A Framework for Multiscale Modeling of Warfighter Blast Injury Protection

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Abstract

Improvised explosive devices (IED) have become the predominant weapon used in recent military conflicts against the coalition forces and in terror acts against civilian populations. IED technology and deployment methods have increased in complexity, and so have the resultant injuries, which require an increase in the sophistication of protection countermeasures and efficacy of medical interventions. Computational injury biomechanics, complemented with model-guided experimental testing can provide valuable support, not only in better understanding of blast injury mechanics, but also in the development of personnel protective armor, injury diagnostics, combat casualty care, and rehabilitation. Contemporary models of injury biomechanics typically focus on a specific loading mechanism and injury type to a single organ (e.g., bone, brain, or lung). IED injuries, however, typically result in polytrauma caused not only by the primary blast wave but also by associated penetrating injures caused by the debris and ejecta from buried IEDs. Computational modeling of blast wave injury poses significant challenges as it involves several physical disciplines such as blast wave gas dynamics, human body biodynamics, injury biomechanics, and trauma pathophysiology as well as a range of spatial and temporal scales. US DoD, in collaboration with academia and industry, is developing computational models and tools for various injury types caused by IEDs. Research projects are exploring experimental and computational tools dedicated to blast wave-induced traumatic brain injury, lung injury, hearing loss, extremity injury, and soldier protection. This paper presents a novel concept and prototype implementation of a multiscale, multiresolution computational framework for modeling human body injury caused by IED blast wave and fragmentation/debris loads. The overall architecture of the framework, major components, and example simulation results of blast injury mechanisms are discussed.

Keywords: Blast Waves, Brain Injury, Military Medicine, Injury Biomechanics, Multiscale Models

Introduction

Improvised explosive devices (IED) have become the predominant weapon in recent military conflicts. IEDs proved to be particularly effective against softer military targets, such as Humvees, trucks and foot patrols. Blast events accounted for nearly 70% of injuries in wounded Service Members in both Iraq and Afghanistan, and are the main cause of traumatic brain injury (TBI) (Eskridge et al., 2012, Heltemes et al., 2012). IEDs have caused even more devastating casualties among civilian populations exposed to terrorist bombing events. Over the last decade, IEDs have evolved to be a formidable threat not only to dismounted soldiers but also to armored vehicles. Buried IEDs are particularly lethal as they not only launch the blast wave toward the target but also projectiles and soil ejecta. Such IEDs typically result in polytrauma involving non-penetrating injuries caused by the primary blast wave, penetrating injures and amputations caused by the debris and ejecta, and behind armor trauma in areas protected by the personal protective equipment (PPE).

Compared to impact-related injury, the mechanisms involved in blast injury are much less understood. Recent improvements in PPE have reduced the severity of thoracic and brain ballistic injuries, but other sensitive organs, such as the brain, eye, ear, groin, genitals, and extremities, remain vulnerable to blast injuries [Curley et al., 2011]. Protection against blast wave TBI is particularly challenging because, in spite of the protective helmet, a significant part of the soldier's head is still exposed to the blast. Until recently, it was not clear how a blast wave penetrates the cranium and causes brain injury and if military helmets protect against it [Zhang et al., 2011, Przekwas et al., 2011, Gupta and Przekwas 2013].

A better understanding of blast wave injury mechanisms can be achieved with a complementary experimental and computational modeling approach. However, computational modeling of blast wave injury poses significant challenges as it involves several physical disciplines, such as blast wave gas dynamics, human body biodynamics, injury biomechanics and trauma pathophysiology, as well as a range of spatial and temporal scales. US Department of Defense (DoD) in collaboration with academia and industry, is developing computational models and tools for various injury types caused by IEDs. This paper presents a novel multiscale computational framework for modeling human body injury caused by IED blast wave and fragmentation/debris loads. Our goal is to design a software tool for modeling IED blast threats and resultant human injuries and to assess biomechanical injury criteria and injury severity scores from injury biomechanics simulation results.

Computational Framework for Multiscale Modeling of Blast Injury

Design of a simulation framework for multiscale modeling of blast injuries involves not only mathematical modeling and numerical algorithms, but also technical specifications for software user scenarios and data analysis. The target applications include: prediction of injury mechanisms, development of improved PPE, evaluation of injury severity, and trauma care. Figure 1 presents the overall architecture of the designed simulation framework. The framework is built around existing CoBi tools [Gupta and Przekwas, 2013].

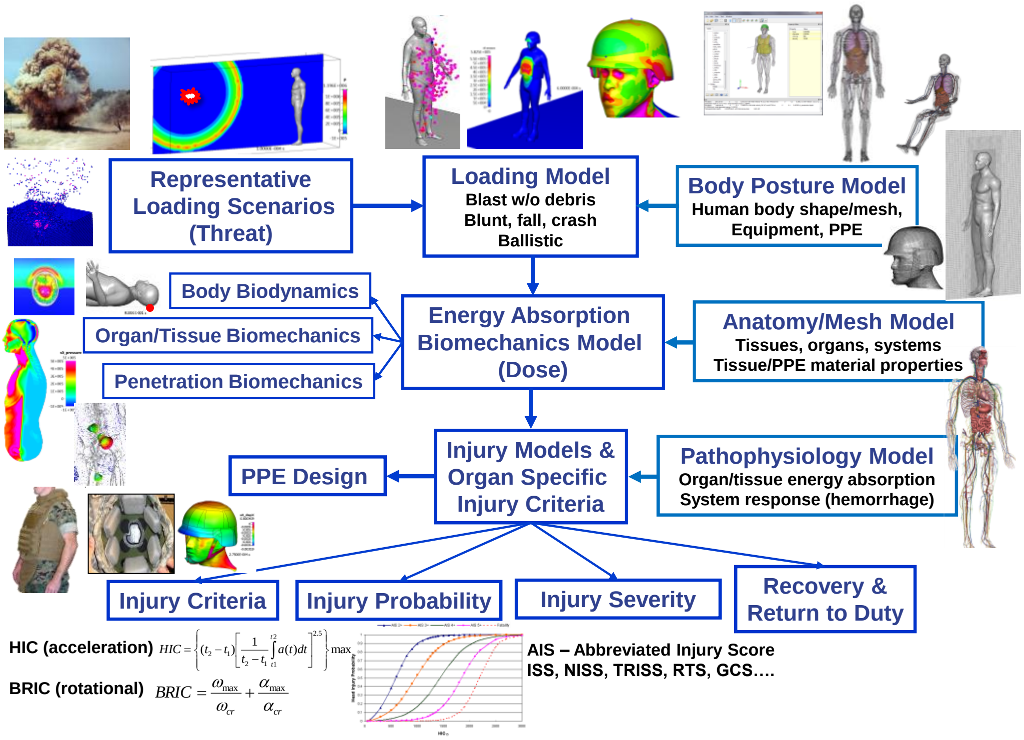

Figure 1. Schematic representation of the computational framework for multiscale modeling of blast wave soldier injury mechanisms, severity, and protection.

The Threat module (top left, Figure 1) selects representative threat scenarios with an IED located above, on or under the ground, and specifies the type and the volume of the explosive charge. A set of test cases is being collected, including problems from benchmark experimental tests and from

IED threats seen in real combat and terrorist explosion events. The Body Posture module (top right, Figure 1) positions anatomical geometry models of the human body in the field of threat. The user can setup both high-fidelity and reduced order human body models with injury susceptible organs, including skin, bones, joints, spine, muscles, brain, lungs, liver, spleen, kidneys, vasculature, and lower extremities. The soldier can be equipped with protective armor (e.g., helmet, vest, boots, soft armor, backpack). An adaptive octree mesh is automatically generated with mesh refinements close to the IED and the human body. The Loading module (top center, Figure 1) computes blast wave pressure and blast wind loads on the entire human body surface, as well as impact loading from IED projectiles and ejecta. The time-dependent loading forces on the human body are used as boundary conditions by the Energy Absorption Biomechanics module, which computes three types of biomechanical responses: whole body biodynamics, biomechanics of internal organs and tissues, and penetration mechanics of fragmentation and debris. The Injury module uses the organ/tissue biomechanics results to simulate two aspects of the injury: primary injury caused by tissue mechanical damage followed by secondary physiological and biological mechanisms. The injury results could be used to calculate injury criteria and injury severity scores. The following sections briefly describe the computational methods, present example results, and identify outstanding challenges.

Human Body Anatomical Geometry and Computational Mesh

The anatomical geometry of a human body was used to generate computational meshes of the outside and inside of the body for blast and biomechanics simulations. Anatomical models can be generated using whole body imaging data (e.g., "Visible Human") [Spitzer, 2006, Segars et al., 2010]. To simulate blast wave dynamics and its interaction with the body we used an adaptive octree mesh refined around the human body surface. The mesh extends throughout the entire blast scene, including the IED and the human body. Figure 2 presents an example octree mesh for modeling blast wave physics using Computational Fluid Dynamics (CFD) tools. Human anatomical geometry was also used to construct the articulated body model for modeling body biodynamics and a computational mesh within the body to simulate organ/tissue biomechanics. Several anatomical geometric models have been developed to study human body/head impact injury biomechanics [Yasuki, 2011, Gayzik et al., 2011, Tan et al., 2011].

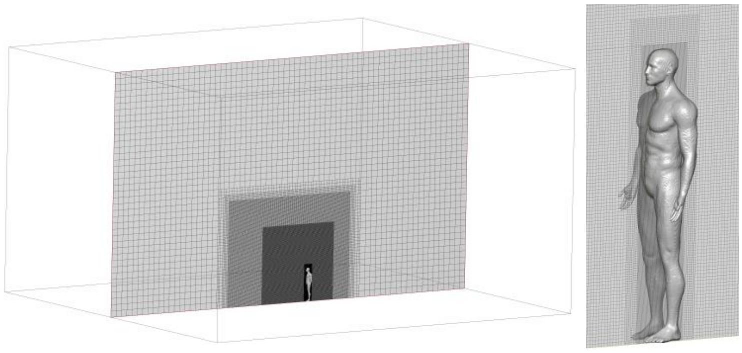

Figure 2. Zonal adaptive octree grid for CFD simulations of blast wave impact on a human body.

Computational Models of Blast Wave and Human Body Blast Loading

A computational model of an IED explosion is often considered as a hallmark multiscale multiphysics problem as it involves four distinct elements: 1) the physics of charge detonation and energy release, 2) the detonation front interaction with soil mechanics and the generation of debris, 3) the gas dynamics of the blast wave, and 4) the blast wave interaction with the human body. We have employed the coupled Eulerian-Lagrangian approach for the interaction between the high explosive detonation products, fragments and soil. A discrete element/particle method (DEM) was used to model the casing fragments and soil through contact and collisions of rigid spherical particles, in addition to the developed Eulerian-based compressible flow solver for gaseous media. This sub-millisecond event is followed by high-fidelity CFD simulations of blast wave propagation toward the human body using CoBi tools with domain decomposition and parallel distributed computing [Harrand et al., 2013]. In the simulations we assumed that the human body inertia is high enough to represent the human as a rigid body [Tan et al., 2012a, Gupta and Przekwas, 2013]. A Lagrangian ballistics model was used to simulate projectile and debris trajectories and their impact on the human body. Figure 3 presents typical simulation results of an IED detonation, debris generation and blast wave interaction with the human body for explosions on and above the ground as well as contour maps of the pressure loading on the human body surface [Tan et al., 2012a].

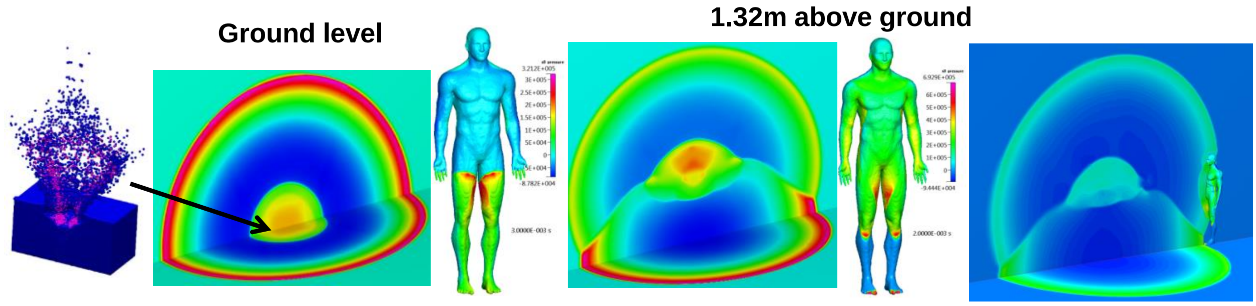

Figure 3. FEM model simulation results of a buried IED detonation, debris generation, and blast wave interaction with the human body for explosions on and above the ground.

The blast wave pressure loads and the forces generated by impacting debris on the entire human body are recorded for the duration of the blast event (10-20 milliseconds) and stored for consecutive human body biodynamics and biomechanics simulations.

Models of Human Body Biodynamics and Biomechanics

The Loading module (Figure 1) generates external forces on the human body for three types of simulations: 1) articulated human body biodynamics modeling of flexible human body translocation in air and body impact on the ground, 2) biomechanical propagation of the primary pressure and shear waves within the body organs and tissues, and 3) terminal ballistics of IED fragments and debris penetrating the human body.

The articulated human body model represents a 1.78m, 84.6kg male with the anatomy divided into 17 body segments, such as the head, neck, upper/lower torso, abdomen, and extremities, connected by flexible anatomically consistent joints. Conic joints constrain the range of joint rotation to imitate contact of the spinous processes. These joints have been defined in terms of locations and shape based on the joint rotations of an average human. To apply the blast loading accurately and efficiently, a time step increment comparable to that in the CFD simulation (10 microseconds) was used to run the multibody dynamics for a period of 6.5 milliseconds. For computational efficiency and to take advantage of the unconditional stability of the implicit multi-body solver, the simulation was restarted at the end of 6.5 milliseconds with a much larger time step of one millisecond, and ran for an additional second. Details of the body model and the Finite Element Method (FEM) biodynamic formulation and its implementation of implicit multi-body dynamics and model validation results can be found in Tan and Przekwas [2011]. Figure 4 presents typical simulation results of a human body response to a shallow buried IED showing human body postures at several time instances.

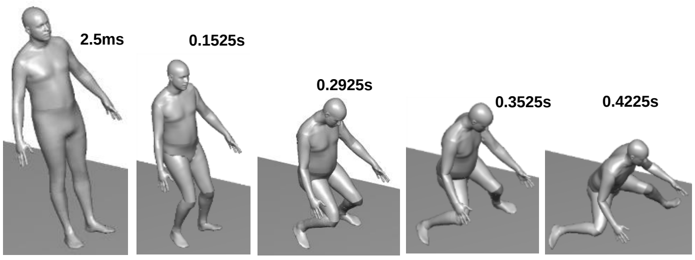

Figure 4. FEM model of articulated human body biodynamics due to blast wave and fragment loadings at different times.

Because of the large inertia of the human body, the body has not started to move yet at 2.5ms after the front impact blast on the body. The visible movement starts approximately 100ms post blast. This justifies our assumption of a rigid body during CFD blast simulations, presented in the previous section. The time required for the human body to impact the ground is on the order of one to two seconds, an order of magnitude longer than the blast loading duration. The predicted human body accelerations during free translocation and decelerations during the ground impact are used to calculate potential injury indicators, such as head injury criteria (HIC). The forces during the body impact on the ground are used as additional loads in the human injury biomechanics model.

By applying the blast loading resulting from the CFD simulation, we could model the biomechanical response of human body organs and tissues during the pressure wave propagation within the body. To simulate these human body biomechanics we used the CoBi FEM solver. Because of the time step increment constraints in the present transient simulations, an explicit time marching solution algorithm was used. Details of the biomechanics model can be found in Tan et al., [2012]. Figure 5 presents the predicted pressure fields and maximum principal strains in two sagittal planes (mid plane and mid left extremity) inside the body at four time instances during the propagation of stress waves through the body, following a free field blast impacting the body from the front.

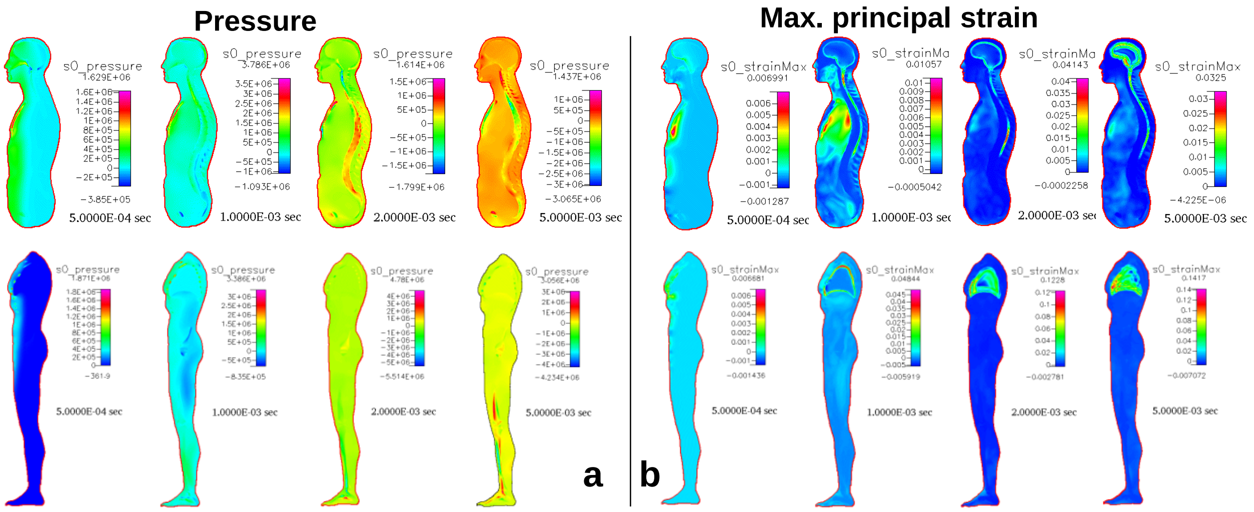

Figure 5. FEM simulation results of biomechanical stress wave propagation through the human body loaded by a blast wave from the front at four time instances after the blast impact (t=05ms, 1ms, 2ms, and 5ms): a) pressure profiles and b) maximum principal strain.

The simulations demonstrated that a stiffer material, like the skeleton, has high pressure, while the pressure in soft materials, like the lung, is much lower (Figure 5a). A relatively high level of strain appears at the interface between the brain and the skull due to the low shear resistance of the brain (Figure 5b). The maximum strain occurs in the lungs because of their softness compared to their surrounding tissue and skeleton. A detailed description and discussion of blast injury biomechanics of the whole body and of the brain has been presented by Tan et al., [2011] and Gupta and Przekwas [2013]. These macro-scale simulations provide the stress and strain fields in all organs and tissues in the body and can be used as a starting point for micro-scale analyses of injury biomechanics of selected tissue structures, such as brain axonal tracks, spinal cord injury, cochlear injury, vascular injuries.

The simulation results of macro- and micro-scale injury biomechanics could also be used to evaluate biomechanical injury criteria (IC) and injury severity scores. Injury scores (IS), such as the Abbreviated Injury Scale (AIS), were developed to classify the type and severity of injury to aid in medical diagnosis. ISs are typically declared as a single number to represent complex and varying degrees of critical illness. Despite this ambiguity, ICs are commonly used in critical medical care. This paper proposes that mathematical models may be used for more rigorous calculation of injury criteria and injury severity scores, including AIS, ISS, TRISS, and RTS, as well as injury scores for specific organs and polytrauma scores. Ultimately a fast running mathematical model of patient specific trauma trajectory may replace conventional single number ISs. The overall procedure for model-based calculation of ICs and ISs, estimation of injury severity probability, as well as prediction of trauma trajectory outcome, is shown in Figure 6.

Figure 6. A procedure to calculate ICs and ISs from computational biomechanics results.

Conclusions

This paper presented a novel concept and prototype implementation of a multiscale computational framework for modeling human body injury caused by IED blast wave and fragmentation/debris loads. The overall architecture of the framework, the major components and example simulation results of blast injury mechanisms were described. A framework has been developed with the interaction between the whole human body anatomical geometry model, the mesh generation, and the individual computational tools, including the CFD blast dynamics and FEM biomechanics. This framework provides a foundation for the development of a user-friendly framework, not only for a better understanding of blast injury mechanisms, but also for the development of personal protective armor, injury diagnostics, combat casualty care, and rehabilitation. Several challenges remain, such as better material properties for high strain rate tissue biomechanics, coupling between macro- an micro-scale tissue biomechanics, tissue damage models for the estimation of the injury location and severity (such as axonal injury and bone fracture), accurate models of penetrating injury, and model validation.

Disclaimer

The views expressed in this paper are those of the authors and may not necessarily be endorsed by the US Army or US Department of Defense.

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