and ML shear stresses.

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Answers to these questions would shed light on the complex spatial and temporal interactions between shear and pressure acting on the plantar surface of the foot.

2. Research design and methods

Shear and Pressure data during walking were collected on 11 volunteers (7Males/4Females, mean age 38 ± 14.5 years), none of whom had (i) gross foot deformities (minor clawing of the toes was permissible), (ii) prior foot surgeries or (iii) foot pain. The protocol was explained to the volunteers before their participation and each signed an informed consent form, which was approved by the Institutional Review Board. Detailed patient characteristics are given in Table 1.

The custom built shear and pressure system consists of a reusable $40 \times 58 \times 0.17$ cm^3 surface stress sensitive film (S3F) (Fonov et al., 2005, 2007) sensitive to pressure and shear mounted on a 60×60 cm^2 6-component force plate that can obtain ground reaction forces (Fig. 1a). The device was mounted in an 8′ × 2′ walkway in such a manner that the top of the stress sensitive film was flush with the surrounding walking surface (Fig. 1b). Shear and pressure data were collected on the left foot, using the 2-step method (McPoil et al., 1999). Subjects initiated walking with the right foot and took a series of 3 steps; data were collected from the subjects' 2nd step. Three bare foot trials were collected for each subject.

The output of the device consisted of three data vectors; vertical, AP and ML shear forces. The process of measuring pressure and shear stress is accomplished in three steps. First, the normal and tangential displacements of the film are optically measured. These displacements are then converted to pressure and shear stress distributions using a physical stress–strain model of the film. Finally the force plate measurements are used to validate and, if necessary, rescale the pressure and shear stress distributions (Chen et al., 2001; Thomas et al., 2004). Note that anterior, posterior, medial and lateral shear acting on the foot, are designated as S_{ant}, S_{pos}, S_{med} and S_{lat}, respectively. The Cartesian coordinates for the locations of the peak stresses occurring in the forefoot and heel were determined for each dataset. Differences in peak pressure and shear location errors were quantified by calculating the Euclidian distances (D) between peak stresses.

Table 1
Characteristics of the subjects.

	Control
No of subjects	11
Gender	7Male/4Female
Age (years)	38 ± 14.5 (20–61)
Weight (lb)	180 ± 23.4 (150–215)

Values are presented as the mean ± standard deviation, with the range in parentheses.

3. Results

The mean peak pressure values in the heel and forefoot were found to be 362 ± 106 kPa and 527 ± 123 kPa, respectively, which corresponds well with previous studies (Cavanagh et al., 1987). Mean peak shear values in the forefoot were higher than in the heel. The peak average shear acting on the plantar surface of the forefoot was directed anteriorly (37.7 ± 7.6 kPa) whereas the minimum average shear was in the posterior direction (17.6 ± 5.7 kPa). For the heel the peak average shear acting on the plantar surface occurred in the posterior direction (21.2 ± 5 kPa) and the minimum average shear in the anterior direction (8.3 ± 2.8 kPa) (Fig. 2a).

In all 11 subjects peak pressure and peak shear for AP and ML occurred at different locations in the heel and forefoot. In the heel, the peak pressure site, on average, was 24.8 mm away from S_{ant}, 17.37 mm from S_{pos}, 20.93 mm from S_{med} and 22.94 mm from S_{lat}. In the forefoot, the peak pressure site, on average, was located 22.79 mm away from S_{ant}, 29.66 mm from S_{pos}, 24.26 mm from S_{med} and 26.67 mm from S_{lat}, (Fig. 2b). In addition the peak AP shear values not only occurred at different locations than the peak pressure values, but also at different times. In the heel, the peak AP shear values occurred prior to the peak pressure value 60.61% of the time, while in the forefoot, it occurred afterwards 57.58% of the time (Fig. 3a and b).

The corresponding shear forces acting in the immediate vicinity of the peak pressure location were examined. The number of occasions when there were outwardly directed forces on either side of the peak pressure location was tabulated; this number of

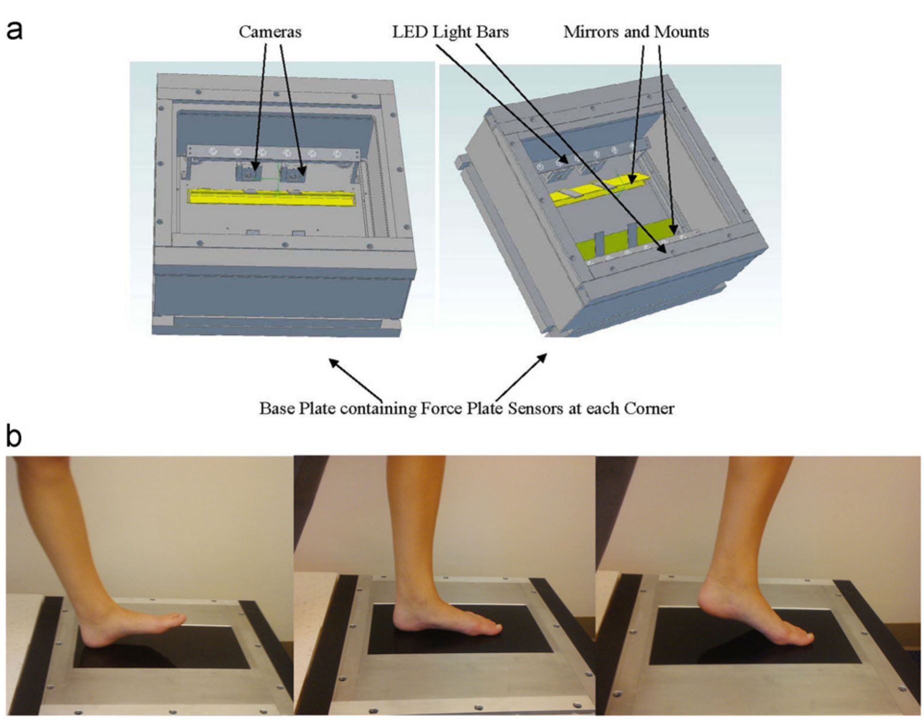

Fig. 1. (a) Representation of the custom built shear and pressure system. The glass plate and polymer film are removed to permit viewing of the internal components. A total of four cameras are used to image the film, although only two can be seen in these views. The mirrors direct the cameras' field of view upward to the film. The light bars provide the illumination for imaging and for excitation of the fluorescent probe in the film. (b) Close up view of a subject stepping on to the shear and pressure platform.