Biomechanics and Injury Mitigation Systems Program: An Overview of Human Models for Assessing Injury Risk in Blast, Ballistic, and Transportation Impact Scenarios

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Warfighter survivability and performance are threatened by blast events, ballistic impacts, and transportation accidents. To design effective injury mitigation strategies, it is critical to understand the nature of the loading event and the manner in which the body responds. APL has developed novel models, both computational and physical, of the human system to measure the body's mechanical response to dynamic loading. These anatomically detailed models have been subjected to live-fire and full-scale tests to determine their durability, repeatability, and sensitivity to loading conditions. Results from initial experiments and simulations have aided in measuring parameters that correlate to injury, determining the effect of personal protective equipment, and providing insights into future injury mitigation strategies. These models are a critical tool in the evaluation and development of personal protective equipment and vehicle safety systems to ultimately reduce the risk of human injury.

INTRODUCTION

Warfighter survivability and performance are threatened by blast events, ballistic impacts, and transportation accidents. The nature of each dynamic loading event may result in distinct injury outcomes that can be further differentiated by such factors as the situational environment, exposure level (dose), and the performance of personal protective equipment (PPE). To effectively mitigate injuries, it is critical to understand the human body's response to these specific events, including the injury mechanisms and thresholds, and to accurately predict risk of injury. The Biomechanics and Injury Mitigation Systems (BIMS) program at APL focuses on developing experimental and computational tools for modeling the human body, realistically simulating events that may inflict injury, and determining the efficacy of existing and novel injury mitigation strategies.

Because of the variety of dynamic loads applied to the warfighter, there is an increased need for experimental and computational human models that can effectively simulate the dynamic response of the human body, are employable in volatile environments, and can serve as a platform for evaluation of PPE.[1–3] Experimental devices, known as physical surrogates, must closely represent anatomical structures, be composed of biomechanically representative simulant materials, and operate as a durable, repeatable test device capable of measuring tissue-level responses. Complementary computational tools, known as finite element models of the human body, are utilized to predict and explain the structural response of the anatomy to various loading conditions and to report the numerical calculations at any location within the model anatomy. Although these models may be used to evaluate the comparative response to a variety of loading conditions, the level of confidence in the results predicted by the model ultimately relies on their validation based on experimental biomechanics data and the correlation of model-predicted parameters to known injury outcomes.

Researchers within the BIMS program have created paired computational and experimental models of the human head, neck, and torso. These human surrogate systems have been customized to measure the internal biomechanical response to blast, ballistic, and transportation crash loadings. The mechanical factors that correlate to injury, such as the magnitude of pressure or strain, dictate surrogate instrumentation and computational model values of interest. In this article, we will provide an overview of the nature of the injurious scenarios and will show specific examples of research efforts performed to effectively model the human body's response to determine the risk of injury and ultimately to investigate the performance of mitigation strategies.

PRIMARY BLAST INJURY

Explosive mechanisms are responsible for nearly 80% of injuries sustained in current military operations, with approximately 25% of those injuries occurring to the head and neck.[4] Detonation of explosive weapons releases a large amount of energy in a very short period of time, which results in blast waves and fragmentation. The injuries sustained from exposure to these events have increased the military focus on nonpenetrating, blast-induced injuries, including traumatic brain injury and injuries to organs within the torso.

Blast-Induced Traumatic Brain Injury

Studies on both large and small animal models have confirmed that exposure to blast waves can generate cognitive impairment and biochemical changes in the brain.[5,6] Although helmet systems have been developed to reduce the potential for penetrating injuries to the head, the efficacy of these systems in mitigating blast-induced traumatic brain injury due to blast wave overpressure remains unclear. Furthermore, the precise injury mechanisms resulting in blast-induced traumatic brain injury are not well understood. However, studies have shown that the key mechanical factors that correlate to injury are an increase in intracranial overpressure and the relative displacement of the brain with respect to the skull and surrounding structures.[7,8]

Human Surrogate Head Model

To experimentally evaluate the effects of blast loading on the brain, an instrumented physical surrogate test device was developed and constructed with representative human anatomy and biosimulant materials. Dubbed the Human Surrogate Head Model (HSHM), the head surrogate consists of the brain, skull, facial structure, and skin, all fabricated using biosimulant materials.[9] The HSHM is capable of integration with a traditional neck surrogate [Hybrid III anthropomorphic test device (ATD)] as well as a more compliant, APL-developed surrogate neck that more closely resembles that of a human. Instrumentation includes pressure and displacement sensors embedded in the brain, accelerometers and angular rate sensors in the chin, and surface-mounted pressure sensors on the exterior of the head.

The APL Shock Tube System, designed and fully characterized to approximate blast loading pressure profiles in a laboratory setting, was used to generate a short-duration pressure wave on the HSHM (Fig. 1) as a precursor to live-fire testing. Intracranial pressure and brain displacement response were measured for three load severity levels to confirm the sensitivity of the system to loading conditions (Fig. 2). The intracranial pressure showed a near instantaneous rise in response as the pressure wave propagated through the skull and arrived at the embedded sensor. Subsequent oscillations within the measured pressure component were largely negligible within 10 ms after the event initiation. However, the displacement of the brain relative to the skull occurred much later in the event and maintained a measurable response well past 100 ms after arrival of the initial shock waves.

Global head translational and rotational displacements in the tests were recorded by high-speed video and angular rate sensors (Fig. 3). Combining this data with information from the brain displacement sensors

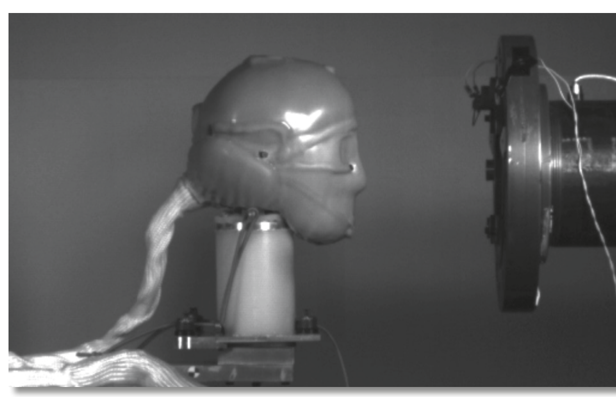

Figure 1. HSHM positioned in front of shock tube.

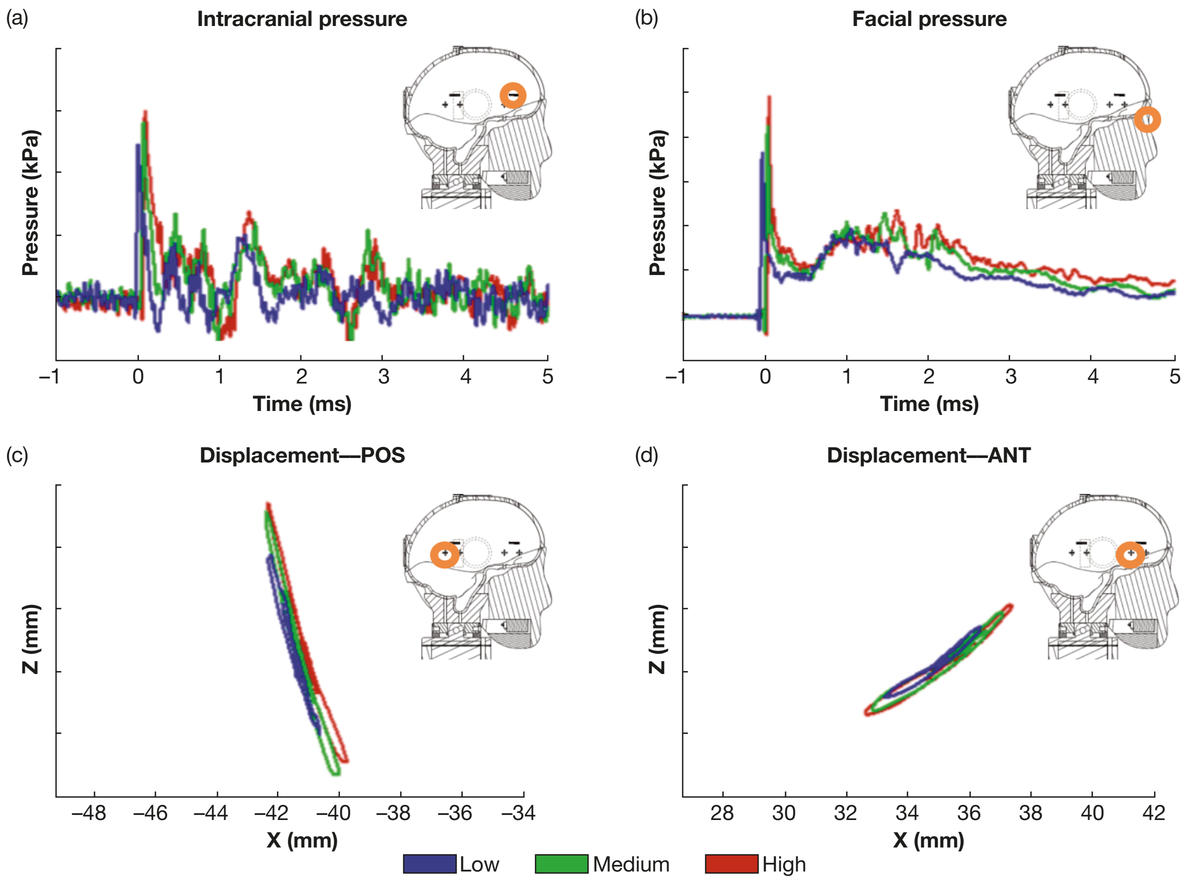

Figure 2. Characteristic pressure and displacement data recorded for three test conditions representing (a) the surrogate intracranial pressure, (b) the pressure on the surrogate face, and (c and d) spatial representations of brain motion relative to the skull. POS, posterior sensor; ANT, anterior sensor.

shows a close correlation between internal and external motion. This relationship suggests that neck compliance, which most strongly influences global head motion, is also the key variable controlling the magnitude and phasing of relative brain motion for this particular loading scenario.

Human Head Finite Element Model

A computational equivalent of the HSHM, termed the Human Head Finite Element Model (HHFEM) (Fig. 4), was developed using the same geometry dataset used to build the HSHM. Biomechanically relevant components of the anatomy, such as the skull, brain, cerebrospinal fluid, brain stem, facial structure, and neck, were included. The model consists of 103,874 nodes, with a total of 127,902 elements. Material property values based on biomechanical experimental testing of biological tissues were input into constitutive equations of the elements to govern the model response during loading.

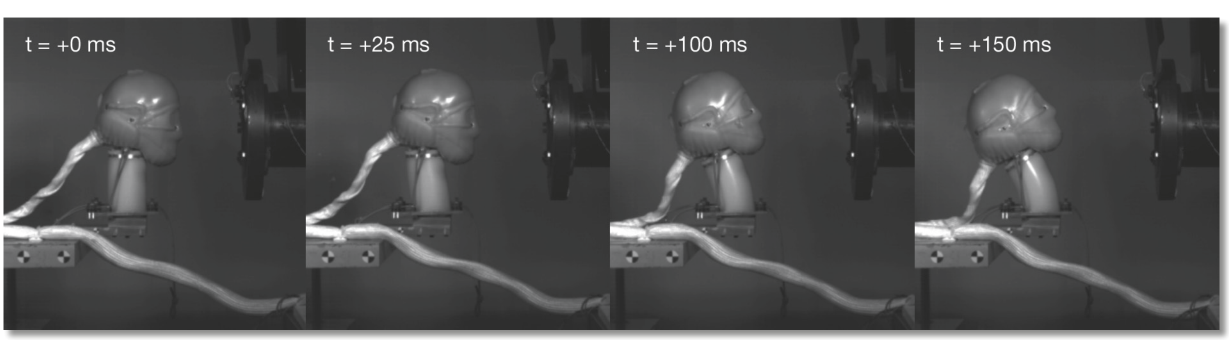

Figure 3. Images from high-speed video of a shock tube test (689-kPa driver) on the HSHM.

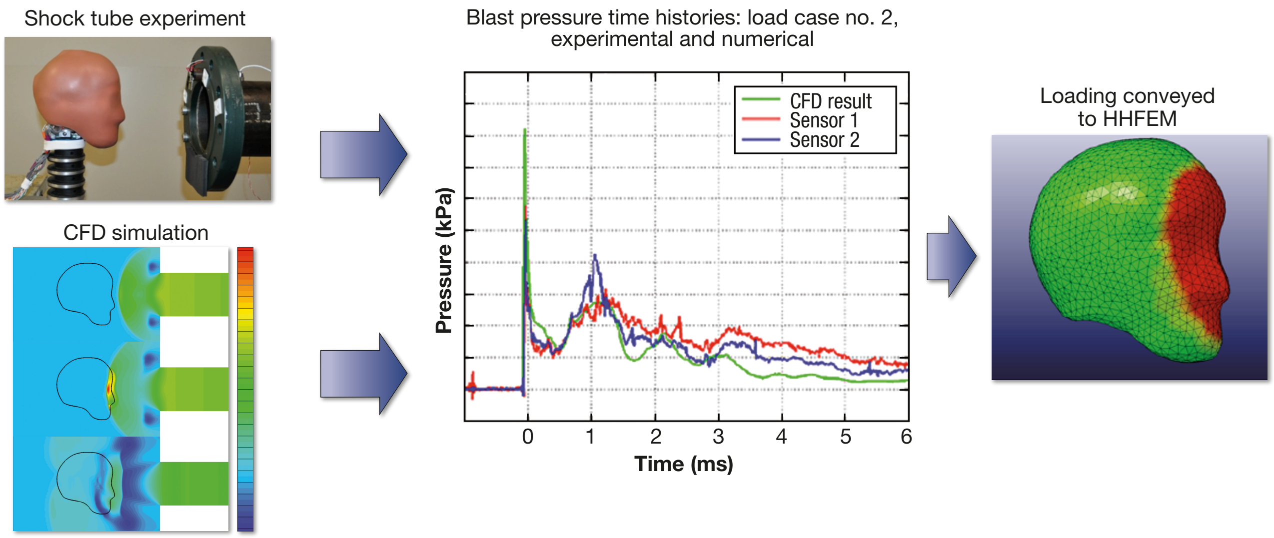

Figure 4. Method for establishing the loading inputs to the HHFEM. The experimental conditions for the HSHM are used to validate the results of the computational fluid dynamics (CFD) simulation. After validation, the loads are conveyed to the HHFEM.

The HHFEM predictions for intracranial pressure and brain motion are verified against the anatomically identical physical surrogate. As part of this model verification process, the pressure loading profiles generated by the shock tube experiments of the HSHM must be precisely simulated and applied to the HHFEM. To accurately simulate blast-wave interaction on the HHFEM surface, a 3-D CFD model was constructed to re-create the experimental shock tube conditions applied to the HSHM. This CFD model included a numerical grid simulating the HHFEM surface (Fig. 4), the shock tube, and the air flow around and within these components. The initial conditions were set to match those of the experimental setup, and VULCAN (Viscous Upwind ALgorithm for Complex Flow ANalysis)-CFD (NASA Langley Research Center) was used to solve full 3-D Navier–Stokes equations. The temporal and spatial distribution of pressure on the HHFEM grid surfaces was collected from the CFD simulation, validated with laboratory experiments, and used as input for the HHFEM loading. This loose model coupling allowed mapping of the pressure profiles to the HHFEM. Once the pressure loads were applied to the HHFEM, the propagation of stress waves through the skin, skull, cerebrospinal fluid, and brain was simulated to determine the brain pressure and displacement response due to the shock tube loading (Fig. 5).

The HSHM provides a level of anatomical biofidelity and novel instrumentation not previously achievable using existing surrogate systems. It generates insight into the propagation of potentially injurious pressure waves into the brain and provides a physical test platform for evaluation of helmet systems. The complementary HHFEM allows the determination of mechanical responses at any location within the human head anatomy and can reveal the important mechanical processes involved in generating the brain tissue responses. These capabilities are critical in determining anatomical sensitivities to injury risk and risk mitigation. In addition, the HHFEM can serve as a design tool to evaluate various design parameters of different PPE concepts.

Blast-Induced Thoracic Injuries

Thoracic and abdominal organs have proven to be very susceptible to injury when exposed to explosive air blast loading in experimental animal models as well as in soldiers (as determined from patient reports).[7, 10–15] The mechanisms behind blast injuries to the thoracic and abdominal organs are the subject of continued research, which will benefit substantially from a model system. Although there are many existing theories aimed at predicting the etiology of lung injury due to blast, recent animal studies have shown that blast injury to the lung is a complex syndrome.[16, 17] Despite efforts

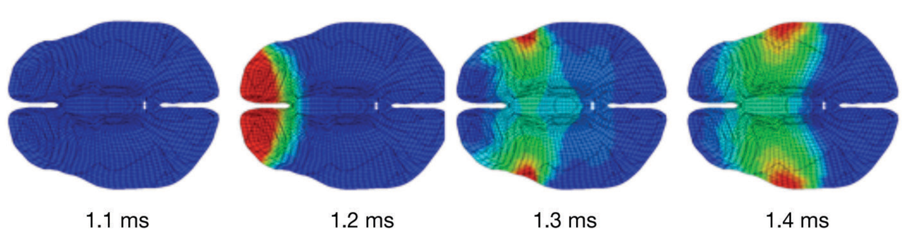

Figure 5. Pressure wave propagation response in a transverse plane of the brain of the HHFEM.

to translate animal injury models to the human body, an increased need has arisen for a durable device with representative human anatomy that allows for the measurement of internal response to external insults. Such a device would ideally be composed of biosimulant materials and would be sensitive enough to discern response differences due to different threat conditions. Furthermore, the device should be capable of predicting the relative efficacy of PPE in reducing measured engineering parameters that correlate to injury.

Human Surrogate Torso Model

The Human Surrogate Torso Model (HSTM) was developed to study internal organ response to dynamic loading events, including blast loading and nonpenetrating ballistic impacts.[2,18] The geometry for the HSTM was determined using anatomical source data from the National Library of Medicine's Visible Human Project; the data were scaled to represent a 50th percentile-sized male of the U.S. population. Anatomic surfaces were initially converted into point clouds specifying the geometry of human thoracic components and exported as individual nonuniform rational B-spline (NURBS) surfaces. Each of these surfaces was translated into 3-D component files and exported to a rapid prototyping system that generated rapid prototyping models. The rapid prototyping models were used to form molds that were then cast with biosimulant materials to create the individual torso components representing a detailed skeletal structure, the major thoracic and abdominal organs, mediastinum, flesh, and skin. The thoracic skeletal structure (vertebral column, sternum, ribs, clavicles, and scapulas) was developed to target mechanical and fracture properties of human bone. The organs (heart, lungs, liver, and stomach) are composed of silicone-based biosimulant materials mimicking the density, durometer, and bulk modulus of human organ tissues. The lungs include glass microspheres cast into the silicone-based materials to reduce density and bulk modulus. The lower gastrointestinal tract is approximated by a hollow intestinal mass to create a gas-filled chamber that allows for variable states of pressurization. Once these structures were assembled, the remaining space was filled with an adipose-muscle tissue biosimulant and encased in a skin simulant material. The torso was integrated with a Hybrid III ATD pelvis to complete the HSTM (Fig. 6). The HSTM contains instrumentation allowing the system to measure pressure response for each individual organ, accelerations of the chest wall, chest compression, and loading along the spine.

A series of initial live-fire tests exposed the HSTM to a range of explosive charge weights in an open-field scenario. These experiments evaluated the human surrogate's ability to capture the high-rate mechanical response of the human anatomy to blast loading, as well as its durability and sensitivity to loading conditions. Three explosive charge weights were used to evaluate a range of threat conditions. These events were visually recorded with a high-speed camera to provide optical tracking of the blast wave propagation. Figure 7 highlights the propagation of the incident shock front and provides the pressure measured within the lung for the three charge conditions. On the basis of the initial pressure rise in the organs, the data indicate the arrival of the incident pressure wave at approximately 2 ms after charge detonation. The arrival of the ground-reflected pressure wave produces a second rise in the organ pressure, with arrival time occurring more than 1 ms after the initial shock arrival. The arrival times were confirmed based on the tracking of the pressure wave propagation observed from the video images.

The HSTM provides the advantage of a repeatable, durable, nonhomogeneous test device complete with skeletal structure and soft tissue allowing dynamic measurement of internal pressures, acceleration, and load as a result of various blast conditions. Embedded sensors within the HSTM detect the arrival of both the incident and ground-reflected pressure waves. For repeat tests, the organ-level response was found to be very repeatable and well within the variation of the loading conditions generated by the explosive charge. Measured organ pressures were specific enough to differentiate between various test conditions, including charge weight and presence of PPE. The HSTM also proved durable, as no damage was sustained during testing.

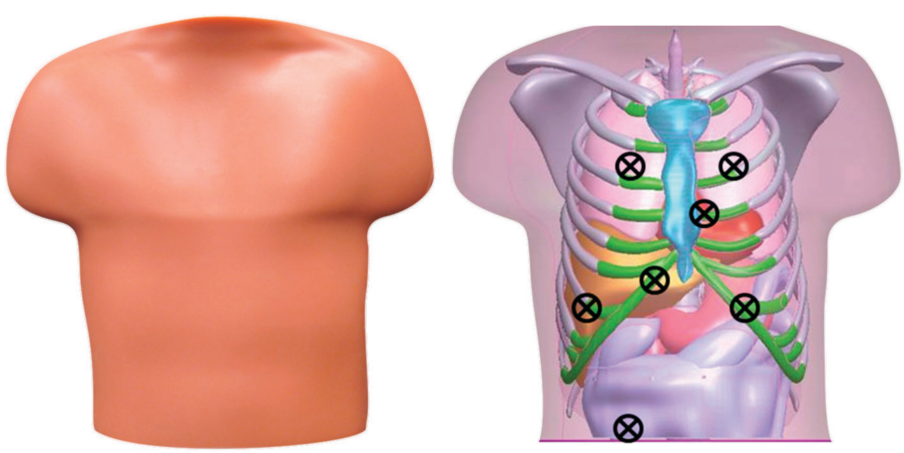

Figure 6. HSTM in final form (left) and sensor locations (right).

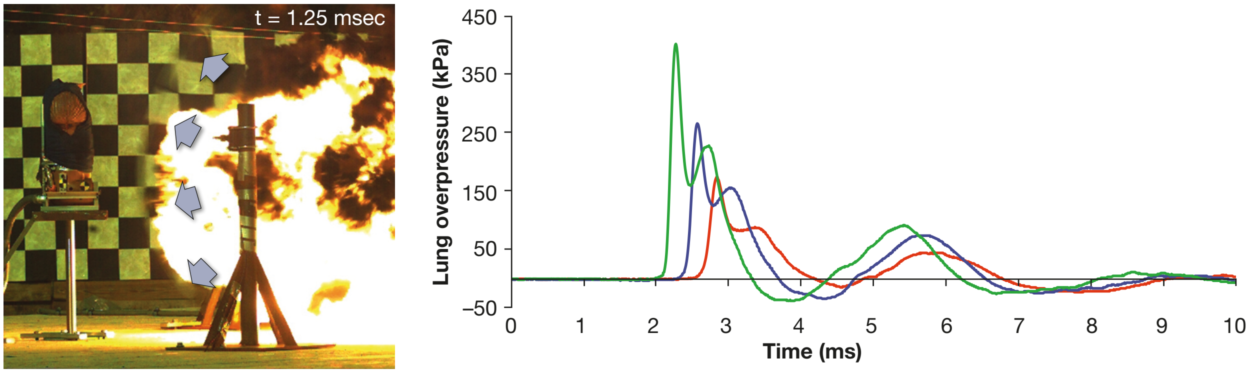

Figure 7. Incident shock wave approaching the HSTM during a blast test (left); upon reaching the torso surrogate, instrumentation in the lungs captures the internal overpressure response for three tests of varying charge weights (right).

BEHIND-ARMOR BLUNT TRAUMA

Nonpenetrating events may occur when either the projectile itself is a "nonpenetrating" (less-lethal) munition or the armor system succeeds in defeating the ballistic round during impact. Body armor is an essential component of personnel protection, mitigating the risk of penetrating ballistic injuries. With more than 5000 U.S. troops wounded or killed by gunshots in Operation Iraqi Freedom and Operation Enduring Freedom and thousands more casualties sustained as a result of fragmentation caused by explosions,[19] armor systems have played a critical role in saving lives. During ballistic impact, soft and hard body armor dissipates impact energy to protect against penetrating injury. Despite the armor's protective attributes, however, the possibility exists for nonpenetrating injury resulting from blunt impact behind the armor, termed "behind-armor blunt trauma."[20–22]

For nonpenetrating ballistic impacts to the torso, the tissue injury mechanisms have been differentiated between high-frequency injuries due to wave propagation and lower-frequency, displacement-related tissue damage.[23] Ballistic impacts to a helmeted head can result in transient back-face deformation and subsequent blunt impact to the cranium. This impact can lead to skull fracture, traumatic brain injury, or both.[24–27] As a result, there is a critical need to understand the injury implications of behind-armor blunt trauma and to develop techniques to determine the efficacy of armor protecting against such injuries.

Behind-Helmet Blunt Trauma

The conditions of the threat impact and the properties of the helmet system influence the magnitude of forces transferred to the skull as well as the shape of the helmet back-face deformation. Subsequently, the magnitude of transferred force and the spatial distribution of this force on the skull influence the risk of fracture. A series of experiments was performed to investigate the

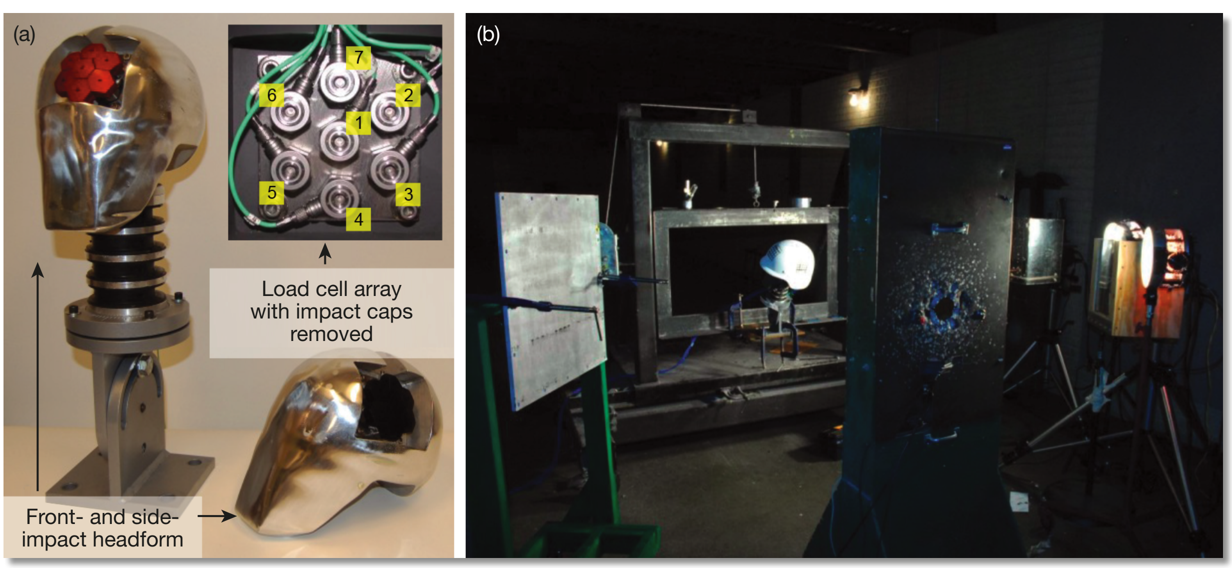

Figure 8. (a) Ballistic Load Sensing Headform including load cell array and pivoting base (courtesy of Biokinetics) and (b) behind-helmet blunt trauma ballistics.

forces transferred from the helmet to the head; these experiments utilized the Ballistic Load Sensing Headform (Biokinetics) (Fig. 8). The influence of threat condition, location of the impact, and configuration of the helmet suspension pad on loads and impulses transferred to the head was examined.[28]

An experimental lightweight helmet system was evaluated during this test series. Two threat conditions were investigated, including the 9-mm full-metal jacket (FMJ) at 427 m/s and the 4-g right circular cylinder (RCC) at 457 m/s. The loads transferred to the skull were measured with a seven-load cell array as part of the Ballistic Load Sensing Headform. Figure 9 shows characteristic force response data, filtered using a digital low-pass filter with a 4.5-kHz cutoff frequency as recommended by the headform manufacturer, for a frontal helmet location. The force measured from each individual load cell as well as the total (summed) force for all load cells are provided (Fig. 9).

Impacts on the front of the helmet and over a helmet pad resulted in the highest measured loads for all configurations. For this test condition, the mean peak force for the 9-mm threat (10,103 N) was twice that of the 4-g RCC threats (4892 N). Impact over a pad resulted in a 30% increase in load for 9-mm FMJ impacts and a 70% increase for the 4-g RCC impacts. Although the summed load increased with the pad, the presence of the pad also modified the force distribution profile on the headform. It was found that the pad reduced force concentration and resulted in a more spatially distributed loading profile. These results have potentially significant implications because both peak force and the distribution of that force are loading parameters influencing the risk of skull fracture.

TRANSPORTATION ACCIDENTS

Transportation accidents, including vehicular and aircraft accidents, are the leading cause of nonhostile deaths and injuries for the U.S. military in theater.[19] The civilian automotive safety community is largely responsible for the current state of the art regarding injury criteria, human surrogates, and the development of effective strategies to mitigate injury due to vehicular accidents. However, in impact scenarios involving rotary wing vehicles or under-vehicle body blast loads, a significant vertical loading component is imparted to the occupant. This vertical loading component is absent in the majority of civilian automotive test evaluations and requires separate consideration. Comparatively limited

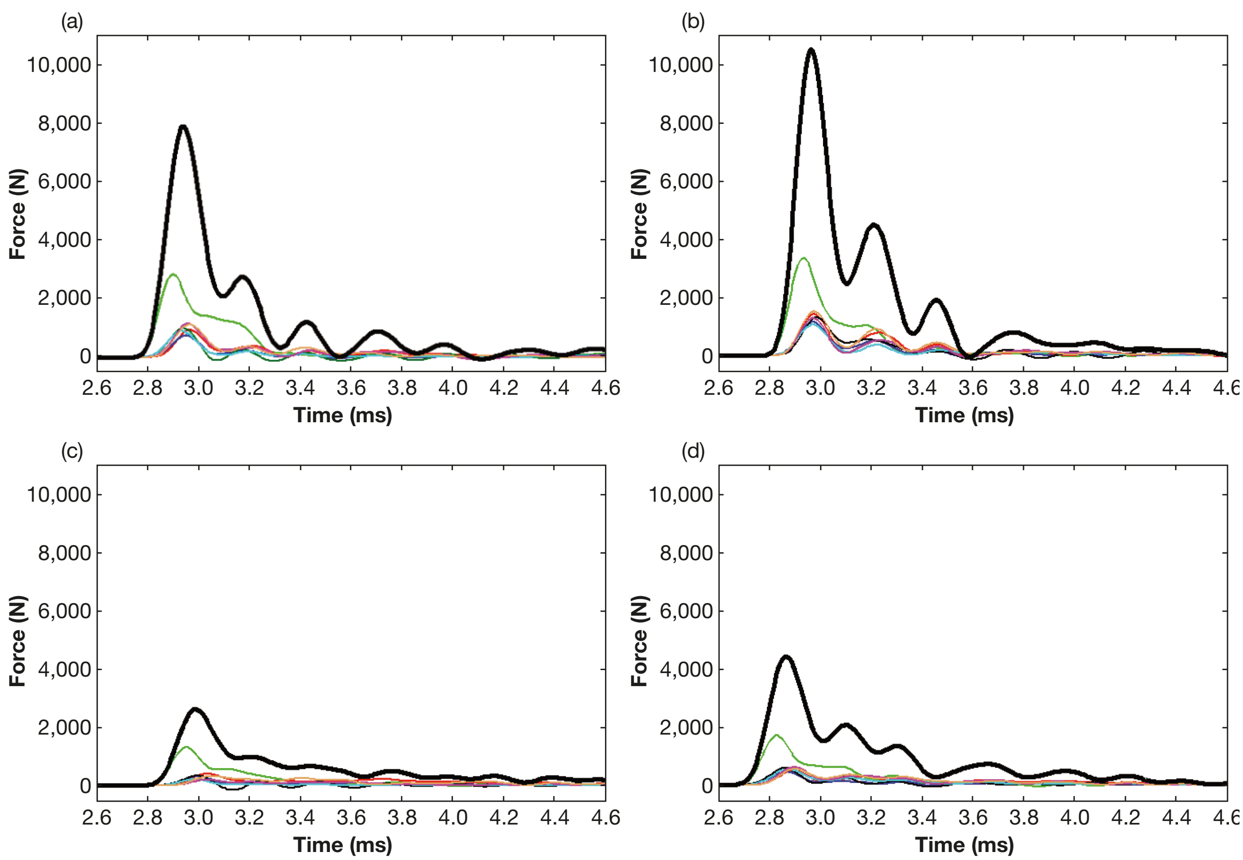

Figure 9. Typical force versus time traces for (a) 9-mm FMJ off-pad, (b) 9-mm FMJ on-pad, (c) 4-g RCC off-pad, and (d) 4-g RCC on-pad frontal impacts.

research has been performed in understanding injury at the local (tissue) level caused by vertical impact and in developing surrogate systems that can measure this response. The robust experimental tools developed previously, including Hybrid II/III ATDs and the global injury criteria that accompany them, have been developed predominantly for automotive impact scenarios focusing on front to back loading. Although recent advances in aircraft crashworthiness have enabled occupants to survive increasing impact velocities, further improvements to injury mitigation require additional knowledge regarding injury risk and complementary tools developed specifically for measuring risk relevant to the vertical loading scenario.

Investigating Thoracic Injuries due to Vertical Loading

Head, neck, lumbar spine, and pelvis injuries are quite common in aviation accidents.[29] Additionally, analysis of injury data trends indicates that soft-tissue injuries, including injury to the heart, aorta, and other thoracoabdominal organ injuries, are frequently observed in aviation fatalities, but their contribution to mortality is unknown.[29] To better understand the human response and potential injury risk to thoracoabdominal soft tissues during vertical loading, APL teamed with NASA Langley Research Center to investigate the response of the HSTM during helicopter crash conditions. The HSTM, as described previously, is a custom-developed human surrogate system complete with hard and soft tissues representing the anatomy of a human torso. The effort to evaluate the HSTM was conducted in two phases with the following primary goals: (*i*) to perform the first-ever investigations of the HSTM in full-scale crash tests for both mild and severe crash scenarios, involving large vertical components and (*ii*) to re-create the impact decelerations using a laboratory crash sled in order to perform detailed parametric evaluations. The data gathered during these evaluations will be used to gain insight into tissue-level injury risk and to validate computational human models with the ultimate goal of improving crew protection.

Full-scale helicopter impact tests (Fig. 10) were conducted to best simulate real-world crash conditions and to establish vehicle deceleration profiles for laboratory re-creation. The Hybrid II ATD and HSTM were evaluated in two helicopter crash tests simulating both mild and severe crash conditions. Both surrogate systems were positioned in the rear seat locations of an MD-500 helicopter and belted using three-point restraint systems standard to this vehicle. Data for the HSTM and Hybrid II human surrogate were compared to determine potential response differences for common measurements (e.g., pelvis and sternum acceleration), and the data unique to the HSTM (e.g., internal organ pressure) were further examined to reveal organ-level responses generated as a result of the crash.

Figure 10. Pre-test MD-500 helicopter with installed deployable energy absorber developed by NASA (inset) and laboratory simulation of the helicopter impact deceleration condition, post test.

The mild crash condition, controlled by a NASA-developed deployable energy absorber that limited impact loads, produced pelvis accelerations that were approximately 30% of those seen in the severe crash condition (12 g in the mild crash versus 40 g in the severe crash). The profile of the pelvis deceleration was very similar for both the HSTM and Hybrid II, indicating the same loading to both human surrogates. The acceleration-based injury criteria calculated for these tests, including the Dynamic Response Index, indicated no risk of serious injury for the mild crash condition but an approximately 50% risk of severe injury for the severe crash condition. The data on HSTM pressure also revealed significantly different responses in the two scenarios. The pressure in the heart increased by more than 700%, while the liver response increased by less than 200% from the mild to severe crash condition (Fig. 11). The analysis also showed that the response trends for the various organs were strongly influenced by the location of shoulder-belt loading on the HSTM. In addition, the accelerometers mounted on the spine indicated that the chest cavity depth increased as a result of the large vertical compression induced on the torso as a result of the vertical impact. This deformation due to vertical loading is not experienced by the Hybrid II mannequin because of its rigid thoracic skeleton.

This effort evaluated the response of a new, more biofidelic human surrogate and compared its response with that of a commonly used legacy surrogate to predict human injury in helicopter crash conditions. Use of the HSTM allowed the collection of global response data, such as pelvis acceleration, as well as organ-level response insight, such as embedded pressure sensor data, that are not possible to obtain using legacy surrogate

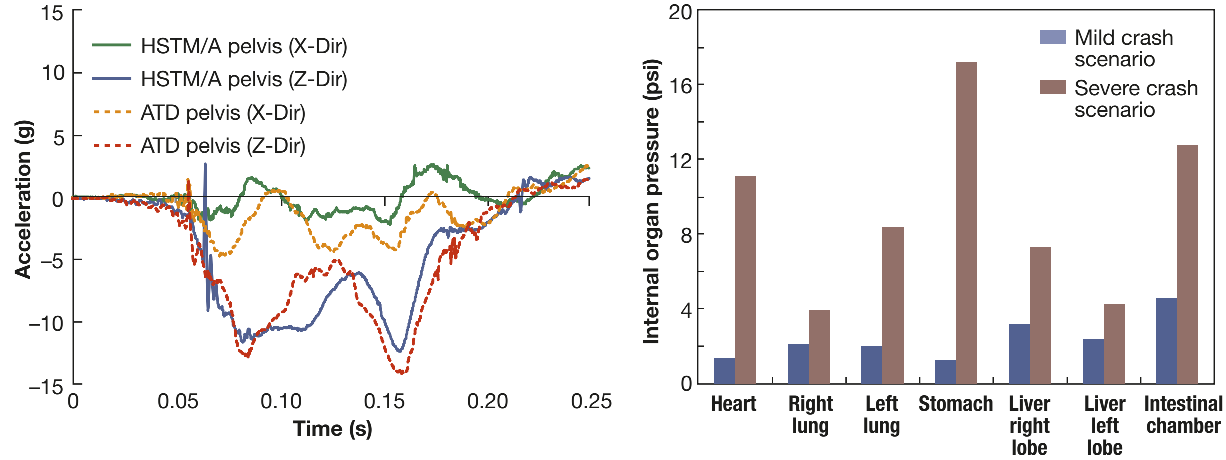

Figure 11. Deceleration response of the HSTM and corresponding Hybrid II (ATD) for the mild crash condition (left) and peak pressure response of the HSTM for the mild and severe crash scenarios (right).

systems. These data will ultimately be used to validate the tissue-level response of an anatomically identical Human Torso Finite Element Model. Once validated, this new system may be used to assist in establishing organ-specific injury criteria and to help refine injury mitigation strategies for crew protection.

CONCLUSION

The extreme physical loading environments experienced by the warfighter put them at heightened risk of serious injury. In an effort to develop effective personal protection strategies, it is critical to understand the nature of the physical insult and the mechanisms by which the body is injured. APL has developed novel human models, both computational and experimental, to determine the nature of the human body and tissue's response to blast, ballistic, and crash scenarios. These models have undergone initial evaluation in live-fire and full-scale testing to demonstrate their capabilities. After thorough validation, these novel human surrogates will become critical tools in the investigation and development of PPE and vehicle safety systems to reduce the risk of human injury.

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