In the instance of a high rate axial load to the lower limb
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Introduction

- In the instance of a high rate axial load to the lower limb as a result of an under-vehicle blast, the soft tissue layer in the plantar region of the foot is the first structure engaged.
- A material characterization of this structure under such loading conditions would provide a better understanding of the load paths to the lower extremity, and accurate material properties for the development of biofidelic anthropometric test devices (ATDs).

Goal

- Given that the current Hybrid-III ATD is known to lack accurate heel compression characteristics for high rate loading, it is the goal of this study to acquire accurate material properties of the human sub-calcanear heel pad under high rate compressive loading.

Methods

- Protocols for the handling of biological materials were approved by the University of Virginia’s Institutional Biosafety Committee.
- Three heel pads were collected from the hind foot region of 2 post mortem human surrogates.
- Heel pads were flash frozen and stored in a morgue freezer at -20°C until materials testing could be performed.
- Two to four tissue samples were cut to approximately 10mm in diameter and 10mm in height from each whole heel pad using a cylindrical boring tool. For ease of cutting, the heel pads were left partially frozen while being prepared.
- Samples were cut perpendicular to the surface of the skin and from the central portion of the pad.
- The quality of each sample was evaluated and those that were not of good cylindrical shape were discarded.
- Samples underwent a battery of ramp and hold stress relaxation tests for material characterization.

Test Conditions

- Materials testing was performed on a bench-top test machine (ElectroForce® 3100, Bose, Eden Prairie, MN).
- Samples were placed on an aluminum stage mounted atop a 250gram capacity Load Cell, and beneath a flat aluminum load platen mounted to a linear actuator equipped with an LVDT to measure displacement.
- Force and displacement data were acquired at 20kHz.

Mathematical Formulation

- The stress output of $$G(t, E)$$, due to the strain input $$e(t)$$, was modeled using quasilinear viscoelasticity (QLV).

$$\sigma(t,E) = \int_{0}^{t} G(t-t') dE(t')$$

- where $$\sigma(t,E)$$ is the instantaneous elastic response and $$G(t)$$ is the reduced relaxation function. Two nonlinear constitutive models were considered for $$\sigma(t,E)$$: First, the tissue was modeled as a 1D material.

$$\sigma(t,E) = a_{1}E + a_{2}E^2 + a_3E^3$$

where $$a_1$$ are constants. Second, the tissue was assumed to be incompressible and isotropic and modeled using an exponential strain energy density function (SEDF).

$$\sigma(t,E) = \mu_{E}E^\gamma (e^{-\gamma t} - 1)$$

where $$\mu_{E}$$ is the elastic shear modulus, $$\gamma$$ is the nonlinearity coefficient, and $$1I$$ is the first invariant of the right Cauchy-Green strain tensor. Assuming uniaxial compression, the 2nd PK stress in the direction of $$\epsilon$$ is derived as

$$\sigma(\epsilon) = \mu_{E}E^\gamma (e^{-\gamma t} - 1)$$

- where $$\lambda = e + 1$$ is the stretch ratio. $$G(t)$$ was chosen to be

$$G(t) = G_0 + \sum_{i=1}^{2} G_i \cdot e^{-\frac{t}{\tau_i}}$$

where $$G_i$$ are the normalized relaxation coefficients and $$\tau_i$$'s are the time constants, $$G_0 + G_1 + G_2 + G_3 + G_4 + G_5 = 1$$, and $$\tau_1 = 0.001s, \tau_2 = 0.01s, \tau_3 = 0.1s, \tau_4 = 1s, \tau_5 = 10s$$.

Results

- Seventeen total compression tests were performed.
- Values for the coefficients of $$\sigma(\epsilon)$$ and $$G(t)$$ were determined through a reduced gradient algorithm (Excel Solver®, Microsoft®, Redmond, WA) to minimize the sum squared error between the model-predicted force and experimental data.
- An average $$\sigma(\epsilon)$$ and $$G(t)$$ were determined through the previously described reduced gradient algorithm for both constitutive models.
- The instantaneous elastic shear modulus was determined to be $$12.6 \pm 3.7$$kPa.

Discussion

- The tissue behaved viscoelastic and spatially nonlinear.
- At strains above 17% the $$\sigma(E)$$ curves began to diverge and the exponential model predicted higher stresses. For strains below 17% the models were approximately equal.
- In sixteen out of seventeen tests, the polynomial model resulted in higher RF values and lower Sum Squared Error indicating a better fit.
- G(t) was nearly identical for both models.
- The shear modulus is in agreement with values reported in the literature; (8-16)kPa.
- A linear viscoelastic model was fit to the data, in addition to both QLV models, but did not capture the ramp and peak stress.
- The assumption of QLV was justified using the method of isochrones. Three isochrones were chosen: $$t_1 = 0.03s, t_2 = 0.10s, t_3 = 0.3s$$ after the peak stress. Stress vs. strain data for each isochron were plotted and fit with an exponential function of $$e^{-\mu_1 t}$$, which provided a better fit over a linear function. Dividing the isochronic curves resulted in approximately constant values indicating no temporal nonlinearity up to 20% strain.

Conclusions

- Material properties of the sub-calcanear heel pad were determined for engineering strains up to 20% and strain rates between (15-35) s⁻¹.
- QLV was validated using the method of isochrones and used to fit two constitutive models to the experimental data.
- The polynomial model indicated a better fit to the data.
- The shear modulus from the exponential SEDF agrees with the values reported in the literature.

Future Research

1. Data will be collected up to 50% engineering strain.
2. Heel pad from the current Hybrid-III ATD will be characterized and the material properties compared to those determined for humans.
3. Material properties will be validated through finite element analyses.

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