Common Helmet Test System for Blast, Blunt, and Ballistic Testing

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Abstract. A variety of disparate headforms and test devices have been utilized to test helmets against blast, blunt and ballistic insults. We have developed a common headform that can be used across all three insults and provides many unique features including on-board data acquisition that potentially eliminates the use of external cables, simplifying set-up and range operations. The common headform consists of a common base combined with modular crown portions customized for the insult of interest. For all test environments, the headform can be equipped with a neck that more closely matches the flexibility of a human neck – far less stiff than the Hybrid III neck. Two crowns were created for blast testing. The first blast crown configuration has an array of 52 potential surface pressure sensor locations, of which the on-board data acquisition system can support up to 18. This modularity allows for a variety of sensor configurations, enabling both general helmet performance studies as well as high-spatial resolution measurements in areas of interest. Along with a subset of these locations for external pressure sensors, the second blast crown configuration has a silicone brain surrogate, and instrumented external and intracranial pressure sensors. The ballistic crown configuration uses an array of load cells under concentric impact caps to provide both central and outer edge measurements of behind helmet blunt impact. This provides both spatial and temporal measurement of the impact forces. Five ballistic crowns were created to support this load cell assembly and enable the measurement of impact performance of a helmet in 5 shot orientations. The blunt crown configuration is designed to be used on a horizontal impactor to more closely simulate real-world impact events and is instrumented to measure kinematics in six degrees of freedom.

1. INTRODUCTION/BACKGROUND

A common headform and biofidelic neck surrogate were developed to evaluate the performance of helmets exposed to blast, blunt and ballistic insults. In addition to eliminating the need for disparate headforms, the common headform and biofidelic neck surrogate incorporate unique features and significant advancements over existing head surrogates. The system includes an internal data acquisition system which greatly simplifies field test setup, is highly modular allowing for many use cases, and uses extensive additive manufacturing fabrication techniques which allows for quick and efficient modifications to the headform designs. The modular system is comprised of the Neck, Common Headform System (CHS) Base, and CHS Crowns. There are separate Crowns for each insult modality:

- Blunt Crown
- Ballistic Crown (5 versions – one for each impact location)
- Blast Crown (2 versions – with and without brain simulant and skeletal features).

2. SYSTEM COMPONENT DESCRIPTIONS

2.1 Neck

Blunt impact and ballistic testing of headforms traditionally uses a rigid mounting to allow exact alignment of the headform to the insult. There is a growing body of evidence that angular acceleration/rotation is likely as important a component in evaluating risk of brain injury as linear acceleration. The Hybrid III Anthropomorphic Test Device (ATD) [1], developed for automotive testing, has a semi-flexible neck that allows the headform to move after impact and allows for measurement of neck forces and head kinematic response. The CHS system can interface with the Hybrid III neck, as well as the biofidelic neck that was developed to allow the headform to move more realistically during ballistic and blast events.

JHU/APL previously developed a human surrogate neck that is more biofidelic than the automotive industry standard Hybrid III neck [2]. JHU/APL's previous neck consists of a vertebral column enclosed in a silicone rubber, and it incorporates elastic cords to mimic the effect of muscles. While this neck

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performs well in the anterior-posterior direction, it was not specifically designed for lateral or rotational motion. The previous neck required resetting the elastic cords between tests to ensure the proper tension. Furthermore, elastic cabling is susceptible to plastic deformation over time. In the current project, the previous surrogate neck was improved by 1) replacing the elastic cords with spring-loaded cables for a more repeatable and easily tunable response and 2) replacing the plastic vertebral column with a dense, flexible silicone core to improve the durability and reduce the cost and complexity of the part, as well as reducing the difficulty of fabrication.

Traditional drop tower blunt impact test protocols, such as those developed by the U.S. Department of Transportation (DOT) [3] and National Operating Committee on Standards for Athletic Equipment (NOCSAE) [4] do not utilize a neck surrogate, while a neck surrogate is used for a horizontal blunt impact testing [5]. Incorporating a neck into a monorail drop tower test system was examined, however there were several complications to consider. The additional length and moment arm created by the neck requires redesign of the anvil platform to ensure alignment with the headform. Maintaining appropriate carriage mass could result in significant changes to the carriage design. Additionally, a restraining device would likely be needed to limit potential damage to a biofidelic neck from excessive extension. The NOCSAE helmet horizontal blunt impact test protocol incorporates a head and compliant neck mounted to sliding platform. Upon impact from a pneumatically driven horizontal impactor, the neck is able to flex while platform slides, allowing angular acceleration to be induced. Due to the its ability to induce angular acceleration and better suitability of testing with a semi-flexible neck surrogate, the horizontal impactor was used to evaluate the CHS system.

Calculations show that springs need to be very stiff to absorb the energy from either a drop tower or a horizontal impactor. Sufficient stiffening of the neck to withstand this impact would significantly decrease biofidelity of the neck for blast, ballistic response, so a decision was made to use the Hybrid III neck for initial blunt impact testing and design the biofidelic neck surrogate primarily for blast and ballistic testing.

The resulting neck design is shown in Figure 1. The main element of the neck is a two-material silicone rubber column with a 63 mm diameter, moderate durometer, high elongation, center core (Silicones, Inc. XP-697) and a softer, more flexible 13-mm thick outer layer (Silicones, Inc. P-656) for a total diameter of 89 mm. It is equipped with five springs located on the periphery. The front spring is preloaded to 22 N and the others are preloaded to 44 N and can be individually pre-tensioned to the desired level. A steel cable is used to compress the spring and neck by transferring the load to the top plate. Flexible tubing encases the cable such that it does not cut into the neck material during bending. The top plate interfaces with the CHS headform using an interface similar to the Hybrid III ATD.

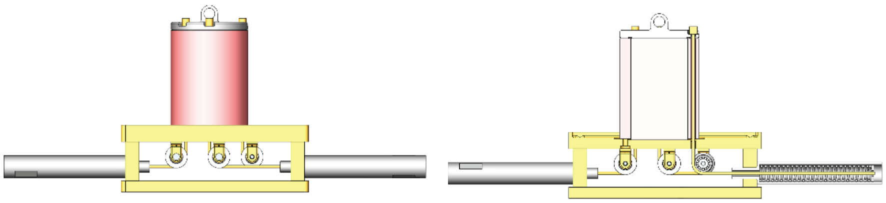

Figure 1. External and cross-section view of flexible neck and spring tension system.

2.2 Common Headform System Base

The three insult-specific crown types, blunt, ballistic, and blast, are attached to the common headform system (CHS) base, a platform that is shared for all of the test conditions. The ballistic and blast crowns have multiple versions to support different insult test locations (ballistic) and different sensing modalities (blast). The CHS base geometry was designed to be compatible with both the ANSUR II Army Anthropometric Survey (50th percentile male) [6] and Army Multi-sized Headform [7] (large) crown geometries. The blast headforms utilize the ANSUR II geometry as it incorporates ears, which allow for the donning of eyewear, and facial topography that is important to blast wave propagation. Since standoff is a major determinant of blunt and ballistic performance, the blunt and ballistic headform crowns reflect the Army Multi-sized Headform geometry, which provides a uniform 23-mm standoff for combat helmets of interest. The geometry of the lower portions of these crowns were modified slightly to blend with the ANSUR II geometry of the common headform system (CHS) base.

The test-specific crowns are attached to the CHS base, a platform that is shared by all of the test conditions (Figure 2). The CHS base shape is based on ANSUR II geometry which is shared with

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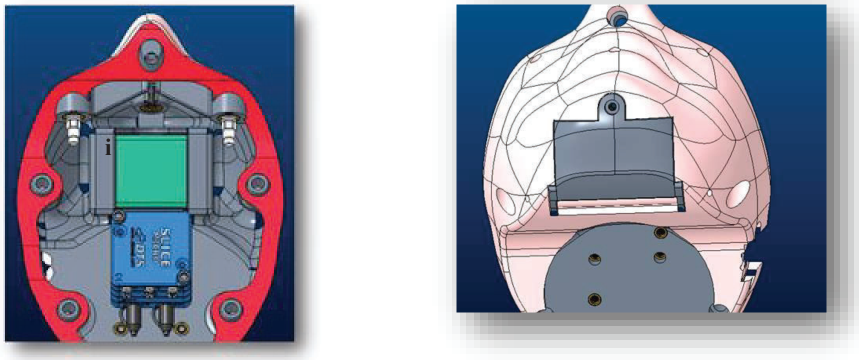
previously used blast headforms [8]. The CHS base is fabricated by selective laser sintering (SLS) of a glass-filled polyamide powder. Five bolts connect the headform crowns to the CHS base. It is equipped with 3 pressure sensor ports (mouth, left and right cheeks) and the 3-axis accelerometer and angular rate sensor package shared by all test configurations.

The CHS base is equipped with a DTS SLICE MICRO for on-board data collection (Figure 3). The SLICE MICRO is a ruggedized data acquisition system that can support up to 24 channels of synchronized data collection with a sampling rate of up to 500K samples per second. Six channels are dedicated to 3-axis acceleration (± 500 g max.) and angular velocity (± 140 rad/sec max.). The remainder are Integrated Electronics Piezo-Electric (IEPE) compatible for measuring additional channels of pressure and force. The system can be powered by an on-board battery, can be set to a buffered cycle data collection mode, and can be triggered by a sensor threshold, allowing for standalone data collection at the site of test. This can greatly simplify data collection for field tests where power and data transfer cables may be burdensome or at risk of damage or causing noise interference.



(a) **(b)**

Figure 2. View of inside of CHS base (a) and battery compartment cover (b).

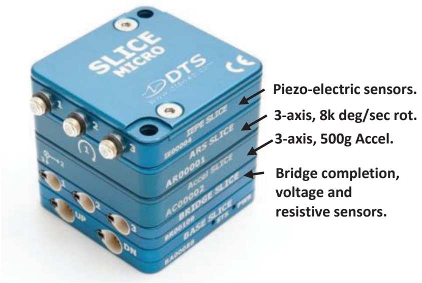


Figure 3. Reconfigurable data acquisition system.

2.3 Blunt Crown

Based on an assessment of peak accelerations from past drop tower test results, the blunt headform was designed to be able to withstand impact forces and resultant accelerations exceeding 500 g at 6 locations: front, rear, crown, right and left sides, and right and left nape. The blunt crown matches the geometry of the Army Multi-sized large headform.

The blunt crown was fabricated by selective laser sintering (SLS) of a glass-filled polyamide powder. It has an external shell supported with an array of cross-members to provide support and rigid response during impact (Figure 4). It is equipped with the accelerometer and angular rate SLICE sensors found in the SLICE MICRO data acquisition system located in the CHS base.

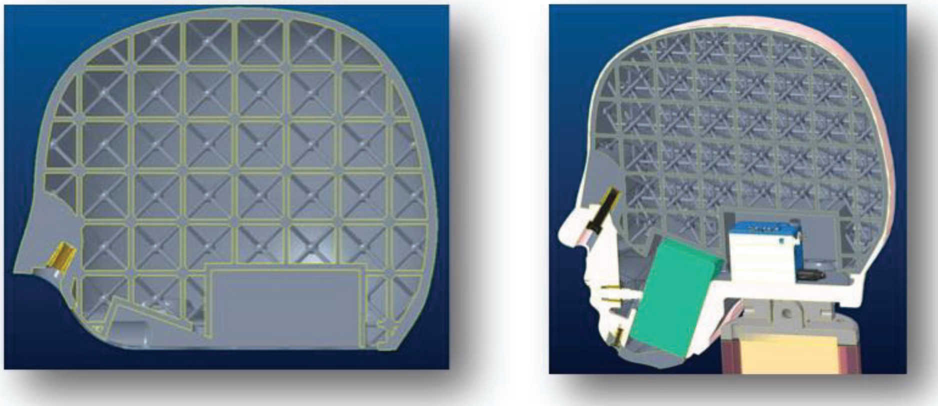

(a) (b)

Figure 4. Section views of the blunt impact crown (a) and crown mounted on CHS base and neck (b).

2.4 Ballistic Crown

The ballistic crown was developed to measure ballistic impact forces behind helmets. The system was designed for a 9-mm NATO bullet at 427 m/s impacting a standard helmet equipped with pads. The crown geometry is based on the Army Multi-sized large headform to provide constant helmet standoff. The ballistic crown system has 5 variants, one for each impact location (front, rear, crown, right and left sides). It was designed to make two force measurements, one at the center, directly behind and in-line with the point of impact, and a second of the peripheral forces surrounding the center impact. The load cells used to make the force measurements have a very short response time to measure the ballistic impact force.

The ballistic crown design has five variants to allow ballistic testing of helmets from the five major directions, front, sides (2), rear and crown. The headform measures force at the center of impact (30-mm diameter cap) and peripheral forces (30 to 90 mm diameter concentric ring) from the axis of nominal impact (Figure 5). The headforms share a common impact module with a load cell array consisting of a center load cell (PCB 224C) and 5 peripheral load cells (PCB 201B05). This allows the center and peripheral caps to each measure forces up to 111kN.

The common impact module is fabricated from stainless steel to ensure a rigid response at the site of impact. The headform crown matches the Army Multi-size headform geometry, and is fabricated by selective laser sintering (SLS) of a glass-filled polyamide powder. Filling the gap between the impact caps and the nominal headform shape is a 12.7-mm thick soft neoprene impact pad molded specifically for the shape of each impact location.

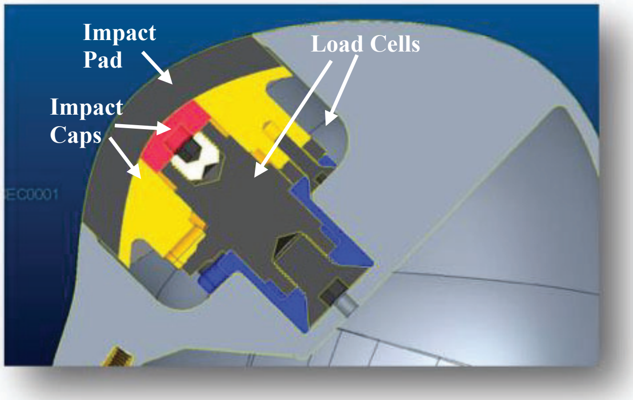
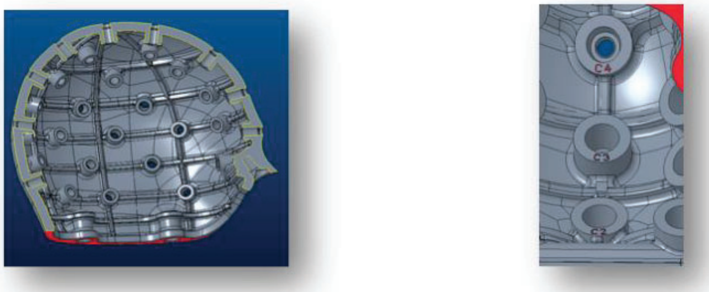


Figure 5. Section view of ballistic impact headform

2.5 Blast Crown - with External Pressure Sensors

Two variants of the blast crown were developed. The first was equipped with a large array of external pressure sensors distributed across the surface of the crown. A large number of possible sensor locations allow for highly tailorable sensor configurations for measuring head surface pressure near, under, and between helmet pads. The external geometry of the blast crown was based on the ANSUR II head geometry.

A blast crown was designed and fabricated that contains an array of 49 pressure ports across the headform surface (Figure 6). Combined with the 3 pressure ports in the CHS base, this provides 52 possible pressure sensor locations. Each pressure port is labelled, inside and out, with a unique identifier to simplify sensor configuration. While each pressure port can be populated with a PCB-113B26 pressure sensor capable of measuring transient pressures exceeding 3400 kPa, the internal data acquisition system limits it to 24 sensors while recording at 200 kilosamples per second. The blast crown was fabricated by selective laser sintering (SLS) of a glass-filled polyamide powder, and the external surface geometry is based on the 50th percentile male ANSUR II.



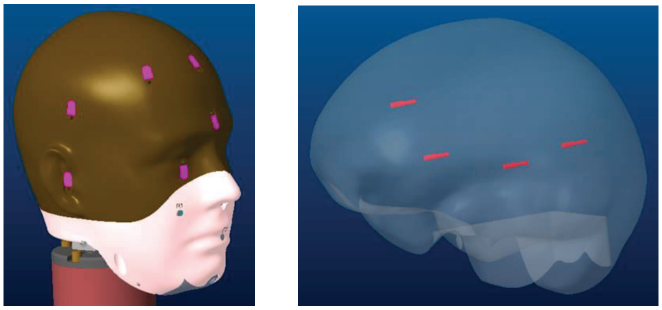
(a) (b)

Figure 6. Blast crown with external pressure sensor ports showing (a) section view and (b) interior port labelling.

2.6 Blast Crown - with Brain Simulant and External Sensors

The second blast crown was equipped with a smaller array of external pressure sensors distributed across the surface of the crown as well as a silicone gel brain instrumented with pressure sensors (Figure 7). The external geometry of the blast crown was also based on the ANSUR II head geometry.

A blast crown was developed that measured not only the external surface pressure in 8 locations (not including 3 locations in the CHS base), but also has an anthropometrically representative skull surrogate and brain simulant equipped with 4 intracranial pressure sensors. This blast crown maintains the external geometry of the previous blast crown with external pressure sensors, but is equipped with thin, pressure sensors (Honeywell Model F) that are bonded to the external surface with internal wire routing. In the hollow cranial cavity, the headform is filled with silicone gel (Dow Corning Sylgard 184). Suspended in the brain simulant are 4 pressure sensors (TE Connectivity EPIH) which allow for the capture of intracranial pressure in both the time and spatial domains.



(a) (b)

Figure 7. Blast Crown with brain simulant. Locations of external pressure sensors (a) and intracranial sensors (b) are shown.

3. TEST RESULTS

Prototype versions of the blunt, ballistic and blast (with external pressure ports) crowns have been tested to demonstrate their performance.

3.1 Blunt Crown Testing using Horizontal Impactor

In order to inform the final design, testing was conducted on an initial prototype of the blunt headform to evaluate the overall performance and durability of the blunt crown, as well as the response of the data acquisition system up to its rated shock resistance of 500 g. This level of impact testing greatly exceeds impact levels seen in typical drop tower tests [9] but was chosen to represent a worst-case testing scenario.

A total of 44 tests were conducted across 7 locations at 4 nominal velocities (2.5, 5.5, 7.44, and 9.35 m/s). A horizontal impactor (Cadex, SB202) was used with the HIII neck, the CHS base, and the blunt crown. The horizontal impactor uses a 96 mm diameter steel semi-hemispherical impactor weighing 14.6 kg which is accelerated to the desired impact velocity with a pneumatically driven piston. The HIII neck and blunt impact headform are mounted on a carriage that can freely slide away after impact. An Advanced Combat Helmet (ACH) with pads was mounted on the headform in accordance with the ACH operator's manual.

The data acquisition system performed well, and the CHS base was undamaged. At the highest two velocities, damage was observed on the blunt crown (Figure 8); the external shell showed slight signs of damage and analysis of computed tomography (CT) scans showed internal lattice struts were broken. The crown impact location was damaged at 7.1 m/s with 2 struts broken while the left nape and side locations were damaged at 8.9 m/s with 3 struts broken at each location. These tests suggest that the initial prototype blunt crown structure has an approximate 300 g limit in this horizontal test. It is important to note that these impact velocities and resulting accelerations are far greater than standard combat helmet drop tower test velocities of 3 m/s and 4.3 m/s [9]. There was also residual powder remaining from the rapid prototype process of the initial prototype.

The examples of the data collected are shown in Figure 9. Both angular rate and acceleration data were filtered at the standard CFC1000 filter specification. For a 5.5 m/s impact velocity, the peak accelerations ranged from 99 to 171 g depending on impact location. The peak angular velocity ranged from 18.8 to 38.5 rad/s. The accelerations measured are in a similar range as those measured by McEntire et al [9].

Based on lessons learned from testing the initial prototype blunt headform, the shell thickness and outer lattice thickness were increased to improve the impact resistance of the blunt impact shell. Additional and larger clearance holes were added to improve the removal of the residual processing powder.

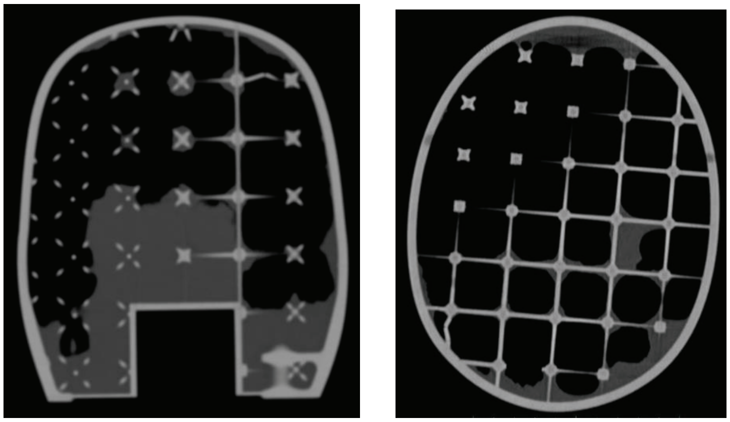

(a) (b)

Figure 8. Examples of damage observed on the left side (a) and nape (b) impact locations.

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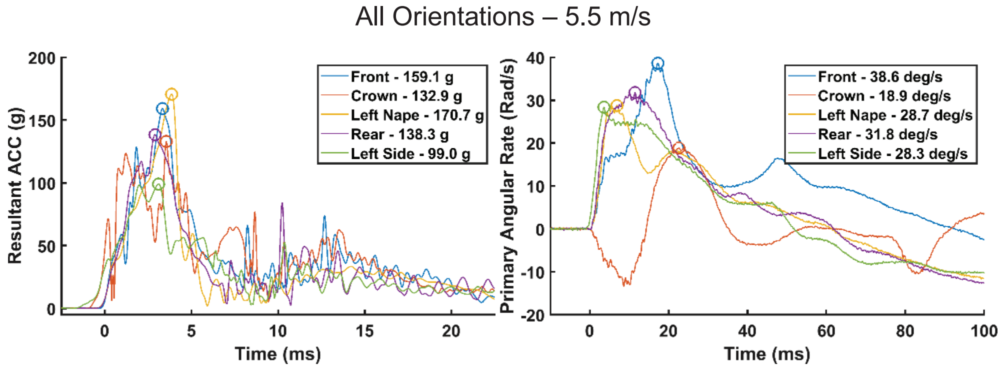


Figure 9. Examples of resultant acceleration and primary axis rotational velocity data collected from 5.5 m/s horizontal impact testing

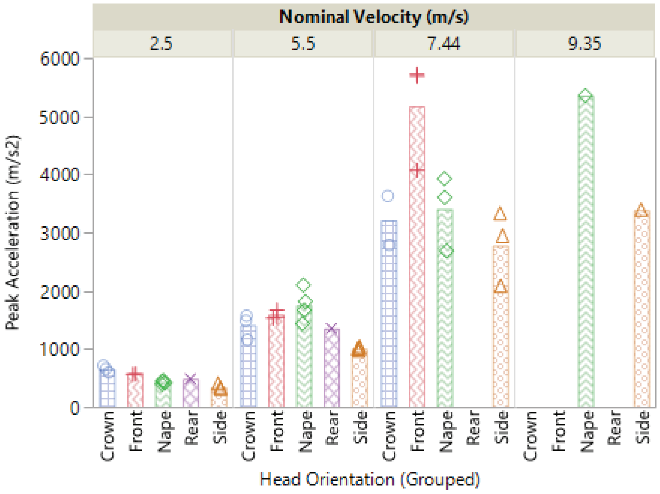


Figure 10. Peak Acceleration measured in horizontal impact testing. Bars represent average peak accelerations for each test condition, and markers represent individual test results.

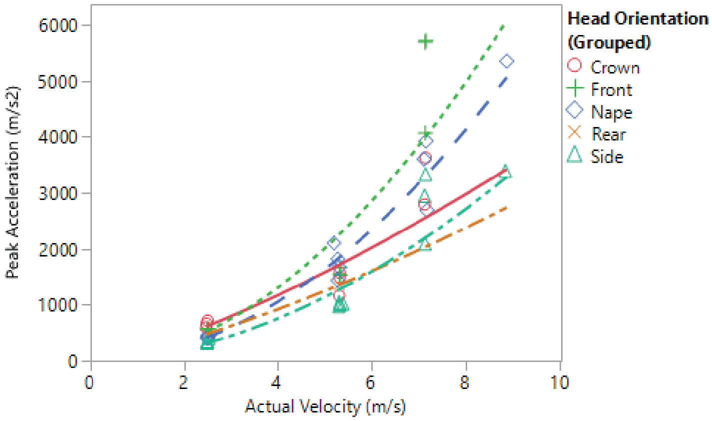


Figure 11. Acceleration data collected from the blunt impact headform at different impact velocities.

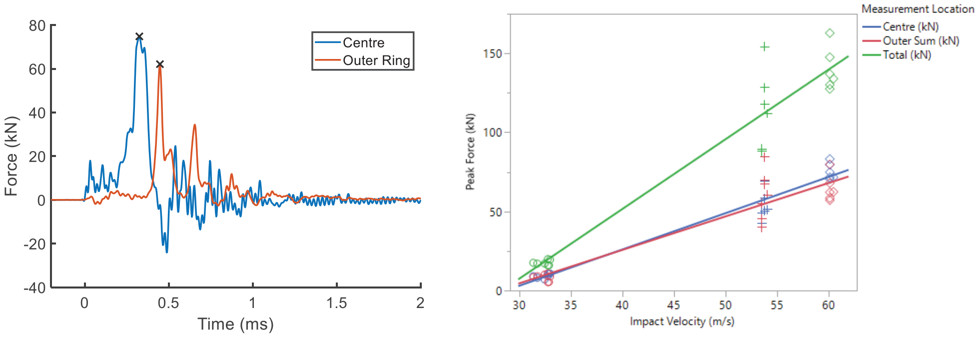
3.2 Ballistic Crown Testing using Air Cannon

Simulated ballistic testing was conducted to demonstrate the performance of the ballistic crown. The impact testing was conducted using a pneumatic cannon to shoot a 62 mm diameter, 67 mm long aluminium projectile, weighing 197g with a 75 mm radius of curvature tip. The projectile impacted the front ballistic crown at velocities ranging from 31 to 60 m/s. Data from 21 tests were collected and analysed to measure how the peak force changed with impact velocity.

(a) (b)

Figure 12. Aluminium projectile used in air cannon testing on front ballistic crown (a). Projectile impact on front ballistic crown (b).

Results showed that the peak forces ranged from 16 to 163kN over the velocity range tested (**Figure 13**). The forces measured on the centre cap and outer ring were similar at each velocity. The coefficient of variation of the total forces ranged from 9-22% for the three nominal velocities. The test results demonstrate the ability of the CHS ballistic crown to provide both spatial and temporal measurement of the impact forces.



(a) (b)

Figure 13. Time-force measurement of projectile impact at 60 m/s on the ballistic crown (a). Peak forces measured at different velocities by the ballistic crown (b).

3.3 Blast Crown with External Pressure Sensor Testing

The blast crown with external pressure sensors was tested in a 91 x 91 cm advanced blast simulator [8] to evaluate the durability and response of the prototype headform, neck, and data acquisition system in a simulated blast environment. In all, 29 shock tube tests were conducted with 3 orientations of the headform (front, side, and rear facing), 2 different helmet conditions (Advanced Combat Helmet and bare), with both the new APL neck and the HIII neck. All tests were run at a nominal 1400 kPa burst pressure diaphragm, resulting in a nominal 115 kPa static peak, 7 ms positive phase duration shockwave.

External to the headform, there was a Pitot pressure sensor (PCB 113A36) to measure the incident pressure wave which was measured at 1 M sample/s. This allowed these data to be compared with data collected by the blast headform.

The data acquisition system worked well with the 9 pressure sensors monitored. The neck, CHS base and blast crown were undamaged. Data was collected at 1 M samples/s by off-board sensors and data acquisition system and compared to the data collected at 200,000 samples/s on the internal data acquisition system (both filtered with a 20 kHz 10-pole Butterworth low pass filter). There were little differences seen due to the reduced sampling rate, however, the pressure sensors in the headform registered higher peak pressures than the external pressure sensors, results that are being investigated further.

Head kinematic measurements from tests using the new, more flexible APL neck were compared to those when using the HIII neck. The flexible neck tests showed about twice the angular displacement of the HIII neck tests with a peak angular displacement time of 115 ms vs 60 ms for the HIII neck. Comparing these results to Murphy et al [2], Murphy showed that a post-mortem head and neck showed a peak rotation of 3 times that of the HIII neck, with the peak angle occurring at about 140 ms after impact. The flexible neck can be retrofitted with different springs that allow for the neck pretension and hence head and neck kinematics to be tuned to a desired level.

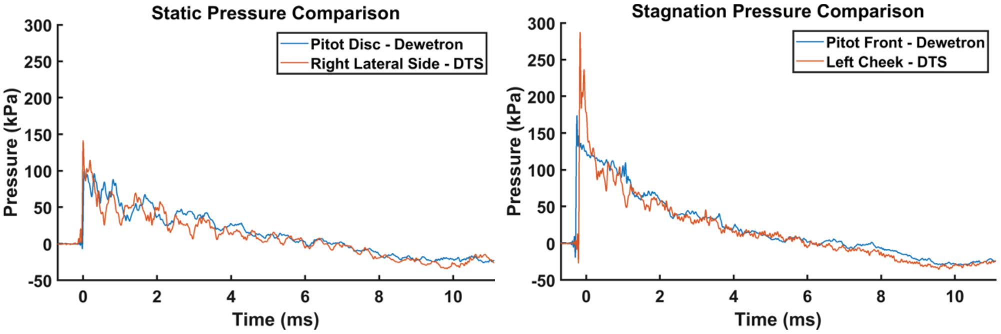


Figure 14. Static (left) and stagnation (right) pressure measured during a shock tube test with 100 kPa static overpressure wave.

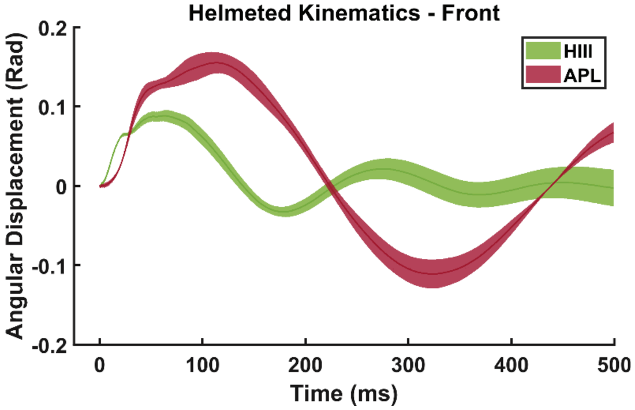


Figure 15. Angular displacement of the headform when exposed to shock tube blast overpressure wave.

4. CONCLUSIONS

A variety of headforms and test systems have been used to evaluate helmets against blunt, ballistic and blast insults. We have developed a common headform system that can be used across all three insults and provides many unique features such as:

- 3-axis accelerometers and 3-axis rotational velocity measurements for capturing 6 degrees of freedom during blunt, blast and ballistic testing
- On-board data acquisition to eliminate cabling during range testing
- A neck that is tunable and more flexible than the Hybrid III providing more human-like response to loading
- Two-zone ballistic impact force measurement to measure the peak forces found behind the helmet as well as the large, lower force surrounding area.

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- Large number of fixed pressure sensor locations that allow for either standardized testing or focused studies in key regions.

These changes provide a wide range of new capability for helmet testing, filling measurement gaps that exist in other headform systems.

Potential future testing includes blunt impact testing at impact velocities more closely matching standardized drop tests, ballistic testing with additional threats of interest, and blast testing of helmets that were designed to protect against blast. Additionally, tuning the pretension of the neck cables would enable the surrogate neck response to more closely matches that of humans.

Acknowledgements

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