A Warrior Health Avatar for Model Based Evaluation of Personal Protective Armor against Blast and Blunt Impact Threats

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Abstract. In combat operations and training, military personnel may be exposed to blast waves generated by explosive devices and by heavy weapon systems such as recoilless weapons. Conventional military personal protective armor (PPA), including helmets and ceramic vest inserts, is typically designed to protect against high energy ballistic impacts. For ergonomic reasons, such armor protects against most sensitive organs (head/brain and the heart). However, blast waves and the debris load the whole body, of which only part is protected by soft armor. There is a need for user-friendly software tools for model-based design and evaluation of personalized PPA. This paper presents a novel concept of a Warrior Health Avatar (WHA) for computational model and wearable sensors-based evaluation and optimization of the PPA used in combat and military training. The WHA framework includes a fast-running blast dynamics model, subject-specific human body anatomy and PPA, biodynamics and biomechanics tools. The WHA generator, validated against the military population ANSUR II database, accounts for the anthropometric and postural variations, weapons and PPA. The fast-running tools can simulate blast and debris loads on the entire human body partially protected by the PPA as well as on blast injury vulnerable organs (head, face, ears, lung, and groin). Reduced-order models are used to simulate the dynamics of pressure load absorption and transmission through the soft and hard armor to the human body. The paper will present example simulations of IED blast loads on a human subject and several examples of blast loads on military personnel in training with heavy weapons, including recoilless shoulder-mounted rifles, mortar, and snipers. Parametric studies can be conducted to analyze and optimize military training protocols. Predicted blast loading on specific organs, brain, in particular, can be used to calculate injury criteria.

1. INTRODUCTION

Blast events accounted for nearly 70% of injuries in wounded U.S. Service members in Iraq and Afghanistan [1-3] with the blast-induced traumatic brain injury (TBI) becoming the “signature” wound inflicted by improvised explosive devices (IEDs). Although moderate and severe TBI can be easily identified and aggressively treated, concussions and mild TBIs (mTBIs) with no other visible wounds have been often overlooked [4]. While most combat-related mTBI cases are expected to recover, persistent symptoms after TBI, such as chronic dizziness, fatigue, headaches and delayed recall of memory, are common [5]. Significantly, these symptoms have been more frequently observed in Servicemembers exposed to multiple low-level blast (LLB) exposures. Moreover, it has been recently observed that military personnel involved in training with explosives such as breachers and gunners could also experience neurological conditions, mainly due to repeated exposures [7-9].

Over the last few decades, the U.S. Department of Defense (DoD) has committed substantial resources in researching ballistic and blast trauma to improve combat casualty care and personal protective equipment (PPE) [6]. The resulting improvements in the PPE and trauma care have mitigated or reduced potential blast and ballistic injury to the thorax, including lung and abdomen. However, vulnerability to face, ear, brain, groin and extremity injury still remain. Protection against blast wave TBI is particularly challenging because, despite the protective helmet, a significant part of the soldier's head and neck is still exposed to the blast. Moreover, because the blast waves traverse the entire human body, the design of an effective PPE for the warfighter should include the entire body. At the same time, any additional or reinforced PPE to be carried by a warfighter in combat conditions has to be balanced against limitations in the warfighter mobility, situational awareness, and physiological stress, including thermal loads and fatigue.

Emerging evidence suggests that Service members exposed to repetitive blast exposure from breaching and heavy weapon firing, even during training, may be susceptible to short-term neurocognitive deficits [9,10]. There is a great need for better understanding and quantification of

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potential injury mechanisms from repeated exposure to blast generating weapons such as artillery, mortar, recoilless rifles, sniper rifles, machine guns, heavy weapons, explosive breaching and others. In December 2017, U.S. President Donald Trump signed into law the 2018 National Defense Authorization Act, which obligated the Secretary of Defense to conduct "Longitudinal Medical Study on Blast Pressure Exposure of Members of the Armed Forces" [11]. These studies, referred to as SEC. 734, include monitoring of blast pressure exposure (Dose) and medical symptoms (Response) of Servicemembers in training. The ongoing longitudinal medical studies, focusing on the Response components, cannot provide complete answers without the precise estimation of the blast Dose. At the recent DoD scientific meeting, it was concluded that complementary experimental and computational studies should be conducted to correlate the Dose-Response effects [12]. It was also concluded that computational models of repeated low-level blast exposure are urgently needed to develop protective protocols guiding the ongoing field tests.

Mathematical models of the blast wave - human body interaction could be used for more accurate calculations and model-based interpretation of the wearable blast pressure sensor data. Both high-fidelity CFD models and calibrated fast-running models of an explosive and muzzle generated blast waves are needed to compute pressure loads on the Servicemembers exposed to the blast. The fast-running models could be used for instruction during training and can aid in rapid, real-time, calculation, collection and storage of person-specific blast loads - the Dose. There is a need for a user-friendly simulation framework for model-based development of personalized protective armor for combat and military training applications.

This paper presents a novel concept of a Warrior Health Avatar (WHA), a virtual human body for computational simulations of blast exposure events, calculation of blast loads on the entire body, evaluation of protective equipment and for development of safer military combat and training operations. The WHA framework includes a fast-running blast dynamics model, subject-specific human body anatomy, the capability to set up the human body posture, outfit the body with wearable sensors, the protective armor and weapons, immersing the body in the blast scene and graphical visualization of predicted blast loads on the body. CoBi-Blast tools are used to conduct blast loading simulations predicting space and time-resolved blast loads on the body and blast injury sensitive organs, human body biodynamics and injury biomechanics [13-17].

2. METHODS

2.1 CoBi Software Suite

CoBi is an DoD open source multiscale multiphysics C++ software tool that was developed by CFD Research. This paper presents CoBi-HBMG (***H***uman ***B***ody ***M***odel ***G***enerator) and CoBi-Blast, a blast dose estimation module of the framework. The key components of the CoBi-HBMG include: anthropometrically accurate setup of warfighter skin model, addition of clothing and protection equipment, and adjustment of posture and position. The key components of the CoBi-Blast module include: characterization of weapon specific blast signature, visual setup for the generation of a warfighter body and the blast exposure scene, and a fast running solver for calculation of blast loads on the entire human body and on injury sensitive organs (face, head, thorax, ears, eyes, neck, groin and others). CoBi-FEM, as the name indicates, is a finite element module in the CoBi framework and is used for a wide-variety of multiscale multiphysics problems.

2.2 Blast Exposure Simulation Framework

Comprehensive computational analysis of human body blast injury involves three major components: 1) generation of a virtual blast scene involving the explosive charge with one or several humans, 2) simulation of blast wave interaction with the human body, and 3) simulation of the injury biomechanics to blast sensitive organs such as the brain and lungs. Figure 1 schematically presents the overall architecture and main components of the CoBi-Blast tools used in this study.

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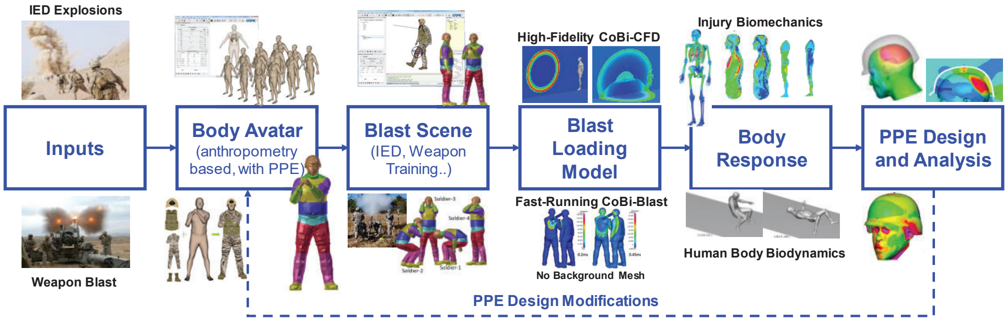

Figure 1. A computational framework for modeling blast exposure and injury in combat and military trading scenarios

The central element of the framework is the parametric anatomical model of a human body, here referred to as the Warrior Avatar, which can be personalized based on subject-specific anthropometric characteristics, outfitted with the protective equipment, articulated and placed in a virtual blast scene. The exterior surface ("skin") and the internal anatomy geometry of the avatar are used to generate corresponding computational meshes for blast loading and injury biomechanics simulations, respectively. CoBi framework enables both high-fidelity CFD and reduced-order fast running simulations of blast dynamics, blast-body interaction and calculation of time-space resolved blast loads on the entire surface of the human body and on the body armor. The blast loading results are used as input boundary conditions for the subsequent simulation of human body biodynamics and injury biomechanics. A more detailed description of the CoBi-Blast framework, validation and military application results can be found in authors' previous publications [6,13-17].

2.3 Generation of Warrior Avatars (CoBi-HBMG)

Computational modeling of a human body injury biomechanics is typically conducted using a "standard" human body anatomy obtained from databases such as Visible Human or Zygote. These databases comprise of carefully constructed mesh models representing a 50th percentile human (e.g., skin and internal anatomy models such as Total Human Model for Safety (THUMS) or Global Human Body Models Consortium (GHBMC) model [18-20]). To simulate military Servicemembers' injury biomechanics and protection, we have developed a framework for an anthropometry-based generation of human body anatomy and calibrated the model on the U.S. Army Anthropometric Survey (ANSUR II) database of body scans of male and female Servicemembers [21-23]. This human body generator can be used to construct human avatars including internal anatomy, and body exterior such as clothing and the protective armor. Figure 2 shows the subject-specific warrior avatar generation steps. The anthropometric data (weight, height, extremity lengths, chest breadth, chest depth, and others) are used as inputs to the principal component analysis (PCA) tools to generate the subject-specific or population of skin models and anatomical geometry of major internal organs (skeleton, brain, lungs, intestine, muscles adipose and others). The human body skin is then used to generate the warrior avatar by incorporating combat clothing and armor and articulating the body to the desired posture. The model setup step is the generation of the blast scene involving one or several avatars and placing the IED charge or the blast generating heavy weapon, e.g., standing gunner team with shoulder mounted recoilless rifle as shown in Figure 2.

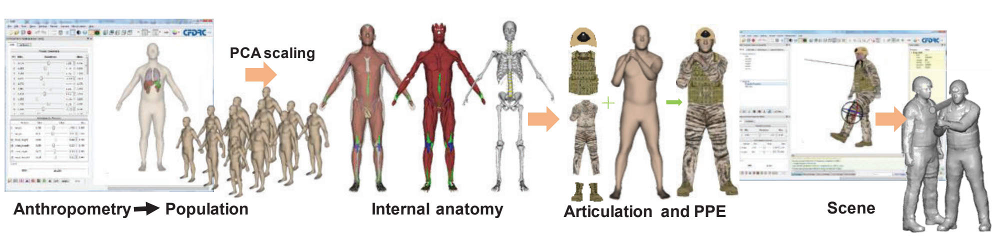

Figure 2. Generation of the warrior avatar and the blast exposure in military trading scene

2.4 Models of Blast Exposure and Injury Biomechanics

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Computational modeling of the blast exposure event can be conducted by using either the high-fidelity CFD type software [13-15] or reduced order fast running models [16]. CFD models are more accurate but require a 3D volume computational mesh for the entire blast scene with fine mesh to accurately resolve the propagating blast wave. In our high-fidelity blast exposure studies, we used CoBi multiscale tools and the adaptive Cartesian mesh with mesh refinement around the human body. In contrast, CoBi-Blast fast-running tools use analytical models to simulate the blast wave dynamics and require only the surface mesh of human body avatars or any of the surrounding shock wave reflecting surfaces. The second approach can be used for parametric simulations of blast exposure and for an "inverse problem" reconstruction of blast loads on the entire warfighter body using data from wearable pressure sensors [16].

In the milliseconds long period of the blast wave interaction with the human body, we assume the body as the rigid object with appropriate wave reflection properties on the body's surface. The recorded pressure traces on the human body surface are then used as loading conditions for subsequent simulations (sequential approach) of injury biomechanics. The individual segmented skin regions (triangulated meshes) are used to record and store the spatiotemporally varying loading conditions associated with corresponding organ models. For the biomechanics simulations, we have used the multiphysics code CoBi-FEM (finite element module in CoBi). The anatomy geometry was used to generate hexahedral mesh using an in-house meshing tool. The different material models used to describe the different body regions can be obtained from the literature [14]. An explicit FE solver was used with a reduced integration brick element and a judicious choice of hourglass coefficients. This mesh element description reduces the computational cost, increases the stability, and minimizes the artificial stiffening.

Overall, the above approach leads to a well-defined sequential multiscale modeling framework, for analyzing the effects of PPE under LLB exposures, where multiple length (from meters for a blast scene, to cm for the brain, to µm for neurons and axons, to nm for axonal cytoskeleton and neuronal synapses) and time scales (from µsec for blast-wave transition over the head, to msec for brain biomechanical responses, to min/hr/days for secondary injury and repair cascade) can be accommodated [17].

The next section presents some of our previous results on human body IED blast exposure; and our new simulations demonstrating the effects of armor and body posture on blast exposure during military training with heavy weapons (using CoBi-Blast fast running tools).

3. RESULTS

3.1 Simulation of IED blast loads on a human body

In our blast exposure simulation protocols, we first use CoBi high-fidelity CFD simulations for detailed human body blast load analysis and assessment of the accuracy of the reduced order fast running simulations using CoBi-Blast. CoBi tools have been validated on range of experimental test cases of free field blast exposure of a human surrogate and exposure of human head physical surrogates in shock tubes [13, 14, 27-29]. Figure 3 shows simulation results for a case of a human body frontal exposure to an experimental explosion of 5lb C4 located at 233 cm away from the human body and 127 cm above the ground. For computational efficiency, a high resolution 1D spherical detonation and blast wave dynamics CFD model results, Figure 3a, were used to establish initial conditions (at t=0.45 ms after the explosion) for the 3D model of blast wave interaction with standing human body, Figure 3b-d. The recorded blast loads on the entire human body were then used as a dynamic pressure boundary conditions for modeling pressure wave propagation inside the body. Figure 3e shows a time sequence of pressure loads on the skin as the wave propagates. Note that the simulation starts at t=0 ms at the instance when the blast wave touches the thorax. The same pressure loading conditions can also be used for modeling human body biodynamics of translocation in air and impact on the ground [17, 37]. As presented below, the human body model can be enhanced by including the body armor, and by adjusting body posture and the orientation relative to the explosive location.

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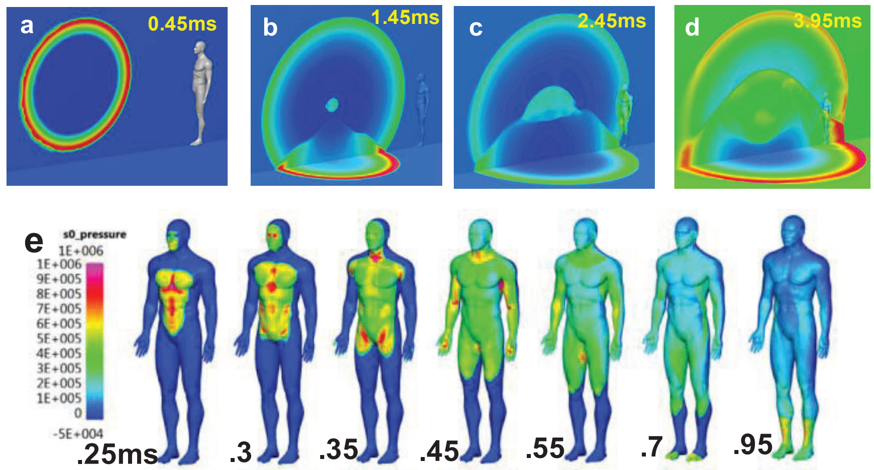

Figure 3. a-d): CFD simulations of a propagating blast wave after explosion above the ground and blast wave interaction with a human body; e): FEM simulation of pressure wave transmission through the human body.

3.2 Simulation of brain injury biomechanics

Protection against blast-induced traumatic brain injury is the most pacing challenge in the ongoing military medical resketch. Computational models of brain injury biomechanics have been used to analyze potential injury mechanisms and to analyze the role of protective head gear including the helmet, eye wear and the hearing protection devices. Figure 4 shows more detailed simulations of the human head and brain response to the blast wave exposure described above. Detailed head anatomy, including skin/scalp, cranium, cerebrospinal fluid (CSF) and brain is simulated. Figure 4a shows three-time instances of the pressure fields in the head central sagittal plane. Figure 4b shows the pressure time traces at three locations in the brain mid-plane (fm-front, mm-middle, and rm rear). Note that the first pressure pulse at the rear of the brain (contrecoup effect) is higher that the initial pressure pulse in the front (coup effect). Figure 4c shows the maximum strain and maximum stain rate in the transverse mid plane of the head. As often reported in the preclinical and human imaging data, our simulations show that most susceptible regions for the brain injury are located in the brain cortical layers, sulci and gyri and the brain-CSF interface.

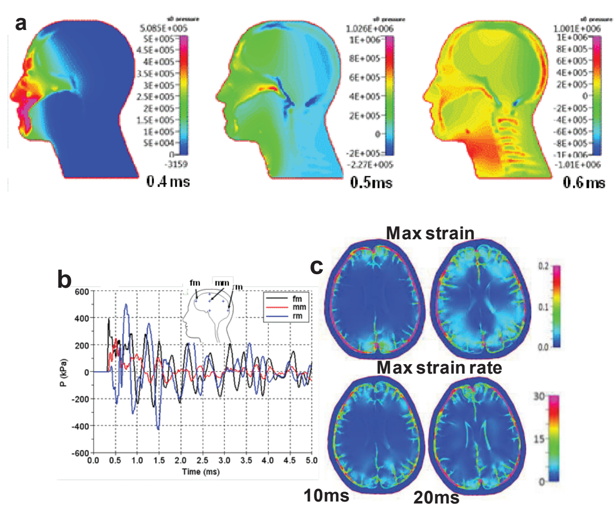

Figure 4. FEM simulations of head/brain biomechanics: CFD simulations of a propagating blast wave after explosion above the ground and blast wave interaction with a human body; e): FEM simulation of pressure wave transmission through the human body.

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3.2 Computational Evaluation of the Head PPE in Blast Exposures

The CoBi framework has been used for evaluation of military PPE against blast injury, including: combat helmets, protective chest vests, helmet retention system, helmet suspension pads, combat boots, protective eye wear and hearing protection devices [29-32]. It is difficult to design PPE against highly variable IED blast exposures but much more feasible against blast exposures during military training. Computational analysis of the protection effectiveness of military helmets against the primary blast wave can be conducted using the sequential process presented above. The CFD blast wave loading on the entire helmeted head, Figure 5a, is used for modeling the dynamic response of the helmet shell, the suspension pads and the skull scalp. Simulations have been performed with and without the suspension foam pads. Figure 5b shows three instances of a frontal blast wave propagating over the helmet and between the helmet-head space, the effect known as the "under-wash". The under-wash wave can reflect from the posterior section of the inner helmet wall (Figure 5b, time t_3) and may impact the head as a much stronger wave than the primary incident wave. Proper design and distribution of the helmet pads can significantly attenuate the under-wash effect. The military helmet can also affect pressure loads on the unprotected parts of the face. Figure 5c presents the reflected pressure fields on the human eyes below the helmet rim, in the nose plane, and in the ear lobe space. The well-known extended helmet standoff distance around the ear lobes is partly responsible for reflecting the frontal incident blast wave from the inner helmet shell into the ear lobe and ear canal, Figure 5c.

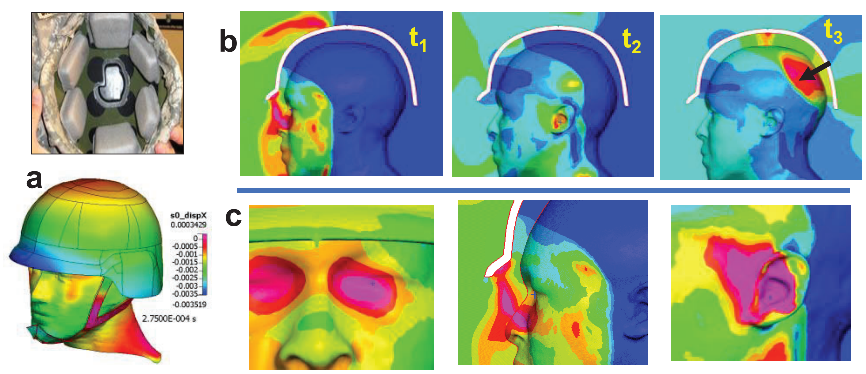

Figure 5. Simulations of a frontal blast wave interaction with a helmeted head, a) military helmet pads and a helmeted human head model; b) blast wave propagation around the helmet without pads, c) pressure loads around the eyes, nose and the ear.

3.3 Simulation of Blast Exposure in Military Training

Here, CoBi-Blast tools are used to demonstrate and validate the applicability of reduced order fast-running blast analysis tools in simulating the blast loads during IED explosions and military training of heavy weapon systems. Furthermore, CoBi-HBMG tools were leveraged for a rapid and realistic reconstruction of training scenes from field images. Figure 6a shows some of the field scenes that are reconstructed from heavy weapon training scenarios. In addition, it also shows the simulation results for back-blast exposure from Carl Gustav weapon system. Free-field sensor data was used to calibrate (i.e., estimate the equivalent blast kernel properties such charge mass and location using CoBi-Blast inverse solver tools) and validate the model. Figure 6b shows some of the initial validation of the model predictions in comparison to the field data [24]. For free-field sensors 1 and 2, the simulation predictions match well with the experimental data. For sensor 3, there are some difference in the second blast peak (due to ground reflection). This could be due to the ground reflection properties (surface type). The back-blast simulations using the CoBi-Blast tools were completed in ~10 mins. on a PC.

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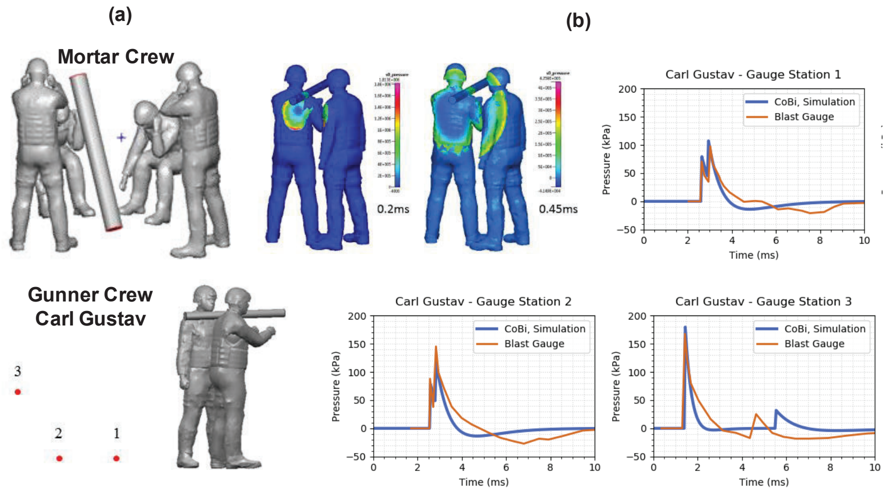

Figure 6. a) Heavy weapon training scenes reconstructed using CoBi human body model generator tools. (b) Simulation of weapon induced blast exposure using CoBi-Blast fast-running tools; and preliminary validation of the Carl Gustav back-blast training scenario.

4. DISCUSSION AND CONCLUSIONS

Recent retrospective studies of injury patterns of U.S. military personnel in combat and military heavy weapons training have considerably contributed to the awareness of the blast injury [1,2, 7-9]. Concurrently, computational studies of human body exposure to blast waves, corresponding body biodynamic and biomechanical responses helped us better understand the blast injury mechanisms of the brain, lungs, spine, and other organs [13, 14, 16,17, 25-32, 33-36]. The major limitation of these and other published studies was the use of a standard size of the human body, typically 50 percental male, represented as a "bare skin" surface geometry. In this paper, we introduce a novel concept of a Warrior Avatar, a virtual scalable human body for computational simulations of blast exposure, injury biomechanics and evaluation of protective equipment. In our CoBi Warrior Avatar framework, the male or female virtual anatomical body, with both the skin and main components of internal anatomy, is generated using subject-specific anthropometric measurements. The body skin model can be also be generated directly by fusing the subject specific skin scan and the facial de-identification step. To conduct the blast wave exposure simulations, the avatar skin model is outfitted with a military combat uniform, personal protective armor, weapons and is articulated to the desired position. We envision that ultimately every Servicemember will have his/her own Avatar, comprising not only the anatomical but also physiological and fitness models. A Servicemember equipped with mobile computing platform and set of wearable sensors could activate the data collection stream during specific events, e.g., weapon training. Such data could then be used for longitudinal monotasking of his/her blast exposures.

At present, it is not possible to quantify blast loading to the warfighter body exposed to an IED blast due to lack of precise forensic data such as body position and orientation relative to the IED and the effects for the surrounding structures. Even if the wearable pressure sensor data were available, it is difficult to reconstruct the blast loads to specific organs. As demonstrated in this paper, computational tools developed by our team can make this task easier. It is certainly possible to reconstruct blast loads on the whole body of a warfighter involved in military heavy weapons training using a photograph of the blast scene, avatars of Servicemembers involved in the blast scene, wearable pressure sensors data and, as described above, the weapon blast signature model [16]. This paper described and demonstrated two modeling approaches for the dynamic reconstruction of the blast exposure scene and calculations of blast loads on the exposed warfighters' bodies: high fidelity 3D CFD models and reduced order fast running models. Each approach has advantages and limitations related to accuracy and computational costs. The main advantages of fast running models are the ease of model setup (no 3D computational mesh needed), the use of the inverse solver problem to reconstruct the whole human body blast loads directly from wearable pressure sensors and the ability to conduct large number of parametric simulations to evaluate the effectiveness of the protective armor and safety protocols.

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Because of the high variability of IED weapons, detonation scenes and corresponding Servicemembers' positions, the design of the personal protective armor is very challenging. This paper has demonstrated that the conventional combat helmets do not protect the exposed part of the head and may even amplify loads to parts of the head, such as eyes and ears. Such injuries can be significantly attenuated by wearing eye ware or helmet integrated visors. Protection of Servicemembers for blast injury during heavy weapons training is much more feasible and is currently under development and evaluation in the U.S. Various protection methods are being explored including hard and soft body armor, improved head, neck and chest protection, use of lower power weapons rounds for training, optimized body postures and other safety protocols.

This study demonstrated the capability to compute the blast loads on a warfighter body from IEDs and during weapons training but also identified needs for future developments. There is a need for more precise specification of blast "dose" parameters on specific organs, in a mechanistic model for calculation of the cumulative "dose" from repeated exposures, for longitudinal monitoring of warfighter post-exposure physiological and cognitive "responses." Such a holistic approach for model-based personalized "dose-response" analysis, currently pursued in the U.S., will have immense benefits in warfighter safety and health.

Disclaimer

The opinions and assertions contained herein are the private views of the author/s and are not to be construed as official or reflecting the views of the Department of the Army or the Department of Defense

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