Loads Associated with Behind Helmet Blunt Trauma: Matched-Pair Load Sensing Headform Tests Correlated with Skull Fracture Severity

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Abstract. Events where ballistic rounds do not completely perforate combat helmets are hypothesised to cause blunt injury [1]. These events and subsequent injuries, termed behind helmet blunt trauma (BHBT), are caused by the rapidly-deforming backface of the helmet striking the wearer and are not well understood. Current and previous helmet testing methodologies and acceptance standards are based on the use and evaluation of the deformation left by the helmet backface in clay. Limitations in clay testing have led to interest in more repeatable mechanical surrogates, potentially for use in First Article and Lot Acceptance Testing. The Adaptable Testing and Load Assessment System (ATLAS) Headform was developed by the Johns Hopkins Applied Physics Laboratory [2] to provide physics-based measurements of backface loading from a live fire BHBT event. This novel, more repeatable, and user-friendly testing system would benefit from establishment of a relationship with human injury to inform testing standards. There are several examples of studies using post-mortem human surrogates (PMHS) to evaluate the injuries seen in these BHBT events [3, 4, 5]. To understand the mapping between physics-based measurements and injury probability, similar ballistic events including round type, velocity, helmet type, impact locations, and fit conditions should be tested on both PMHS and the ATLAS Headform system. This study compares sixty previously-conducted PMHS BHBT test results [5] with sixty-five ATLAS Headform results across a range of relevant ballistic doses and impact locations. These studies used the same type of helmet and fit conditions targeting a consistent standoff between the helmet and head, and live ammunition. These matched-pair tests were conducted to provide associated fracture lengths, injury severity, peak load, and force impulse for a similar BHBT event. The relationship between loading conditions and skull fracture can be used for comparison to similar predictive models for related injury types, human computational model validation, and future performance standard development.

1. INTRODUCTION

Combat helmets are designed to protect the wearer against many threats. As a crucial part of ballistic personal protective equipment, helmets are evaluated for their ability to stop complete penetration of specific ballistic threats while limiting the amount of helmet backface deformation (BFD). While the implications of stopping a round from completely penetrating are fairly clear, the implications of a round not fully penetrating the helmet and subsequently deforming are less understood. The rapid deformation of the backface of these helmets can impact the head and cause an injury termed behind helmet blunt trauma (BHBT). BHBT may include scalp contusions, scalp lacerations, skull fractures, and brain injury and has the potential to be fatal [5]. To mitigate this risk, ballistic tests are conducted on combat helmets mounted on headforms, but the relationship between BFD loading and injury is not well characterised. This limits the ability to create test standards that are relevant to reducing human injury.

Various headform testing has been conducted to evaluate BFD loading using live ammunition striking helmets. BFD loading is dependent on helmet impact location, suspension pad configuration, and projectile characteristics influencing deformation response. Two testing methods are favored, one being clay-backed headforms and the other being load cell-backed headforms. Clay headforms measure the deformation in clay caused by the helmet BFD and typically must not exceed a certain threshold [6]. These clay headforms suffer from a lack of repeatability stemming from the clay's less-controlled formulation and exacerbated by the specific geometrical constraints for helmet and headform interactions [7]. Conversely, load cell-backed headforms have been evaluated and are favored for their repeatability and temporal (dynamic) measured response for blunt ballistic testing, for example the Biokinetics Ballistic Load Sensing Headform [8], the Force Reaction Evaluation Device [9], and the load sensing headform developed by the researchers at the University of German Federal Armed Forces [10]. One of these load cell testing platforms is the Adaptable Testing and Load Assessment System headform (ATLAS) developed by the Johns Hopkins Applied Physics Laboratory (JHU/APL). The ATLAS is a

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newly developed test platform and has design features that allow for high-throughput armour performance testing [2]. There is great interest in gathering data on this headform associated with BHBT loading. While comparisons of headform results and computationally predicted injuries have been made [10], the direct relationship between BFD loading measured with mechanical headforms and actual experiments recreating human BHBT injury has not been established, hindering the ability to assess human injury risk. This results in non-injury-based helmet performance standards that may limit the optimisation of future helmet systems in protecting from BHBT. There is a clear need to study the phenomena of BHBT across a range of relevant loading conditions to establish a relationship between non-penetrating ballistic events and injury risk.

Previous studies have been conducted on postmortem human subjects (PMHS) to determine the relationship between loading to the skull and injuries [11, 12, 13]. Very few studies have been conducted with BHBT loading parameters [3, 4, 14], which are low mass and high velocity. In addition to the need for a more comprehensive PMHS BHBT injury study to determine the potential injuries from these events, having associated BFD loading parameters (e.g. clay deformation, peak load, etc.) with these injuries could form the basis for future helmet BHBT performance standards.

For this current study we leveraged the PMHS model, wearing light-weight helmets struck by live ammunition, to understand the relationship between BHBT loading and human injury (at four locations) and associated loading and armour performance measurements made by the ATLAS Headform. These relationships represent preliminary injury prediction models for BHBT and could be used to develop future helmet testing methods, performance standards, and more protective armour designs.

2. METHODS

2.1 Projectile and Helmet Combination

The same projectile and helmet combination was used for all tests in this study. The projectile chosen was a 124 grain, 9 mm full metal jacket, while striking velocities were intentionally varied ranging from 298-423 m/s to achieve research goals. The helmet was a modern lightweight helmet constructed primarily out of ultra-high molecular weight polyethylene. Each helmet was shot once at one of four locations, the crown, front, left side, and rear. Impact locations on the helmet were chosen in order to replicate the common test locations during helmet qualification testing. (Figure 27). Helmets had pads and suspensions systems installed according to the manufacturer's instructions. Pads included in the helmets were 1.27 cm thick made of expanded polypropylene, positioned behind each impact location. Due to the placement of the pads, the impact location on the crown of the helmet was between two pads and the impact location on the side of the helmet was offset (i.e., not-centred) with a pad behind. Both the rear and front impact locations were directly centred on a pad.

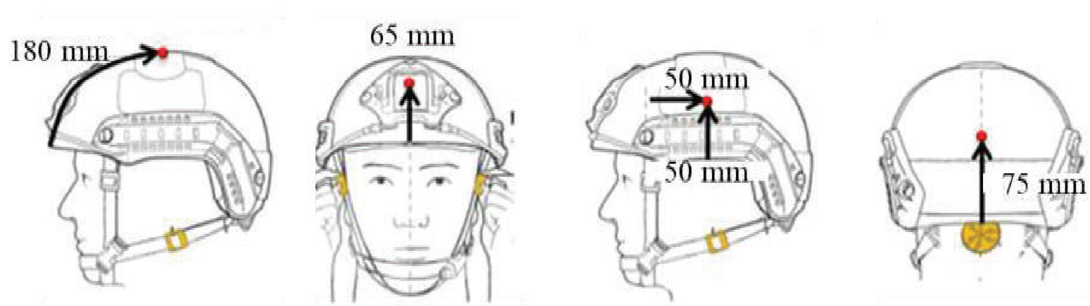

Figure 27: Helmet impact locations (red circle) for (left to right) crown, front, left side, and rear. Numbers (in mm) indicate distance measured across the surface of the helmet, along the direction indicated by the arrow

Tested locations for PMHS anatomical impacts were varied due to normal anatomical variation of skull bone and suture location as well as from the steps taken to get desired impact obliquity on the helmets (Figure 28). Crown impacts were on the mid-sagittal plane and posterior to the bregma (which is located at the intersection of the coronal and sagittal sutures). Front impacts were on the mid-sagittal plane and were approximately 10 cm above the most superior aspect of the orbits. The impact on the left side of the head was approximately 10 cm above the auditory meatus, perpendicular to the Frankfort plane on the parietal bone. The rear impact was on the midsagittal plane just below the lambdoid suture on the occipital bone.

Figure 28: Approximate anatomical impact locations for the crown (red), front (green), left side (blue), and rear (purple)

2.2 PMHS Testing

2.2.1 PMHS Specimens

All PMHS specimens were fresh-frozen, thawed, un-embalmed head-neck complexes. The donor inclusion parameters and criteria that were targeted were age (18-61 years), gender (male), race (any), and absence of known medical history that may influence tissue response (e.g., absence of skull disease or head trauma). All specimens were comprised of intact skulls and external soft tissue (i.e., scalp and muscles), as the latter has been found to significantly influence skull fracture risk [3]. Since proper fitment of the helmet system being tested was necessary to remove additional variability in outcomes, specimens were selected with target specifications of head width (15.3 – 16.0 cm), head length (19.6 – 20.5 cm), and head circumference measured at the eyebrow level (56.0 – 59.0 cm) according to the fit documentation from the helmet manufacturer.

2.2.2 PMHS Specimen Preparation and Testing

Specimens were prepared by dissecting the lower cervical spine to expose the vertebral bodies to be potted in polymethyl methacrylate. Various electromechanical sensors were installed on the specimens, including strain gauge rosettes, acoustic emission sensors, intracranial pressure sensors, and 6 degree-of-freedom accelerometer packages. The results from the electromechanical sensors are not the focus of this paper and are not discussed further. Care was taken to install the sensors in a way that would not disrupt tissue at the impact site or introduce any loading of the BFD to potentially influence injury.

Prepared PMHS specimens were secured with a custom fixture securing the potted lower cervical neck to a rigid test frame. This custom fixture positioned the head-neck system in an inverted position, which used gravity to achieve more realistic specimen positioning due to the lack of active neck muscle tension.

After donning the helmet on the specimen, an internal helmet-surface to head standoff distance of 23 ± 0.5 mm was achieved for all shot locations. Standoff between the outside of the helmet shell to the surface of the head was measured using a FaroArm® (FARO Technologies, Lake Mary, FL) to remain consistent with the testing standard as well as between tests within this study. The thickness of the helmet shell was measured using precision calipers in order to determine proper standoff. Projectile velocity measurements were obtained using Oehler Research Model No. 57 (Oehler Research, Austin, TX) infrared screens with counter chronographs (universal counters, Hewlett-Packard model No. 53131A).

2.2.3 PMHS Forensic Evaluation

Following ballistic testing, the heads underwent Computed Tomography imaging with and without the helmet. Anatomical dissections were completed within two days of ballistic testing. For the anatomical

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assessments, an external examination of the scalp and impact location was completed before reflecting soft tissues to expose the skull surface. An internal examination was then conducted by opening the calvarium to inspect the inner skull layer and soft tissue structures (e.g., dura and brain). Detailed notes and photo-documentation were collected, specifically noting fracture type (e.g., linear, depressed), severity, location, and length. The length of the fractures in this study were obtained by measuring unique fracture lines on both the inner and outer table of the skull and combining them for a total fracture length metric. Complex and comminuted fractures were analysed after dissection through photo-documentation, measuring the boundaries of each piece and summing the inner and outer table fracture lengths. Images from the CT scan were reviewed and injuries documented. A medical report was provided for each test. Results from the anatomic dissection and CT scan were coded with Abbreviated Injury Scale (AIS) 2005 © updated 2008 [15] for each documented injury. No injuries to the dura mater or brain parenchyma were observed in this study. However due to the limitations of the PMHS model, injuries to these structures, including concussion and a more severe brain injury, may occur under similar conditions in a living individual. For each test, the maximum AIS was determined (MAIS). The dissections, review of CT scans, preparation of reports, and injury scoring were performed by a board-certified forensic pathologist with extensive trauma experience

2.3 ATLAS Headform Testing

The ATLAS Headform was developed to evaluate the ballistic performance of combat helmets as an alternative to the current clay-based approaches used to measure the potential for BHBT [2]. The ATLAS Headform is a platform that can accommodate different impact locations, helmet sizes, and helmet geometries via incorporation of a modular head structure. The system uses a piezoelectric force sensor with a measurement range up to 111 kN (Force Sensor Model 224C/FCS-DI IC, PCB Piezotronics), to provide a temporal measurement of impact force transmitted to the head. Importantly, as a result of the design of this system there is no need to reposition the stationary base, post, and load cell for different impact locations; rather, the head configuration changes around the load cell, as can be seen in Figure 29.

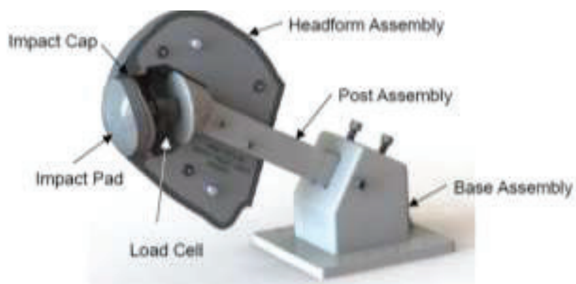

Figure 29: Schematic of the JHU/APL ATLAS Modular Headform system.

To swap configurations, the user removes the single-use neoprene impact pad, stainless steel impact cap, and polymer headform (2 pieces) and swaps them out with components for a different impact location or headform size. These modular components are held in place with magnets, alignment features, and/or friction and thus do not require mechanical fasteners. The ATLAS Headform was designed such that, when the helmet is seated properly on the headform, there is 23 mm of standoff between the helmet shell and headform and perfect alignment and zero-degree obliquity between the projectile, helmet and load cell.

For the ballistic test series, the ATLAS Headform load cell was connected to a signal conditioner (Model 482C05, PCB Piezotronics). The signal conditioner was connected to a high-rate data acquisition system (SIRIUS R4, Dewesoft, Trbovlje, Slovenia) that recorded load cell time history data. Data was collected at a 1 MHz sampling rate with a 5th order Bessel analog anti-aliasing filter with a 100 kHz cutoff frequency. No other digital filtering was applied to the data and force signal oscillations, potentially caused by system resonance and BHBT loading dynamics, were present in the force-time histories. All electronic systems were simultaneously triggered with the signal disruption of a frangible paper breakscreen disrupted by the incoming projectile approximately 1.5 m from the impact. Data was post-processed in MATLAB (MathWorks, Natick, MA). The data features were the peak force defined as the maximum of the signal, time to peak force defined as the duration between the trigger and peak force, and impulse computed by integrating the force-time history over 1 ms (Figure 30).

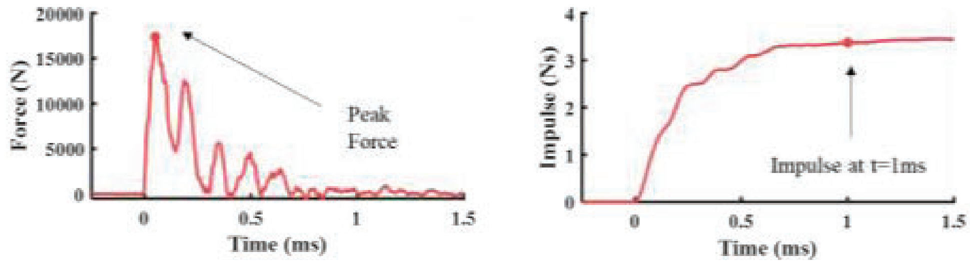

Figure 30: Example (left) force and (impulse) time histories and corresponding peak force and total impulse at 1 ms.

A sample size of four repeated tests were conducted at each of four impact locations and at each of four discrete impact velocities that were evenly spaced and spanned the range of impact velocities used for PMHS testing for a given location, for a total of 65 ATLAS Headform tests. Linear regressions were fit to the ballistic conditions versus loading results for each impact location, quantifying the relationship between ballistic conditions (e.g. striking energy, which was varied) to ATLAS peak load and impulse. The relationship between ballistic conditions and ATLAS headform results are not presented in this paper. However, these linear regressions all had high coefficient of determinations (e.g. R^2 values) with the lowest being 0.869. This higher coefficient of determination is influenced by the repeatability of the ATLAS headform system and the linear relationship between ballistic velocity and load response at the tested ballistic condition, which are deemed adequate for this ballistic testing application. These resulting relationships were used to evaluate the equivalent loading in the PMHS tests across the different studies and impact locations for specific testing ballistic velocities. These matched-pair load and impulse values were evaluated for their ability to predict injury in the PMHS data set.

3. RESULTS

The range and average results from PMHS injury data (i.e., MAIS and fracture length) are compared to loads evaluated at the ballistic conditions of each PMHS test (Table 14). One case from the rear test group had a disputed fracture and is not included in the results. Overall, assessed MAIS values were seen ranging from 1 – 4 and fracture lengths ranged from 0.0 (no fracture) to 142.0 cm. The associated matched-pair test loads ranged from 9.6 kN to 22.6 kN. The impulse ranged from 2.62 to 3.81 Ns.

For those tests with no fracture, the MAIS was 1 or 2 depending on the extent of the scalp injury. Total fracture length trended with MAIS. Complex and comminuted vault fractures have higher AIS severities, 3 and 4 respectively, and typically have increased fracture lengths compared to simple vault fractures (AIS severity of 2).

Injury results, organized by impact location and ATLAS derived metrics, can be found in Figure 31. Generally, increased loading corresponded with fracture and injury severity. However, there was a large region of mixed results, where peak loads and impulses seen with non-fracture cases were 17.3 kN and 3.34 Ns. Alternatively, the lowest peak loads and impulses for fracture cases were 10.9 kN and 2.67 Ns, respectively. The associated forces and impulse with crown fractures were greater than the loading associated with other location. The front impact location had the lowest loading associated with those tests.

Table 14. Average loading and injury outcomes organised by impact location

Impact location	Maximum AIS	Number of Outcomes	Average Peak ATLAS Load (kN)	Average ATLAS Impulse (Ns)	Average Total Fracture Length (cm)
Crown	1	4	15.9±1.57	3.21±0.14	0.0±0.0
	2	3	17.8±0.71	3.39±0.06	10.0±7.1
	3	2	19.0±0.96	3.49±0.09	41.0±11.3

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	4	2	21.5±1.10	3.71±0.10	125.0±17.0
Front	1	7	11.1±1.00	2.75±0.09	0.0±0.0
	2	3	12.4±1.27	2.88±0.12	21.0±1.4
	3	8	14.4±2.42	3.05±0.22	38.0±17.4
	4	2	17.2±1.60	3.31±0.14	36.0±4.7
Left Side	1	7	13.1±1.37	2.91±0.15	0.0±0.0
	2	2	14.0±1.09	3.01±0.12	6.9±6.1
	3	4	15.6±1.44	3.18±0.16	44.9±41.4
	4	2	15.1±1.41	3.13±0.15	96.7±2.8
Rear	1	5	11.6±1.06	3.00±0.13	0.0±0.0
	2	1	14.9±0.00	3.39±0.00	3.5±0.0
	3	6	13.3±0.74	3.20±0.09	38.1±33.6
	4	1	13.1±0.00	3.17±0.00	56.2±0.0

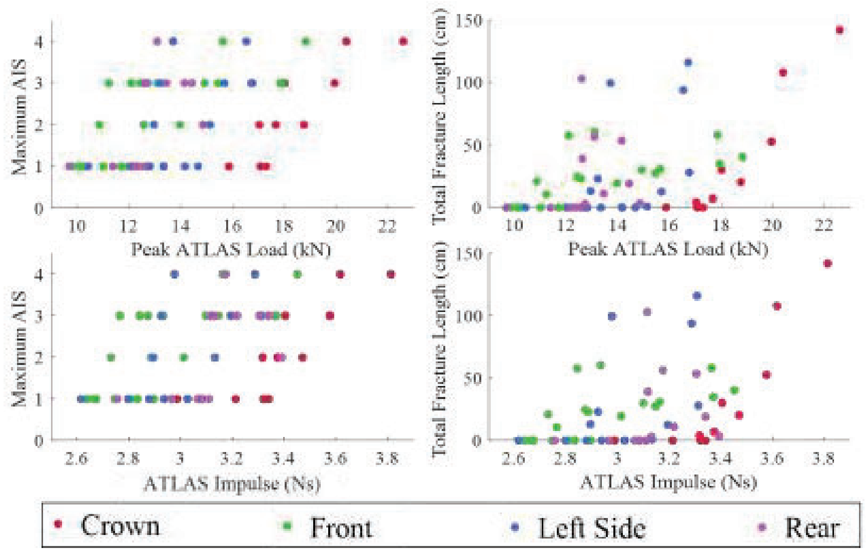

Figure 31: Scatter plots of the peak ATLAS Load (N) versus Maximum AIS, grouped by impact location (Left Top). Peak ATLAS Load versus total fracture length, grouped by different impact location (Right Top). ATLAS Impulse versus Maximum AIS, grouped by different impact location (Right Bottom)

Peak ATLAS load and impulse were fit, using a linear regression, to total fracture length for each impact location (Figure 32). Non-fracture cases were omitted from the regression in order to establish a predicted threshold of fracture (e.g intercept) and not weighing the regression with many non-fracture cases (n=24). All locations indicated a relationship of increasing load with respect to fracture length, aside from the rear location. The crown results are the only results that showed a coefficient of determination over 0.9. P-values for linear coefficient of ATLAS loading variable were lowest for the crown location (0.0009) and varied between 0.2427-0.4272 for the other locations.

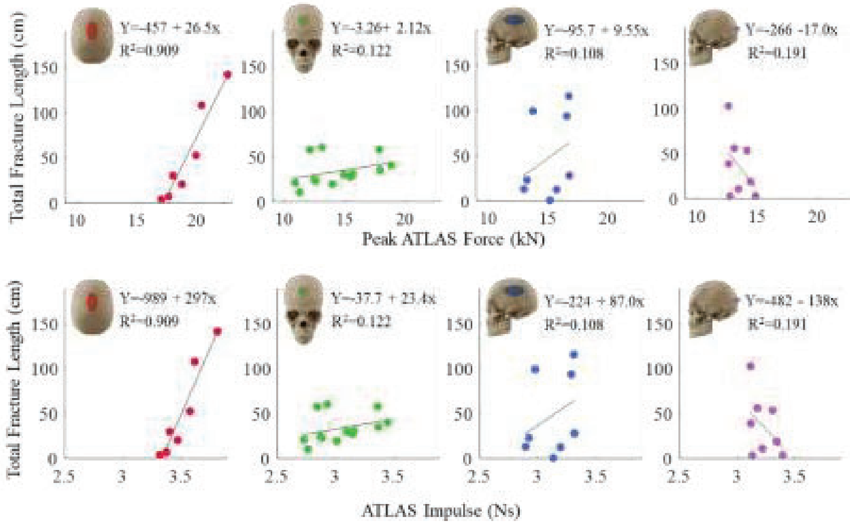

Figure 32: Linear regression of maximum ATLAS load and total fracture length for each impact location - crown, front, left side, rear from left to right (Top) Linear regression of maximum ATLAS impulse and total fracture length for each impact location - crown, front, left side, rear from left to right (Bottom)

4. DISCUSSION

4.1 ATLAS Loading

The main objective of this study was to provide a relationship between BFD loading and fracture outcomes using a matched pair testing methodology. In previous studies [16, 17], clay headform results showed large variations in clay deformations associated with a single ballistic and armour condition. For this reason, the ATLAS Headform was preferred for conducting these matched pair testing with the PMHS conditions.

The ATLAS Headform provides repeatable results across repeated conditions with the same ballistic conditions and same impact location. This was measured by the coefficient of variation, which is the ratio of the standard deviation of a repeated condition set with the mean of that set. The ATLAS headform tests had coefficients of variation ranging from 2.4%-11.1% and 0.2%-5.6% across all locations for peak load and impulse, respectively, and are a lower amount of variation to comparable clay tests. The lower coefficients of variation for the impulse measurements are due to the complete transfer of momentum of the ballistic round to the load cell in all tests. Peak loads have higher coefficients of variation, where varied pad interactions at different impact locations (e.g. loading directly over a pad for front and rear, or loading between pads for crown) may influence rise time and peak magnitudes. The repeatability in the results of the ATLAS Headform allows for more confidence in the associated loading metrics to human injury and fracture. The loading and injury results show a general trend of increasing dose resulting in increasing injury. The forces observed in this study are, on average, higher than fracture tolerances observed in literature from ballistic, blunt and motor vehicle crash loading [13]. It is hypothesised that fracture tolerances may be higher in BHBT due to the faster loading rate, shorter duration, and lower effective loading masses than in other loading scenarios [18]. The measured impulse values observed in these tests were generally in agreement with total ballistic momentum, however some tests saw higher measured impulse values than total ballistic momentum. This may be due to a number of factors influence the impulse delivered to the load cell such as helmet backface elastic rebound away from the load cell or due to the integration of post peak oscillations in the force-time history. It is noted that the ATLAS Headform steel impact cap and neoprene impact pad have a different stiffness than the human skull and scalp, likely resulting in a different force response than what a PMHS experiences during ballistics impact. While additional work is needed to evaluate the differences between the two, prior helmet testing resulted in similar residual backface deformation with the PMHS and the ATLAS headform, suggesting the dynamic helmet deformation interacts similarly with the human head and surrogate [19]. Ultimately, the ATLAS headform's steel impact cap and neoprene impact pad are integral

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to its durability, which is critical to First Article and Lot Acceptance Testing that requires repeat evaluation.

4.2 PMHS Injury Models

While developing a relationship between AIS and BHBT loading can be helpful when understanding the implications of injury, the categorical nature of the AIS injury scores limits the ability to comprehensively model the data. While there is an implicit assumption that injury response has a monotonically increasing relationship with the loading, there is no knowledge as to the correspondence between monotonically increasing injury outcome categories. Practically, there is little to no information gained by characterising a lower threshold of injury (e.g. MAIS 1: scalp injury) when attempting to characterise the higher threshold of injury (e.g. MAIS 4: complex and comminuted fractures) other than the observation that higher thresholds of injury happen at higher loading conditions. These categorical relationships are best suited for binomial regressions and have been shown in other studies [20]. Additionally, the correlation of AIS to loading shows a large area of transition, where injury results from equivalent loading ranged from 1 to 4 maximum AIS results. This is due to potential influences such as geometrical uniqueness of impact locations with respect to one another, biological variance of fracture tolerance, and underlying anatomical features that may affect fracture and injury severity.

There are distinct advantages to using continuous variables like fracture length to create predictive models. These models strengths are their simplicity and ability characterise the relationship between the two variables with higher statistical power. Additionally, fracture length can be considered a biomechanical failure response, one that may be correlated to other human body models, such as finite element method models. Additional fracture based failure models can be leveraged to have a better theoretical understanding of the mechanicals involved in the loading and response. Future studies should further investigate the relationship between fracture length and measured load with the goal of creating these predictive relationships for the BHBT condition.

4.3 Impact Location Differences

There are differences in the relationships between BHBT loading and BHBT injury that are observed at different locations. Using a BHBT loading assessment method, such as the ATLAS Headform, allows for the combination of helmet, padding and threat interactions at each location to be evaluated together. This testing methodology should, ideally, measure loading equivalently at each location so the results of this data can be used to understand injury thresholds of each anatomical location. Ultimately, the differences observed across impact locations could provide insight on human injury risk.

The data from this current study indicates that the front location has lower fracture tolerances, or lower loads required to fracture the skull. This can be observed by noting that relatively lower forces and impulse are associated with higher fracture lengths and maximum AIS scores, as compared to other locations. In increasing order of fracture tolerance: the rear, side and crown have higher loads associated with similar injuries and fracture lengths. When evaluating skull fracture risk there is no consensus on the ordinal ranking of fracture tolerances of the skull as many studies have different loading methods as well as impact locations [21]. Therefore, it is hypothesised that the specific geometries of the PMHS skulls used in the study may have a great influence on the BHBT injuries and associated loads. Previous studies have utilised PMHS to evaluate the physical and mechanical properties of the skull [21]. These studies have found the flexural properties of the skull to be highly dependent on skull thickness. Additionally, it is known that the amount of flesh present at an impact location can influence loading [13], primarily by distributing load from the BFD, not unlike a helmet pad. It is important to identify the anatomical variations at the impact location to understand the potential influence on injury. There is no clear guidance established as it relates to skull and scalp thickness at different locations of the head [22, 23]. Using the CT scans, the scalp and skull thickness were characterised for these PMHS test impact locations [24]. For these specimen, the front and crown location had the lowest scalp thickness at 3.9 mm and 3.4 mm mean thickness, respectively. The scalp thicknesses of the left side and rear were the highest at 6.3 mm and 5.7 mm mean thickness, respectively. The mean skull thickness results for the impact locations in our study revealed higher values for the front (8.1 mm) and rear impact location (8.6 mm) than the crown (7.0 mm) and left side (6.3 mm). Variation of the skull thickness across the tests in this study were similar at each location. While the front impact location has relatively high skull thicknesses, it has the lowest scalp thicknesses of any impact location in our study. This may be a major factor in the fracture tolerance to BFD loading at this impact location. Additionally, proximity to the anatomical structures like the frontal sinus should also be considered when evaluation injury risk to locations on the frontal bone as they may also influence fracture patterns. Ultimately, different injury risk functions for different impact locations may have major implications on helmet performance standards and design, where one may have higher performance standards for vulnerable areas of the skull.

4.4 Study Limitations

The ATLAS Headform can measure peak forces and total impulse but does not capture the spatial distribution of loading that could affect injury results, due to the fact that is a single sensor in combination with an impact cap and skin pad. Melvin [25] describes a strain energy approach to skull fractures that highlights different dominating fracture mechanisms dependent on impactor type. Without an understanding of BHBT loading shape over time, it may be unable to predict the fracture tolerance due competing failure mechanisms. This might hinder the ability of setting a helmet performance standard based on load and impulse alone. For example, one might expect higher fracture risk with a "sharper" loading shape versus a "rounded" shape. However, it is recommended that further research be conducted to understand the relationship between shape characteristics and BHBT injury.

While a strength of the current study was the use of a single helmet type for all ballistic data collected with PMHS and load-sensing headforms to ensure strong matched-pair conditions, these injury outcomes are relevant for a single helmet and projectile type. Care must be taken to interpret these results in context of other helmet systems, particularly with different energy or BFD profiles engaging the head.

Finally, this study only evaluates four nominal impact locations with a limited amount of PMHS samples. The severity of outcomes seen in this study are dependent on the tolerance to failure as well as underlying anatomical features (e.g. blood vessels, sinuses) with respect to the impact location. Further studies and models should explore all potential impact locations before extrapolating the results to untested impact locations with additional samples to provide an increase in the robustness of the response predictions.

5. CONCLUSION

A total of sixty non-penetrating ballistic impacts against helmeted PMHS specimen have been completed in addition to sixty-five matched-pair ATLAS Headform tests. Helmets were tested at four locations (front, rear, crown, and side) with ballistic conditions to span injurious loading regimes that were then measured by the ATLAS in matched-pair tests to generate loads to be associated with the injuries. All tests sustained injury. Skull fractures types included linear, depressed, and comminuted and measured to obtain the length of the fractures of the inner and outer table of the skull. The data indicated that different impact locations have differing sensitivity to skull injury with the crown and front location showing the highest and lowest resistance to skull fracture of the locations in this study, respectively. Loads were generally higher than those seen in other head trauma studies, and the crown location was the only location with strong correlations between loading and injury (fracture length). With these preliminary relationships from loading on a testing platform (ATLAS Headform) and human injury, steps can be made to mature helmet testing standards to incorporate human injury risk. With better helmet testing methods and baseline injury data sets, future armour and testing standards can provide advantages to the warfighter, increasing survivability.

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