Development of a Simplified Torso Surrogate based on Selected Biofidelity Corridors for the Assessment of the Ballistic Performance of Soft Body Armor.

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I. INTRODUCTION

The ballistic performance of body armour is dependent of the way the armour is supported. Current standardised methods for testing body armour are prone to operating errors and all offer different boundary conditions which are not representative of how body armour is worn [1-3]. To optimise body armour systems, a test method measuring true *as-worn* performance is needed. There is also a growing interest for evaluating the performance of armour past its failure point (overmatch regime) to better predict injury outcomes when the armour is defeated. We embarked on the development of a simplified torso surrogate with increased biofidelity that would limit inter-laboratory variability on the measured ballistic performance of armour but also offer capabilities for assessing injury outcome, namely skin perforation and depth of penetration in soft tissue, upon armour defeat. We started by consolidating relevant historical data and proposing an initial set of biofidelity corridors for the local dynamic compliance of the torso, the skin penetration threshold and the resulting depth of projectile penetration (DoP) in soft tissue. We then investigated different variations of a simplified torso physical model with the following components: an outer skin (epidermis), an under layer (dermis), and a soft tissue simulant. The objectives of this short communication are to introduce the set of proposed biofidelity corridors and present promising results obtained from an initial torso surrogate designs.

II. METHODS

Three PMHS studies on low velocity impact to the torso [4-6] were reviewed based on their potential relevance to the scenario of a deforming soft armour against the human chest [7]. The deformation-time (D vs t) biofidelity corridors from [5], obtained for the impact of a 45 g, 38mm diameter short baton at 60 m/s on the epigastric and hypogastric regions of the abdomen, was found to be the most representative. A new single corridor was built from the overlap between the epigastric and hypogastric corridors from [5] (Figure 1). The higher and lower bound of the new corridors are given by:

$$D_{avg.Eck} = 0.117 + \left[33.10\left(1 - e^{-1.499t}\right) \right] \pm 7.5\% \quad (1)$$

Skin perforation datasets from four independent studies covering a range of projectile sectional density (SD) and geometry were used to construct a biofidelity corridor correlating skin ballistic limit V_{50} to projectile SD. (Figure 1). These studies respectively used a 127 gr, 9 mm bullet [8], a 17 gr Fragment Simulating Projectile (FSP) [9], a 1.34 gr soda lime glass sphere and a 4.28 gr brass sphere [10]. Skin V_{50} datasets not used in the fit were plotted over the proposed corridor and also showed acceptable agreement. The corridor bounds were obtained from fitting high and low bounds from the individual dataset with a logarithmic function, given by:

$$V_{50.low} = -44.40 \ln\left(SD\right) + 151.93 \quad (2)$$

$$V_{50.high} = -54.10 \ln\left(SD\right) + 192.22 \quad (3)$$

A biofidelity corridor relating projectile velocity to depth of penetration (DoP) in soft tissue was obtained from the work of [11-12] for the penetration of a 17 gr FSP in four areas (thigh, abdomen, thorax or neck) of pig and goat specimens. A logarithm fit was done to the thorax and abdomen combined data. For 0 mm penetration, the fit yields a velocity of 92 m/s, which falls within our skin perforation corridor. The higher and lower bounds were set to a half corridor vertical spread of 26 mm. The proposed DoP corridor equation is:

$$DoP = 160.7\left[\ln\left(V_i\right)\right] - 727 \pm 26mm \quad (4)$$

The development of the initial design of the simplified torso surrogate followed an iterative process. The iteration started with the ballistic testing of skin material candidates with a small caliber gas gun against the four projectiles used for the corridor definition (Figure 1 a-b). The V_{50} of candidate materials were obtained from the averaging of projectile velocity for five perforation and five non-perforation cases within a maximum range of 20 m/s. Then, different soft tissue material candidates were tested with the best skin material candidate using a large bore gas gun against the Eck 45g short baton round at 60 m/s. For each combination, the baton displacement vs time response was measured using high speed imagery (Figure 1 c) and compared against the

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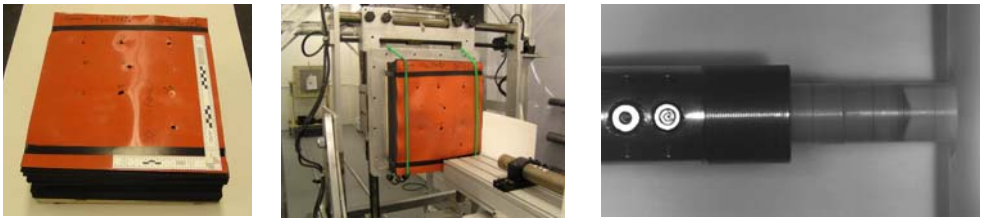
compliance biofidelity corridor. The best torso surrogate was retested ballistically for skin V_{50} and DoP response. If further modification was required to the surrogate configuration, then the iterative process was continued.



a b c

Fig. 1. a. Example of proposed backing construction, b. Ballistic test set-up and, c. High-speed video tracking baton round for during compliance backing compliance test.

III. INITIAL FINDINGS

Upon evaluating a number of thermoplastic elastomer materials, it was found that a combination of a 1/16 in thick Shore A 50 silicone rubber and a 6.35 mm thick neoprene foam grade 2A1 was a promising option for a skin simulant. The definition of a robust perforation criteria, based on the complete perforation of the neoprene layer, was critical to match the biofidelity corridor across the entire range of projectile SD. Different grades and stacks of 6.35 mm thick neoprene foam layers were tested as a soft tissue simulant. The layered design allows for an easy measurement of DoP by simply counting the number of perforated layers. Based on its compliance response, it was found that a stack made of 15 layers of neoprene foam (five layers of grade 2A5 over 10 layers grade 2A2) showed the best agreement with the proposed corridor. DoP response was more difficult to match as a non-uniform layering of the pack resulted in a by-linear DoP response. Figure 2 shows the response of our initial torso surrogate design against the three proposed biofidelity corridors.

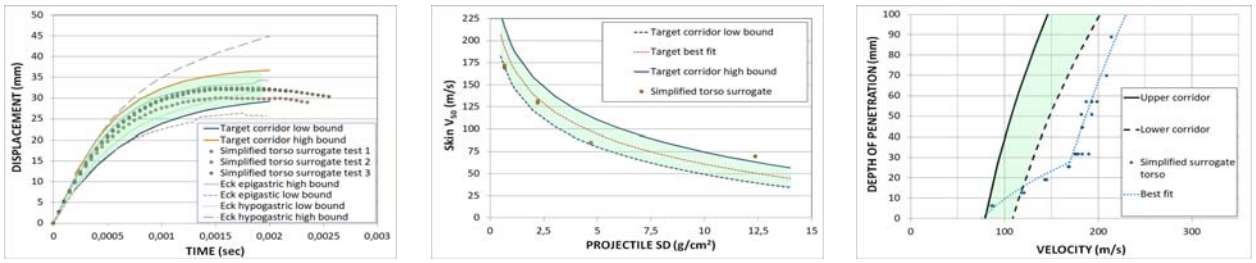


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Fig. 2. Response of simplified torso surrogate design against proposed biofidelity corridors for: Local torso compliance (a), Skin perforation threshold (b) and Soft tissue depth of penetration (c).

IV. DISCUSSION

The process of matching all three biofidelity corridors is not trivial as converging on the compliance biofidelity leads to diverging on the DoP response. Matching the DoP response may be less critical since it does not affect the dynamic mechanical coupling with the armour being tested. As such, a transfer function between the DoP response of the simplified torso surrogate and that of human soft tissue could be defined. However, such transfer function would benefit from a monotonic behaviour of the torso surrogate, which will require a single material type for the soft tissue simulant. This is the focus of an on-going research.

V. REFERENCES

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