Mechanical response of the human sub-calcaneal heel pad under high rate compression

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Abstract

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. Characterization of this structure under such loading conditions would provide greater understanding of the load paths to the lower extremity, and accurate material properties for the development of biofidelic anthropometric test devices (ATDs) and computational models. Given that the current Hybrid-III ATD is known to lack accurate heel compression characteristics for high-rate loads, it is the goal of this study is to acquire accurate material properties of the subcalcaneal heel pad under high-rate compressive loading.

All biological handling protocols were approved by the University of Virginia's Institutional Biosafety Committee. Eight heel pads were collected from the hind foot region of four donors. Five cylindrical tissue samples, approximately 10mm in diameter and 10mm in height, were cut perpendicular to the surface of the skin from each whole heel pad and used for compression testing. All samples were tested using a bench-top test machine, BOSE ElectroForce 3100. The samples were placed on an aluminum stage mounted on a 250gram capacity force transducer, and beneath an aluminum load platen mounted to a linear actuator equipped with an LVDT to measure displacement. To verify contact, the load platen was lowered at a rate of 0.01mm/s toward the tissue until a tare load of 1.5grams was measured. Samples were then subjected to a battery of ramp and hold stress relaxation tests with engineering strains up to 50% and rates of at most 30s-1. Force displacement data were acquired at 20kHz.

Initial analysis of the data indicated the tissue to be non-linear and viscoelastic. For this reason a Mooney-Rivlin hyperelastic constitutive model with time dependent material coefficients was used to model the experimental data. The hyperelastic and viscous contributions to the material's response were separated using Fung's quasi-linear viscoelastic theory. The 1st P-K stress was determined to be a third order polynomial and used to model the instantaneous elastic response. A six term prony series with five time constants fixed at decades of 2.5, 10, 100, 1,000, and 10,000ms was used to model the normalized relaxation of the tissue. The tissue was modeled under the assumptions of isotropy and incompressibility.

Numerical values for the material coefficients were determined through the least squares method. Coefficients of the model from non-precondition tests are C10= C01= (0.013±0.004)Pa, C20= C02= (0.005±0.002)Pa, C11 = 0Pa and were found to be significantly higher (p = 0.018) than those determined for preconditioned tests. The values of the normalized relaxation coefficients were determined to be (0.87±0.03), (0.04±0.01), (0.03±0.02), (0.02±0.01), (0.02±0.02) for the respective decades and (0.02±0.02) at infinite time. The effectiveness of the model was validated by its ability to accurately predict the stress response to an arbitrary strain input at similar rates and amplitudes to that of the ramp and hold tests. In almost every case the model predicted the experimental response well (R2 = 0.96).