Experimental Validation of a Computational Design: A Human Body Model Inspired Cervical Spine Surrogate for Primary Blast Injury Assessment

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I. INTRODUCTION

Anthropometric test devices (ATDs) are critical tools for investigating injury mechanisms and prevention, particularly in blast and ballistics testing. Since the widespread adoption of explosives in modern warfare during World War I, research efforts have focused on penetrating (secondary) and blunt force (tertiary) traumatic injuries [1]. As modern-day military personal protective equipment (PPE) has evolved to improve secondary and tertiary trauma survivability, higher numbers of overpressure (primary) injuries have been reported prompting the need for future investigation [2, 3]. Contemporary ATDs are costly, inhibiting widespread use in potentially destructive blast testing, and lack biofidelic representation of the soft tissue for primary blast injury (PBI) prediction. Human Body Models (HBMs) have previously been used to successfully investigate the effects of blast on hard and soft tissue [3–5]. However, physical models are still needed to examine the effects of novel PPE. This work is part of an ongoing effort to develop a high fidelity, low cost ATD capable of providing accurate and easily interpretable data regarding blast related injury risk. This requires not only incorporation of phantom organs for PBI investigation but maintaining skeletal components capable of capturing biofidelic gross movements for continued assessment of secondary and tertiary blast injuries. This study aims to design and validate a structurally optimised cervical spine surrogate inspired by a validated HBM.

II. METHODS

The four-step process outlined in Figure 1 was used to design and validate the novel cervical spine surrogate. The osteoligamentous cervical spine of the Global Human Body Models Consortium 50th percentile male pedestrian model (GHBMC-M50-OLS) was isolated and subjected to planar motion in LS-Dyna (Ansys, USA). Force-deflection data was collected by applying a load to C1, while holding C7 stationary for both extension and lateral bending. The area under the curve for the resultant plots was calculated to determine elastic energy, which served as a target behavior metric during topology optimisation.

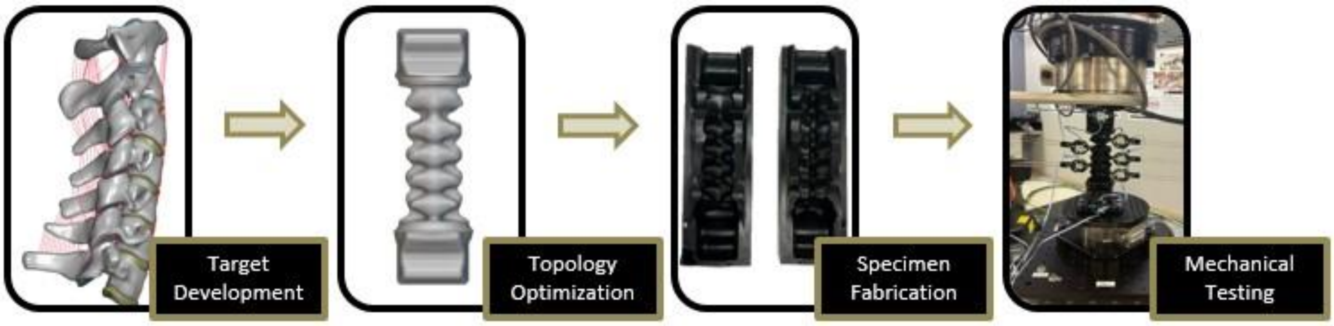

Figure 1. *Workflow for cervical spine surrogate development*

Topology optimisation was conducted using nTop (NY, USA), a computational design software. The GHBMC-M50-OLS geometry was used to establish baseline anatomically-inspired design regions for mechanical optimisation. The passive design region was constructed by scaling and blending the cervical vertebrae and ligaments, defining a continuous body to which material can only be added during optimisation. The active design region surrounds the passive design region and is defined by the outer boundary of a simplified volume representing the average male neck. Provided with the elastic modulus and Poisson's ratio of an off-the-shelf, urethane-based, two-part resin selected for fabrication, the optimisation was tasked with determining the optimal geometry capable of meeting the target behavior established by the GHBMC-M50-OLS in extension and

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lateral bending.

Upon generating a design replicating the GHBMC-M50-OLS's planar behavior, a custom two-part mold was designed and fabricated on an M1 printer (Carbon, USA). End caps designed to interface with the testing fixtures were included on either end of the neck design. Using the Flexane 80 liquid resin (Devcon, USA) defined during optimisation, a physical prototype of the neck was cast. The prototype was locked into the corresponding fixtures on the pedestal of the Kuka KR300 Ultra robot (Kuka, GER). Using SimVITRO (Cleveland Clinic, USA), a biomechanical testing software for controlling the Kuka, and an optical tracking system (NDI, CAN) for monitoring markers at each vertebral body, the surrogate was subjected to single moment loading. The exact trajectories deployed by the robot were then exported and recreated using the GHBMC for direct comparison.

III. INITIAL FINDINGS

Comparison of the experimental test data and the computational results for the GHBMC-M50-OLS in planar motion are shown in Figure 2. In flexion, the applied 2 N-m moment loading resulted in 17.5° of angular displacement. Running that same time-angle trajectory computationally, it was determined a 0.5 N-m load would be required to replicate that path with the GHBMC osteoligamentous cervical spine. Similarly for extension, the fabricated neck displaced 27° under the Kuka's 2 N-m moment while the GHBMC only required 0.7 N-m. In the lateral bending directions, the GHBMC required 2 N-m to displace 13.5° in both the left and right lateral bending. Experimentally, the fabricated neck did not have as perfectly symmetric behavior on both sides and saw 13.5° at 1.9 N-m in left lateral bending, and 12° at 1.8 N-m in right lateral bending. These results are accompanied by human subject data collected under relevant conditions by Liu *et al*., representing the average and range of male neck motion in each direction [6].

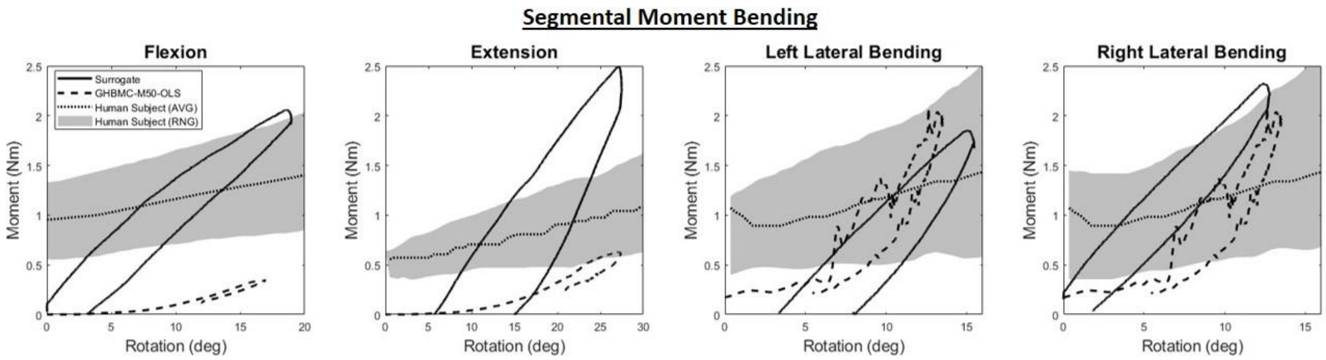

Figure 2. *Surrogate, GHBMC-M50-OLS, and representative human subject data for moment bending*

IV. DISCUSSION

We present a novel method for designing a low-cost, biofidelic cervical spine surrogate for evaluating gross motion of the head as part of a next-generation blast ATD. By optimizing the design to achieve compliance on par with the GHBMC and the complexity of the human neck, the data collected from sensors located within the skull of the head surrogate is anticipated to yield more accurate injury risk predictions for relevant blast injuries. In the future, further testing, both computational and experimental, will be done to evaluate the performance of the complete ATD.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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