The Injury Tolerance of the Upper Extremity from Behind-Shield Blunt Trauma Mechanisms

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I. INTRODUCTION

Behind-armour blunt trauma (BABT) may occur when protective equipment undergoes rapid deformation as a result of projectile impact. While risk to a user has been characterised for body armour and helmet injury risk, ballistic shields, supported by a user's arm, have no known standards for protecting against BABT. When a bullet strikes a shield, the energy is absorbed, leading to back-face deformation (BFD) [1]. This may lead to injury of the user's hand, wrist, forearm, or elbow, often in close proximity to the back of the shield. The injury tolerance of these regions has been investigated in some previous studies, typically focusing on automotive or fall configurations, which differ from BABT in their speed, duration and direction of loading. As such, new standards developed specifically for this scenario are necessary to ensure shields provide adequate protection for users. Furthermore, as user size may govern the resulting injury tolerance, injury thresholds may be needed to represent populations of different anthropometrics.

Previous work by our group has characterised the loading profile that occurs at the upper limb resulting from shield BFD [2]. In this, a WorldSID (Humanetics, USA) upper extremity Anthropomorphic Test Device (ATD) was augmented with force sensors mounted at specific locations of interest and tested under behind-shield ballistic conditions. Forces were measured between 3 kN and 19 kN, depending on the stand-off distance, defined as the gap between the back of the shield and the front of the sensor/user's arm, and impact durations were on the order of 0.5 ms [2]. The purpose of this study was to create equivalent conditions in the lab and develop injury risk functions for two anatomical locations – the hand and forearm – under behind-shield impact conditions, for 5th percentile males.

II. METHODS

Testing was conducted using a pneumatic impacting apparatus equipped with a 434 g projectile instrumented with force sensors. The ATD arm was used to calibrate the apparatus to generate impacts representing a range of stand-off conditions. As the velocity could not match that of the shield due to apparatus limitations, applied force and impact duration were targeted. Due to instrumentation limits on the ATD, data were extrapolated to generate parameters for stand-off distances below 10 mm.

Post-mortem human subjects (PMHS) were sectioned mid-humerus and potted in a block of cement. Specimens were selected to closely represent the 5th percentile male population and were limited to be below the 15th percentile in both donor weight and height. The PMHS hand was affixed to the testing handle (representing that of a shield) using tensor bandages, such that the metacarpals were positioned in front of the handle (Fig. 1). Impact locations were identified via palpation to be the midpoint of the forearm length and the mid-proximal epiphysis of the third metacarpal. As each limb was impacted at two anatomical locations, the order was randomised to eliminate any potential sequencing effects.

A pilot specimen was used to conduct a stepwise investigation of the fracture threshold, whereby increasing impacts replicating different stand-off distances were applied (controlled by increasing the velocity of the projectile). Once fractures were observed (confirmed by x-ray), the remaining specimens were then impacted at the injury-inducing conditions. Output measures included impact velocity, projectile force-time trace, peak force, impact duration, impulse, and momentum at fracture, and fractures were classified by a radiologist.

III. INITIAL FINDINGS

The pneumatic impacting apparatus was able to replicate the peak forces at 20 mm, 15 mm, and 10 mm

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stand-off distances (from previous ballistic testing) within 5%. The corresponding projectile velocities were 1.6 m/s, 5.3 m/s, and 9.8 m/s, respectively. Impact durations were from 0.5 ms to 1.1 ms. Conditions were extrapolated to represent stand-offs of 7.5 mm, 5 mm, 2.5 mm and 0 mm, which were achieved at velocities of 11.3 m/s, 12.4 m/s, 13.4 m/s and 15.0 m/s, respectively.

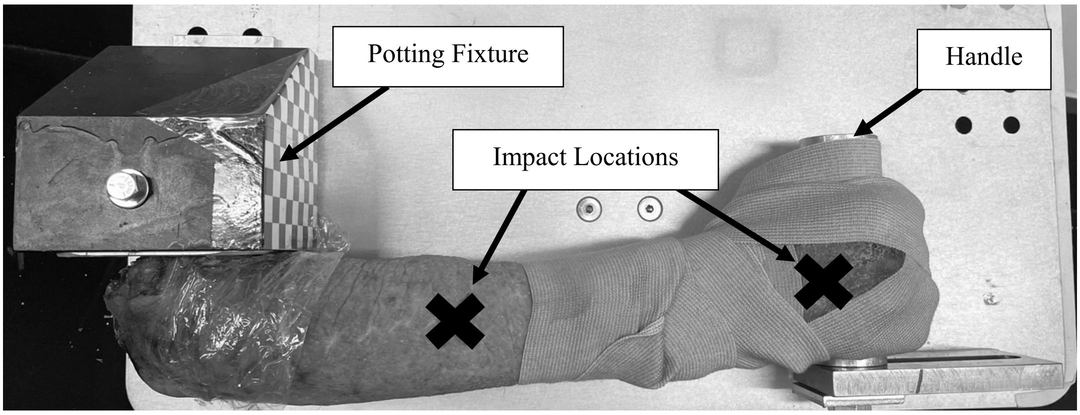

Fig. 1: PMHS preparation, where impacts were applied to the metacarpals and the mid-forearm.

Five PMHS have been tested to date. The pilot specimen failed at the hand under the conditions representing the 10 mm stand-off (force of 1477N), and at the forearm under conditions representing a 7.5 mm stand-off (force of 1304N). The remaining specimens fractured on average at conditions representing 5 mm and 2.5 mm stand-offs, indicating some accumulation of damage from repeated impacts in the pilot. As such, the pilot was excluded from further analysis (Table I).

TABLE I

MEAN (SD) CONDITIONS FOR FAILURE TESTS AT THE HAND AND FOREARM FOR FOUR SPECIMENS (PILOT EXCLUDED)

Location	**Impact Velocity (m/s)**	**Peak Force (N)**	**Duration (ms)**	**Impulse (N*s)**	**Momentum (kg*m/s)**
Hand	13 (0.8)	2350 (1077)	5.3 (1.3)	3.6 (0.4)	5.7 (0.4)
Forearm	13.7 (1.1)	2197 (782)	6.4 (5.1)	3.9 (1.5)	5.9 (0.5)

IV. DISCUSSION

This is the first known study to investigate the injury tolerance of the upper limb from shield BABT where the force-time profiles applied in the lab were consistent with previous ballistic tests. Given the unique parameters of this scenario (high loading rate), the tolerance of the upper limb to these impacts must be investigated under representative conditions. Unsurprisingly, forces in the ATD were much higher than in the PMHS, as the ATD flesh analogue was removed to prevent damage to it. The average failure forces were similar to those from previous studies (hand force of 3.0 kN [3], forearm force of 2.0 kN [4]). The effect of PMHS size on injury tolerance will be explored through equivalent tests on 50th and 95th percentile specimens, facilitating the development of injury risk corridors for males of different sizes exposed to this unique high-rate scenario.

Upon completion of testing, survivability curves will be developed and 10% risk of fracture limits identified. These will be translated to the WorldSID ATD through impact testing at the corresponding limit conditions, ensuring translation of the testing performed herein to future ballistic shield safety evaluations. This work is an important step towards the development of standards to assess injury from BFD (not previously addressed for the upper limb), ultimately leading to increased user protection.

V. REFERENCES

[1] Bolduc, *et al.*, *PASS*, 2018.
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[3] Carpanen, *et al.*, *J Mech Behav Biomed Mat*, 2019.
[4] Pintar, *et al.*, *Stapp*, 1998.