Frangible optimised lower limb surrogate for assessing injury caused by underbelly blast

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I. INTRODUCTION

Vehicle underbelly blast caused by antivehicular landmines or improvised explosive devices (IED) [1] is a common source of lower limb injuries for vehicle occupants. Lower limb surrogates such as the MiL-Lx or the Hybrid III are currently used to estimate the injury risk caused by underbelly blast by giving an output of the load transferred during the blast [2]. However, they cannot provide information on fracture patterns and mechanisms, due to their rigidity.

The aim of this project is to develop and validate a low cost, frangible, biofidelic lower limb surrogate. This will provide additional information to that given by the current anthropometric testing devices, enabling the investigation of fracture patterns and mechanisms associated with underbelly blast, leading to physiological testing of mitigation measures. Furthermore, it will lead to a reduction in the use of cadaveric material and increase the repeatability and reproducibility of experiments for a reasonable cost.

II. METHODS

Biofidelic predictive structural mesoscale finite element models (FE) of long bones in the lower limb were implemented following the methodology presented in [3]. Physical equivalents were then produced using additive manufacturing including joint features. A bulk material was designed to represent soft tissue, which has a structure shown in Figure 2. Mechanical tests will be conducted at several stages of the manufacturing process, at material level, on individual bones, and on the full leg surrogate. A 'characteristic relationship' is to be derived to relate the mechanical behaviour of the nylon surrogates to bone.

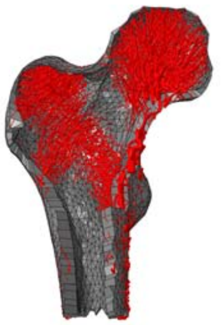

Fig. 1: Longitudinal slice of a preliminary proximal femur FE model, with cortical and trabecular bone displayed in white and red respectively.

Fig. 2: Longitudinal slice of a full femur with muscle tissue surrounding it, with cortical bone in dark grey, trabecular bone in red, muscle tissue outer layer in light grey and muscle tissue inner structure in dark blue.

Distinct generic models of a femur, a tibia, and a fibula were built using shell and truss elements to model cortical and trabecular bone respectively, based on surface geometry information extracted from clinical CTs. The initial cross-section of the structural elements was then iteratively adapted under loading conditions corresponding to walking, sit-to-stand/stand-to-sit, and stair ascent/descent based on a bone remodelling algorithm inspired by Frost's Mechanostat [3-4]. The loading conditions were obtained from experimental gait data using a musculoskeletal model of the lower limb [5]. A preliminary slice of the proximal femur from the adapted model is displayed in Figure 1. The structural models will be manufactured in nylon using selective laser sintering (SLS). Because of print size constraints, each bone was divided into parts, to be assembled using screw-thread mechanisms. The knee (distal femur + patella + ligaments + proximal tibia) will be printed as one part to ensure good ligament fixations to the bone. A gel moulded into a manufactured lattice (Fig. 2) will provide a

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bulk material to represent the soft tissue around the bones. A preliminary print of a full femur is shown in Figure 3.

Tensile material tests were conducted on nylon samples with varying cross-sections and directions of print with displacement rates varying from quasi-static to 5000 mm/s. Four-point bending tests will be conducted on thick hollow cylinders to investigate the influence of the screw-thread assembly.

III. INITIAL FINDINGS

To date tensile material tests have been conducted on nylon for displacement rates of up to 5 mm/s. The stress vs strain curves obtained for a circular cross section sample of 1 mm diameter are shown in Figure 4, indicating that the material becomes more brittle with an increased strain rate. This finding indicates that the strain dependent behaviour of nylon could be similar to that of bone, in particular at higher strain rates [7].

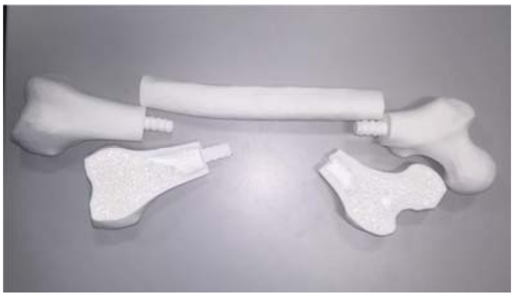

Fig. 3: Picture of a preliminary proximal model print

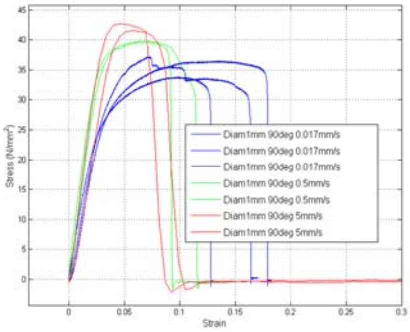

Fig. 4: Stress vs strain curves for tensile tests conducted on cylindrical nylon samples with a diameter of 1mm for strain rates of: 0.017 s^{-1}, 0.5 s^{-1} and 5 s^{-1}

IV. DISCUSSION

Axial and bending failure tests will be conducted on individual bones, and compared to the results of corresponding failure simulations. Finally, the full leg surrogate will be tested in a simulated blast scenario using a validated antivehicle, underbelly, blast-injury simulator, AnUBIS [6]. Results at all testing stages will be compared to bone behaviour to isolate the characteristic relationship required for interpretation of future tests performed on the surrogates.

The lower limb surrogate response to simulated underbelly blast will be compared with data from cadaveric experiments available in literature, which has been used to validate the MiL-Lx and Hybrid III [8]. It will also be compared to simulated response obtained using the computational model and a damage elasticity failure algorithm which has been developed in the research group. Furthermore, the damage suffered by the surrogates will be assessed and compared with bone fracture patterns and soft tissue injury mechanisms reported in literature. Finally, the model can be extended to the pelvic region to investigate injury mechanisms characteristic of the lower body region.

The main applications for this model are ballistic, blast and impact studies, as well as various other biomechanical testing scenarios and surgical training.

V. REFERENCES

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