The material properties of the human heel fat pad across strain-rates: an inverse finite element approach

Grigoris Grigoriadis, Nicolas Newell, Spyros D. Masouros, Anthony M. J. Bull

I. INTRODUCTION

Anti-vehicular (AV) landmines and improvised explosive devices (IEDs) have been widely used in modern military operations with the majority of the survivors' injuries reported to affect the lower extremities. Intra-articular fractures with high rates of amputation and poor outcome are mainly related to the "deck-slap" injury that occurs due to the floor of a vehicle deforming rapidly above an explosion [1]. Energy is transferred from the floor to the hind foot through the heel fat pad, a complex structure which consists of fibrous chambers surrounding and retaining adipose tissue. Although the energy damping capacity of the fat pad is considered to be crucial in daily activities such as walking [2], its material behaviour at loading rates associated with injury is not well documented. The aim of this project is to characterise the material behaviour of the heel fat pad across different strain and strain-rate levels. Results from tests on small samples extracted from the tissue are likely not to be representative due to the complexity of the microstructure; therefore an inverse finite element (FE) method was utilised in conjunction with experiments with the fat pad intact.

II. METHODS

A human cadaveric foot was dissected to isolate the intact calcaneus with the fat pad attached to it. The distal surface of the calcaneus was then submerged into bone cement with the fat pad remaining on top. Quasi-static compressive (displacement rates of 0.01-0.1 mm/s) and drop (impact velocities of 0.4-3.5 m/s, mass of 7 kg) tests were performed. For the quasi-static tests, the cross head of an Instron 5866 materials testing machine (Instron Inc., Norwood, USA) was displacement driven to compress the fat pad up to an estimated maximum strain of 50% while forces were recorded using a load cell. The impactor of a Dynatup 9250HV drop rig (Instron Inc., Norwood, USA) was set at different heights (2-64 cm) from the specimen and released (Fig. 1a). Force and acceleration were recorded through an accelerometer and a load cell located on top of the impactor.

A subject specific FE model of the cadaveric foot was developed in MSC.Marc (MSC.Software, v.2013.1, Santa Ana, CA, USA) based on MRI and CT scans of the specimens segmented using Mimics (Materialise HQ, v.15.01, Leuven, Belgium). Both quasi-static and drop tests were simulated (Fig. 1b).

In the literature, the fat pad has been shown to exhibit a hyper-elastic behaviour under compression which is strain-rate dependent [3-4]. A material formulation combining the above properties of the tissue was implemented. The hyper-elastic term was represented by an exponential equation. The strain-rate dependency was implemented using a power law; this is based on the Cowper-Symonds formulation developed for work hardening and used previously to simulate strain-rate dependency of other soft tissues [5]. Specifically, the Young's modulus of the material is defined as:

$$E = \left(C_0 \varepsilon^{\sum_{i=1}^{n} C_i \varepsilon^i} \right) \cdot \left(1 + \left(\dot{\varepsilon} / C_D \right)^{1/C_P} \right)$$

where ε is strain and $\dot{\varepsilon}$ is strain rate. The constants of this formulation (n, C_{0-n}, C_P, C_D) were obtained through a non-linear optimisation algorithm until numerical and experimental response matched to minimum error.

G. Grigoriadis is a PhD student (tel: +44 20 75942646; email: gg2111@imperial.ac.uk) and N. Newell is a research associate, both in The Royal British Legion Centre for Blast Injury Studies, Imperial College London, UK. S.D. Masouros is Lecturer in Trauma Biomechanics and in the Department of Bioengineering, The Royal British Legion Centre for Blast Injury Studies, Imperial College London, UK. A.M.J. Bull is Professor of Musculoskeletal Mechanics in the Department of Bioengineering and Director of the Royal British Legion Centre for Blast Injury Studies at Imperial College London, UK.

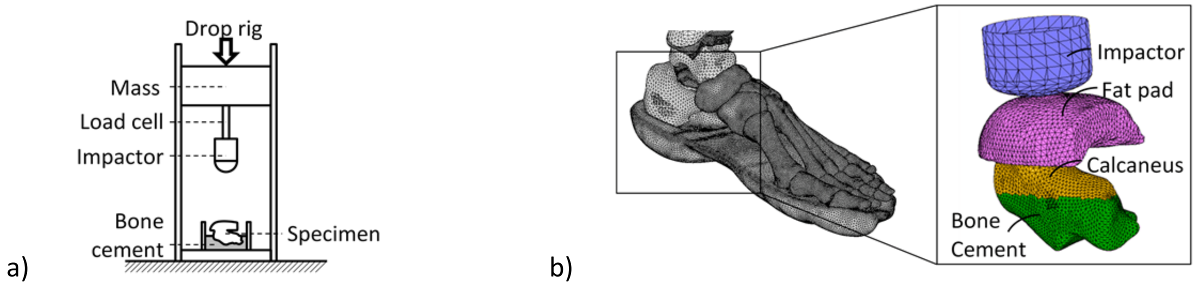

Fig. 1. a) The experimental set-up of the drop test. b) The computational model of the total lower limb and the model to simulate the quasi-static and drop tests. Bone cement is non-deformable and fixed around the bone while the impactor is set to impact the fat pad with the respective velocity of the experiment.

III. INITIAL FINDINGS

Based on the results from one cadaveric specimen, the quasi-static behaviour can be described by a simple exponential equation resulting in an average error of 5% (Fig. 2a). Similarly, increasing strain rate resulted in a stiffer material behaviour (Fig. 2b).

Fig. 2. a) Experimental and numerical results for the quasi-static test. The good match indicates that the derived material formulation is adequate (n = 1, C_0 = 25.6 kPa, C_1 = 13.6). b) Comparison between experimental and numerical results for a drop test of a velocity at impact of 1.3 m/s. The numerical results based on the quasi-static formulation (QS) do not predict the experimental output. Using the power law (CS) for strain-rate dependency (C_P = 0.95, C_D = 1.1 s^{-1}), the FE model is able to simulate closer the result of the drop test.

IV. DISCUSSION

Sensitivity of fat pad to strain and strain rate has been established by previous studies [3] and confirmed by this study while material models have been developed previously for low strain rates [4]. Direct comparison to experimental studies deriving material properties of the fat pad is not possible as they are using isolated plugs extracted from the tissue [3][6] or indentation techniques [7]. However, the quasi-static formulation proposed here describes a stiffer material than these studies; this is expected considering the different experimental procedures. Results from another four cadaveric specimens will also be obtained and analysed to derive the average material behaviour of the human heel fat pad.

Accurate prediction of the forces transferred proximally to the leg requires an accurate implementation of the material behaviour of the fat pad. As the strain rate at which the fat pad is loaded when in contact with the floor of a vehicle is not constant, the material formulation proposed can predict the behaviour of the fat pad across strain rates. These material properties will be implemented in an FE model of the foot (Fig.1b) able to simulate events with variable loading rates such as underbody blast.

V. REFERENCES

[1] Ramasamy A, et al, *Crit Care,* 2011.
[2] Jahss MA, et al, *Foot Ankle,* 1992.
[3] Miller-Young JE, et al, *J Biomech,* 2011.
[4] Natali AN, et al, *Med Eng Phys,* 2011.
[5] Snedeker JG, et al, *J Biomech*, 2005.
[6] Ledoux WR, et al*, J Biomech,* 2007.
[7] Erdemir A, et al*, J Biomech*, 2006.