Development of a Finite Element Model of the WIAMan Lower Extremity to Investigate Under-body Blast Loads

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Abstract

Occupants of military vehicles are likely to be subjected to an under-body blast (UBB) resulting from anti – vehicular land mines and improvised explosive devices (IEDs). For years the automotive industry has successfully used human anthropomorphic test devices (ATDs) to help quantify the occupant injury risk over a wide range of impact scenarios. However, it has been proven that these ATDs are inadequate when it comes to accurately measuring the response of the human to under-body blast loading. Therefore, a new dummy concept, called WIAMan (Warrior Injury Assessment Manikin) is being developed together by various research institutions and industry leaders. A numerical model of the lower leg was developed in LS-DYNA® based on CAD geometry of the dummy. Material models in LS-DYNA were assigned based on high and low strain-rate tests to model the viscoelastic behavior of the soft tissue used to represent the flesh, heel pad, foot plate, and tibia compliant element of the dummy leg. 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 lower extremity (WIAMan-LX) model. The proposed numerical models of materials exhibiting viscoelastic responses show good correlation to the test data at both high and low strain rates. Simulations of the entire WIAMan-LX correlate well to the WIAMan physical dummy tests. Additionally, a comparison of the WIAMan to Hybrid-III and post-mortem human surrogate (PMHS) tests is presented. Future work includes further validation of the model and correlating the responses of the dummy to risk of human injury.

Introduction

IEDs became a serious threat to the protection of US armed forces during the conflicts in Afghanistan and Iraq. Advancements in personal protection and pre-hospital treatment have increased the survival rate for a blast victim but have also led to a surge in severely debilitating lower extremity injuries [1]. In a survey of 3,575 extremity wounds, explosive munitions accounted for 75% of injuries[2]. The United States Army Research Laboratory (USARL) is leading an effort to develop a novel ATD for use in Live-Fire tests and vehicle development efforts. Once completed, the WIAMan dummy will be the first whole-body ATD designed specifically for measuring responses to accelerative loads resulting from an under-body blast (UBB) event. UBBs that occur in theatre are likely to be the result of an improvised explosive device [3]. When detonation of an explosive device under a vehicle occurs, high forces are transferred to the vehicle floor primarily by means of the expansion of the detonation products and energy transfer from soil ejecta [1]. The proximity of the lower leg/ankle/foot complex to the floor of the vehicle makes the lower extremity highly vulnerable to UBBs.

Anthropomorphic test devices (ATDs) were developed by safety researchers to assess human injury during an automotive impact event. Therefore, current ATDs have been optimized to mimic the kinematic and dynamic responses of a human during the frontal and side impact loads common in automotive collisions. Studies of automotive lower extremity injuries indicate peak combined axial-bending loads in the foot and tibia occur between 15 and 20 milliseconds [4-8]. In contrast, the detonation of an anti-vehicular landmine imposes a primarily vertical (axial) impact. Deformation of the vehicle floor can occur within 5 milliseconds following detonation and loading of the lower extremity reaches its peak within less than 10 milliseconds [9, 10]. Due to the vertically accelerative nature of the blast event, it has been questioned whether current ATDs are capable of being used to asses and quantify improvements to vehicle safety. Several studies have used either the Hybrid-III or THOR dummy for anti-vehicular mine tests and concluded that the dummies demonstrate poor biofidelity at high loading rates [11-14]. The purpose of developing the WIAMan dummy is to improve upon the shortfalls of existing ATDs.

The rapid increase in computational power has made numerical models efficient and valuable tools to supplement experimental research. In this study, a computational model of the WIAMan lower extremity (WIAMan-LX) was developed and validated against a single experimental loading case. Once further validation is completed, the WIAMan FE model will be used in conjunction with the physical dummy to assess human injury risk during UBBs and improve vehicle design.

Methods

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

A finite element model of the WIAMan lower extremity (LX) was developed in LS-DYNA® (LSTC, Livermore, CA) as a tool to evaluate potential design changes prior to manufacturing a physical dummy leg. The WIAMan-LX was developed as a maturation of the existing Military Lower Extremity (Humanetics, Plymouth, MI) to be more robust, biofidelic, and feature improved instrumentation and data acquisition capability. The WIAMan-LX FE model has 212,001 nodes with 164,755 hexahedral elements and 22,027 tetrahedral elements, all of which are defined as deformable. All the parts, hardware and instrumentation used on the physical dummy were explicitly modeled in order to minimize discrepancies between experiments and simulations. Likewise, the entire test rig was modeled using deformable hexahedral elements. Revolute joints on both the leg and the test rig were modeled by applying sliding contacts to the appropriate hardware. In the lower leg model (Fig. 1), a single joint at the knee restricts the lower leg to posterior-anterior motion. Two ankle joints allow the foot to independently move in both dorsi-plantar flexion and inversion-eversion. Appropriate contacts were applied to the rest of the model to mimic the physical dummy. The leg consists of five highly compliant components: the foot flesh, foot plate, calcaneus cap, tibia damping element and the leg flesh. The purpose of incorporating deformable components is to absorb energy and bring dummy responses closer to that of PMHS, improving the biofidelity of the dummy.

Figure 1. The WIAMan-LX which includes all components from the knee clevis to the foot. Shown here both fleshed (left) and defleshed (right)

High and low tension and compression tests showed the strain rate dependency of the different soft materials. Viscoelastic material models for the leg flesh, foot flesh, foot plate, calcaneus cap and tibia damping element were developed in LS-DYNA (MAT 181) based on the data recorded in coupon uniaxial tests. These material models were validated using the test data before being implemented in the WIAMan FE model. Material models for the non-compliant components of the model (e.g. steel and aluminum) were defined based on literature data.

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

A testing rig was developed at MCW to simulate loading of the lower leg when an UBB occurs underneath a military vehicle. In theatre, this injury would typically occur when the floor of the vehicle impacts the foot in a seated posture. The simplified loading conditions imposed by the test rig are desirable for ensuring the repeatability of the tests. Figure 2 shows a diagram of the rig with a WIAMan-LX in position. The plate is set in motion when the opposite end of a lever arm is struck by the drop mass. Rollers allow free motion of the rig along the vertical axis. The dummy leg attaches to the rig at the knee joint. Other than different adaptors used to connect the WIAMan, Hybrid-III and PMHS legs to the test rig, the tests were performed under nearly identical conditions. The rig consists of an impactor plate and femur bar. SAEJ211 sign convention was followed for all tests.

Overall, a wide range of input load scenarios were tested to facilitate the development of the WIAMan-LX model. Hybrid-III tests were done to provide a comparison to the WIAMan dummy. PMHS tests were conducted to develop non-injurious human response corridors as well as to assess the biofidelity of the WIAMan. This paper focuses on the validation and comparison of only one loading scenario. For this scenario, an unbooted WIAMan-LX was tested with the ankle, knee and femur joints situated initially at 90 degree angles. The foot was settled against the impactor prior to the impact. The impactor was accelerated to a peak loading rate of approximately 2 meters per second within a 5 millisecond time frame. This loading scenario was also applied to the Hybrid-III dummy and PMHS. Figure 3 compares the input conditions for the WIAMan, H-III, and PMHS tests respectively. The time histories of foot plate velocity were integrated from acceleration data recorded from an accelerometer at the center of the plate.

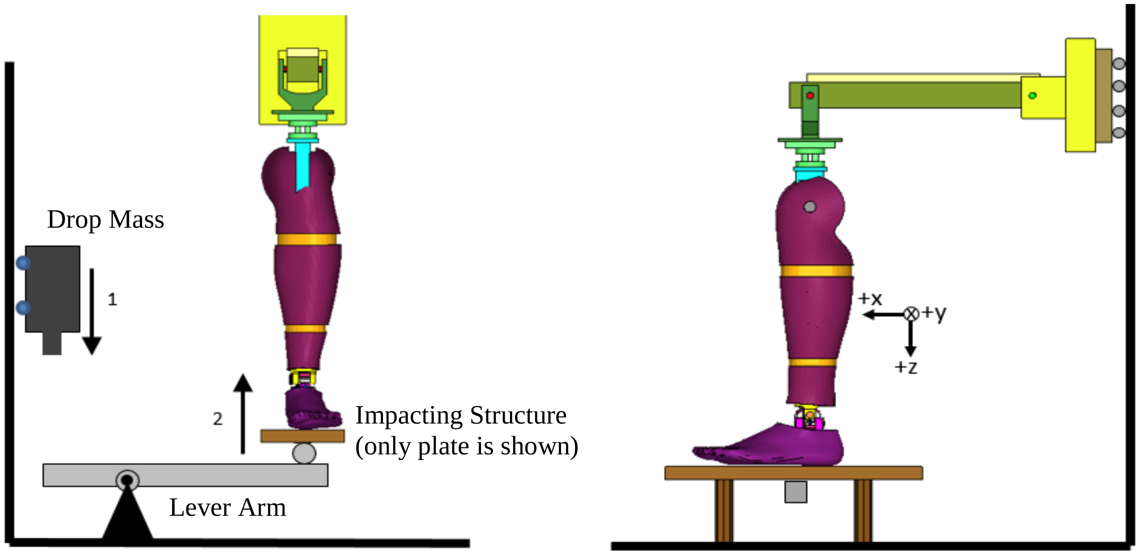

Figure 2. Frontal (left) and side view (right) of the test rig with an attached WIAMan-LX showing the procedure of events leading to an impact. First, the drop mass falls from a predetermined height to impact the lever arm. The lever arm transfers the load to the impacting structure.

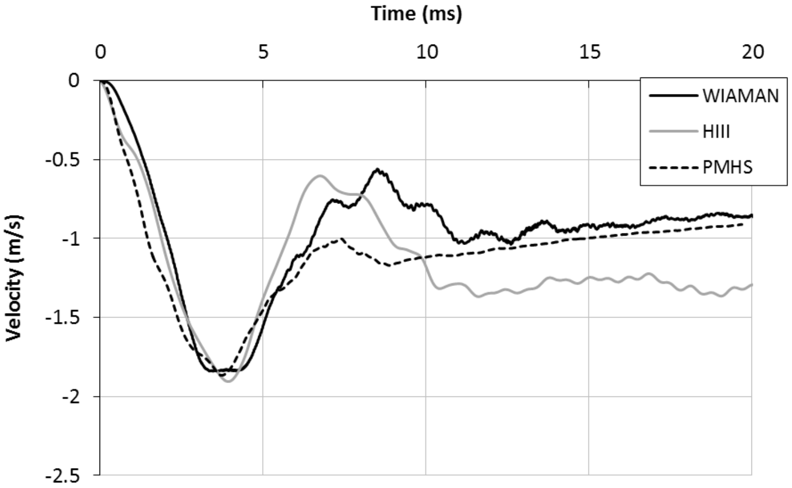

Figure 3. The time histories of the impactor plate: The solid black line for the WIAMan velocity is an average of three tests. The grey line for the Hybrid-III dummy is from a single test. The dashed line for the PMHS input is an average of six tests.

Two, 6-axis load cells embedded in the heel and tibia, respectively, transduce the force and moment time histories in the leg. One additional load cell was incorporated into the test rig above the tibia adaptor. The additional load cell will be referred as the knee for the purpose of comparison. The load cells are explicitly modeled in LS-DYNA and their outputs are given by DATABASE_CROSS_SECTION_SET cards. Two six-degree-of-freedom sensors measure the linear accelerations and rotational velocities of the foot and tibia. The sensors in the FE model are represented by the CONSTRAINED _INTERPOLATION_LOCAL card. Using this card, the motion of a single dependent node is interpolated from the motion of a set of independent nodes(LS-DYNA Keyword Manual). The location of these devices in the WIAMan-LX model is shown in Figure 4.

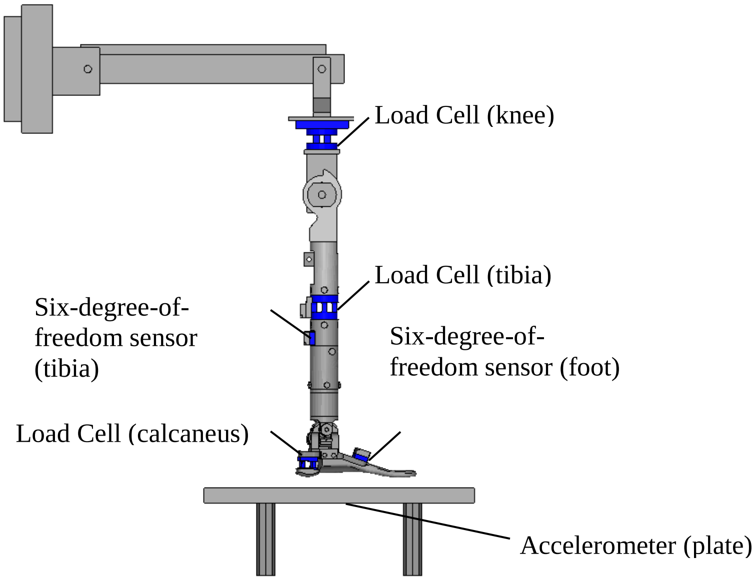

Figure 4. Location of sensors for the WIAMan-LX experiments and simulations. The flesh part is not represented in the current picture.

Results and Discussion

Typically during a UBB event a compressive load will be applied to the tissue of the lower leg. Therefore the focus for this study was accurately replicating high and low speed compression tests. 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. Results for the validation of four material models are shown in Figure 5.

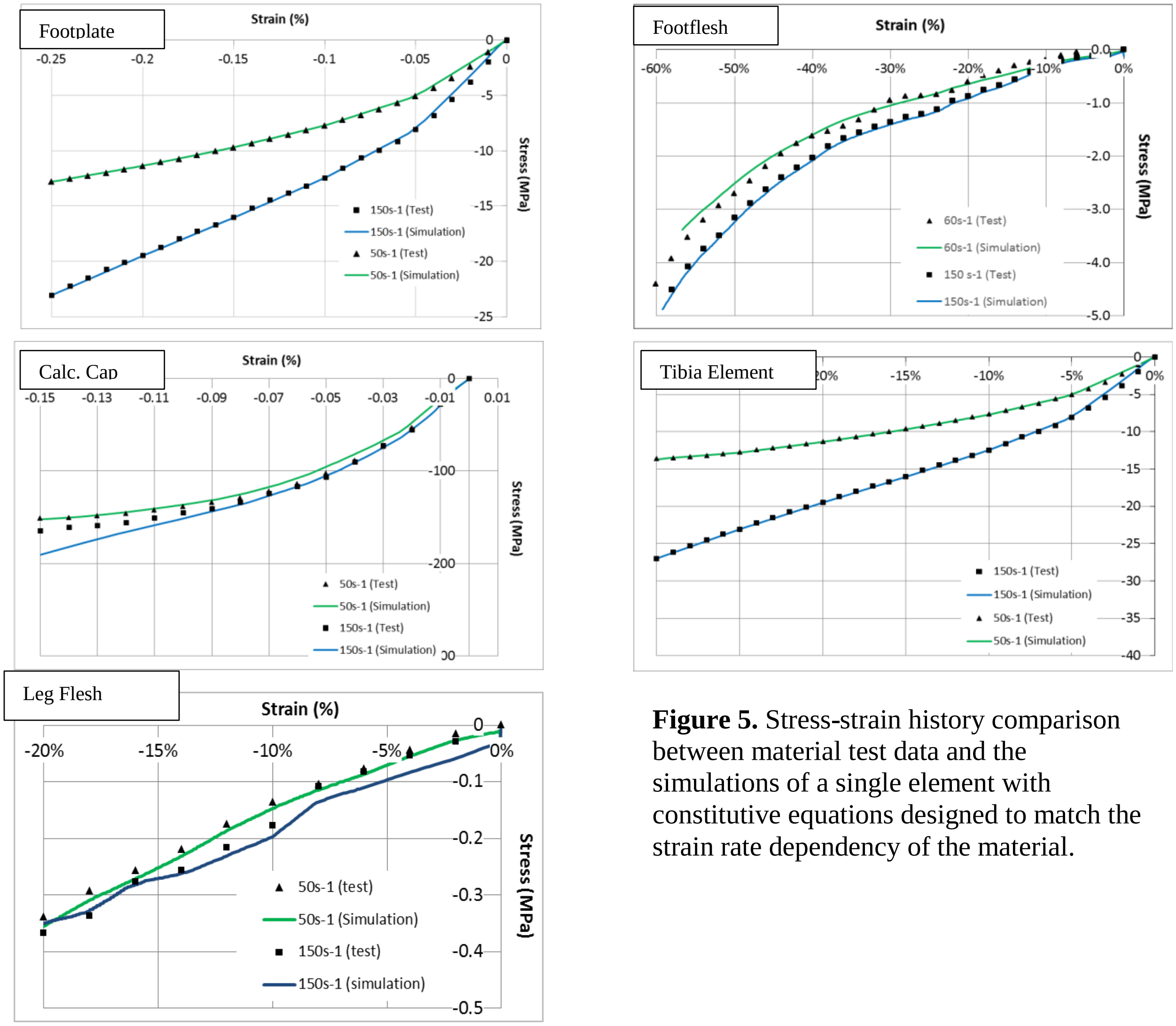

Figure 5. Stress-strain history comparison between material test data and the simulations of a single element with constitutive equations designed to match the strain rate dependency of the material.

The WIAMan-LX FE model closely predicted the dummy response for the 2 m/s initial impact unbooted load. A very good force predictability along the primary (Z) loading direction was recorded at the knee load cell location. The load cells in the calcaneus and tibia are over-predicting the peak forces in the Z-direction by approximately 33%. The six-degree-of-freedom sensor in the foot accurately predicted angular rotation about the local y-axis. CORA scores are provided to offer a numerical correlation between the simulations and test data. The average CORA score of the signals presented here is 0.803. A score greater than 0.7 is generally considered to be favorable. Based off this threshold the WIAMan FE model is shown to be capable of accurately simulating the responses of the physical model. Results from the WIAMan-LX simulations are compared to the test data in Figure 6.

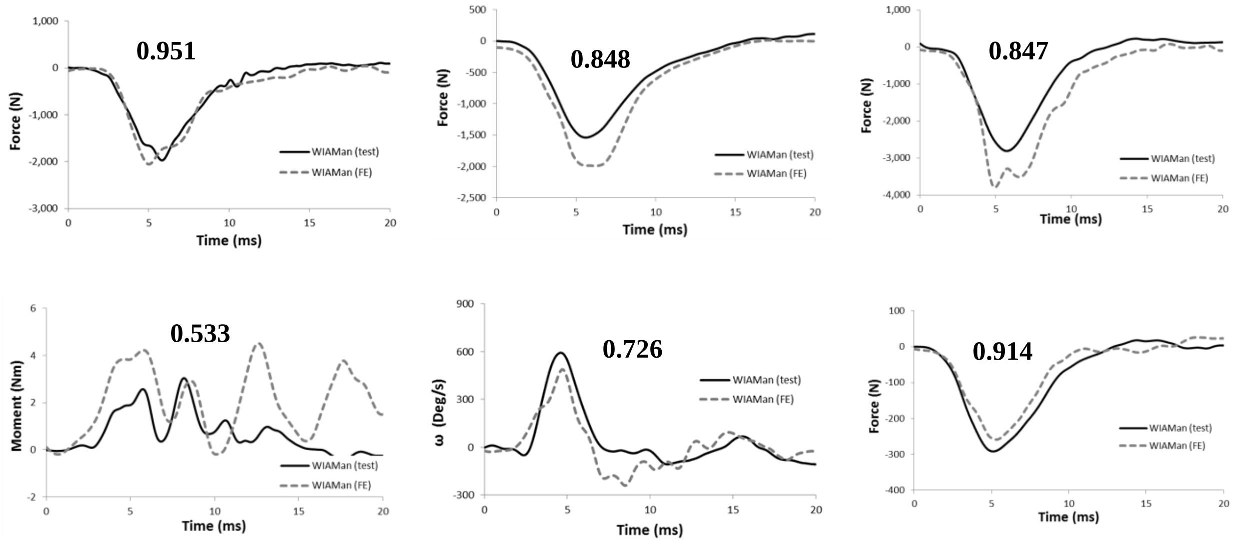

Figure 6. Model validation of the 2m/s unbooted scenario: (a) knee force z-direction (b) heel force z-direction (c) tibia force z-direction (d) knee moment z-direction (e) foot angular velocity y-direction (f) heel force x-direction. Cora scores shown on each graph. Total Cora score is 0.803

The WIAMan results were also compared to Hybrid-III and PMHS where applicable (Fig. 7). Limited data acquisition inherent in PMHS testing and discrepancies in sensor location between the Hybrid-III and WIAMan-LX dummies make it difficult to directly compare responses. It was decided the best comparison could be made at the knee load cell because of its location on the test rig and not on the lower extremity. No transformations were made to accommodate for any slight differences in signal locations. It can be seen that the WIAMan dummy is bringing the response closer to that of a human than Hybrid-III (Fig. 7). The corridor presented for PMHS is the standard deviation calculated from the results of 6 PMHS tests.

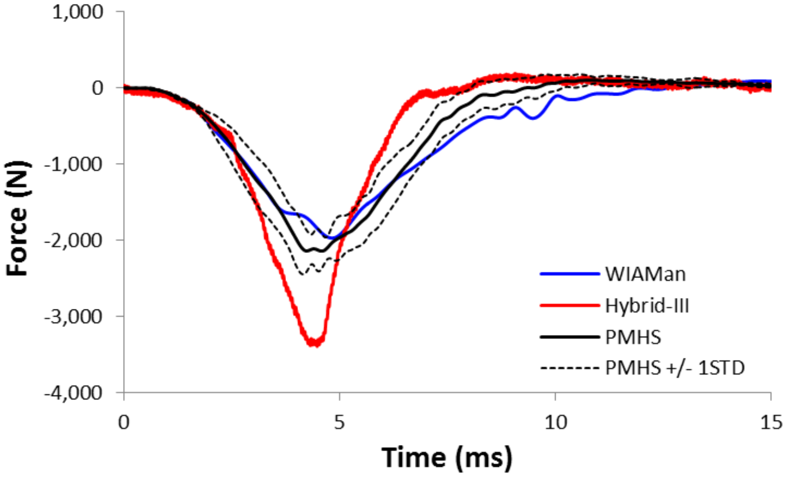

Figure 7. Physical dummy test results - WIAMAN-LX and Hybrid-III compared to PMHS

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. The FE model was developed prior to the construction of the dummy, and was used as a tool for designing the dummy to be robust and biofidelic. 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. To improve the predictive capabilities of the FE model it must be further validated against higher rate loading conditions, booted and unbooted. Determining the sensitivity of the model to test conditions such as initial angles at the ankle and knee joints would be another beneficial study to conduct. In the future, efforts may be made to simplify the model (e.g. rigid parts, coarser mesh, simplified joints) to increase its computational efficiency. Now that the model has been partially validated, it can continue to be used as a valuable tool to improve the design of the dummy.

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