2017 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) TECHNICAL SESSION
AUGUST 8-10, 2017 - NOVI, MICHIGAN

CALIBRATION AND VERIFICATION OF DETAILED HYBRID III 50TH PERCENTILE MALE ANTHROPOMORPHIC TEST DEVICE (ATD) BASED ON EXTENSIVE MINE BLAST TESTS

Morten Rikard Jensen, PhD.
CertaSIM, LLC
Castro Valley, CA

Mike Honaker
General Dynamics Land Systems
Sterling Heights, MI

Alex Boglaev
General Dynamics Land Systems
Sterling Heights, MI

ABSTRACT

The work presented here comprises preliminary results for calibrating the IMPETUS Afea Hybrid III 50th percentile Male ATD for a blast scenario. The calibration of the ATD model based upon the requirements defined for frontal crash impact are presented followed by a discussion of the blast survivability tests that were performed at General Dynamics Edgefield Test Center in South Carolina. The model setup for the calibration based upon the blast tests are presented which includes a discussion of the seating and blast models. Preliminary numerical results for Lumbar and Lower Tibia forces are compared with the experimental results. The correlation was good and calibration of the remaining critical parameters continues.

INTRODUCTION

Improvised Explosive Devices (IEDs) are a major cause of warfighter injuries. The battlefield is a dangerous environment and enhancements in vehicle protection are critical. Studying the effect of a mine blast on the vehicle structure is central to improvements in vehicle designs. However, to fully assess the effectiveness of a design it is necessary to include the effect of the blast on the warfighter and that is why an ATD (Anthropomorphic Test Device) has to be included in the design process.

ATDs are invaluable in the design of both military and commercial vehicles. The first whole body ATD, Sierra Sam, was built in 1949 for the US Air Force [1]. Since then many other types have been developed, the Hybrid II, SID, Tuff Kelly, etc. [1] and in most cases the development has been driven by the automotive industry to improve the safety of commercial vehicles. The Hybrid III ATD is an integral part of the design process to assess automotive designs for safety. The defense industry has also adopted the same philosophy and so the Hybrid III ATD is currently being used to assess survivability of the warfighter for vehicle impact but also for the blast environment. However, the loading that results from a blast event is quite different than an automobile frontal crash because the major loading is characterized by large vertical forces. But the physical response of the Hybrid III is focused on automotive industry standards for crashworthiness which means front and side impact and the standards for calibrating a numerical model of the Hybrid III ATD also focuses on the same response parameters. This makes it questionable to use them when applied to mine blast scenarios [2] and the same problem also occurs when applying a Hybrid III model to drop tower tests [3]. The WIAMan (Warrior Injury Assessment Manikin) project [4] was initiated several years ago to better quantify injury associated with mine blast events and it is currently still in development and not ready for widespread use. In the meantime the Hybrid III is still the workhorse for the underbody blast design and testing of military vehicles.

The work presented here highlights a detailed model of the Hybrid III 50th percentile Male ATD that was developed for the IMPETUS Afea Solver®, an Explicit Non-linear Transient Finite Element Code. The geometry of the ATD model is based upon the standards published by the NHTSA (National Highway Traffic Safety Administration). The ATD is calibrated to the standard requirements specified in [5] and [6]. To calibrate an ATD for blast events requires blast test data. Blast survivability tests using instrumented ATDs were performed at the General Dynamics Edgefield Test Center in South Carolina. A Hybrid III 50th percentile physical ATD was used in the tests. The ATD was placed in a seated position in a rig and buried charges were detonated in a very controlled and repeatable manner under the rig in order to collect the necessary injury data. The tests were performed in July 2016. The test data can now be used to calibrate the ATD, focusing on response parameters such as Pelvic Acceleration, Lumbar Force, etc. This paper provides a short introduction to the ATD, shows the results of a few selected configurations as verification of the calibrated ATD for the automotive industry. Furthermore, the mine blast experiments are presented along with preliminary simulation results for the lumbar and lower tibia forces.

THE ATD MODEL

The ATD project was initiated in 2012 by IMPETUS Afea AS and the Norwegian Defense Research Establishment (FFI) with the goal of developing a virtual ATD to capture the impulse and deformations that occur during a blast event. The Hybrid III 50th percentile male ATD was chosen since it represents the average size of a warfighter and is often used in live-fire blast testing of combat vehicles. The SAE standards provide a basis for calibrating the ATD Model. The ATD is equipped with the standard leg components used in the automotive industry and is show in Figure 1.

Figure 1: *The ATD is based on the geometry of the Hybrid III 50th percentile Male ATD.*

The first step in the project was to create the finite element model based on the documentation in [7]. The meshing took several iterations and a mix of elements of different orders was applied to fully utilize the benefits of the IMPETUS element technology. The model takes advantage of accurate high order elements (quadratic and cubic) where accuracy is needed and linear elements in those sections that are appropriate to maximize computational efficiency. This includes both hexahedron and tetrahedron elements. Figure 2 shows a mix of the different element types used in various portions of the ATD.

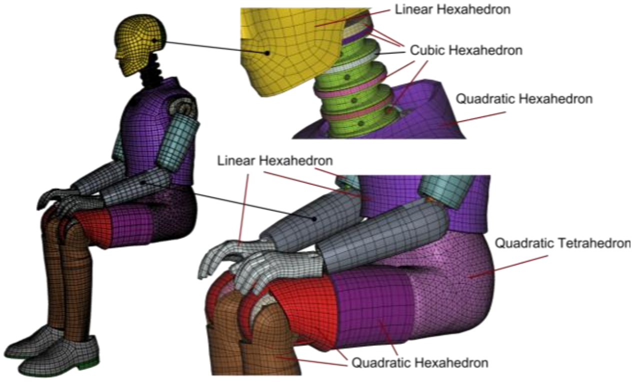

Figure 2: *The ATD makes use of a mixture of linear and higher order elements.*

An ATD model is in itself rather complex, but the complexity increases significantly when implementing it within a full vehicle model. Therefore, it is of vital importance to have a good file structure and dataflow. One needs to be able to identify parts quickly in large models. To ensure this, the model is organized in seven different assemblies, where each represents a certain clearly identifiable region of the ATD. The seven assemblies are:

- Head
- Arms
- Legs
- Feet
- Upper Torso
- Lower Torso
- Neck

The assemblies are shown individually in Figure 3. Each of the assemblies is presented in detail in [8] where the data flow, files and positioning are clearly described.

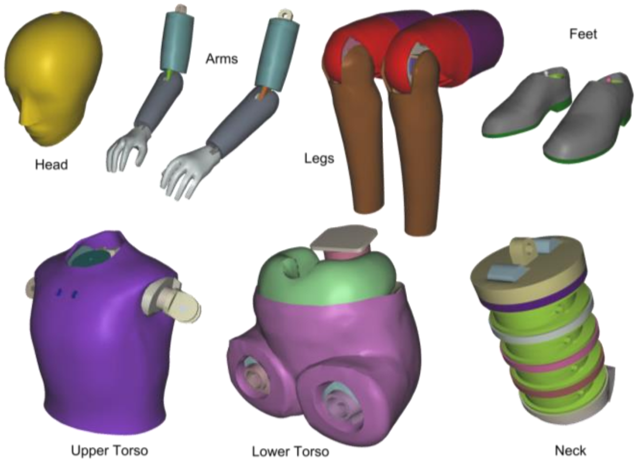

Figure 3: *The ATD makes use of seven different assemblies. The positioning of the parts (i.e., angles of the limbs) is based upon the blast test set-up.*

VERIFICATION FOR FRONTAL CRASH

The Hybrid III 50th Percentile ATD was developed for automotive crash testing and with that comes calibration tests specified for the automotive industry. The first step to certify the Hybrid III 50th Percentile Blast dummy involves satisfying those requirements. The tests used for the calibration of the ATD follow the guidelines in [5] or [6] depending upon the set-up as defined for each test. The calibration work was performed by IMPETUS Afea AB and FFI. In the later stages, CertaSIM, LLC was also involved. In total nine different calibration tests where successfully completed, leading to an accurate ATD that can be used for crash test simulations. The tests, well known in the automotive industry, are as follows:

- Head Drop Test
- Neck Flexion Test
- Neck Extension Test
- Thorax Impact Test
- Knee Impact Test
- Knee Slider Test
- Upper Foot Impact Test
- Lower Foot Impact Test
- Static Foot Impact Test

Verification and documentation of all the above calibration tests have been performed and described in [8]. In the following sections, the Neck Flexion, the Knee Impact Test and the Foot Test from the verification work are briefly described and the results shown.

Neck Flexion Test

The Neck Flexion Test consists of the Neck and Head assembly mounted on a pendulum which includes the brackets. The test results for the neck initially bending forward then backwards are show in Figure 4.

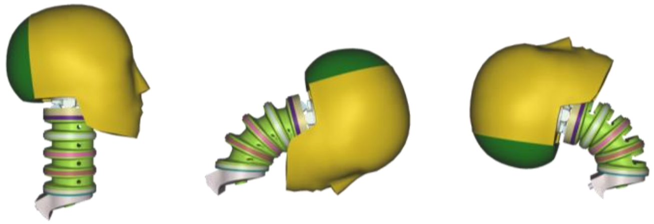

Figure 4: *Finite Element set-up for the Neck Flexion Test.*

The Hybrid III User's Manual J2856 [5] is the standard on which this calibration is based. A pendulum is released to allow a free fall from a given height that makes it achieve a velocity between 6.89 m/s and 7.13 m/s. The pendulum is deaccelerated according to values in the standard. In the numerical simulation the pendulum is not modeled but the Pad Sternum is used. A prescribed velocity is defined to represent the motion in the experimental set-up. The Pad Sternum is located in the lower Torso assembly which is the only part added besides the Neck and Head assemblies.

The performance specifications are given in [5], covering rotation and moments. Rotation is referenced to a horizontal plane passing through the base of the skull. Maximum rotation of the D-plane should be 64° to 78° with respect to the pendulum and must occur between 57 and 64 msec after impact. Furthermore, the head rotation versus time curve must cross the zero angle between 113 and 128 msec. Figure 5 shows that the modeled results are within the requirements.

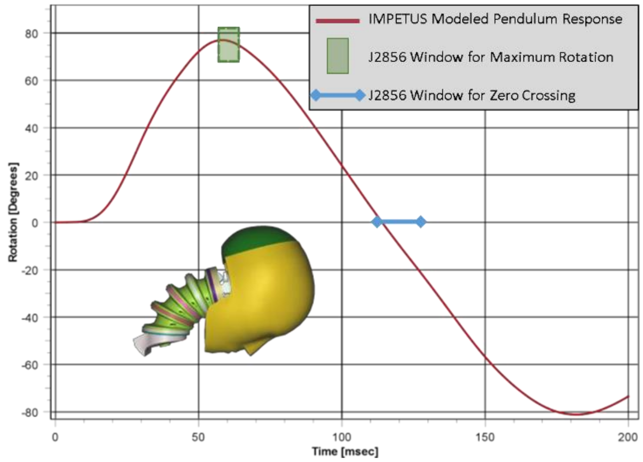

Figure 5: *Numerical results for Neck Flexion compared with J2856 [5] maximum rotation and zero crossing, showing agreement with the requirements.*

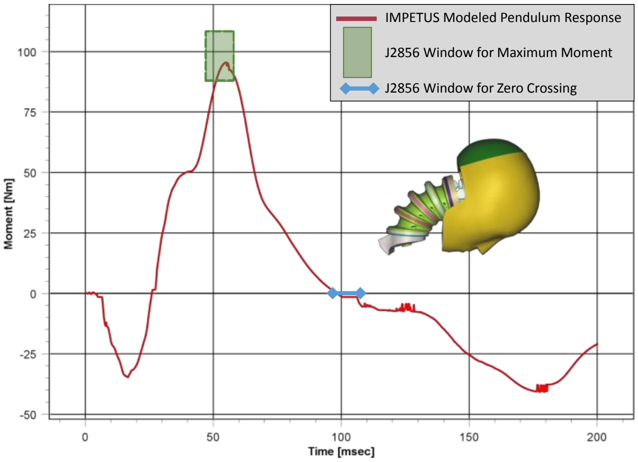

Figure 6: *Numerical results for the Neck Flexion Test compared with the specification in J2856 [5] showing the model is in agreement with the moment requirements.*

There are more requirements for the computed moments where the maximum moment of the head around the global Y-axis must be between 88.1 N-m and 108.4 N-m occurring between 47 and 58 msec. Also, the decaying part of the moment versus time curve must cross the zero axis between 97 and 107 msec. Figure 6 shows that the numerical results are within the requirements, where the maximum moment is 95.5 N-m and the zero crossing occurs at 98 msec.

Knee Impact Test

The Knee Impact Test is defined in [5]. The leg is impacted by a 5 kg rigid probe with a velocity of 2.1 m/s. Figure 7 shows the model set-up.

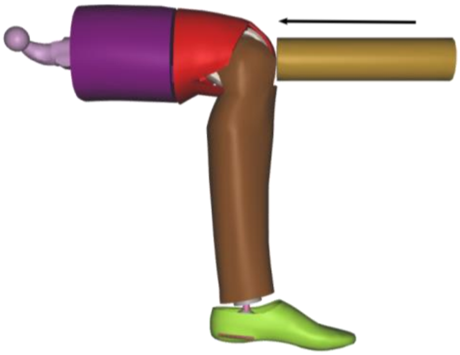

Figure 7: *The set-up for the Knee Impact Test.*

The knee assembly consists of several parts as illustrated in Figure 8 where some of the optional parts mentioned in the standard [5] are selected for the model. The main parts involve the knee components: knee flesh, cap, bone, etc. since the test focuses on behavior of the knee from a frontal impact.

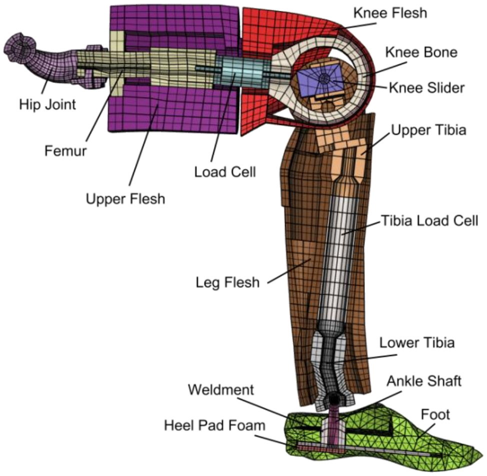

Figure 8: *The components in the Knee Impact Test Model.*

The impact force is used as the response parameter for calibration of the model. The peak force on the knee needs to be between 4,715 N and 5,782 N. Figure 9 shows that the maximum value of the force is well within the limits given with the peak at 5,157 N.

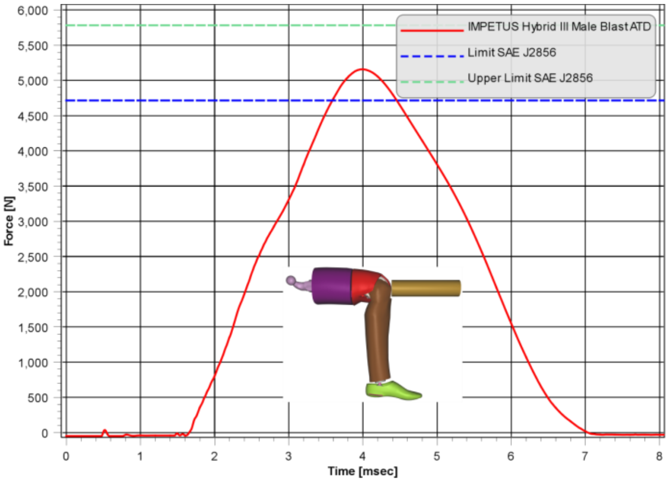

Figure 9: *The peak force value for the Knee Impact Test is between the required limits.*

Foot Test

The Foot Test is not a calibration test but an inspection test that is performed by the ATD manufacturer on new parts to ensure that the design gives the expected result. If a part is damaged these tests can also be performed by the end user of the ATD. The set-up is the foot assembly and heel pad foam as described in [5] and shown in Figure 10.

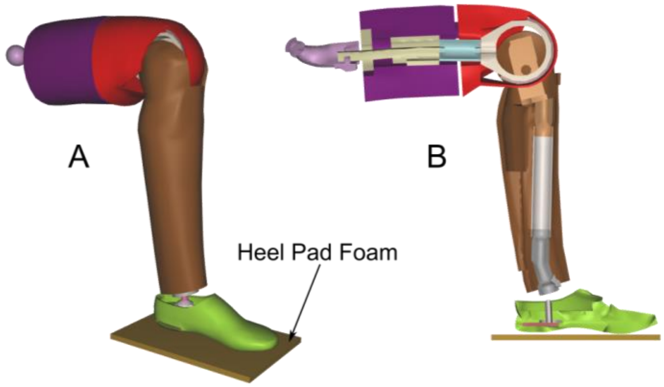

Figure 10: *Set-up of the Foot Test as modeled, following [5]. A: Whole set-up. B: Half model shown in order to see the parts used.*

This is a static compression test since the loading is 15 mm/min according to the standard. The force deflection curve has to be within a specified corridor. The curve is to be offset so that zero displacement is at a force of 1 lbf (4.5 N). In the numerical model this curve is found by cross plotting the force and displacement for the ground in the global Z-direction. The numerical result is plotted together with the corridor in Figure 11 showing the response is well within the required limits.

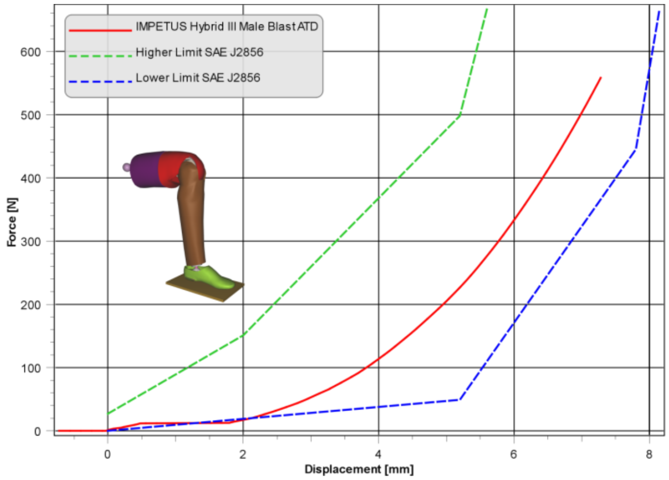

Figure 11: *Numerical result within the limits required in [5].*

MINE BLAST TESTS

There is very little specific and useful information about blast tests of an ATD that can be found in the open literature. In general, relevant information as charge size, blast impulse, etc. are presented as normalized values. Furthermore, the accuracy of the blast test is important because it is used to validate numerical models. Blast event experiments have to be under very controlled and consistent procedures which require a very professional and knowledgeable staff. Based on these observations, CertaSIM, LLC chose the GD Land Systems Edgefield Test Center located in South Carolina to perform the tests. There were three days of blast tests performed with a Hybrid III 50th Percentile ATD. A series of tests were carried out in July 2016 according to an experimental matrix as shown in Table 1.

Table 1: *Mine Blast Shot Matrix.*

Shot Number	Tibia Angle
1	90°
2	90°
3	90°
4	90°
5	110°
6	110°

The test structure itself is composed of thick-section steel in order to produce a rigid structure that transmits loads to the floor and seat with a minimum of flexural motion. The lower floor of the structure is constructed of 6” thick steel, while the sidewalls are made of 3/8” steel plate. The blast delivers a shock load that rapidly accelerates the entire structure. This load is delivered to the seated ATD through the seat structure and cushion, and also through the floor plate on which the ATD’s feet are placed. The floor plate of the structure consists of a 3/16” thick aluminum panel bolted to an aluminum L-bracket frame which is subsequently bolted to the steel floor of the test rig. A foam cushion is placed on the rigid seat and a thinner foam piece is placed behind the back of the ATD. A harness is used to strap the ATD to the seat.

In addition to 56 channels of instrumentation on the ATD, the test rig was also instrumented with three 2,000 g LOFFI mounted accelerometers. One accelerometer was placed on the lateral steel beam under the seat in order to record the input to the cushion and ATD. Another was placed on the vertical seat back. The third accelerometer was placed on the floor plate. Two sets of high-speed video were also recorded during the shots, one from a tower located above the test rig and another from the side, at speeds of 5,000 and 1,000 frames per second, respectively. This data provided a time history of the motion of the test rig. Figure 12 shows the initial position of the test rig for one of the 90° blast tests and the lifting of the cage during the test.

Figure 12: *Blast experiments at General Dynamics Edgefield Test Site. Top: Initial position of the 90° test. Bottom: Motion of the fixture during the blast event.*

The blast testing followed procedures described in NATO Standard AEP-55 [9], including measurement of soil density and moisture content in the test pit. The soil was excavated and repacked between each firing. The high explosive consisted of C4 charges packed into a cylindrical shape with a diameter/height ratio of 3. The soil overburden was 4”, and the charge was centered under the fixture. The standoff distance from the soil surface to the bottom of the test rig was 17”. Two to three firings can be obtained within a single day since it takes a considerable amount of time to repack the soil, place the charge, position the ATD, and document the set-up. Positioning of the ATD has been shown to be important for injury responses [10] and should be done with care.

In the work presented here the lumbar and tibia forces in the vertical direction were selected as response parameters of interest. The repeatability of the experiments was in general found to be very good as shown in Figure 13 where the lumbar force in the vertical direction for Shot # 3 is plotted together with the result for Shot # 4.

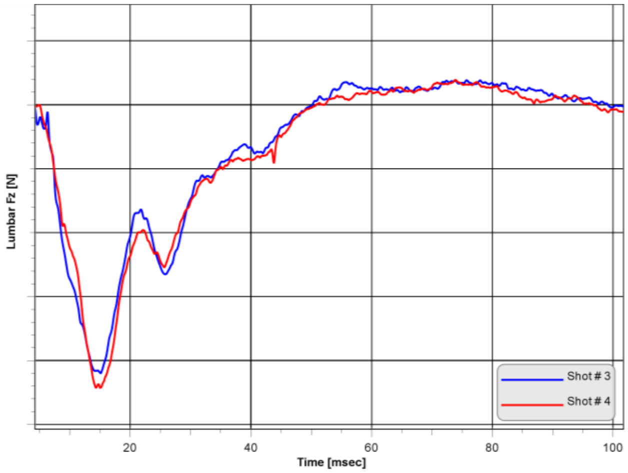

Figure 13: *Experimental results for the vertical lumbar force in Shot # 3 and Shot # 4, showing good repeatability.*

VERIFICATION FOR MINE BLAST

A numerical model was developed for the blast set-up including the ATD and the fixture. The numerical ATD is the exact same one used in the crash verification simulations described earlier. For the blast event, two simulations were carried out, namely, seating due to gravity followed by a transient dynamic blast event. This approach is commonly applied, see [11]. Both simulations are described in short in the next sections, while a more detailed description can be found in [8]. At the end of this section selected numerical results are compared with experiments.

Seating of the ATD

The goal of this simulation is to seat the ATD prior to testing and hence obtain the correct position and compression of the seat cushion prior to the blast loading. Since IMPETUS is an Explicit Solver mass damping has been applied as well as conventional mass-scaling to obtain a quasi-static simulation, with a minimum amount of kinetic energy. Figure 14 shows the initial seating of the ATD and the configuration as well as the final compression of the foam cushion. The results from the seating process were then used in the blast simulation. The solver relies on GPU Technology for massively parallel processing and using a workstation with a single NVIDIA Tesla K40c GPU resulted in a simulation time of ~9 hours to complete the gravity loading phase.

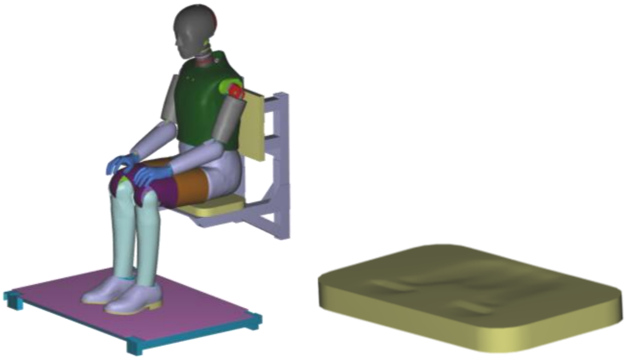

Figure 14: *Settling of ATD due to gravity. Left: Initial position and set-up. Right: Final seat cushion compression.*

Modeling of the Blast Event

In the experiments the motion of the fixture was recorded and used as the basis to simulate the blast event based on real experimental data. The instrumentation data from the seat-bottom accelerometer was used to calculate the seat displacement during the event, and this was used as input to the simulation of ATD response. This allows the focus to be fully on the response of the ATD, without regard to the structural response of the test fixture. The displacement is applied to the seat and floor frame.

An example of the input to the seat is shown in Figure 15. This is the integrated data from the LOFFI-mounted accelerometer on the lateral steel beam supporting the seat pan during Shot #3. The data represents the velocity of the beam during the first 500 msec of the event, showing the vibration of the seat structure in response to the initial blast loading, as well as the subsequent free fall due to gravity. The actual input to the numerical model was the displacement history of the seat, which was calculated by integrating the velocity history shown in the figure.

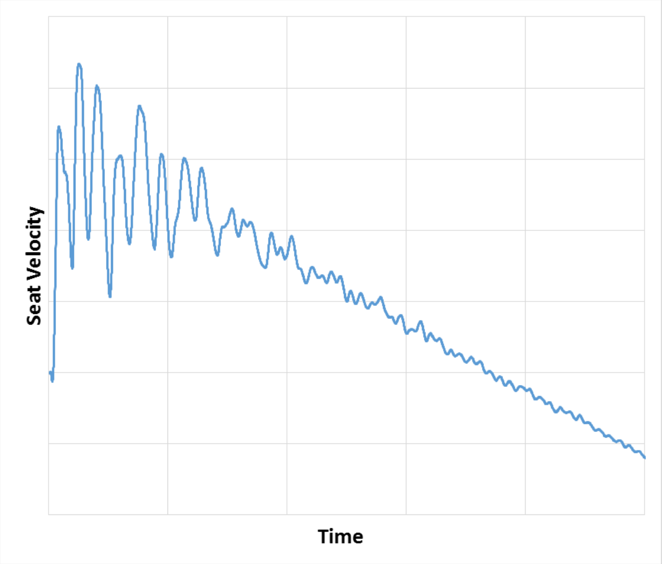

Figure 15: *Velocity history from the LOFFI-mounted accelerometer placed under the seat pan in Shot #3.*

During the initialization of the model, the results from the first run, the seating model, are included which means that the ATD is seated and the foam compressed at time zero for the blast run. This is a transient dynamic event with a simulation time of 100 msec. Again using a workstation with a single NVIDIA Tesla K40c GPU for the computation took around 7 ½ hours to complete the simulation. Figure 16 illustrates the position of the ATD at 100 msec for both the numerical simulation and experiment Shot #3. It is seen that the ATD response is visually similar.

Figure 16: *The ATD in the blast model at 100 msec. Left: Numerical model. Right: Image from high-speed video of Shot # 3. The seat and floor frame are displacement controlled with sampled values from the experiment.*

With a successful simulation of the blast event, the injury criteria can now be studied. All relevant information is gathered with sensors and written to the *dummy_sensor_1.out* file for post-processing.

Lumbar Compression Force

Figure 17 illustrates the location of the Lumbar Spine, which experiences large forces during a blast event. Minimizing this force is critical to protection against injuries.

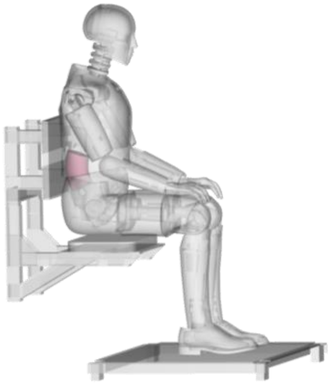

Figure 17: *Lumbar Spine in the ATD.*

A time history comparison of the numerical and experimental results (Shot #3 & #4) together with the experimental maximum and minimum band is illustrated in Figure 18.

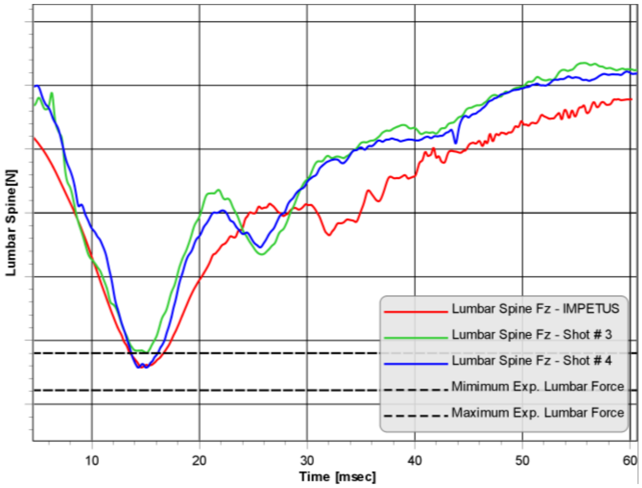

Figure 18: *Comparison of the numerical and experimental vertical Lumbar force showing reasonable matching.*

During the calibration of the Lumbar force it was found that the material properties for the foam in the seat significantly influences the magnitude of the peak force. Foam material properties from experiments performed by GD Land Systems were applied to the model. The loading on the ATD is significantly different from the load cases obtained in the previously shown SAE cases and revealed that parts of the ATD model needed to be improved. For example, it was determined that a change in joint stiffness and a change in the local coordinate system for the Lumbar force sensor was required.

It can be seen from the comparison that the numerical result follows closely the trend of the experimental time history. (The numerical result is time-shifted to overlay the peak obtained from the experiments owing to the delays associated with the physical blast and instrumentation system, which are not present in the numerical simulation.) It is very encouraging that the value and shape of the peak force is captured very well. Adding to this is the fact that the motion applied to the fixture is based on Shot # 3.

Lower Tibia Compression Force

The left and right Tibia are in the lower part of the leg, very close to the impact area during an under belly mine blast event. Thus, the Tibia forces need to be investigated to estimate the damage to the warfighter. The location is shown in Figure 19.

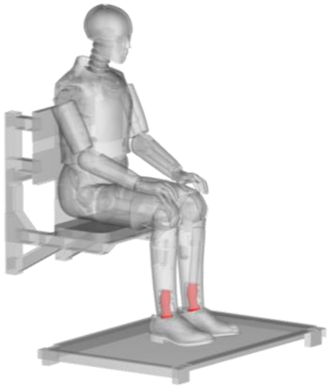

Figure 19: *Location of the left and right Lower Tibia in the ATD.*

The end result of the current calibration is seen in Figure 20 (Left Tibia) and Figure 21 (Right Tibia), where numerical data from the simulation is plotted together with experimental data from Shots #3 and #4 for comparison.

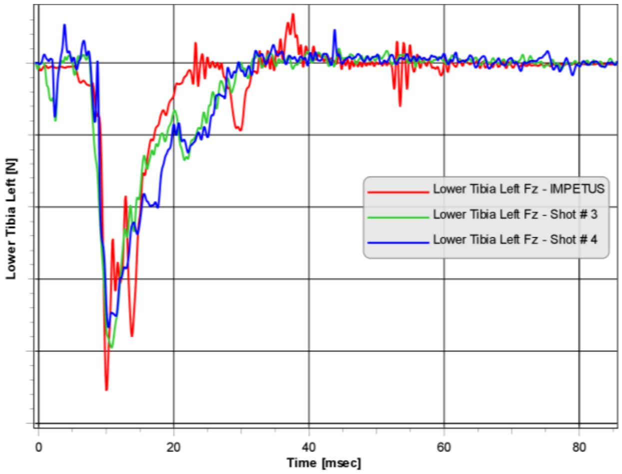

Figure 20: *Comparison of the numerical and experimental Left Lower Tibia force in vertical direction. Reasonable matching is seen.*

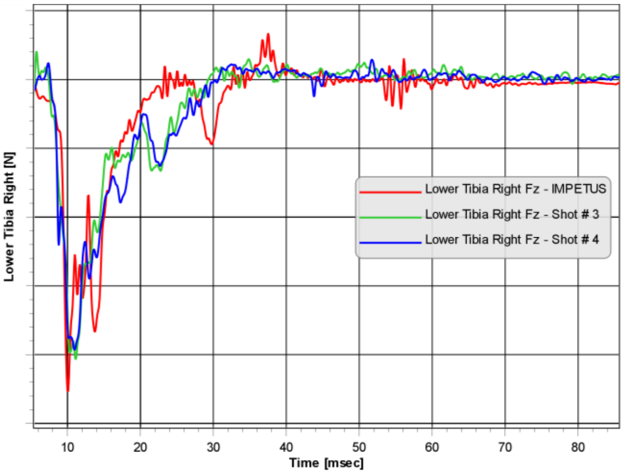

Figure 21: *Comparison of the numerical and experimental Right Lower Tibia force in the vertical direction. A reasonable matching is seen.*

The material behavior of the shoes was found to have a strong influence on the force values in the Lower Tibia. Furthermore, noise was seen in the force response which was related to the setting of the stiffness in the related joints. Both Figures 20 and 21 show a reasonable correlation between the numerical obtained values and experimental data from Shot #3 and #4.

SUMMARY

The IMPETUS model of the Hybrid III 50th Percentile Male ATD is described and three different SAE calibration cases have been verified, though a total of nine calibration tests exist for the ATD. A total of six blast tests were carried out at the General Dynamics Edgefield Blast Site and the measured injury results were presented. The experimental data was used to calibrate the numerical ATD for vertical loading as seen in a mine blast event. This is ongoing work – the first selected response parameters considered were the Left and Right Lower Tibia as well as the Lumbar Spine Force. These preliminary results show reasonable agreement between numerical and experimental data leading to a promising final calibration.

Current ongoing work is calibration of the Pelvis Acceleration and verification of the Dynamic Response Index (DRIz). The final step will be to place the ATD in a vehicle in a seated position with an under-belly IED loading for comparison with experimental data.

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