A Finite Element Model of a Dummy Lower Extremity for Investigating the Injury Risk of Vehicle Occupants during Underbody Explosion Events

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ABSTRACT

Improvised explosive devices (IEDs) and anti-vehicular (AV) landmines targeted United States military vehicles throughout the conflicts in Iraq and Afghanistan. Injuries sustained by the occupants of these vehicles are severely debilitating and difficult to treat. The occupant's feet are usually in contact with the vehicle floor making the lower extremity highly susceptible to injury during an under-body blast (UBB). Therefore, vehicle improvements must be made to effectively mitigate the extreme forces of an UBB event so they cause minimal harm to the occupant. It has been proven that current anthropomorphic test devices (ATDs) such as the Hybrid-III are inadequate when it comes to accurately measuring the response of the human to blast loading. Therefore, a new dummy, called WIAMan (Warrior Injury Assessment Manikin) is under development. The main objective of this study was to validate the unbooted WIAMan lower limb FE model so that it can be incorporated into a whole-body model of the ATD. A numerical model of the dummy lower extremity was developed for LS-DYNA by a multi-institutional research team. Material models in LS-DYNA were generated for the soft parts of the dummy based on high and low strain rate data. The WIAMan FE model was simulated under identical conditions as the experiments done on the physical dummy. A comparison between the outputs from the simulation and the test data was used to validate the unbooted WIAMan-LX model. To assess the biofidelity of the dummy and demonstrate the limitations of automotive ATDs, a comparison between the WIAMan, Hybrid-III and PMHS tests was also done.

INTRODUCTION

IEDs and AV landmines are used to inflict serious damage on military vehicles and injury upon their occupants. Loading characterized by high acceleration is imparted to the underbelly of a vehicle following the detonation of an IED or landmine (Pandelani et al., 2010). If not properly attenuated, the blast impulse causes extreme deformation of the vehicle floor which can impact the lower extremity of seated occupants (Nilakantan and Tabiei, 2009). In a survey of 3,575 extremity wounds, IEDs accounted for 36% of the total and explosive munitions in general accounted for 73% (Owens et al., 2007). Often these injuries are severe enough to require amputation or result in death.

In order to effectively counter the threat of IEDs and AV mines, military vehicles and personal protective equipment (PPE) should be bolstered. The current criterion suggested by NATO to assess lower limb injury specifies that the Hybrid-III dummy be used (NATO, 2007). However, studies have shown that the Hybrid-III dummy is too conservative when it comes to evaluating vertical accelerative loads (Babir, 2005; Bailey et al., 2013; Newell et al., 2012; Quenneville and Dunning, 2012). To address this issue, the United States Army Research Laboratory has led the effort in developing a new anthropomorphic test device (ATD) called the WIAMan that is designed specifically for UBB testing.

The purpose of this study is to validate a numerical model of the WIAMan lower extremity (WIAMan-LX) at a sub-injurious loading rate of 2 m/s. Once further validation is complete, the lower extremity model will be implemented in a whole-body computational model used to assess injury risk and improve vehicle design.

METHODS

Model Development

Preliminary FE modeling effort as well experimental testing was done prior to the work presented in this paper. The Medical College of Wisconsin (MCW) has designed and conducted tests on the WIAMan and Hybrid-III dummy leg models as well as on post-mortem human surrogates (PMHS). Additional experimental data came from the United States Army Tank Automotive Research, Development and Engineering Center (TARDEC). Meshing of the WIAMan leg and test fixtures was performed by Corvid Technologies and Johns Hopkins Applied Physics Lab.

A finite element model (Figure 1) of the WIAMan-LX was developed in LS-DYNA® (LSTC, Livermore, CA) as a tool to evaluate the strength of design and locate possible failure modes prior to building the surrogate leg. In this case, lower extremity is defined as the tibia shaft, ankle, foot and surrounding flesh. The WIAMan-LX was designed to be an improvement of the existing MIL-LX dummy (Humanetics, Plymouth, MI). All the components, hardware and instrumentation incorporated in the WIAMan-LX were explicitly modeled using solid deformable elements to accurately locate points of structural weakness. There are 186,782 elements that make up the model. Of those elements 12% are tetrahedral, all of which make up the leg flesh surrounding the tibia. The remaining 88% of elements are hexahedral.

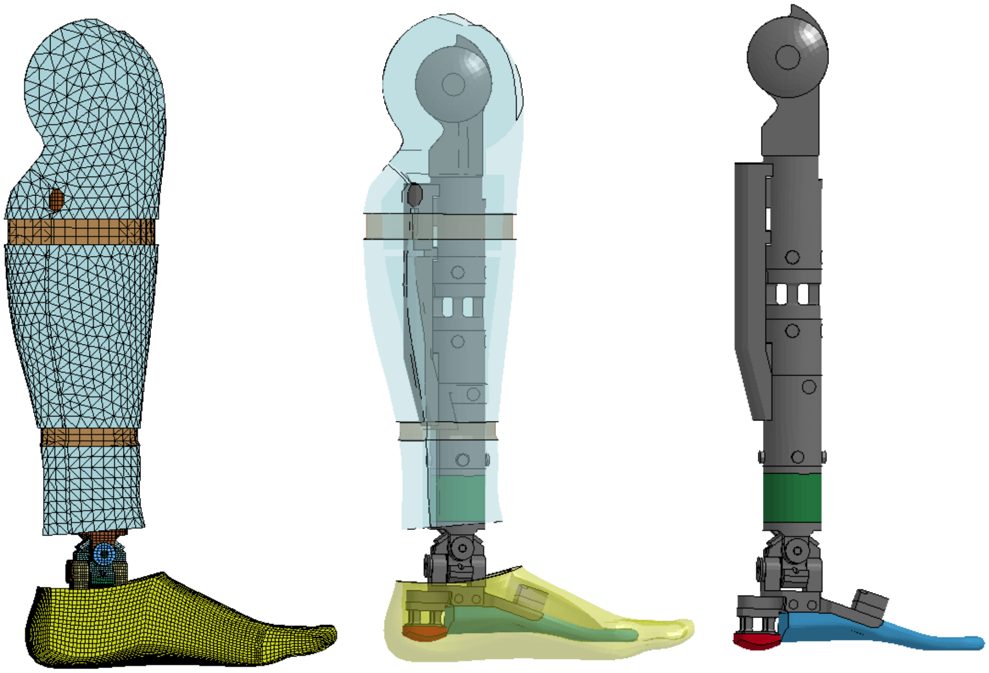

Figure 1: All parts of the WIAman-LX with foot flesh (yellow), leg flesh (cyan), heel pad (red), footplate (blue) and tibia compressive part (green) shown in color.

To absorb the energy generated during blast-induced accelerative loads and maximize the biofidelity of the new WIAMan-LX, several compliant elastomer and polymer parts were built into the dummy. These parts are the leg flesh, foot flesh, heel pad, footplate, and a damping element in the tibia shaft. Table 1 summarizes the materials and constitutive models for each compliant part.

Table 1: Compliant parts in the WIAMan-LX dummy and model

Part Name	**Material Type**	**LS-DYNA Model**
Foot Flesh	Polyurethane Elastomer	MAT 181
Leg Flesh	Polyurethane Elastomer	MAT 181
Heel Pad	Acetal Resin	MAT 181
Footplate	Polyurethane Elastomer	MAT 181
Tibia Compressive Element	Butly Rubber	MAT 181

Material properties of the flesh, heel pad, footplate, and tibia compressive element were determined through a series of uniaxial compression tests performed at strain rates ranging from

$0.01s^{-1}$ to $1000s^{-1}$. MAT_SIMPLIFIED_RUBBER was chosen to simulate each of the five components in LS-DYNA. The stress-strain behavior of the materials at discrete strain rates were used to develop the FE material models for each part. The materials were validated in LS-DYNA by explicit simulation of a single element before implementing them into the lower extremity model. A cube element was deformed uniaxially at a velocity corresponding to an experimental strain rate (Figure 2).

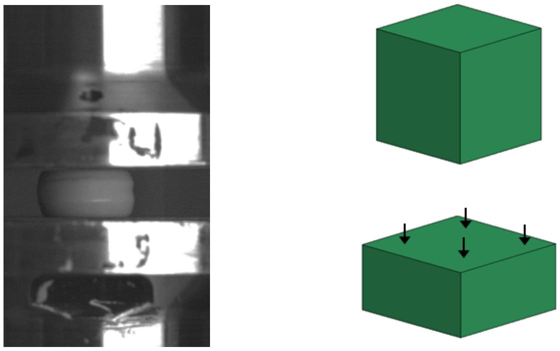

Figure 2: Experimental compression of a test specimen at constant strain-rate (left) Numerical simulation of a cube element at an equal strain rate (right).

Physical Experiments on WIAMan LX, Hybrid-III lower leg, and Human Surrogates

A series of tests were performed on the WIAMan LX, Hybrid-III LX, and post-mortem human subject (PMHS) leg-foot-ankle complexes. The Hybrid-III 50th percentile male ATD is recommended by NATO for conducting vehicle qualification tests (NATO, 2007) so it provides a benchmark that the WIAMan responses can be compared to. PMHS tests were performed to generate Biofidelity Response Corridors (BRCs) to evaluate the biofidelity of WIAMan and the Hybrid-III. Six PMHS leg-foot-ankle complexes with no protective equipment were loaded at impact velocities of 2m/s. Additional PMHS tests were conducted at speeds of 4 and 6 m/s. However, injuries were observed at these velocities and therefore could not be used in BRC generation. SAEJ211 sign convention was followed for all tests. This paper focuses on the validation and comparison of the WIAMan at the 2 m/s loading scenario.

The test rig (Figure 3) used to simulate loading of the lower leg when an UBB occurs underneath a military vehicle was developed at MCW. In theatre, the force transmission to the leg occurs primarily as a result of local floor deformation. However, for these experiments the scenario was simplified to enhance the repeatability of the procedure. The impact is transmitted to the lower extremity by a plate located underneath the foot. For ATD tests, the center of gravity (CG) of the impactor was aligned with the vertical axis passing through the tibia. The plate is set in motion when the opposite end of a lever arm is struck by a drop mass. The motion of the plate was restricted to the X-Y plane by guiderails. Rollers allow free motion of the upper rig along the vertical (Z) axis while all other degrees of freedom are constrained. Specific adaptors were developed so the WIAMan LX, Hybrid-III LX, and post-mortem human subject (PMHS) lower legs could be proximally secured to the rig near the knee joint.

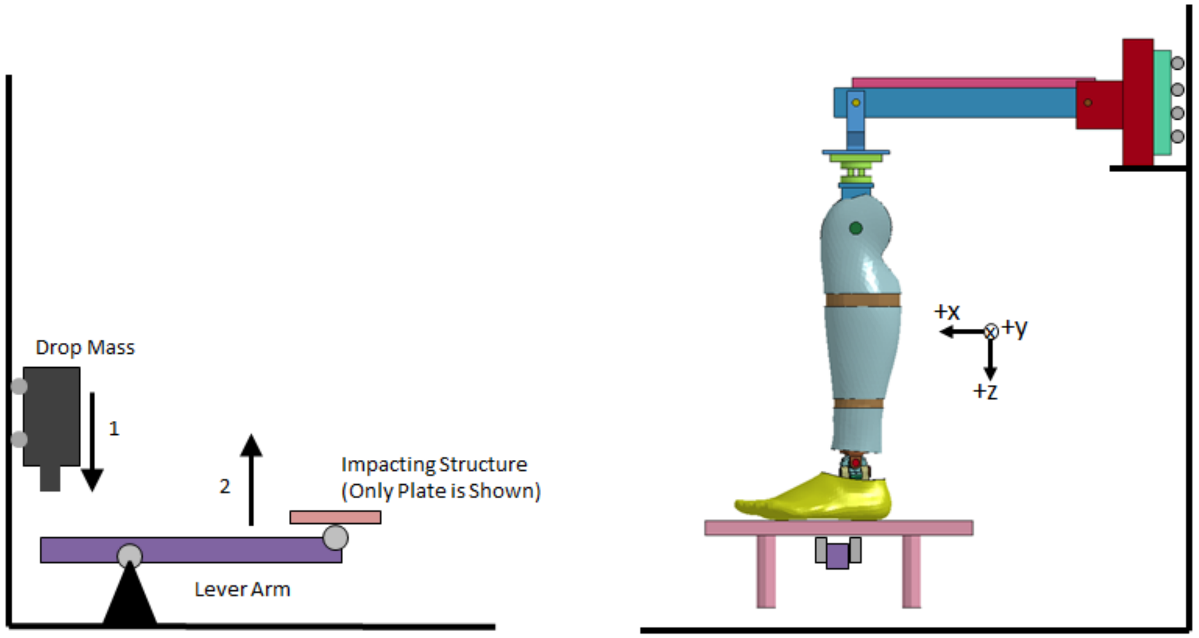

Figure 3: Diagram of the MCW test fixture showing the sequence of events leading to impact (left) and WIAMan-LX positioned in the fixture (right).

A total of six instruments were used to transduce kinematic and dynamic responses of the WIAMan-LX (Figure 4). A load cell was incorporated into the rig above the leg adaptor near the knee. Given that the location of data acquisition equipment varies between surrogates, this load cell provided a point at which both experiments and simulations of the WIAMan, Hybrid-III and PMHS could be quantitatively compared. Data from an accelerometer in line with the CG of the plate was integrated to find velocity profiles and determine the repeatability of tests. The velocity profiles were subsequently used as input conditions for FE simulations. Additional sensors include load cells in the heel and tibia as well as accelerometers on the superior side of the foot and the posterior side of the tibia.

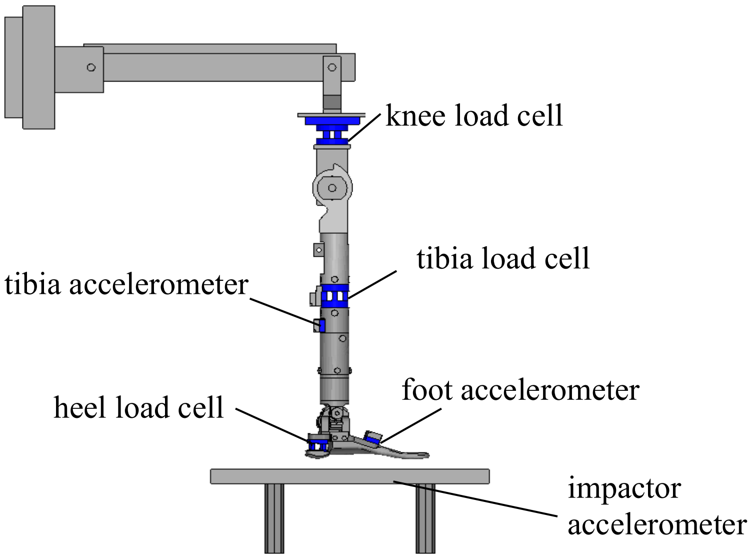

Figure 4: Location of sensors in the WIAMan-LX experiments and simulations.

RESULTS

Comparison of Hybrid-III, WIAMan and PMHS Experiments

One of the primary design criteria for the WIAMan-LX was improved biofidelity compared to existing models. The WIAMan, Hybrid-III and PMHS surrogates were tested under nearly identical conditions. For the three different surrogate tests, the knee load cell is currently the only instrument that is present for each one. The surrogate responses are compared at the knee and results show the WIAMan to be more biofidelic (Figure 5b). It is also shown that impact velocities were similar across the three tests (Figure 5a). Finite element models can be used in future work to compare the WIAMan, Hybrid-III and PMHS to a greater extent.

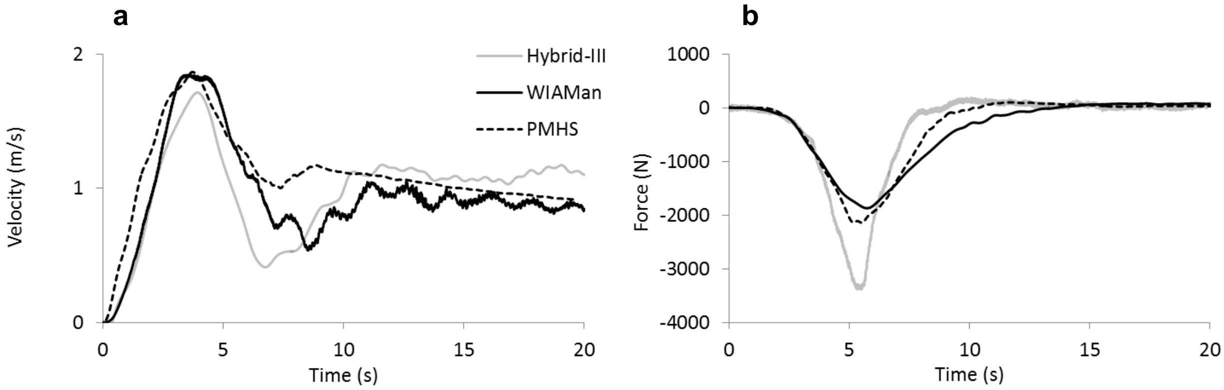

Figure 5: Physical dummy test results of WIAMAN-LX and Hybrid-III and PMHS for (a) impactor velocity and (b) knee force

LS-DYNA Material Validation

The viscoelastic material models in LS-DYNA were able to accurately estimate the stress response recorded in the experimental data. A cube element was deformed using a prescribed strain rate and the stress-strain histories were compared to experimental data (Figure 6). The stress-strain responses varied greatly between the different materials. The foot flesh was validated to a compressive strain of 60% while the less compliant foot plate is only validated to 10% strain. The polyurethane elastomer that makes up the foot flesh shows significant viscoelasticity at strain rates between 50^{-1} and $150s^{-1}$. The viscoelasticity of the other four materials is much less pronounced at these strain rates.

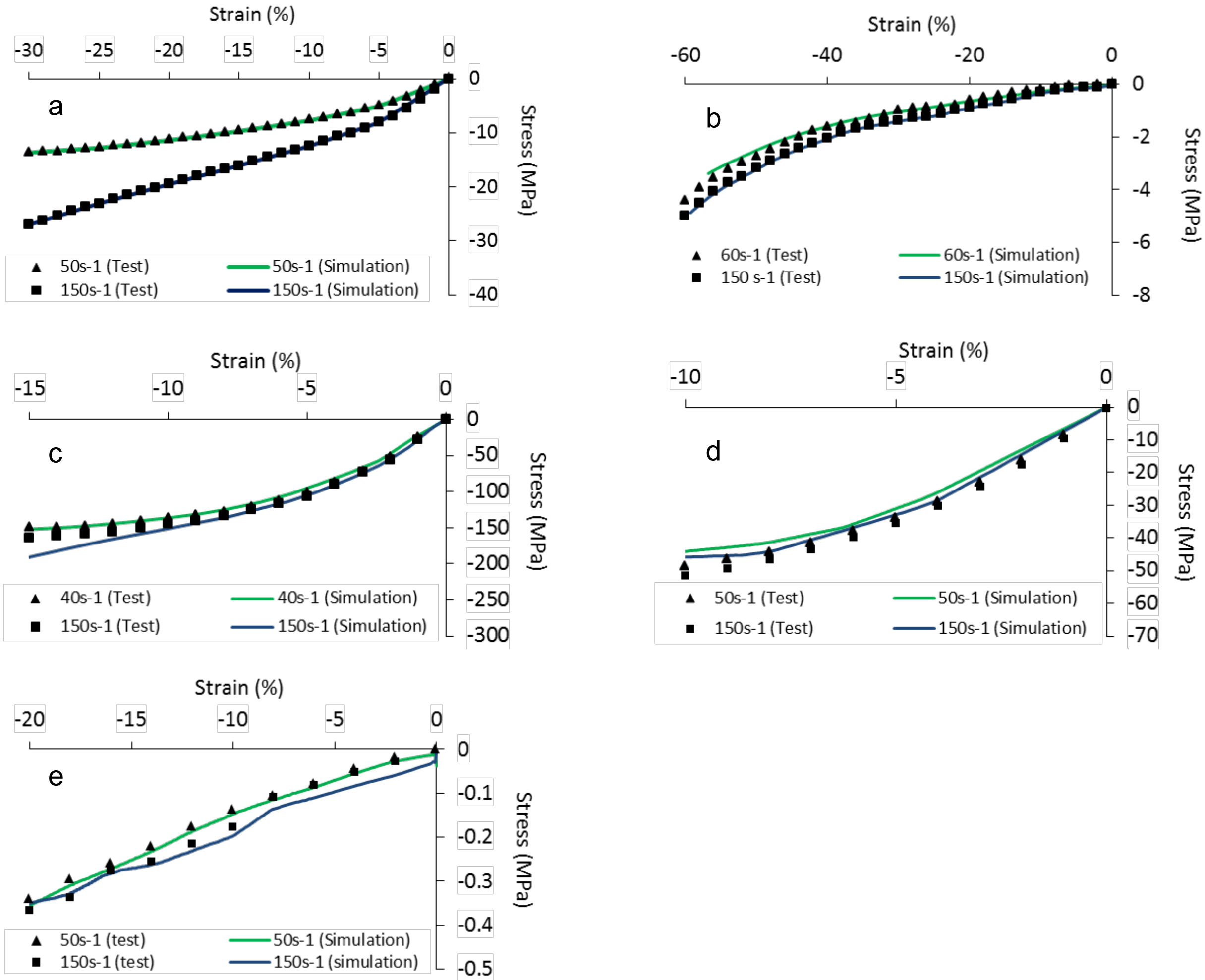

Figure 6: Validation of LS-DYNA MAT 181 materials for the (a) tibia compressive element (b) foot flesh (c) heel pad (d) foot plate and (e) leg flesh.

WIAMan LX Validation

To compare the experimental WIAMan results to the response of the computational model, signals are categorized as either primary or secondary. Forces and accelerations along the longitudinal (Z) axis of the tibia are designated primary. Bending moments about the Y axis in the SAEJ211 convention are also primary signals. Calibrating the model to these signals is crucial for model validation and injury prediction during vertical loading. Three tests were performed on the WIAMan-LX at an impact velocity of 2 m/s. When simulated under test conditions, the WIAMan-LX FE model showed good correlation to the experimental data (Figure 7).

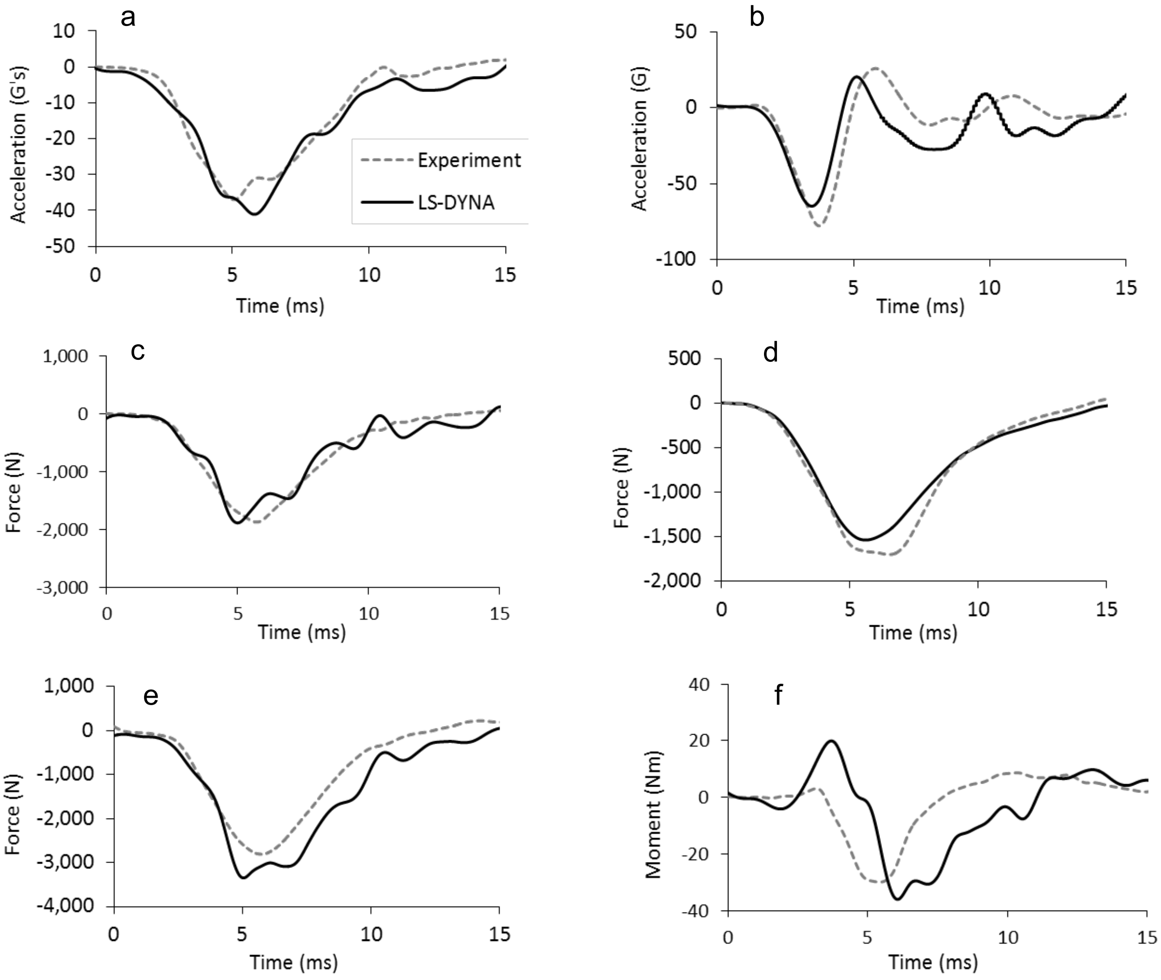

Figure 7: WIAMan LX validation for (a) tibia acceleration in the Z-direction (b) foot acceleration in the Z-direction (c) knee force in the Z-direction (d) heel force in the Z-direction (e) tibia force in the Z-direction and (f) tibia moment about the Y-axis

DISCUSSION

The goal of this study was to develop and validate a numerical model of the WIAMan lower extremity in a non-injurous loading scenario. A novel ATD is needed for under-body blast tests because the Hybrid-III dummy has been shown to an inadequate predictor of injury. This study as well as others reported in literature show that the stiff response of the Hybrid-III lower extremity results in poor biofidelity in vertical loading scenarios. Initial tests conducted on the WIAMan indicate it is more biofidelic, especially in the primary axial loading direction.

A finite element model of the original WIAMan lower extremity design was validated against experiments where the ATD was struck by an impactor at 2 m/s. This impact is lower than what is considered to be a blast scenario. The validation was performed at 2 m/s in order to establish the FE model was capable of predicting the ATD responses prior to testing greater impact velocities. Furthermore, during six PMHS experiments in which no PPE was used, 2 m/s was the threshhold beyond which injury occurred. Biofidelity respone curves cannot be developed if a fracture occurs during testing. This means that assesments of biofidelity of the unbooted WIAMan and Hybrid-III can only be made at the sub-injurous level of PMHS experiments. To ensure that the FE model is robust it should be further validated against higher rate loading conditions. The model should also be simulated and validated with PPE. In order to simulate the WIAMan LX equipted with a combat boot, the boot model must first be independently validated. It is crucial to include PPE in future tests and simulations because this better represents what occurs in theatre and allows more extreme condtions to be tested.

CONCLUSION

A WIAMan lower extremity FE model has been developed and validated against experimental data. The model showed to accurately predict dummy response under vertical accelerative loading similar to that experienced during an under-body blast event. Comparing the response of the WIAMan dummy and the Hybrid-III dummy to PMHS, it is shown that the design of the WIAMan is more biofidelic. Now that the model has been partially validated, it can be implemented into a whole-body finite element model of the dummy.

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