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A validated numerical model of a lower limb surrogate to investigate injuries caused by under-vehicle explosions

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ABSTRACT

Under-vehicle explosions often result in injury of occupants' lower extremities. The majority of these injuries are associated with poor outcomes. The protective ability of vehicles against explosions is assessed with Anthropometric Test Devices (ATDs) such as the MIL-Lx, which is designed to behave in a similar way to the human lower extremity when subjected to axial loading. It incorporates tibia load cells, the response of which can provide an indication of the risk of injury to the lower extremity through the use of injury risk curves developed from cadaveric experiments. In this study an axisymmetric finite element model of the MIL-Lx with a combat boot was developed and validated. Model geometry was obtained from measurements taken using digital callipers and rulers from the MIL-Lx, and using CT images for the combat boot. Appropriate experimental methods were used to obtain material properties. These included dynamic, uniaxial compression tests, quasi-static stress-relaxation tests and 3 point bending tests. The model was validated by comparing force-time response measured at the tibia load cells and the amount of compliant element compression obtained experimentally and computationally using two blast-injury experimental rigs. Good correlations between the numerical and experimental results were obtained with both. This model can now be used as a virtual test-bed of mitigation designs and in surrogate device development.

1. Introduction

Under-vehicle explosions cause high-rate axial loading of the lower limbs of occupants; this injury mechanism has been particularly prevalent in recent conflicts in Iraq and Afghanistan and is likely to continue to be common in future conflicts and in post-war humanitarian efforts (Ramasamy et al., 2009). This injury mechanism often results in severe lower limb injuries that are associated with a high amputation rate and very poor clinical outcomes (Ramasamy et al., 2012, 2011).

Anthropometric Test Devices (ATDs) are mechanical representations of the human musculoskeletal system, designed to be biofidelic in terms of anthropometry, articulations, and structural response. Their designs have been developed predominantly for use in the automotive industry and are generally agreed to be robust, reliable testing tools (Crandall et al., 2011). Current NATO standards (STANAG-4569) recommend that vehicle design is assessed through the use of either the Hybrid-III or the MIL-Lx ATD, both of which have built-in tibia load cells. The output of the tibia load cells can be used to provide an indication of the risk of injury to the lower extremity through the use of injury risk curves derived from cadaveric experiments. The response of the Hybrid-III leg, however, has been shown to be stiffer than that of a human lower limb in simulated under-vehicle explosions; the load rate in the Hybrid-III has been measured to be more than double that measured in cadaveric specimens, rendering it unsuitable for assessing mitigation technologies below the foot (Bailey et al., 2013; Newell et al., 2012b). The MIL-Lx was developed specifically to improve the biofidelic response in the under-body blast scenario (McKay, 2010). It differs in design to the Hybrid-III in that it has a straight tibial shaft and a 70 mm length rubber compliant element in the mid-tibia.

Numerous experiments have attempted to replicate the loading transferred to the lower limbs of occupants during under-vehicle explosions. Bailey et al. (2013) used a blast rig consisting of two independent sleds (the hammer sled and the carriage sled) mounted on a track to impact both cadavers and ATDs. The cadaver/ATD is positioned on the carriage sled and impacted at both the seat and foot pan by the hammer sled at velocities between 7.6 and 14.2 m/s, corresponding to accelerations between 234 and 686 g. The shape of the input acceleration is adjusted through the use of blocks of polyurethane. The peak forces

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measured by the MIL-Lx lower tibial load cell ranged between 3.77 and 6.46 kN, while the Hybrid-III measured between 6.96 and 14.4 kN. The force in the tibia of the cadaver was measured using a bone cell (array of strain gauges bonded around the tibia, calibrated to measure load); the resultant peak forces were between 3.3 and 6.3 kN.

Newell et al. (2012b) also tested the MIL-Lx and Hybrid-III legs using an anti-vehicle under-body injury simulator (AnUBIS) in which cadavers/ATDs rest on a 42 kg plate that is pneumatically accelerated upwards (Masouros et al., 2013). The compression of the combat boot observed with the MIL-Lx matched closely with that observed with the cadavers, whereas that observed under the Hybrid-III was much greater, thus suggesting that the response of the Hybrid-III deviates from that of the human limb in an under-vehicle explosion.

While a number of physical experiments have been undertaken using ATDs to investigate the loading observed during under-vehicle explosions, this has not been the case numerically. Finite element (FE) models offer a cost-effective alternative to expensive experimental setups, allowing the simulation of multiple scenarios through alteration of modelling input parameters. One numerical investigation of note is that of Dong et al. (2013) who developed an FE model of a lower extremity to predict the minimum axial force required to cause fracture. Their model was used to determine the critical maximum velocity of the floor plate to cause tibia fracture at a range of knee flexion angles. They found that, as the angle increased, the critical velocity increased. Aside from the long run time, one limitation of Dong et al.'s model is that it is subject specific. The development of a surrogate lower limb model, whose behaviour in comparison to a large number of cadaveric results is known, may provide a more powerful tool in predicting injury, since it can be used in conjunction with injury curves that have been developed through analysis of a large number of cadaveric tests.

This study, therefore, aims to develop an FE model of an ATD able to predict its response in simulated under-body blast. Recent findings have shown that the MIL-Lx ATD may be more biofidelic than the Hybrid-III ATD and, to the authors' knowledge, there are no published FE models of the MIL-Lx. Hence, the MIL-Lx is the focus of this study. The accuracy of the model is assessed by comparing the computational results with those obtained experimentally in two blast-injury experimental rigs.

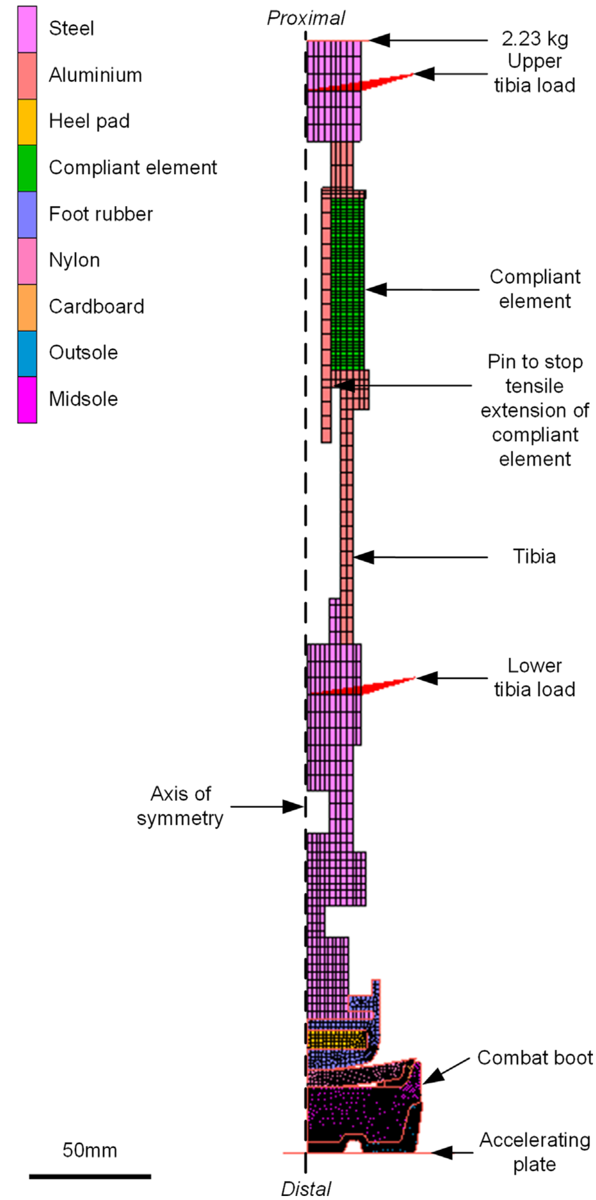

Fig. 1. Graphical representation of the model geometry.

2. Methods

A non-linear, implicit, axisymmetric FE model of the MIL-Lx ATD with a Meindl Desert Fox combat boot (Lucas Meindl GmbH and Co, Kirchanschoring, Germany) was developed in MSC.Marc (2013 Release, MSC.Software, Santa Ana, CA, USA) (Fig. 1). Whilst the axisymmetric geometry has some disadvantages in terms of accurately representing non-axisymmetric features such as the MIL-Lx forefoot and combat boot, the advantages provided in terms of simplifying the model and reducing computational time were judged to outweigh those disadvantages.

2.1. *Model geometry*

Measurements of the MIL-Lx were taken using digital callipers and a ruler while measurements used to create a geometry of the axisymmetric combat boot were taken from computed tomography (CT) images (HMX ST 225, Nikon Metrology Ltd., Tring, UK). Due to the model being axisymmetric a number of simplifications had to be made, the most notable of which is at the foot where just the heel of both the MIL-Lx and combat boot were measured, and the effects of the forefoot on load transfer proximally were assumed to be negligible. The MIL-Lx 'flesh' surrounding the tibial shaft was not included in the experiments conducted on AnUBIS (Newell et al., 2013), and was not included in the numerical model.

2.2. *Material properties*

Material properties of the outsole, midsole, foot rubber, heel pad, and compliant element were obtained through dynamic, uniaxial compression tests. Using a drop weight rig (Instron Dynatup, Model 9250-HV, High Wycombe, UK), a 6.45 kg mass with a flat tup was dropped from heights of 2, 20 and 50 mm onto samples harvested using an 8 mm biopsy pen and shaved to size using a lubricated blade such that the samples were approximately 4.9 mm thick. The samples were placed on a rigid, aluminium anvil which incorporated a load cell. The tup and anvil were lubricated with a thin layer of a multi-purpose synthetic grease lubricant (Superlube, Loctite Corporation, Düsseldorf, Germany) to reduce the friction. Force, measured at 25 kHz using a National Instruments PXIe data acquisition system (Newbury, Berkshire, UK), was converted to a stress using an average of 3 measurements of the diameter made with digital callipers (resolution $\pm$ 0.01 mm). Strain was calculated through analysis of high speed video footage (2000 fps, Phantom V12.1, Vision Research, Bedford, UK). The stress–strain curves were input into the FE software and both a 5-term Mooney-Rivlin hyperelastic model and 3-term Ogden material model were fit to the data. The formulation that had the smallest relative error was then used for that particular material. This resulted in a 5-term Mooney-Rivlin hyperelastic material model being used for the foot rubber, heel pad, and compliant element and 3 term Ogden models being used for the outsole and midsole. In the case of the midsole, a porous material, a 3 term Ogden foam material model was used. Validity of each material model was confirmed through the development of an axisymmetric FE model of the dynamic uniaxial compression test described above to ensure that each material model was accurate and stable up to the strains that were expected; this was 65% engineering strain and no simulation described later in the text exceeded that. The material model was considered accurate if the predicted peak force and time to peak force was within 5% of those observed experimentally.