Real-Time Patient-Specific Evaluation of Deep Plantar Tissue Stresses in Diabetic and Healthy Subjects Using the Hertz Contact Theory

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INTRODUCTION

Elevated stresses in deep plantar tissue of diabetic naturopathic patients were associated with an increased risk for foot ulceration [1]. However, in the clinic, only interfacial foot pressures are being measured to evaluate susceptibility to ulcers. Therefore, it is essential to develop a real-time patient-specific monitoring method which enables quantification of internal stresses in addition to the interfacial pressures. Internal stresses can be evaluated by numerical or analytical methods. Real-time patient-specific modeling by means of commercial finite element (FE) codes is not clinically applicable due to the complexity in representing the foot geometry and tissue mechanical properties. A real-time patient-specific FE code which calculates internal plantar tissue strains/stresses was previously developed in our lab [2]. Yet, this real-time model requires the computer power of a PC laptop, which prevents utilization of the system during daily-life activities. The alternative, analytical method is based on the Hertz contact theory. The relative simplicity of calculations with this theory allows to use less computer power, e.g. a pocket PC, and hence to evaluate the internal plantar stress in real-time during daily-life activities such as stair climbing and walking on different surfaces by means of a mobile small device. The Hertz contact theory was unsuccessfully applied to evaluate pressures between the foot and a midsole [3], however, this theory was not yet applied to study internal tissue stresses and particularly the internal plantar stresses in the diabetic foot.

AIMS AND OBJECTIVES

A first aim of this study was to develop a patient-specific real-time foot stress monitor that can be used both inside and outside the lab. A second aim was to compare internal plantar stresses in diabetic and healthy subjects equipped with the monitor during daily-life activities, in order to test whether the monitor can distinguish between diabetics and normals.

METHODS

The biomechanical model for stress calculations considers the heel and metatarsal head pads, where most ulcers occur. For calculating stress concentrations around the bone-pad interface, plantar tissue is idealized as elastic and incompressible semi-infinite bulk (with properties measured by means of indentation), which is penetrated by a rigid sphere with the bone's radius of curvature (from x-ray). Hertz's theory is used to solve the bone-pad mechanical interactions, after introducing correction coefficients to accounts for the large deformations of the plantar pad during gait. Foot-shoe forces are measured continuously to solve and display the principal compressive, tensile and von Mises plantar tissue stresses in real-time. We conducted a sensitivity analysis in order to examine the ability of our biomechanical model to be utilized in a subject-specific monitor. Finally, we developed a real-time subject-specific portable stress monitor on a portable digital assistant platform (Axim x51v, Dell Co.) using a LabView 8 PDA module (National Instruments Co.) (Figure1).

Figure 1: Portable real-time subject-specific stress monitor

We conducted studies with groups of healthy subjects (N=6, 4 males and 2 females) and diabetic subjects (N=10, 5 males and 5 females). Plantar interfacial pressures and internal stresses under the calcaneus were evaluated during gait at natural speed on a flat surface and during stair climbing, for both groups. In addition, we evaluated the internal tissue stresses during gait on a mild slope of 3.5 degrees for the healthy group. The differences between stress parameters obtained for gait on a flat surface, up/down a slope and up/down the stairs were studied, in addition to the differences in stress parameters between the two subject groups.

RESULTS

Results from the sensitivity analysis showed that a small change in an input parameter ($\pm 20\%$), i.e. bone radius of curvature (*R*), plantar pad elastic modulus (*E*) and the calcaneal reaction force (*F*), resulted in a smaller change in the peak internal compression stress (P_0). In addition, it was found that among the three input parameters *R* had the strongest effect on P_0 and *E* affected P_0 more than *F*.
Results from subject studies showed that in healthy subjects peak internal compression stress at the calcaneus region was about 3-fold greater than the interface pressure. Maximal internal stresses occurred during heel strike, and decreased thereafter until heel lift. We found no statistical difference between gait on a flat surface and going up/down a mild slope. However, internal stresses under the calcaneus during gait on a flat surface were significantly higher than when going up/down the stairs. When comparing the internal stresses between diabetic and healthy subjects, we found that the internal stresses at the calcaneus region of diabetics were significantly higher than those of healthy subject ($p<0.001$) (Figure 2).

DISCUSSION

We succeeded in developing a stress monitor that is based on Hertz contact theory and in evaluating internal stresses in the plantar pad for individuals during daily-life activities. The limitations of the proposed model include the accuracy needed in measuring the bone radius of curvature and plantar pad elastic modulus, as revealed in our sensitivity analysis. In addition, when comparing our results to the literature [2], we found that our model moderately underestimated internal stresses predicted by real-time FE. The mild underestimation of internal stresses is likely to be attributed to lack of tensile loading of the plantar pad by the plantar fascia (not represented herein) and also, to a not-dense-enough sensor area to capture the whole heel reaction force. Nevertheless, the monitor could clearly distinguish between healthy and diabetics which indicates on its clinical utility.

CONCLUSION

We conclude that the present stress monitor is a promising tool for real-time patient-specific evaluation of deep plantar tissue stresses, in order to protect diabetic patients from foot ulceration. The present studies can now be extended to determine tissue injury threshold from the internal plantar stress data.

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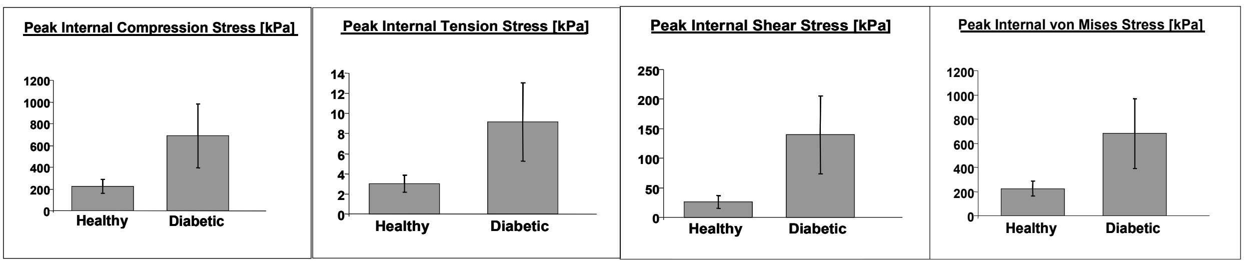

Figure 2: Mean Internal stress data for all subjects. Error bars represent standard deviations.