Incapacitation Prediction for Readiness in Expeditionary Domains: An Integrated Computational Tool (I-PREDICT) – Assessing the injury risk in Behind Armor Blunt Trauma

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I. INTRODUCTION

With advancements in computational capabilities, in-silico techniques like finite element (FE) human body models (HBMs) have been used to simulate the response of the human body to complex dynamic events [1-5]. Compared to traditional experimental methodologies, these computational models are cost-effective, parameterisable and can provide information at the tissue level where damage originates and corresponds to system-level injury. Despite their benefits, computational models still have limitations. Most HBMs represent an average 50th percentile male in terms of overall anthropometric measurements and do not consider uncertainty and variability in model inputs. These average, deterministic models cannot accurately predict the risk of injury across a target population that exhibits natural variability in mechanical tissue properties, anatomical morphology and environmental loading conditions [6]. Biological variability in material properties, overall size and anatomical differences can significantly impact the structural response of the human body to mechanical loading, which significantly affects injury risk [7-8]. To address this concern, the DoD-funded I-PREDICT Future Naval Capability (FNC) has developed a probabilistic HBM that considers the uncertainty and variability in material properties and external boundary conditions. As such, our probabilistic framework computes a probability of injury relevant to a particular population under consideration. In this study, the I-PREDICT HBM is used to assess non-penetrating injuries caused by blunt trauma resulting from deformation of the back face of body armour (behind armour blunt trauma, BABT). The probabilistic response was compared to clay-test standards to validate body armour. We hypothesised that the results would not agree with safety standards derived from clay deformation depth.

II. METHODS

Experimental Testing

A custom-made 0.35 kg indenter, designed to mimic the typical backface deformation of hard armour, was used to conduct BABT clay tests in accordance with the NIJ 0101.06 standard. Roma Plastilina #1 clay, in a 56 x 56 x 14 cm box with a metal frame and plywood backing, was heated to 40°C in an oven and calibrated by dropping a metal sphere three times from a height of 200 cm, resulting in indentations ranging from 17 mm to 21 mm deep. The clay was flattened and subjected to multiple indenter shots, with the depth of each indentation measured by a depth gauge and the clay box scanned in 3D using a depth camera. A high-speed camera was used to determine mean velocities and standard deviations corresponding to both a 44 mm (current standard for hard body armour certification) and a 58 mm (proposed new standard) clay deformation.

Computational Modeling

Finite element simulations were performed in LS-DYNA using an impactor with identical specifications to the clay tests and driven into the I-PREDICT HBM with different impact velocities equal to the range measured in the clay tests. A low-velocity impact condition was also tested as a baseline analysis. Apart from the initial velocity, the initial impact location (±20 mm in the frontal plane) of the indenter and 27 tissue properties (obtained from literature) were implemented as random variables in the I-PREDICT HBM. 450 analyses were performed to generate a response surface model for injury prediction of each organ of interest. The response surface was then sampled 1000 times using a Latin Hypercube Sampling (LHS) technique to predict the injury risk in a population. To date, BABT impacts to three anterior torso impact sites (Fig. 1) have been analysed – the heart, liver and lower abdomen. Probabilities of Military Combat Injury Scale (MCIS) injuries [9] were reported for the organ closest to the impact locations – heart, liver and spleen, by employing a hierarchical approach that originates at the tissue-level to predict organ-level injury (Table I). Additionally, an aggregate incapacitation score, defined by the New Injury Severity Score (NISS) [10], was calculated by converting an MCIS score to an AIS (Abbreviated Injury Scale) score and squaring and summing the top 3 highest AIS scores.

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III. INITIAL FINDINGS

Following a regression analysis, it was found that the mean velocities corresponding to 44 mm and 58 mm clay displacements were 39 m/s and 49 m/s. We took half of the impact energy for the 44 mm clay displacement as the baseline impact case (20 m/s). Simulations with an initial velocity of 20 m/s, 39 m/s and 49 m/s indicate that the most severe injury risk (MCIS- and NISS-based) occurs when the impactor hits the heart, followed by impact at the liver and lower abdomen (Table I, Fig. 2).

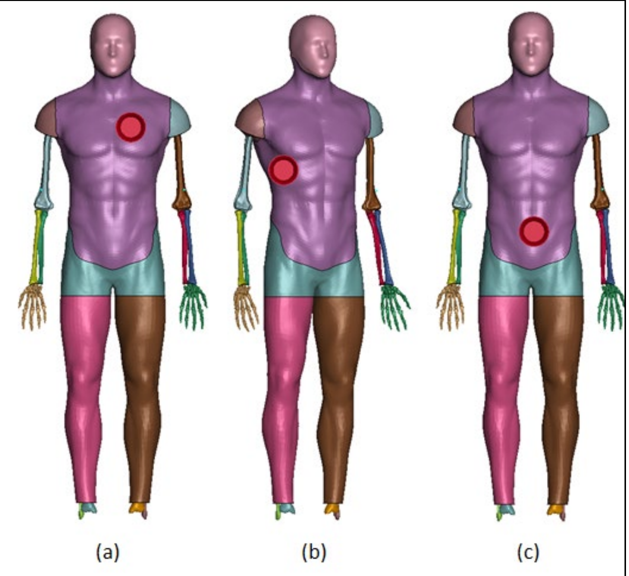
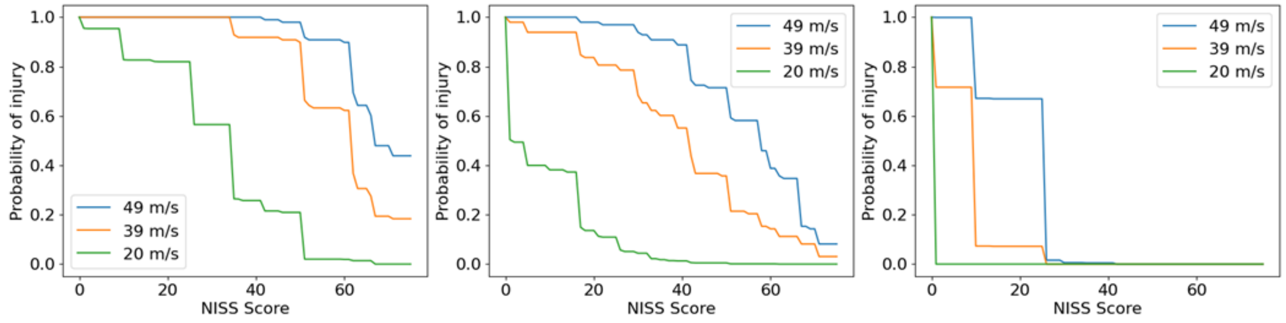


Fig. 1. Three impact sites tested: (a) heart, (b) liver and (c) lower abdomen.

TABLE I: MCIS-BASED INJURY PROBABILITIES FOR ORGANS WITH THE HIGHEST RISK OF INJURY AT THERE IMPACT SITES. MCIS 5, 4, AND 3 CORRESPOND TO LIKELY LETHAL, SEVERE, AND SERIOUS INJURIES.

Location	Velocity	Organ	MCIS 5	MCIS 4	MCIS 3
Heart	20 m/s	Heart	1	71	
	39 m/s	Heart	51	48	
	49 m/s	Heart	78	21	
Liver	20 m/s	Liver		16	14
	39 m/s	Liver	11	48	28
	49 m/s	Liver	20	57	14
Lower abdomen	20 m/s	Spleen			
	39 m/s	Spleen		7	64
	49 m/s	Spleen		66	33



(a) (b) (c)

Fig. 2. NISS-based injury risk curves for three impact sites, (a) heart, (b) liver and (c) lower abdomen, for three impact velocities

IV. DISCUSSION

In this study, the natural variability in material properties and impact conditions were considered in BABT analysis to develop an organ-level MCIS injury risk metric, as well as a NISS-based overall injury risk curve. Based on the NISS score for velocity corresponding to the current standard for certification (39 m/s), the heart impact is the most severe, with a 98% chance of a NISS score of 20, followed by the liver and lower abdomen impact with an 80% and 6% probability of a NISS20 injury score, respectively. This suggests that current protection standards may result in severe injury in some locations and no injury in others. Using the approach outlined in this study, it is possible to create injury risk curves tailored to specific populations, which can then be used to improve armour certification and design standards.

V. ACKNOWLEDGEMENTS

This research was supported through Office of Naval Research contract MTEC 18-04-I-PREDICT (W81XWH1590001): Incapacitation Prediction for Readiness in Expeditionary Domains: an Integrated Computational Tool (I-PREDICT).

VI. REFERENCES

[1] Shigeta, K., *et al*., ESV, NHTSA, 2009. [2] Iwamoto, M., *et al*., *Traffic Inj Prev*, 2015. [3] Shoell, S., *et al*., *Traffic Inj Prev*, 2015. [4] Zeng, W., *et al*., *Front Bioeng Biotechnol*, 2021. [5] Cronin, D., *et al*., *J Biomech Eng*, 2021. [6] Iraeus, J., *et al*., *J Mech Behav Biomed Mater*, 2020. [7] Nicolella, D., *et al*., *J Biomech*, 2006. [8] Nicolella, D., *et al*., ASME BED, 2001. [9] Lawnick, Mary M., *et al*., *J Trauama*, 2013. [10] Osler, T., *et al*., *J Trauama*, 1997.