Warfighter Protection: From Benchtop to Battlefield

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ABSTRACT

Our warfighters are exposed to an increasing variety and severity of ballistic, blast, and underbody blast threats on the battlefield. These threats lead to complex injuries that are not well understood, making protection and treatment challenging. Studying injury mechanisms is critical for our warfighters, but recreating these events is dangerous, costly, and difficult to control. To that end, the Johns Hopkins University Applied Physics Laboratory (APL) has developed several test methods, test surrogates, and models that are being used to controllably create battlefield threat conditions in a laboratory environment and investigate effects of these threats on the human body. Models range from in vitro *cellular models to physical test surrogates to computational models of the human body. This article describes some controlled laboratory test methods and test surrogates and devices APL has developed and used to simulate ballistic, blast, and underbody blast battlefield conditions, and provides examples of their use and applicability to understanding battlefield injury.*

INTRODUCTION

Today's warfighters face increasingly varied and severe threats. Ballistic rounds and armor to protect against them date back many years, but today's high-energy ballistic threats have led to the emergence of new injury mechanisms and have presented challenges in designing effective armor. For example, blast exposure from improvised explosive devices has become common on the battlefield.[1] Such blasts propagate pressure waves, or blast waves, through the air and subsequently generate stress waves in armor and in the underlying biological tissue. Although blast wave mechanics are becoming better understood, their implications on injury remain a subject of significant study. Thus, armor is currently not designed to protect against blast waves. Detonation of an improvised explosive device under a vehicle (known as an underbody blast, or UBB) can result in yet another class of injury mechanisms. These mechanisms are also not well understood, so mitigation strategies, again, are lacking.

Our warfighters need improved personal protective equipment (PPE) to shield them from ballistic, blast, and UBB exposure. However, before we can develop optimal armor solutions, we must better understand injury mechanisms. There are some common requirements in investigating battlefield injuries, whether injuries result from ballistic, blast, or UBB threats. First, because battlefield conditions are inherently complex and variable, benchtop evaluations of injuries must balance replication of the mechanical environment with the ability to create tailorable and repeatable exposures to the threat. Once test exposures representative of a battlefield threat can be repeatedly recreated within the laboratory, test subjects must be identified.

In studies of battlefield injury, test subjects could include animals, postmortem human subjects (PMHS), *in vitro* models, physical surrogates, or computational models. Although PMHS have the relevant physiology, many of their pertinent biological mechanisms are no longer active. Animals offer the advantage of being living systems, but when testing on animals, researchers must determine how to scale their findings to humans. Testing on both animals and PMHS is costly, subjects are limited, and there is significant subject-to-subject variability. *In vitro* models can provide important insights into local biological mechanisms, but they do not represent the global physiology or response of animals or PMHS. Existing physical models of the human, colloquially referred to as crash test dummies, were not designed with the unique high-rate nature of the battlefield ballistic or blast environment in mind. Their instrumentation is not fast enough, nor does it capture all of the metrics of interest for battlefield injuries. Further, their rigid components do not respond in the same way the human body does, thus compromising biofidelity, the degree to which a model can replicate the real biological system on which it is based. For some scenarios, experimentation is too costly or time consuming, or there are just too many variables to investigate. As a result, investigators often prefer to use computational models. These models allow researchers to control and methodically examine variables and can produce large amounts of data for evaluation.

When studying the human body's response to battlefield threats, use of lab-scale test devices, methods, and models enables researchers to study battlefield injuries without having to address biological or live-fire variations. To that end, APL has developed several methods for simulating exposure to various battlefield threats, as well as devices and methods for investigating the effects of these threats on the human body. APL has designed *in vitro* models and physical test surrogates to enable investigation of particular injury mechanisms or physiological responses of interest, incorporating biofidelity aspects most important for those specific scenarios and simplifying other aspects. Because specific use scenarios were considered during their design, the models and devices are robust and practical. APL has also developed and used computational models of the human body. These models provide insight into injury mechanisms in scenarios where experimentation is not possible or practical. This article describes some controlled laboratory test methods and test surrogates and devices APL has developed and used to simulate ballistic, blast, and UBB battlefield conditions.

BALLISTIC THREATS AND INJURY

Helmets and body armor have traditionally been worn to prevent ballistic projectiles from penetrating the body. However, helmets and body armor become deformed when they stop a projectile: the material opposite the side of impact protrudes and makes contact with the body. This backface deformation (BFD) could put the PPE wearer at significant risk of severe injury, even when the projectile does not penetrate the armor. These injuries are often referred to as behind-helmet blunt trauma (BHBT)[2] and behind-armor blunt trauma (BABT).[1,3,4]

Currently, the effectiveness of PPE is assessed using clay. Clay is placed behind the armor, a ballistic projectile is fired at the armor, and the depth of the BFD into the clay directly behind the location of impact is measured.[5] This approach has a number of limitations, including variation in the properties of the clay formulation, lack of dynamic and injury-based metrics for assessing the effectiveness of the armor, and an uncertain ability to effectively measure the armor's performance under a wide range of conditions. APL has developed several alternative methods for simulating ballistic impact and investigating effects of ballistic impact on the human body.

Development and Use of Controlled Lab Test Methods

As an alternative to live-fire ballistic testing, APL developed a laboratory pneumatic cannon system (Fig. 1a) and specialized projectiles (Fig. 1b) to simulate ballistic BABT and BHBT loading conditions. Alterna-

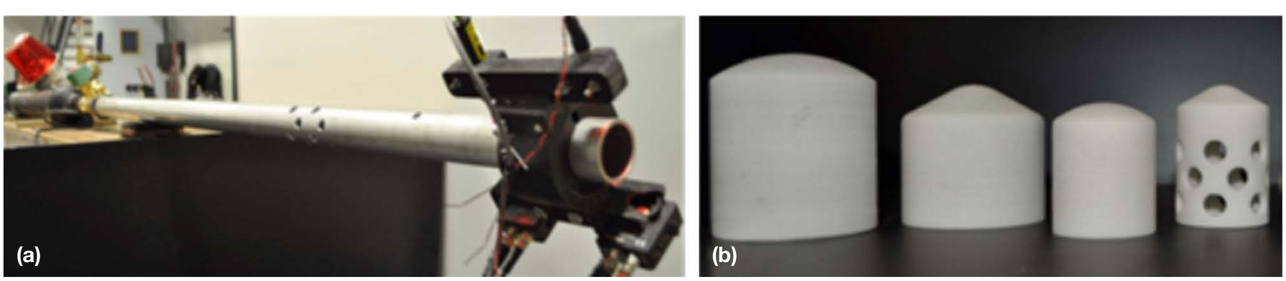

Figure 1. (a) APL's pneumatic cannon system and (b) projectiles developed to simulate BABT and BHBT loading conditions. The radii of curvature of the armor BFD range from 12 to 100 mm.

tive testing approaches are necessary because live-fire ballistic testing is expensive, it can be difficult to obtain the necessary material (such as armor) to conduct the tests, and the combination of test and armor variability complicates interpretation of the results. The pneumatic cannon system can simulate the forces and displacements the warfighter experiences with armor BFD by implementing customized projectile shape, velocity, mass, and material. Unlike more common laboratory devices, such as drop towers and impact sleds, the pneumatic cannon system replicates loading magnitudes (up to 25 kN) and rates (up to 150 m/s) in the range of ballistic events. This system provides a highly repeatable, low-cost, quick-turnaround, and accessible alternative to live-fire ballistic tests for many lab-scale and preliminary studies of BABT and BHBT. The pneumatic cannon system has proven to be beneficial in efforts to develop improved test devices,[6] understand and predict injuries,[7] and better protect the warfighter.

Development of Test Surrogates

When developing test surrogates for ballistic loading, designers must consider the strength of the structures and materials under dynamic loading. Depending on the application, it may be preferable to design the surrogate so that it can mimic specific injuries, such as rib or skull fractures, or it may be preferable to create a less biofidelic but more robust structure that can be repeatedly tested with different ballistic threats. Injury criteria are not well understood, so integrating sensors to quantify metrics such as force, pressure, and acceleration can provide data on the mechanical effects of ballistic loading on the body. Test surrogates must be specifically tailored for the intended use, body region, and armor type to maximize the usefulness of the resulting data.

Helmet Evaluation System

APL is developing a next-generation headform system for the Army that will support first article testing and lot acceptance testing of new helmets. This system is an alternative to the current clay-based approach to measuring the potential for BHBT. To address the limitations of the clay-based approach, the headform must be able to measure the behind-helmet impacts for the various levels of BFD associated with emerging helmet and projectile types. The headform system must also be able to make repeatable measurements, eventually enabling evaluation against an acceptance threshold linked to injury risk. The solution must be cost effective and based on reliable engineering measurements so that independent test laboratories can use it in first article testing and lot acceptance testing.

Six designs, depicted in Fig. 2, were conceptualized and investigated. They include four concepts based on force measurements: one with a single large-capacity load cell at each impact location (Fig. 2a); one with a load cell array at each impact location (Fig. 2b); one with the entire head surface covered with load cells (Fig. 2c); and one with a stationary load cell array (or single cell) with modular head components that attach to surround the array, enabling measurement in all locations and for all head sizes (Fig. 2d). A fifth design (shown in Fig. 2e) incorporates both force measurement and intracranial pressure measurement into biofidelic materials. The sixth concept (shown in Fig. 2f) relies on metallic witness plates to capture permanent deformation, which can then be used to calculate the impact forces.

The modular headform (Fig. 2d) was selected for development. Tests using this system result in repeatable behind-helmet force data, facilitating quantitative comparisons of armor solutions. Perhaps most important, all components, materials, and geometries can be customized as threats, armor solutions, and testing needs evolve. This flexible platform can be adapted to evaluate a variety of helmet types and sizes simply by 3-D printing new head structures.

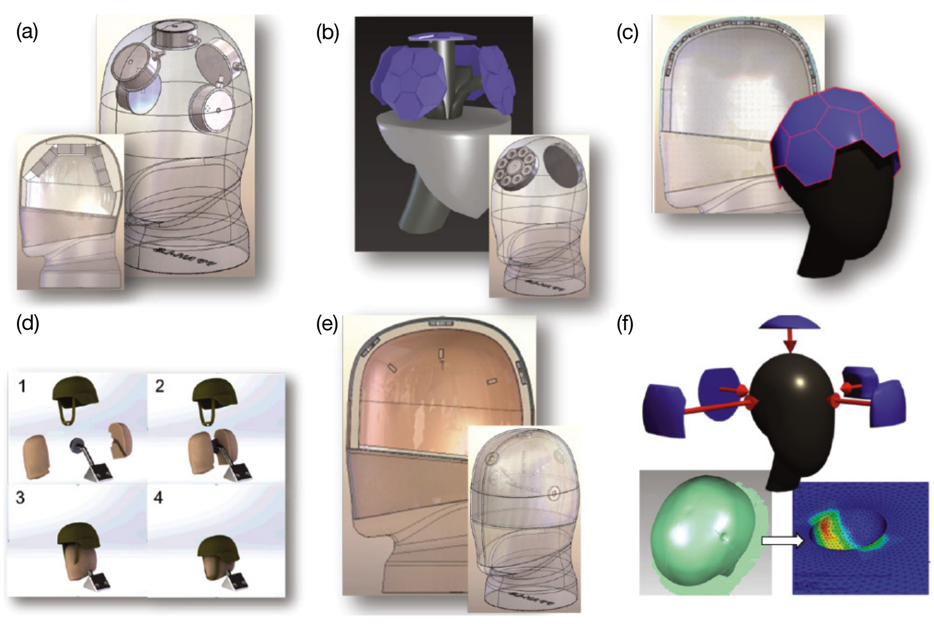

Figure 2. Headform design concepts with (a) a single load cell; (b) a load cell array at each impact location; (c) the head surface covered in load cells; (d) a modular headform; (e) a biofidelic headform with skull force and intracranial pressure sensing; and (f) a headform with metallic witness plates.

Skull Surrogate Material

To study the risk of skull fracture and the mechanisms in BHBT-related impacts, APL conceptualized and fabricated a biofidelic skull surrogate material designed to fracture with loads and patterns similar to those of human bone. The surrogate replicates both the physical structure and the relevant mechanical properties of the skull. Human cranial bone is composed of two hard outer layers (cortical tables), which primarily govern the strength of the skull, and a soft cellular inner layer (diploe), which acts as a shock absorber that influences the mechanisms of skull fracture. Material development chiefly focused on the cortical tables because they dominate the absolute strength properties of the bone.

Targeted properties included fracture toughness, tensile strength, and modulus. Fracture toughness is a measure of the bone's ability to resist cracking. The strength and modulus of a bone dictate how it will deform and break under loading. An epoxy-based, fiber-infused material was found to best replicate the properties of the cortical tables. The team used this formulation to fabricate cortical tables for several sandwich skull structure candidates, with the middle layers consisting of commercially available foams as the porous diploe component. Mechanical testing of the sandwich skull structures was conducted to quantify bending strength and evaluate impact fracture patterns of the simulants. By using these data, the team identified the optimal materials for incorporation into a final surrogate design.

The selected formulation was constructed into flat panels and used in a series of ballistic tests to investigate BHBT injury mechanisms. Two fracture types were observed during the tests. The first, due to a penetrating impact, caused the surrogate to punch in when the projectile entered it and to bevel out when the projectile exited (Fig. 3).[8] Interestingly, this is typical for exit wounds from gunshots to the head. The second fracture, which occurred in a non-penetrating case (Fig. 3b), resulted in a fracture pattern on the top (impacted) surface that emanated linearly from the point of impact, whereas the pattern on the bottom surface was linear and surrounded by a concentric ring. The difference in observed fracture patterns between the top and bottom cortical layers indicates that the diploe served as a shock buffer, preventing fracture in the top cortical table from propagating directly through to the bottom table. Thus, the two tables fractured independently, consistent with fracture behavior in real skulls.

Since completing development of the initial skull surrogate, APL has demonstrated the ability to manufacture the skull surrogate materials into 3-D geometries in the form of hemispheres. Recent advances in additive manufacturing may enable this surrogate material to be

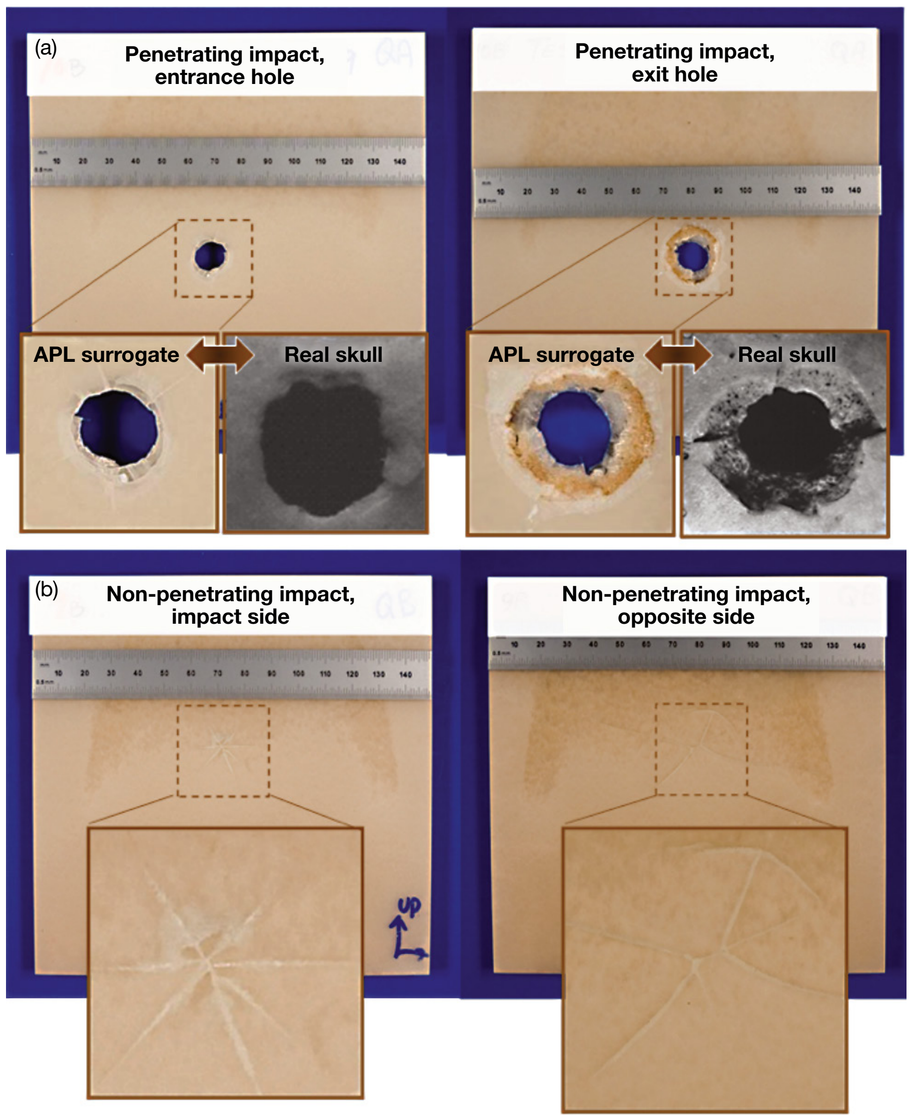

Figure 3. Fracture pattern in the APL skull surrogate (a) following penetration with 64-grain right circular cylinder and (b) following a non-penetrating impact. Similar fracture patterns in real skull are shown for comparison. (Portions reprinted from Ref. 9, with permission from Elsevier.)

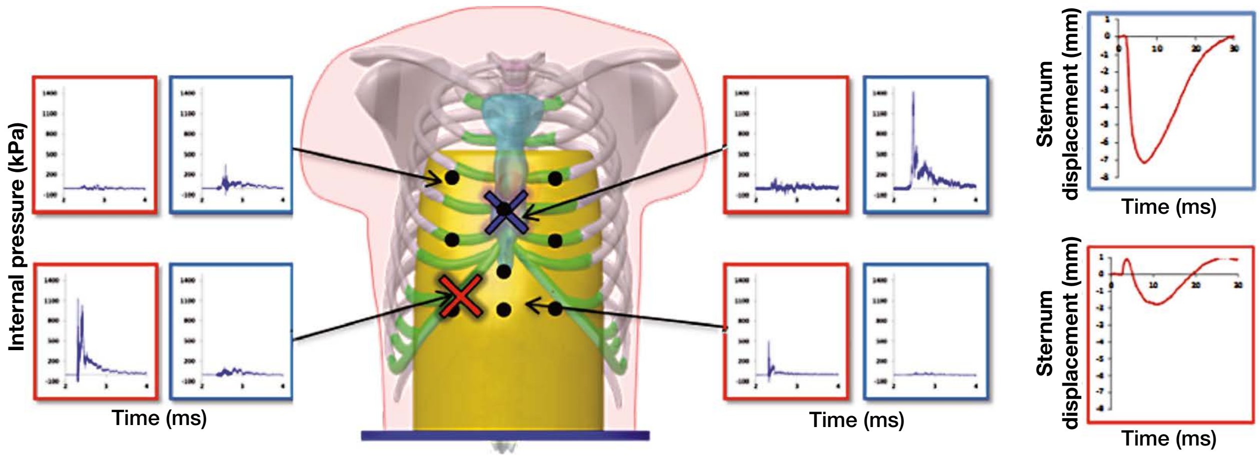

Figure 4. Characteristic pressure responses and chest wall compression at the sternum during impact to different anatomical/armor locations (the red *X* marks the shot location on the lower right rib, and the blue *X* marks the shot location on the center of the rib cage). A pressure response for each of the four sensors and a sternum displacement from a sensor behind the blue *X* are shown for each of the two shot locations.

created in more complex geometries that better simulate human skull, enabling its use in more detailed injury investigation studies.

Human Surrogate Torso Model

APL developed a test device, the Human Surrogate Torso Model (HSTM), that is representative of the human torso's form factor, structure, and material response and enables repeatable dynamic measurements, unlike the clay-based method. Supported by the Office of Naval Research, the HSTM is composed of biosimulants tailored to simulate the mechanical responses of soft-tissue and skeletal structures.[4,10] Embedded within the HSTM is a full instrumentation suite of accelerometers, custom-developed displacement sensors[11] affixed to the skeletal structure to measure kinematics, and a distribution of sub-miniature pressure sensors in the intrathoracic soft tissue to quantify pressure wave propagation and biomechanical response to non-penetrating ballistic impacts.

Under BABT loading, the HSTM's skeletal and internal pressure response is sensitive to both impact velocity and anatomical location (Fig. 4).[4,12,13] Additionally, live-fire tests have demonstrated the HSTM's ability to measure distinct, biomechanically based responses between differing armor systems in their as-worn form factors. The capabilities embedded in this surrogate system have the potential to improve our understanding of energy transmission through the body and to elucidate correlations with injury. This improved understanding could inform test standards for BABT and contribute to injury risk mitigation for the warfighter.

Computational Tools

Soldiers are overloaded with heavy gear and armor. To strategically lighten warfighters' loads, we need to understand how to protect them without overburdening them with unnecessary armor. Anthropometric data are currently used to size protective gear according to the height, weight, and dimensions of key body parts of the wearer. However, the ability to more accurately predict internal anatomical measurements, such as organ size, shape, and location, based on external anthropometric characteristics as well as demographics (e.g., race, age, and gender) could enable development of more personalized and effective body armor products.

APL developed a computational pipeline capable of rapidly processing a patient's thoracic computed tomography (CT) images[14,15] to produce a multi-organ statistical shape atlas. A novelty and advantage of the pipeline is that it provides information not only about the shape variations for each individual organ but also about how the organs scale with respect to each other in the body. The critical technical challenge was determining how to segment organ geometries from medical CT scans using a rapid and automated approach (Fig. 5). Meeting this challenge enabled researchers to quantify a large data set of geometries from CT images of subjects spanning a range of demographics; this data set was then processed in the pipeline.

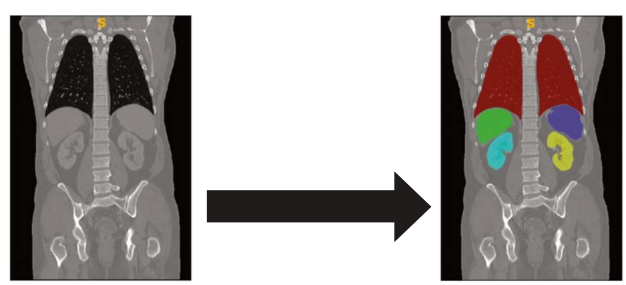

Figure 5. Automated segmentation of internal organ anatomies using the APL-developed computational image process pipeline.

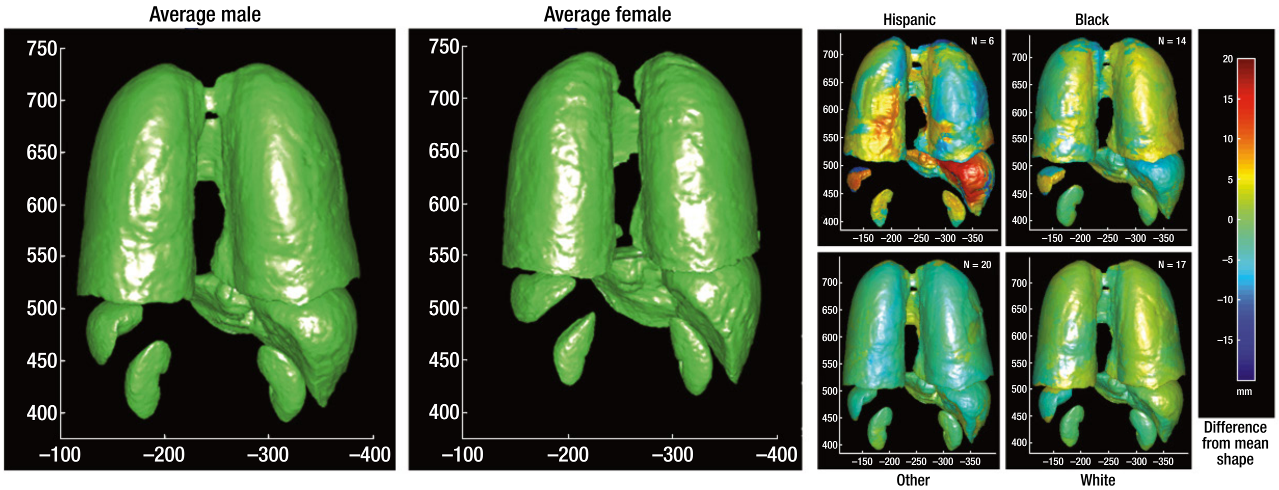

Figure 6. The left and middle images, respectively, show organ geometries of the average male and the average female established by a statistical shape atlas. In the right image, organ geometries of the average male are shown according to a selected demographic characteristic (race), where color indicates the deviation from the mean shape of average male organs.

These geometries were compiled into a statistical shape atlas to provide a means of identifying relative differences in organ shape, size, and location between demographic and anthropometric data on patients (Fig. 6). The current method and pipeline analyzes the lung, liver, kidneys, and spleen, but the capabilities are extensible to other organs and body structures. External anthropometric measurements were extracted for each patient from their medical data sheets or from landmark-based measurements using the CT images. Additionally, the team evaluated a method to enable prediction of internal geometries from anthropometric and demographic information. In the future, these capabilities could potentially be applied to the design of custom-fitted armor, tailoring protection to individual warfighters while also lightening their loads.

BLAST THREATS AND INJURY

Understanding the mechanics of an explosion is a critical aspect of studying injuries attributed to blast exposure. Most injuries from a blast event fall into four categories:

1. Primary blast injuries occur from the overpressure wave interacting with the body.
2. Secondary blast injuries are penetrating or perforating wounds and are caused by charge fragmentation or sand and dirt from buried charges impacting the body.
3. Tertiary blast injuries are characterized by whole-body acceleration from the blast wind and include falling-type injuries such as contusion (bruising), broken bones, and internal bleeding.
4. Quaternary blast injuries, such as thermal, chemical, or nuclear burns, can result from proximity to the fireball.

Injury resulting from primary blast to the head, or the direct effects of exposure to an overpressure wave, is not well understood. Traumatic brain injury (TBI) has been called the "signature injury" of warfighters in recent conflicts and also affects 1.7 million civilians each year in the United States alone.[16] Despite the tremendous investment in TBI research, the underlying biomechanical and molecular causes are poorly understood, and studies face significant challenges in reproducibility and scalability to humans because of the complex nature of the disease. Reliable biomarkers for TBI diagnosis and prognosis remain elusive, and few, if any, new therapeutics have been developed for use in a clinical setting. We need a greater appreciation of the molecular, cellular, and tissue-level responses to TBI to facilitate a greater etiological understanding of this type of injury. Increased understanding may give rise to new pharmaceutical mechanisms of prophylaxis, treatment, or both. This requires new models and standardized injury exposures in the experimental arena, and APL has developed several methods for either simulating or investigating effects of blast exposure on the human body.

Development and Use of Controlled Lab Test Methods

Live-fire blast tests are most representative of combat blast exposure, but they must be conducted at specialized facilities with personnel who are trained to safely prepare high-energy explosives. The high cost of live-fire testing often prohibits researchers from completing a large series of tests and attaining statistical data for many variables. Additionally, test results can be sensitive to numerous factors such as atmospheric effects and test-to-

Figure 7. Live-fire blast tests are prone to environmental and experimental artifacts. The image on the left depicts an ideal test in which the headform is subjected to a symmetrical shock wave, and the image on the right depicts debris jetting directly at the headform, despite nominally similar test conditions.

test variations in detonations. For example, Fig. 7 shows still images from high-speed video taken during live-fire testing. The image on the left depicts an ideal test in which the headform is subjected to a symmetrical shock wave, and the image on the right depicts debris jetting directly at the headform, despite nominally similar test conditions. More controllable conditions and isolation of the pressure wave are clearly needed to enable effective study of primary blast effects.

Some laboratory devices can simulate the critical aspects of blast exposure. These devices allow researchers to conduct many tests, and the data from these tests can complement findings from a limited set of live-fire tests. Many laboratory shock tubes have been designed to test small specimens or to characterize materials, but they are not large enough to accommodate the study of larger-scale injury mechanisms or full-scale body armor components. To address this gap, APL designed and developed a large-scale Blast Overpressure Simulator System (BOSS) specifically for these purposes (Fig. 8). The 3 ft × 3 ft cross-sectional test area allows the system to accurately mimic the pressure wave generated in a live-fire blast as it traverses around larger test articles, such as helmet systems. By tailoring the driver gas, diaphragm material, and configuration, a range of blast wave conditions can be replicated, as shown in Fig. 9. The BOSS is instrumented with 12 ports that house pressure sensors to measure overpressure along the inner walls of the tube and a pitot probe to measure total and static overpressure within the fluid flow. The BOSS is currently being used to develop a methodology to evaluate head-borne PPE.

Figure 8. The Blast Overpressure Simulation System (BOSS).

Development of Test Surrogates

Researchers have used numerous models to study different elements of blast-induced injury, ranging from highly engineered anthropomorphic surrogates to computational models to biological models. Three types of biological models are available: *ex vivo* tissues used for experimentation immediately after they are harvested from the animal model; *in vitro* models derived from animal models but maintained in culture under varying conditions; and *in vivo* models, intact live animal models.

Each of these models has unique benefits and drawbacks depending on the specific mode of injury and analysis to be performed using them. However, no single system is uniquely suited to studying varying aspects of blast-induced injury. APL has specifically designed solutions for investigating blast effects on the head and the associated genetic and cellular responses and mechanisms. These solutions include a physical surrogate, an *in vitro* model, and computational models. All are described further below.

Human Surrogate Head Model

APL has developed a family of instrumented human surrogate headforms designed specifically to help researchers understand the effects of helmets during

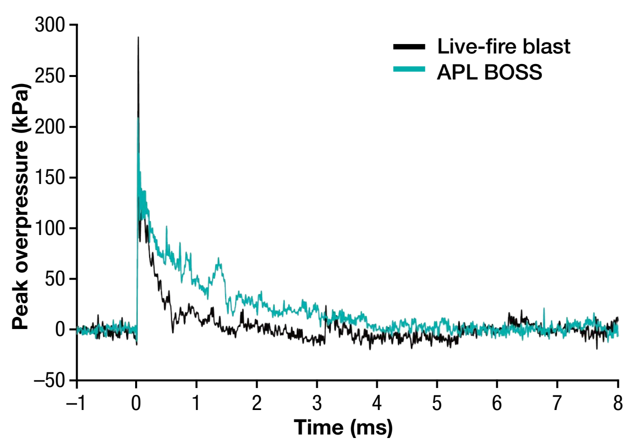

Figure 9. Comparison of pressure profiles in live-fire blast testing and the APL-developed BOSS.

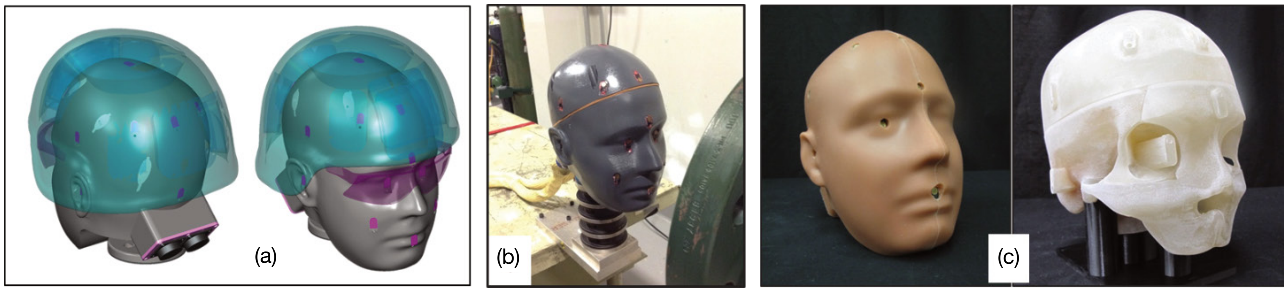

Figure 10. (a) A schematic showing the geometry of a headform outfitted with a helmet and eye protection; (b) a basic headform; and (c) an enhanced headform surface with internal skull anatomy shown separately.

blast loading. The headforms' external geometries are based on data from the Army Anthropometric Survey,[17] and the headforms can be readily outfitted with head-borne PPE (Fig. 10a). The basic headform (Fig. 10b) is of solid construction and is instrumented with an array of pressure sensors on the surface. The enhanced headform (Fig. 10c) includes skin, skull, sinus cavities, and a simulated brain and is instrumented with an array of pressure sensors both on the surface of the skull and embedded in the brain. Both headforms include an accelerometer and angular rate sensor package. Researchers have recently conducted tests in the BOSS using the headforms to investigate how a blast pressure wave interacts with a bare headform versus a helmeted headform. Results from these tests demonstrate that tests are repeatable using both the headform and the BOSS (Fig. 11); these results may inform future helmet designs and help to advance the field of blast protection (Fig. 12).

In Vitro *Model*

In vitro models are commonly used in TBI research because they are accessible, relatively inexpensive, and easy to analyze for various responses to injury. The roundworm *Caenorhabditis elegans* has been used extensively as a model for biomedical research because of the high level of similarity of its nervous system compared to humans.[18–20] As a model organism, *C. elegans* can be easily cultivated in a lab, enabling high-throughput experiments at low expense, yet it is complex enough to have relevance to injury mechanisms resulting in TBI in humans. For example, *C. elegans* has a fully developed and well-characterized nervous system consisting of approximately 300 neurons and over 50 glial cells whose locations and connectivities are well defined.[21] Exposure of *C. elegans* to blast trauma is predicted to result in a molecular response that is similar to the cellular trauma experienced by humans.

APL's recent research efforts[22] have focused on characterizing the *C. elegans* molecular response to blast injury, both inside a headform (Fig. 13, a–c) and in a petri dish. Researchers have detected the organ-

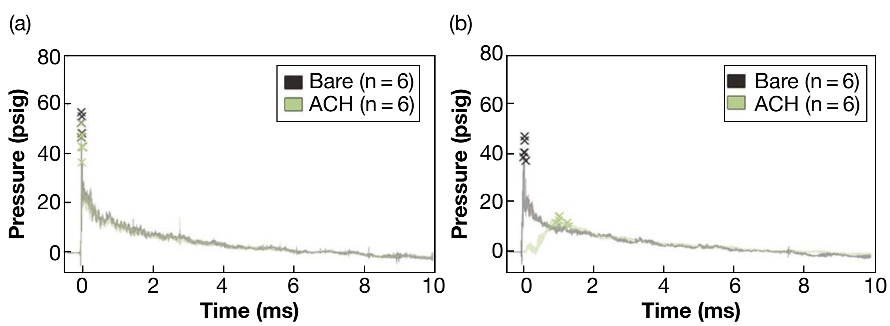

Figure 11. Average corridors for measured pressures (average of six tests ± 1 standard deviation) in (a) mouth and (b) at the front center pad, comparing pressures incurred by bare and helmeted (basic) headforms and showing the overall repeatability of tests using the headform and BOSS.

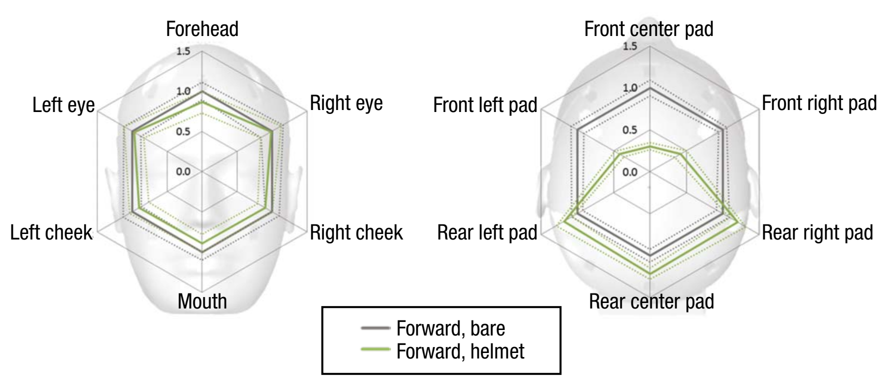

Figure 12. The effect of helmet presence on pressures measured at various locations within the basic headform for forward-facing orientation. Gray shows the bare headform, and green shows the helmeted headform.

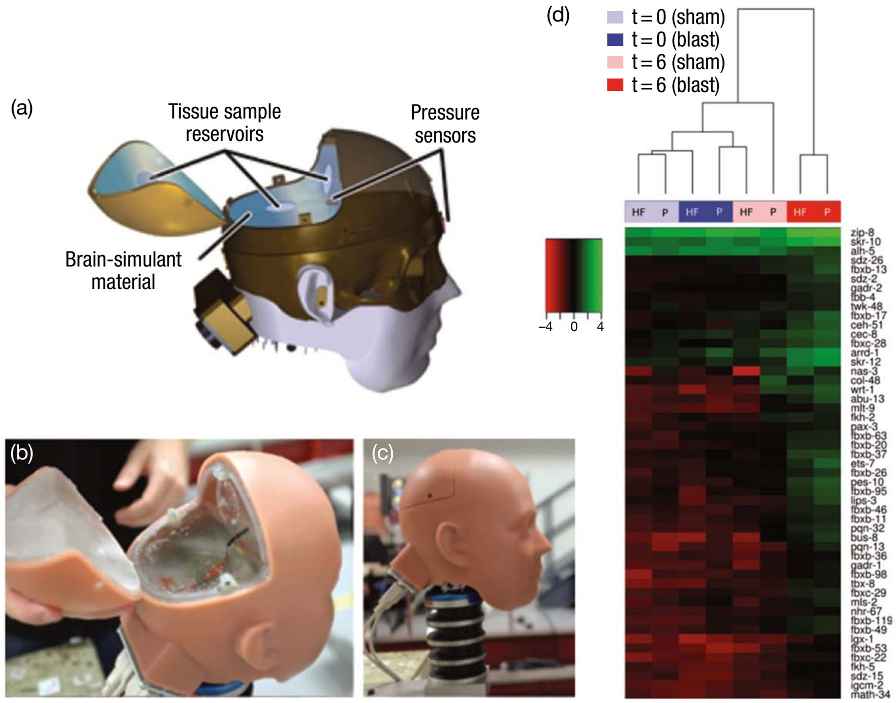

Figure 13. (a–c) Insertion of biological materials into the headform surrogate. (d) Differential transcriptional expression detected in *C. elegans*, in both the headform (HF) and petri dish (P), after exposure to blast overpressure.

ism's acute transcriptional responses after it is exposed to blast overpressure (Fig. 13d). By using this *in vitro* model, researchers can correlate mechanical exposure and biological outcome. High-throughput biofidelic testing enables researchers to hypothesize about TBI mechanisms and evaluate current and future protection systems when coupled with a headform system. Future research efforts revolve around validating the observed C. *elegans* phenomena in mammalian systems.

Computational Models

A computational model that provides insight into blast wave–induced stress and strain distributions at every point within the body can contribute to our knowledge of injury mechanisms. Such a model enables researchers to quantitatively test whether a proposed injury mechanism is likely, given the ranges of mechanical parameters that exist. Computational tools can provide insight into the complex, nonlinear, dynamic nature of the processes involved and the ways that the mechanical effects interact with each other.

Given the prevalence of TBI, head models aimed at understanding wave propagation and associated injury mechanisms are the subject of significant research. The head interacts with a blast wave on multiple timescales, including during pressure transmission (<1 ms) where overpressure is directly refracted into the brain; during head movement (40–80 ms), where the momentum transfer due to the blast wave results in movement of the head; and during differential movement of the skull and the inside of the brain, due to dynamic load effects and the constraints of the neck. The relative motion (primarily differential rotation) of the skull and the inside of the brain causes strains in the brain tissue; these strains are determined by the mechanical properties of the brain and the interior constraints in the skull.

APL developed a detailed finite element model (FEM) of the brain, the interior shape of the skull, and the internal brain membranes to study the head biomechanics during these multiple timescales (Fig. 14a). To model the earliest phase of blast wave and head interaction, researchers used pressure transmission, a coupled fluid-structure modeling technique, to evaluate pressure propagation through the brain for varying blast orientations. These simulations provide information about varying stress magnitudes and concentrations that result inside the head as a function of the head geometry and blast

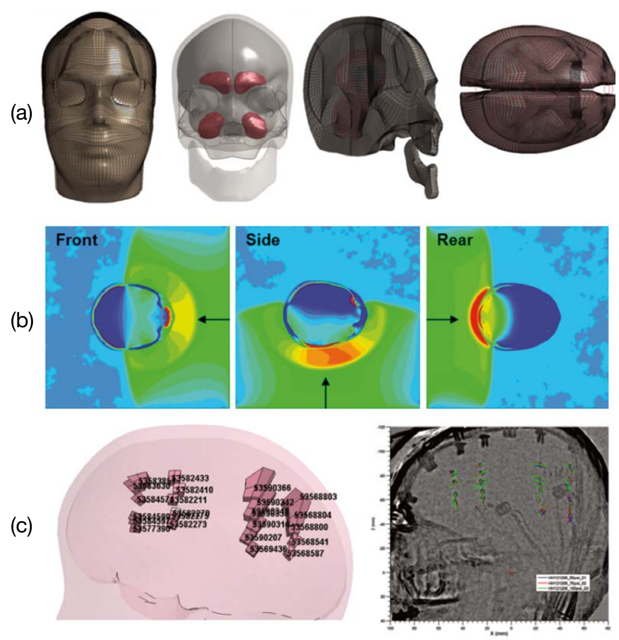

Figure 14. (a) Components of the computational head FEM. (b) FEM predicted brain tissue strain compared with (c) experimentally measured relative motion between brain and skull.

direction. This head model was also used to compute the relative motion of the different parts of the brain during the second phase of the blast wave and head interaction. These simulations were compared with experimental results (Fig. 14c) to verify the accuracy of motion calculations and strain distributions. The FEM head models have recently been integrated with helmet protection systems so that researchers can evaluate the influence of suspension pad configuration on blunt impact and blast loading protection.

UBB THREATS AND INJURY

The use of improvised explosive devices in UBB events has heightened interest in evaluating the effects of vertical loading. While military vehicle hull designs have evolved to mitigate some effects of these attacks, the energy imparted during a UBB event still results in debilitating injuries to the vehicle's occupants.[23–25] These events are characterized by short-duration, high-amplitude acceleration of the vehicle structure. This loading transfers to the vehicle occupants directly via the vehicle floor as well as indirectly through the seat system.[26] Additionally, when occupants move during the event, their bodies may impact the vehicle's internal structures. The transferred loading results in a range of skeletal and soft-tissue injuries, including injuries to the head and neck,[27] upper and lower extremities,[28,29] and spine.[24,25,30]

It is difficult to study these events because much of the existing research, such as study of aircraft ejection, does not approach the impact velocities or loading durations that are characteristic of the UBB environment. To address this gap, APL is working to develop test devices and human models to enable better understanding of UBB injury and mitigation.

Development and Use of Controlled Lab Test Methods

Researchers often simulate UBB events by conducting explosive testing using either full vehicle systems or specialized blast rigs. Because these test methods are inherently complex and chaotic, it is difficult to repeat specific loading conditions in tests; this is one of the primary difficulties in studying UBB. Further, the time-intensive preparation for such tests greatly reduces the throughput of testing.

Establishing a controllable and repeatable test methodology is essential for elucidating the effect of each input variable (i.e., peak velocity, time to peak, and duration of loading) on the resulting response of the human body. To address these difficulties, APL developed a laboratory test device, named the Vertically Accelerated Load Transfer System (VALTS), capable of reproducing loading conditions relevant to those experienced during UBB events.

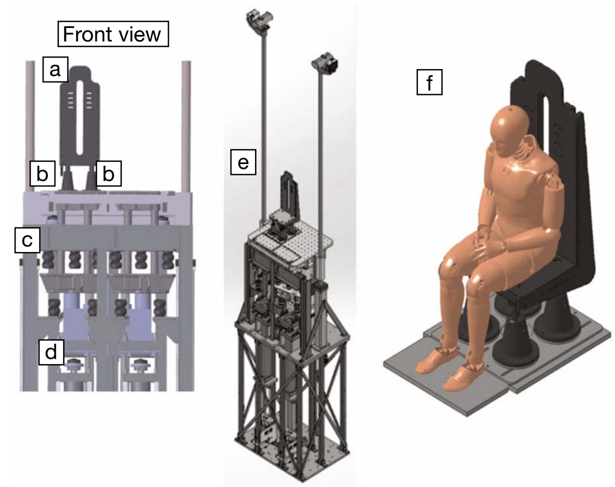

Figure 15. CAD model of VALTS. (a) Seat system, (b) foot platforms, (c) displacement limiting stops, (d) pulse shaping materials, (e) isometric view of primary platform, and (f) CAD of seated and positioned Hybrid III (HIII) test device.

The Vertically Accelerated Load Transfer System

The VALTS (Fig. 15) is a unique laboratory device designed with multiple impact test platforms that simulate the complex and dynamic loading of UBB events.[31,32] This system enables three types of loading scenarios that can be operated independently or in conjunction with one another to fully characterize the effects of the UBB environment on whole-body PMHS or surrogates in a variety of seat systems and simulated vehicle structures:

1. Local deformation loading, in which a controlled accelerative impulse is delivered to the feet
2. Global rigid body motion loading, in which a controlled accelerative impulse is delivered to the seat
3. Slam-down impact of the vehicle, in which a controlled deceleration impulse is applied via a braking system

Loading is controlled by pneumatically propelled impactors that strike the test platform(s), enabling a wide range of precise, repeatable, and representative UBB input impulses to be delivered to the test articles. The VALTS was built within a laboratory setting, with supporting high-speed data acquisition systems to record system and specimen responses, as well as a full suite of high-speed camera and motion tracking systems to characterize specimen kinematics.

Development of Test Surrogates

There remains a significant gap in our understanding of the human body's response to and injury tolerance for vertically accelerated loading conditions that warfighters may be exposed to in conditions of UBB events, helicopter crashes, or aircraft ejections. To advance injury mitigation solutions, we need to increase our knowledge of the human body's response to vertical loading and develop tools and techniques to predict injury risk under these conditions. Such advancements range from developing improved anthropomorphic test devices (ATDs) to enable better transmission and interpretation of the response to vertical loading, to developing entirely new test devices that more accurately represent the human body's response to this type of loading, to using validated computational models of the human body to guide ATD design and comprehensively characterize the human skeletal and soft-tissue responses to these exposures. Computational models can also be used to predict response under conditions that may be impractical for laboratory testing.

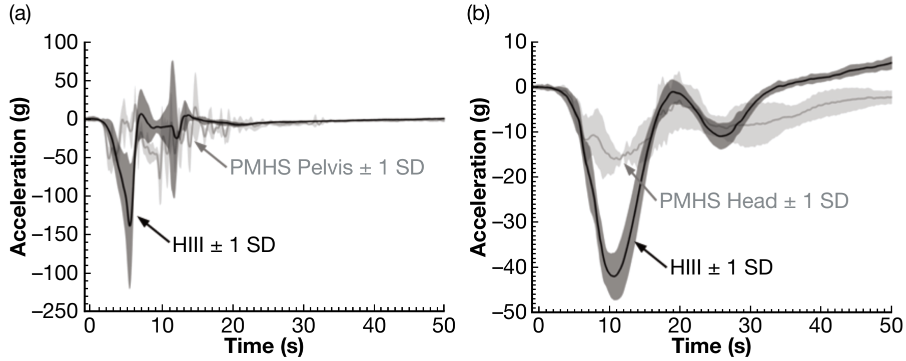

Figure 16. Comparison of PMHS and Hybrid III (HIII) vertical acceleration responses in (a) pelvis and (b) head.

Evaluation of ATDs for Studying UBB Injuries

The Hybrid III (HIII) ATD, which was originally developed for frontal impact conditions in vehicle crash assessment standards, has been broadly used to evaluate injury for a variety of loading conditions, including vertical UBB assessment. However, the HIII is limited in its utility to assess the safety of vehicles exposed to UBB, as it is not sufficiently robust for loading in the vertical direction. The HIII's mechanical and instrumentation designs also are not optimized for this purpose. Using the VALTS, initial testing of the HIII under simulated UBB loading has shown that the HIII acceleration magnitudes are substantially higher than those experienced by human occupants (Fig. 16).

To address this gap, APL and a world-class consortium of university collaborators are working with the Army to provide the underlying biomechanics research necessary to develop an improved ATD called the Warrior Injury Assessment Manikin (WIAMan), designed to enable assessment of injuries due to extreme vertical loading events (Fig. 17). APL is working to provide biomechanical design targets and injury risk data to inform the overall WIAMan ATD development in simulated blast loading. Once completed, the WIAMan ATD should inform improved designs of vehicle and seat systems in a variety of vertical loading environments.

Computational Models

APL developed a whole-body computational model and applied it to study the effects of UBB loading on the human body. The original anatomical geometry was adapted from the National Library of Medicine's Visible Human Project. The team applied a multistep process to the original geometry to create a generalized geometry representing a 50th-percentile male, while preserving all the essential force-bearing functional anatomical details for accurate load transfer and injury analysis. Using lumbar spine as an example (Fig. 18), the geometry was obtained from the reconstructed whole-body geometry, a finite element mesh was generated, preserving anatomical details of the vertebral body, and all the functional ligaments were simulated using spring elements, as demonstrated in the medical illustration in the figure.

APL has conducted extensive experimental research to hierarchically validate the computational human models for warfighter injury prediction. Again, using lumbar spine as an example, the team conducted high-rate material-properties testing of spine tissues using the modified split Hopkinson pressure bar to quantify bulk and shear moduli under UBB relevant loading rates, as input for the models (Fig. 19a). The team also conducted component vertebral body crush tests to obtain structural force-displacement relationships and vertebral body strength under high-rate compression (Fig. 19b).

Figure 17. Seated WIAMan ATD on VALTS.

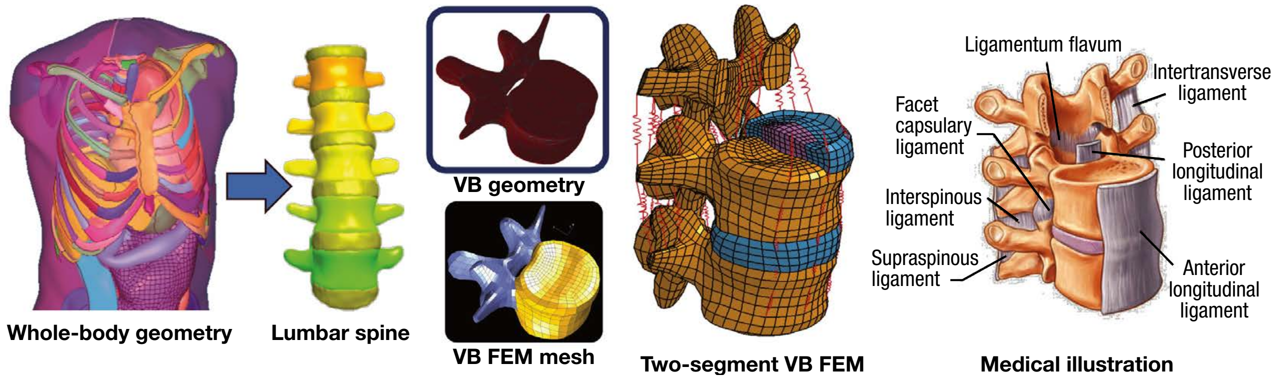

Figure 18. Illustration of model generation from the reconstructed geometry of the human body into FEM representing all the functional anatomy of a lumbar spine segment. VB, vertebra.

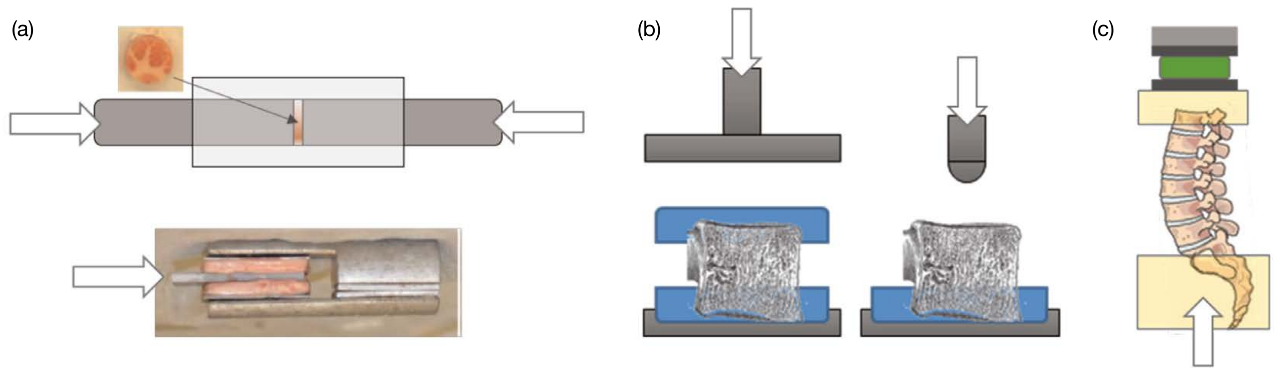

Figure 19. (a) High-rate tissue-level material testing was conducted to provide bulk and shear moduli. (b) Component vertebral body crush testing was conducted to obtain structural force-displacement behavior. (c) Subsystem level testing was conducted to ensure accurate representation of lumbar spine lordosis and force/moment transmission.

And, finally, researchers carried out subsystem testing of whole lumbar spine segments to ensure accurate representation of the lumbar spine lordosis and force/moment transmission across the lumbar spine subsystem (Fig. 19c).

Finally, each validated subsystem model, including head/neck, thorax, lumbar, pelvis, and lower extremity, was integrated into the APL whole-body human model (Fig. 20, a and b) and verified against full-body exposure at a variety of postures to ensure proper transmission of the UBB loading from each body segment.

Stress-strain responses and force/moment transmission along the internal skeletal system (Fig. 20c) from these computational models enable researchers to determine mechanical responses at any location within the human body and to do so with a level of biofidelity and detail that is not achievable with physical experiments and surrogate systems. These models can be used to reveal the injury-producing process and the key biomechanical parameters involved. These capabilities are critical in assessing the risk of injury to warfighters under various exposure scenarios. These UBB computational human models can also be used as a design

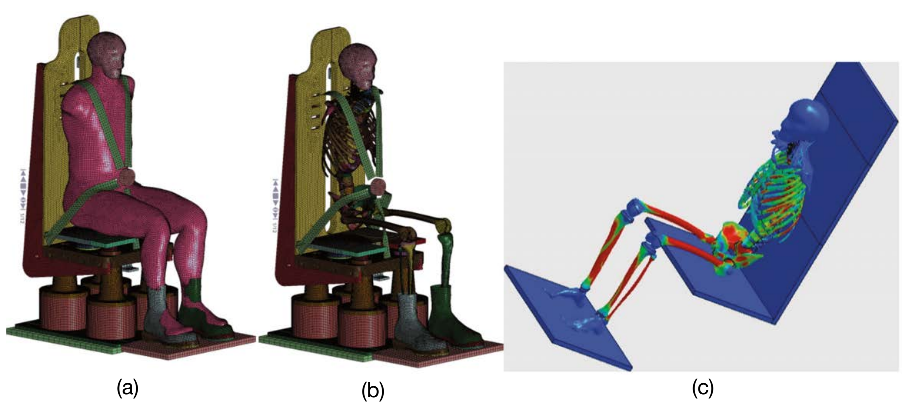

Figure 20. APL whole-body computational model situated in the VALTS system showing (a) the underlying skeleton and (b) the stress distribution across the skeleton (c) during a simulated UBB loading.

tool to optimize design parameters and short-circuit the development/testing cycles of mitigation systems for improved UBB protection.

LOOKING FORWARD

To better protect our warfighters while simultaneously lightening their loads, we must develop armor materials with equivalent ballistic protection but lower areal density. Incremental advances in armor materials are not likely to keep pace with evolving threats, so APL is researching novel classes of materials, structures, and manufacturing approaches.[33,34] The next several years will reveal the true potential of these new materials and will hopefully enable realization of new classes of armor and advancements in PPE.

Although advanced materials could lighten armor, they may increase BFD. The higher-energy rounds used in modern-day warfare require that greater kinetic energy be dissipated at a much faster rate.[35] Energy that is not dissipated by deformation of the armor or fragmentation of the round is transferred to the underlying structure—the warfighter. Significant BFD could trigger a variety of new and less-understood injury mechanisms. Understanding these trade-offs and their implications on warfighter protection and safety is critical when designing next-generation PPE.

The methods, surrogates, and models developed at APL will be invaluable for assessing trade-offs and for gaining insight into evolving injury mechanisms. With these tools, researchers can recreate battlefield-relevant loading conditions in the laboratory and investigate the associated effects on the human body. By using these specialized techniques and devices, researchers are able to make critical observations, characterize wave propagation information, collect biomechanics data, and evaluate armor performance. With this information, researchers can begin to build a comprehensive understanding of how injuries are caused and, importantly, how they can be prevented on the battlefield through the use of improved PPE.

ACKNOWLEDGMENTS: This material is based on work supported by the following organizations: the Office of Naval Research (Contract W911QY-12-C-0008); the U.S. Army Contracting Command-Aberdeen Proving Ground, Natick Contracting Division (Contract W911QY-15-C-0039); the Naval Sea Systems Command (Contract N00024-13-D-6400, Task Orders VKW01 and VKW02); the U.S. Army Research Laboratory (Naval Sea Systems Command Contract N00024-13-D-6400, Task Order VKP01); the U.S. Army Medical Research and Materiel Command Office of Research Protections (Grant W81XWH-09-2-0168); and APL (independent research and development funding).

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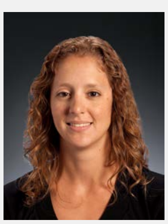

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