Protection of the Foot and Ankle in Under-Body Blast

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I. INTRODUCTION

The use of improved explosive devices (IEDs) has been increased in recent armed conflicts. When a vehicle is attacked by an IED, the explosion causes deformation of the floor of the vehicle and the transmission of a high-rate axial loading to the lower limb of the occupants. This incident often leads to difficult-to-treat fractures in the ankle and foot and partial amputation of the lower limb [1]. The use of efficient mitigation strategies, such as blast mats and boots, can improve this outcome. Biomechanical tools, such as finite element (FE) models, can facilitate the design of mitigation strategies by assessing their efficacy in mitigating blast. The aim of this study was to develop an FE model of the lower limb with various mitigation strategies able to simulate under-body blast. This model can help to understand the function of mitigation strategies, quantify their effect and develop new ideas for combat boots and blast mats that can shift the injury pathways and minimise its burden.

II. METHODS

Geometries for the FE model were obtained after segmenting the computed tomography (CT) scans of a post-mortem human subject (PMHS) lower limb (male, 35 years old) using Mimics (Materialise, Louvain, Belgium). Prior to scanning, the ankle joint was set at 0° of dorsiflexion while the tibia was set to be vertical to the ground using a digital inclinometer. The structures of the model, including cortical and trabecular bone, cartilage, ligaments and soft tissues of the plantar foot, were inserted in Hypermesh (Altair Engineering, Troy, MI) to create the mesh consisting of hexahedral, wedge and quadrilateral shell elements (Figure 1). Material properties based on previous lower limb studies [2-4] were applied using MSC.Patran (v2017, MSC.Software, Santa Ana, CA, USA).

The loading scenario was simulated using a non-linear explicit solver MSC.Dytran (v2017, MSC.Software, Santa Ana, CA, USA). The model simulates the impact of a rigid floor to the lower limb as a result of an under-body blast event. The 15 kg rigid floor is driven upwards to reach a maximum speed of 5.2 m/s (time to peak velocity of 10ms) and was restricted to move upwards in the direction of the impact. The proximal ends of the tibia and fibula were also restricted to move in the direction of the impact, while the rest of the limb was represented by a mass of 12 kg also fixed on the distal end of the bones (Figure 1). Two versions of the model have been developed, one with and one without combat boot designs. The advantage of using a non-linear explicit solver for this model is that it allows a fast modification or adjustment of the geometric and material properties of components. This allows for the redefinition of mitigation system properties in a timely manner.

The second version of the model allows the user to tune the material properties and dimensions of combat layers and assess which set of parameters optimises the protective ability of the design (Figure 2). The tool also allows the inclusion of honeycomb structures within the combat boot design. Honeycomb structures have been explored in countermeasure designs for other blast contexts [5]. The mechanical behaviour of honeycomb structures is captured using a user defined material model and its location near the heel aims to maximise the protective ability of the boot by minimising force transmission to the tibia through the heel. The results and outcomes of the finite element models are illustrated in MSC.Patran.

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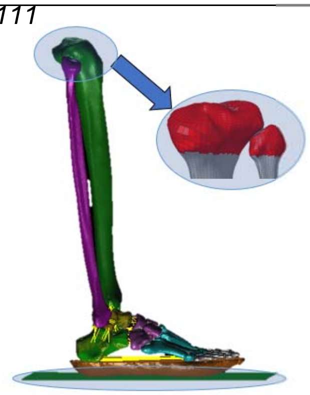

Fig. 1. FE model of the lower limb.

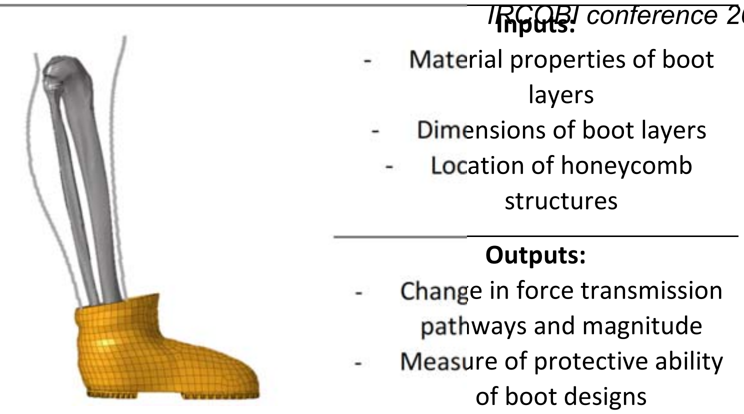

Fig. 2. Design tool for combat boot.

III. MODEL VALIDATION

The PMHS lower limb used for the model development, was exposed to loading typical of under-body blast (5.2 m/s within 15 ms) with and without a combat boot using an anti-vehicular under-body blast injury simulator (AnUBIS) previously developed by [6]. The moving plate of the simulator was instrumented with an accelerometer (350C23, PCB Piezotronics, NY, USA) and two force sensors (200C20, PCB Piezotronics, NY, USA) located under the heel and the metatarsal heads of the specimen. Ten strain gauges were attached on different locations on the tibia and the calcaneus of the specimen (Figure 3A). An X-Ray Fluoroscan (Vertec, Reading, United Kingdom) was used to assess whether the specimen has fractured during the tests (with and without protection). The inputs of this experiment were used to validate the finite element lower limb model.

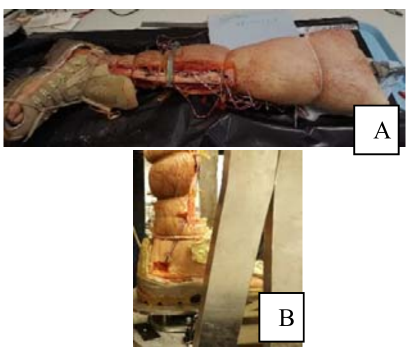

Fig. 3. Specimen before test.

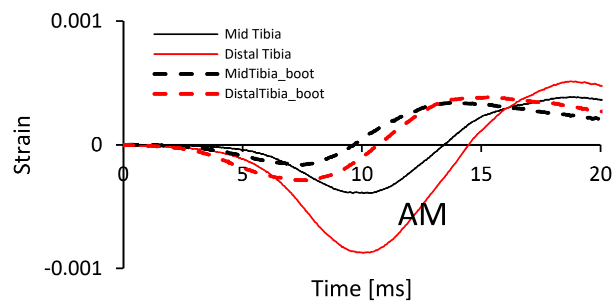

Fig. 4. Strain measured by a strain gauge located at the anteromedial side of the tibia in tests with and without protection.

IV. DISCUSSION

The tool presented in this study allows the design of a blast mitigating boot for under body-blast scenarios. By tuning the relevant properties of the components of mitigation systems, its mitigating efficacy can be optimised. Future work will be conducted to ensure that the experimental and numerical results match while the response of the model will also be compared against previous experimental studies.

V. REFERENCES

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