Role of Indenter Design on Lung and Liver Impact Kinematics and Injuries in Behind Armour Blunt Trauma

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I. INTRODUCTION

Personal protective equipment in the form of body armour is intended to protect the Warfighter from ballistic threats. When successfully defeated, the threat's kinetic energy is transferred to the body armour resulting in material damage and backface deformation. (BFD) The deformation parameters are influenced by the threat kinetics (e.g., round type, mass, impact speed, obliquity) and armour type (e.g., hard, soft, material, backing). This dynamic deformation onto the human thoracoabdominal regions can produce injuries referred to as behind armour blunt trauma (BABT). To improve body armour standards and enhance Warfighter safety, it is important to conduct laboratory studies for the development of regional thoracoabdominal tolerances, i.e., injury criteria [1]. To develop generalised injury criteria, studies in the automotive and other disciplines have used specific/custom impact delivering systems, such as sled equipment and electrohydraulic test devices. Human cadavers are the preferred biological surrogate choice when skeletal fractures are the focus [2]. A similar paradigm is necessary for BABT applications to develop generalised injury criteria, with the recognition that injuries are physiological, and organs are affected. Thus, impacts generalising BFDs should be delivered to live biological surrogates with appropriately designed indenter(s). Recent studies have used a hollow spherical indenter design [3]. The indenter's impact surface shape and insult dynamics may influence load transmission and injuries to the biological surrogate. Studies are needed to explore this issue. The objective of this study is to investigate the role of the indenter impact surface shape and insult dynamics via parametric finite element (FE) modeling for BABT impacts to the liver and lung regions of the thoracoabdominal complex.

II. METHODS

Six indenter designs were evaluated. The first hemispherical indenter (ID1) was designed based on high-speed images of hard body armour BFD onto a biological surrogate during a live round impact [4]. The indenter had a diameter, dome height, and length of 100 mm, 30 mm, and 90 mm, respectively. The second indenter (ID2) had the same dimensions, except it had a wasp body design with a minimum diameter of 40 mm at the centre of its length. The third indenter (ID3) was a right circular cylinder with the same length and diameter. All three indenters in the first series had a mass of 230 g. The second series of indenters had the same dimensions and shapes, but the mass was reduced to 150 g. They were termed as ID4 through ID6, for the spherical, wasp, and right circular cylinders, respectively. Two impact velocities were considered, 30 m/s (termed as cases ID1 through ID6) and 60 m/s (termed as cases ID7 through ID12 with the same ID1 through ID6 indenter designs). Impacts were delivered to the liver around ribs 7 and 8 and to the lung around ribs 4 and 5 using the mid-size male Global Human Body Models Consortium (GHBMC) FE model [5]. Automatic surface-to-surface contact was defined between the whole-body HBM and the indenters. Peak rib and lung strains, and liver strain energy densities were used to evaluate the role of indenter design, i.e., shape and size. Using a strain energy density threshold of 11 μJ/mm^3 for the liver, rib strain threshold of 2.7%, and lung strain threshold of 15.4%, the potential for skeletal and organ injuries was obtained [6-9].

III. INITIAL FINDINGS

The kinematics were such that the indenter compressed the respective thoracoabdominal organs via local rib cage deformations. Rib strains were the greatest around the region of the impacting surface of the indenter. At low velocity, all three shapes and both weights did not produce lung injuries or rib fractures for lung impacts, and this was also true for liver injuries for liver impacts. However, rib fractures occurred for all cases except for the low mass, low velocity case (ID6 case, Table 1) in liver impacts. At the high velocity for the larger mass indenter, all three shapes produced both organ injuries and skeletal fractures. In contrast, for the low mass indenter, all shapes produced skeletal fractures for liver impacts (except one case), and liver injuries for the wasp shaped

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indenter (ID11 case, Table 1). Chord and cylinder indenters did not produce liver injuries in liver impacts at high velocity for the low mass indenter.

Table 1. Summary of results for 3 indenter shapes, 2 mass and 2 velocities. Green and red cells show the pattern of biomechanical injury metrics that were below and above their individual thresholds. See text for details.

Indenter	Case	Mass (g)	Velocity (m/s)	Liver impact		Lung impact	
				SED µJ/mm^3	Rib strain (%)	Rib strain (%)	MPS
Chord	ID1	230	30				
Wasp	ID2	230	30				
Cylinder	ID3	230	30				
Chord	ID4	150	30				
Wasp	ID5	150	30				
Cylinder	ID6	150	30				
Chord	ID7	230	60				
Wasp	ID8	230	60				
Cylinder	ID9	230	60				
Chord	ID10	150	60				
Wasp	ID11	150	60				
Cylinder	ID12	150	60				

IV. DISCUSSION

This is the first study to compare the responses of skeletal and organ structures for BABT applications focused on thoracoabdominal injury criteria. Results from spherical indenters (ID1, 2, 4, and 5) are applicable to BABT because their impact surface design approximates the BFDs of hard body armour. Peak strains and strain energy densities from the simulations represented intrinsic responses. As expected, all metrics had greater magnitudes as indenter mass and velocity increased. It should be noted that injury estimations were based only on the peak metrics and impact velocities. The severity of these injuries according to the American Association of Surgery for Trauma (AAST) Scale was not be assessed. Organ trauma is temporal due to factors such as haemorrhage and pulmonary function, which can only be determined from a live animal model. Despite this limitation, these results show that indenter shape and size play a role in the intrinsic mechanics of BABT impacts to thoracoabdominal regions. These findings can be used in the design of experiments for testing biological surrogates to cover a spectrum of BFD profiles for BABT applications. Such tests are needed to develop generalized injury criteria (injury risk curves) to improve the existing the current clay based BABT standard of 44 mm used for all regions covered by the body armour. The present model-based parametric analysis indicates that the effect of body wall design has less of an effect than impact surface shape (spherical versus flat), with the flat surface producing lower peak metrics. In other words, flater surface is protective based on velocity considerations. Analysis using energy, energy density, and momentum metrics is the next step in the analysis of indenter design on BABT biomechanics. Live animal BABT experiments are necessary to confirm these findings and to develop human thoracoabdominal regional injury criteria. This study provides parametric evidence of the influence on BABT injury metrics of variations in impactor shape and dynamics.

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