INTRODUCTION

The Hydraulic Plantar Soft Tissue Reducer (HyPSTR) is an MRI compatible device that applies dynamic loading profiles to a subject’s foot while gated MRI captures soft tissue deformation. The combination of force and image data is used to calculate plantar soft tissue stiffness, which has been shown to be significantly different in subjects with/without diabetes [1]. Diabetes mellitus can lead to ulceration in the foot, and eventually amputations [2]. Ulcers may form at regions of high internal stress, which motivates the use of MRI to obtain volumetric information, as opposed to external deformation measurements [3,4] or one-dimensional ultrasound probing [5,6]. Finite element (FE) models can use this force and three-dimensional image data to conduct inverse FE analyses to determine patient-specific material properties, which in turn can be used to improve foot simulations under a variety of loading scenarios.

METHODS

Verification data and calibration curves were obtained to ensure that the motor and control electronics could accurately transmit displacements through plastic, water hydraulic tubing to the loading platen in the MRI core. Applied force was measured indirectly from system pressure and matched with the appropriate MRI time stamps for 16 loading/unloading phases during a periodic (5s) sine-wave displacement protocol. Gated MRI was synchronized with a peripheral pulse unit signal so that cardiac MRI gating protocols could be used to obtain 16 images of the tissue deformation at custom rates. Distances between anatomical landmarks were measured in pixel units with segmentation software and converted to mm.

Ankle foot orthosis (AFO) was designed from carbon fiber and leather to secure the foot and lower leg to the loading apparatus during testing (Figure 1). The HyPSTR can be fitted with an ultrasound adapter, for pilot testing or adjusted to test forefoot tissue properties, or left or right feet.

Figure 1: HyPSTR slave cylinder (black) and loading jig. The ultrasound probe adapter (bicolor, yellow/red) is connected to the loading platen.

Two subjects were tested. Subject A had no history of diabetes and was 93 kg in mass, 180 cm tall, and 43 years old. Subject B had type II diabetes and was 70 kg in mass, 170 cm tall, and 31 years old.

RESULTS AND DISCUSSION

Image data (Figure 2) for Subject B shows maximum tissue compression near the tenth acquisition phase. The first three phases appear to be unloaded (force data from the HyPSTR was 0N). This is due to the heel preconditioning that occurs after the subject is secured in the AFO. The gap that forms between the platen and foot is not completely avoidable, without pre-loading the subject.
A loading/unloading stiffness curve was obtained for both subjects (Figure 3 for subject B, subject A not shown). The magnitude (approx. 200N) and velocity (approx. 3.5 mm/s) of the deformation was mostly elastic (i.e., there was no significant hysteresis, Figure 3). Fat pad stiffness is generally thought to increase exponentially with strain [3], which could still be true for these subjects at higher strains. Subject B tissue was 2.65 times more stiff than Subject A (data not shown here) in the final 0.06 mm of compression. This agrees with trends in the cadaver sample data from Pai and Ledoux [1].

**CONCLUSIONS**

The HyPSTR represents progress toward measuring patient-specific, dynamic heel pad stiffness. Currently there are limitations in platen velocity (0.2 Hz) that need to be addressed in order to test compressibility at a more physiologic rate (1 to 10 Hz). Still, the data indicate that the HyPSTR can differentiate between dynamic stiffnesses of subjects with and without diabetes.

**REFERENCES**


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