PLANTAR PRESSURE DISTRIBUTION IN THE DIABETIC FOOT DURING PUSH-OFF: NUMERICAL SIMULATION USING THE P-VERSION OF THE FINITE ELEMENT METHOD

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INTRODUCTION

The most common cause for diabetic plantar ulcers is excessive plantar pressures in the presence of sensory neuropathy and foot deformity. Proper footwear fitted with a total contact insert (TCI) or TCI with a metatarsal pad are the standard of care for reducing forefoot plantar pressures, although research has not clearly indicated optimal size, location and material properties of orthotic components. One key aspect for achieving this goal is to develop three-dimensional computational models of the foot for enhancing and evaluating a broad range of orthotic device components.

METHODS

In modeling a complex system like the human foot, it is necessary to make simplifying assumptions regarding topological details, constitutive laws, material properties and boundary conditions. Such simplifications are acceptable only if they do not significantly affect the data of interest, in this case the pressure distribution in the regions of the metatarsal heads at push-off. In our investigation, the complexity of the model was increased hierarchically, until the computed pressure distribution was no longer affected by the restrictive assumptions incorporated in the simpler models. The three-dimensional internal structure of the foot was determined using data from SXCT [1], while the reference pressure distribution was measured using the F-scan system [2] with the pressure sensor taped to the subject's foot.

We considered the structure of the foot to be characterized by bone, cartilage, flexor tendon, fascia and tissue. The material properties for the bones were assumed to be linear. Cartilage with linear elastic material properties was included between bones to simulate the flexibility of the connection between bony structures. Muscles and fat were lumped into a single material type (tissue) with nonlinear elastic properties obtained for each individual using an indentor testing device [3]. Fascia and flexor tendon were also incorporated into the model and the properties were assumed to be linear elastic.

RESULTS AND DISCUSSION

Figure 1 shows the section taken through the second metatarsal of the foot in the push-off position of a 63 year-old, male, diabetic subject, with a history of a plantar ulcer. Simpler models were constructed by removing the cartilage between phalanges, or by not including the fascia or the flexor tendon in the model in various combinations.

The p-version FEA program StressCheck was used for the numerical simulation. The influence of the different modeling considerations in the pressure distribution in a region 15 mm proximal and 20 mm distal from the center of the metatarsal head was compared with the one obtained with the F-scan system.

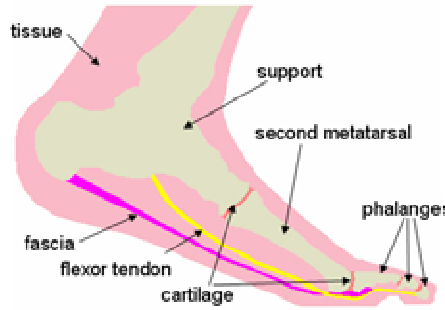

Figure 1: Segmentation for the most complex model considered for analysis.

Predicted and measured pressure distributions were compared in four patients with diabetes and a history of neuropathic ulcer and the agreement was found to be generally good (typically within 12% error in L2 norm) as shown in Figure 2.

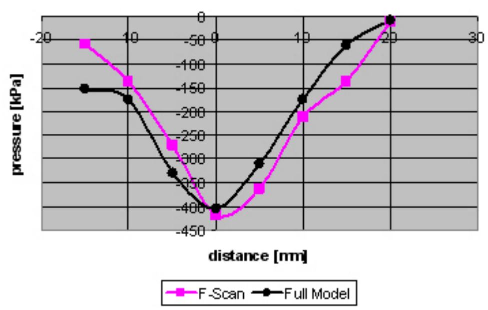

Figure 2: Measured (F-Scan) and computed (Full Model) pressure distributions under the 2nd metatarsal head.

CONCLUSIONS

Initial validation of our computational model is reasonable and future work will seek to determine optimal characteristics of orthotic devices and footwear to distribute plantar pressures evenly.

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