JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 28 (2013) 111–124

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Research Paper

Blast effect on the lower extremities and its mitigation: A computational study

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ARTICLE INFO

Article history:
Received 7 March 2013
Received in revised form
5 July 2013
Accepted 6 July 2013
Available online 19 July 2013

Keywords:
Lower extremity injury
Bone fracture
Blast wave
Numerical modeling
Energy absorption

ABSTRACT

A series of computational studies were performed to investigate the response of the lower extremities of mounted soldiers under landmine detonation. A numerical human body model newly developed at Wayne State University was used to simulate two types of experimental studies and the model predictions were validated against test data in terms of the tibia axial force as well as bone fracture pattern. Based on the validated model, the minimum axial force causing tibia facture was found. Then a series of parametric studies was conducted to determine the critical velocity (peak velocity of the floor plate) causing tibia fracture at different upper/lower leg angles. In addition, to limit the load transmission through the vehicular floor, two types of energy absorbing materials, namely IMPAXX® foam and aluminum alloy honeycomb, were selected for floor matting. Their performances in terms of blast effect mitigation were compared using the validated numerical model, and it has been found that honeycomb is a more efficient material for blast injury prevention under the loading conditions studied.

1. Introduction

Anti-vehicular (AV) landmine and improvised explosive device (IED) explosion may cause catastrophic structural failures of military vehicles and induce injuries/fatalities of the crew. When an AV explosive charge is detonated under a vehicle, a shock wave with intensive energy is generated. It is transmitted to the vehicular floor in microseconds and then results in large acceleration and deflection of the floor plate, which in turn applies high loads to the lower extremities of the occupants to induce injury. Such lower extremity injury incurred to mounted soldiers has long-term consequences on combat readiness and wellbeing of injured veterans (NATO Report, 2007). However, its injury mechanisms and thresholds are still poorly understood. The current knowledge of the lower extremity injuries were mainly obtained from a civilian crash environment, which is very much different with the underbelly blast loading conditions. Without proper knowledge, protective devices for mitigating such injury caused by landmine and IED blast cannot be effectively designed.

To test the blast effect on the lower extremities, a number of physical leg surrogates have been developed using engineering materials (Pandelani et al., 2010a, 2010b). However, these dummy legs have limited biofidelity in high loading rate regime

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http://dx.doi.org/10.1016/j.jmbbm.2013.07.010

and they cannot be used to study the human body response once bone fracture is initiated. To eliminate such limitations, post mortem human subjects (PMHS) were used to produce military relevant bone fracture. Yoganandan et al. (1996) conducted a series of impact tests on below knee PMHS lower limbs to develop a quantitative relationship between injury and biomechanical parameters such as tibia axial force and specimen age. The impact velocities were mainly in the range of 3.4–7.6 m/s. However, these studies were representative of car crash, where the lower extremities would experience much lower accelerations or strain rate levels. Therefore, the data cannot be directly applied to the blast events. McKay and Bir (2009) performed similar tests at higher speeds up to 11.6 m/s. But according to Wang et al. (2001), the average velocity of a medium sized armored vehicle floor plate exceeded 12 m/s following an AV mine blast. Quenneville et al. (2011) tested fixed, isolated tibias by applying short duration axial impulses at the highest impact velocity of 12.4 m/s. More recently, Jin et al. (2013) carried out the impact tests with the highest velocity of approximately 20 m/s using a high speed loading system. In the aforementioned cadaveric tests, due to the limited sample size and the significant difference in the age, height and weight of the specimens, the kinematic results and injury data have relative large variations.

Considering the high cost and low repeatability of blast tests, numerical models (frequently finite element or FE models) have been increasingly used as an effective alternative for such circumstances. Nilakantan and Tabiei (2009) used a Hybrid-III crash dummy FE model to simulate the AV blast response of the occupant's lower extremity at different postures and acceleration levels. Kraft et al. (2011) built a FE model for lower leg-foot complex under the high-speed vertical loading. But the boundary conditions applied were not consistent with the actual constraints since the knee and upper leg were not modeled. Also the model was constructed with tetrahedral elements, which might increase the material stiffness, particularly when deformation is large. Suresh et al. (2012) improved a previously developed Wayne State University human model (WSUHM) to simulate the influence of leg posture on the force and bending moment of the leg under vertical impulsive loading. However, this model was not validated against experimental data.

In the present study, the Suresh model (Suresh et al., 2012) was further improved to simulate two series of experimental studies (McKay and Bir, 2009; Jin et al., 2013) and the model predictions were validated against test data in terms of force-time histories in the tibia as well as the bone fracture pattern. Based on the validated model, the tibia axial force causing fracture was found. Then parametric studies were conducted using the validated model to determine the critical velocity (peak velocity of the floor plate) causing tibia fracture at different upper/lower leg angles. In addition, to limit the load transmission through the vehicular floor, two types of energy absorbing materials, namely IMPAXX® foam and aluminum alloy honeycomb, were selected for studying the effect of protective structures. Their respective material models were implemented into a plate FE model, which was integrated with the validated WSUHM model, to be described in Section 2. Performances of these two classes of energy absorbing material in terms of lower extremity injury prevention were compared.

2. The Wayne State University Human Model (WSUHM)

2.1. Geometric modeling

A previously developed and validated numerical human model (Wayne State University Human Model, or WSUHM) (Belwadi et al., 2012) served as the basis for simulating blast-loading responses. WSUHM represents the size of a 50th percentile male but it was calibrated for automotive related impacts. Recently, this model was modified to study the in-vehicle lower extremity response due to simulated blast (Suresh et al., 2012). The new model consists of 3,54,603 hexahedral elements with an average mesh size of 3 mm on the legs and feet, which is sufficiently fine to ensure the computational stability under the high strain rate and large deformation conditions. The mesh sensitivity was checked for minimum mesh size of 2 mm. A 33% decrease in the average mesh size had no evident effect on the tibia response indicating that the model is considered converge. Due to the need for conducting a number of parametric studies, no finer mesh was studied. This leg/foot complex can be used to simulate seated or standing soldiers with different postures. Fig. 1 shows the modified WSUHM with close-up views of the knee and foot details. In the present study, the entire model was built with Hypermesh 10.0 (Altair Co. Troy, MI) and ANSYS ICEM 12.1 (ANSYS, Pittsburgh, PA). All simulations were performed using LS-DYNA 971 (LSTC, Livermore, CA) MPP version.

2.2. Material modeling

When subjected to intensive loading such as blast, tissues would experience very high strain rates. As a result, their mechanical response can be highly strain-magnitude and strain-rate dependent. A recent computational study was conducted by the U.S. Army Research Laboratory on the lower extremity injury of infantry vehicle crew under AV landmine explosions (Kraft et al., 2011). The results indicate that when the strain rate of the tibia is as high as 200 s^{-1}, bone becomes brittle and its failure stress increases but failure strain decreases. Compared to the low rate loading conditions, a completely different fracture pattern was observed at high strain rates. Therefore, to better understand and accurately predict the blast effect on the bones, it is imperative that the high rate constitutive behavior of bony materials, e.g. a Cowper-Symonds type formulation is applied, where the flow stress can be calculated as a function of quasi-static yield stress and the parameters related to strain hardening and strain rate effect:

$$\sigma_Y^d(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p) = \sigma_Y^s(1 + E_{\tan}\varepsilon_{eff}^p) + \sigma_Y^s\left(\frac{\dot{\varepsilon}_{eff}^p}{C}\right)^{1/P} \quad (1)$$

with σ_Y^s and σ_Y^d being quasi-static yield strength and dynamic flow stress, respectively. ε_{eff}^p and $\dot{\varepsilon}_{eff}^p$ are effective plastic strain and effective plastic strain rate, respectively. E_{tan} is tangent modulus describing strain hardening effect. P and C are two strain rate related parameters. In the current study, all bony materials were modeled in this way using MAT_24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) (LS-DYNA keyword User's manual). The detailed material cards used in the LS-DYNA