Peak Plantar Pressure and Shear Locations

Relevance to diabetic patients

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Diabetic foot ulcers burden the U.S. health care system with an annual cost of approximately $6 billion (1). Based on the mechanical etiology of diabetic foot lesions, investigators tried to establish a relationship between ulcer occurrence and plantar pressures. Mostly, peak pressure has been chosen as an ulcer predictor. However, previous studies have yielded only moderate correlations between peak pressure and the occurrence of diabetic foot lesions (2–4).

Surprisingly, in one study that examined whether plantar ulcer locations matched peak pressure sites (4), only 38% of the ulcers developed under the peak pressure area. Therefore, foot pressure was labeled as a "poor" predictor of diabetic ulcer occurrences and their location (3).

Effectiveness of diabetic ulcer prediction and prevention depends on an understanding of plantar soft tissue mechanics and the complete nature of foot-ground interactions. Further investigation of plantar shear in addition to pressure is essential to minimize the neuropathic ulcer prevalence.

The purpose of this study was to find whether the peak pressure and shear under the feet of diabetic patients occur at different locations. If confirmed, shear distribution may explain the deviation between peak pressure and ulcer locations and potentially help researchers design more effective interventions.

RESEARCH DESIGN AND METHODS — Thirty volunteers were recruited, among whom 10 had diabetic neuropathy. The remaining nondiabetic subjects served as control subjects. Subjects with gross foot deformities (except minor toe clawing), prior foot surgeries, and foot pain in both feet were excluded. The protocol was explained to the volunteers who signed an informed consent form approved by the institutional review board.

A custom-built shear and pressure platform (5), 80 sensors (12.5 × 12.5 mm) arranged in an 8 × 10 array, was used to collect local barefoot forces. The forefoot region was of primary interest because diabetic ulcers most frequently occur in this area (6–7). The two-step method was preferred because of its characteristics similar to the midgait method (8). Five trials on a surgery-free foot were conducted for each subject.

Resultant shear forces were calculated from anteroposterior and mediolateral components. Peak vertical and shear force magnitudes and their sensorwise locations were extracted throughout the stance phase. Division of forces by sensor area provided peak pressure and shear stress values. Differences in peak pressure and shear locations were quantified by the distance between their corresponding Cartesian coordinates (*D*). A *t* test ($\alpha = 0.05$) was performed on *D* to reveal differences between peak pressure and shear sites due to diabetes.

RESULTS — Of the 30 volunteers, 12 were women. The diabetic group had a mean ± SD age of 64 ± 9 years and weight 97 ± 27 kg, whereas the control group were aged 50 ± 17 years with weight 70 ± 12 kg. *D* values were found to be 2.3 ± 1.2 and 2.5 ± 0.9 cm for diabetic and control subjects, respectively, with no significant difference ($P = 0.718$). In 20% of the diabetic patients, peak shear occurred at the same site as the peak pressure. Six (60%) had their peak shear site >2.5 cm apart from the peak pressure site. In control subjects, the ratio for occurrence at the same site was zero. *D* was >2.5 cm in seven control subjects (35%). Figure 1 displays a diabetic subject's representative peak stress profiles, where peak pressure occurred under the second metatarsal head, whereas peak shear was under the hallux ($D = 4.6$ cm).

CONCLUSIONS — Peak pressure has frequently been assessed in the literature. Other pressure variables, such as pressure-time integral, have not been studied thoroughly in prospective studies to reveal a possible correlation with the ulceration sites. Murray et al. (9) has reported a 57% ulcer incidence at high pressure areas; however, it was not clear whether all wounds were observed at peak pressure points. They also disclosed the relationship between callus and ulcer locations, which may be a consequence of excessive shearing since frictional forces have previously been shown to cause hyperkeratosis of the human and animal tissues (10–11). Cross-sectional studies that assessed pressure values at ulcer sites showed higher correlations than the prospective studies (12–14). It is unclear, however, how the change in the tissue characteristics and plantar topology, during the progress of a lesion and after it is healed, altered the pressure values obtained.

Shear combined with pressure has also been associated with ulcer incidences (15–21). Among plantar shear studies, Pollard and Le Quesne's work (15) indicated overlapping locations for peak pressure and shear. However, 2.3–mm thick individual sensors attached to the sole almost certainly created localized loading

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A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

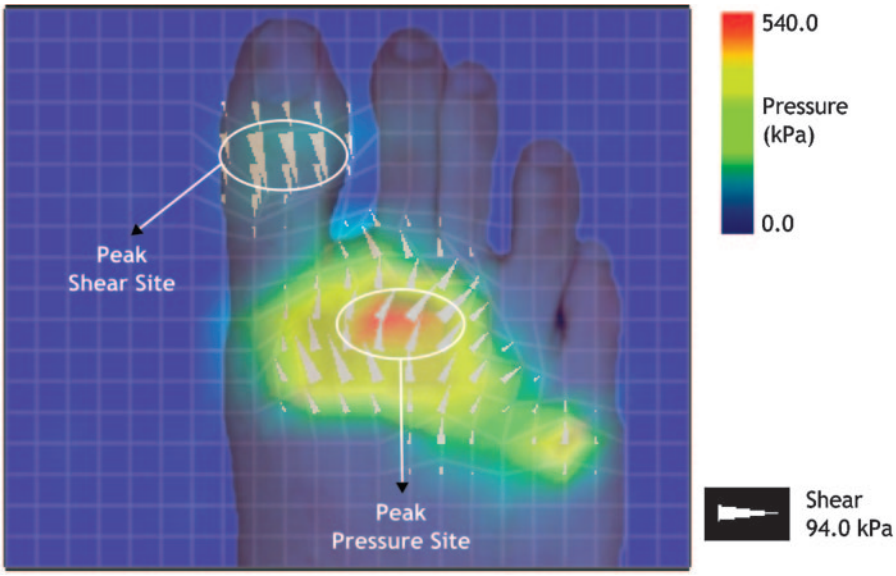

Figure 1—*Comparison of peak plantar pressure and resultant shear sites of a representative diabetic subject. Data were visualized by FootVis software (Infoscitex, Waltham, MA).*

under the subjects' feet. Another study nonquantitatively revealed that peak pressure and peak shear sites overlapped in only one-half of the diabetic subjects (22). The device used in this examination, however, was limited in terms of spatial resolution.

The current study has shown that peak plantar pressure and shear sites may differ in diabetic neuropathic subjects. Peak pressure has frequently been assessed in the literature. Other pressure variables, such as pressure-time integral, have not been studied thoroughly in prospective to reveal a possible correlation with the ulceration sites. In fact, the distribution of peak shear sites relative to the peak pressure sites did not show any definitive trend since the shift was in varying directions.

Interestingly, two diabetic subjects had peak pressure and shear occur at exactly the same location, while no control subject exhibited such a distribution. Plantar shear distribution depends on local frictional properties of the sole, gait velocity, and, most likely, the internal muscle activity. Occurrence of peak pressure and peak shear at the same location may be partly explained by the muscle atrophy seen in some diabetic patients (23).

This study had limitations related to the spatial resolution and overall size of the device. Only walking at a self-selected speed was assessed, and this was restricted to barefoot locomotion. While conditions inside the footwear may not alter the outcomes significantly, this idea should be validated by using an appropriate method of measuring in-shoe plantar shear distributions.

Our results may establish the first step toward understanding why only a moderate ratio of diabetic foot ulcers develops at the peak pressure sites. Future work should address the questions about the presence of an association between the peak shear sites and ulcer sites, as well as the association between temporal and spatial differences in pressure and shear stresses.

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