Development of the THOR-5F crash test dummy FE model and synergy with design support

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ABSTRACT

Alongside the hardware development of the THOR (Test Device for Human Occupant Restraint) 5th percentile female crash test dummy in cooperation with NHTSA, the development of the THOR 5th FE model is also well underway. The THOR 5th is an advanced small female crash test dummy and referred hereafter as THOR-5F. The main objective of the current paper is to describe detailed FE model development and biofidelity evaluation of the THOR-5F FE model. The paper also presents design support using the FE modeling for the THOR-5F ankle joint hardware design.

As with all FE models, geometry, material modeling and structural connectivity are of focus when developing the THOR-5F FE model. All the instrumentation and sensors are accurately realized in the model. Furthermore, it has first-hand access to the physical counterpart that allows the model to incorporate the latest hardware design features. The THOR-5F FE model is then evaluated against over 20 biofidelity tests from head to toe for functionality and performance evaluation. The current paper presents selected biofidelity test validations.

The THOR-5F FE model showed promising functionality and performance for the evaluated biofidelity validation cases. Concurrent development of the FE model enabled the hardware team a possibility to evaluate the concept design aimed to meet the biofidelity requirements, reduce design cycle and reduce production cost by performing the FE analysis prior to manufacturing hardware parts. This paper illustrates in particular the ankle design improvement in the THOR-5F hardware supported by the FE analysis. Such synergy between hardware and FE complements each other for the improved hardware design and better model predictability and performance.

The first FE model of the THOR-5F will be released in the 3rd quarter of 2017. This highly anticipated model will consist of a state-of-the-art mesh and appropriate connectivity, instrumentation, basic material models and preliminary validations to all available biofidelity tests to ensure the model functionality. The model will be validated rigorously against additional test load cases as they become available.

INTRODUCTION

A total of 32,675 people lost their lives in motor vehicle crashes in 2014 [1]. In the same year, a total of 42% of passenger vehicle severity and property damage incidents occurred that resulted from the passenger vehicles with initial point of impact in the front of the vehicle [1]. The similar trend of front initial point of impact in vehicles was observed in other vehicle types such as light and large trucks. This data suggests that the frontal crash mode is one of leading causes of fatal and serious injuries to the occupant despite the enhancements in occupant protection during frontal crashes and should be given prime focus.

One such program for the frontal crash safety by National Highway Traffic Safety Administration (NHTSA) is the United States New Car Assessment Program (US NCAP). The US NCAP requires use of Hybrid 3 (HIII) 50th percentile male and 5th percentile small female adult anthropometric test device (ATD) commonly known as “crash test dummies” for its full width frontal barrier vehicle test protocol to evaluate the vehicle crashworthiness and occupant protection in frontal crashes. The crash test dummies are also employed by government, industry and non-government agencies in a variety of vehicle crash testing for the evaluation of occupant protection performance.

One of the emerging areas in occupant protection is the development and implementation of sophisticated and more biofedilic (human like) crash test dummies to be used in the evaluation of vehicle performance. One such crash test dummy, the Test device for Human Occupant Restraint (THOR) is an advanced frontal ATD that incorporates improved biofidelic features and significantly expanded instrumentation enabling crash test engineers to investigate injury pathways not included in the design of the Hybrid III family dummies currently being used in US NCAP frontal test protocol. The THOR dummy concept was sought in 1980’s as an advanced frontal ATD for both the adult male 50th percentile and small female 5th percentile representations similar to the Hybrid III 50th and 5th dummies, respectively. The earlier prototype for the THOR-5th percentile dummy was developed in early 2000’s. Recently, the THOR 5th percentile small female advanced ATD hardware is under development as a possible successor to the HIII 5th percentile crash test dummy.

Concurrent to THOR-5F hardware development, the presented work highlights development of the THOR-5F ATD finite element (FE) model. Although this dummy FE model is evaluated for a variety of biofidelilty loading conditions which is required for the hardware to meet, the current paper is limited to present selected biofidelilty loading conditions in the head, neck, thorax, and lower leg regions of THOR-5F FE model. Additionally, the paper also presents the ankle joint design support for the hardware design and development with the support from the FE simulations.

THOR-5F FE MODEL DEVELOPMENT

As described earlier, the THOR-5F is an advanced frontal ATD with a lot more complex features and measurement capabilities. It has a total of 174 data channel capabilities and extensive biofidelilty requirements. The THOR-05 FE model incorporates all the complex features in great details. All the sensors and instrumentation are modeled in the FE model to have similar injury predictive capabilities as the hardware. Since the THOR-5F FE model development has been carried out concurrently with the development of the dummy hardware, this has allowed the model developers to ensure that the latest hardware changes are represented in the model in the most physical way.

Figure 1 shows the THOR-5F FE model representation and also the mid sagittal sectional view of the model to highlight the interior features. The total THOR-5F FE model element count is more than 0.6 million and the node count is less than 0.5 million with a time-step size close to 0.7 micro-second which is in line with the common industry practices and user expectations.

The THOR-5F model is currently being evaluated against over 20 biofidelity tests to ensure the model functionality. Only selected cases as described in Table 1 are presented in the current study. A detailed test plan containing additional component, sub-assembly and full dummy level validations for a wide variety of loading conditions at various levels of complexity is under way to ensure that model’s predictive capabilities are as high as possible.

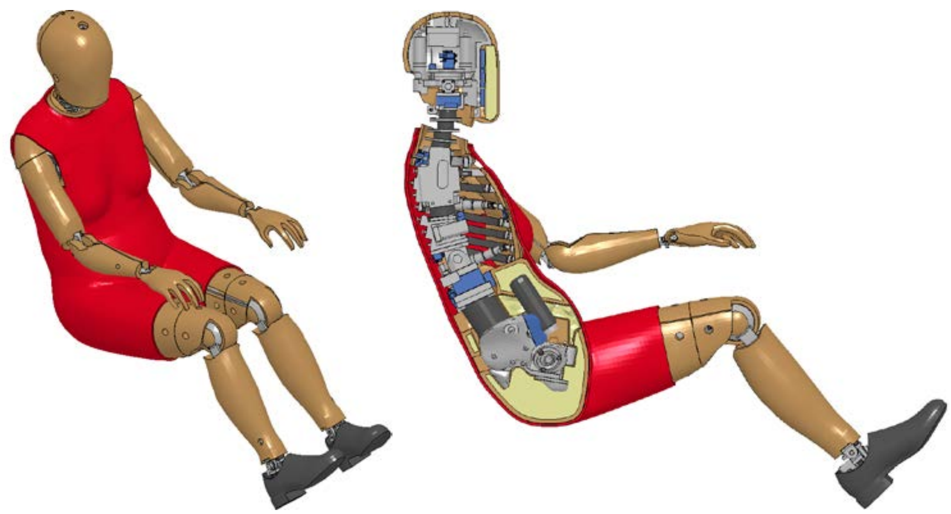


Figure 1. THOR-5F FE model with mid sagittal sectional view (on right).

Table 1. Biofidelity Test Evaluation for FE model.

Region	Load-Case [Reference]
Head	Forehead Probe Impact [2]
Neck	Frontal Flexion (Mini Sled) [3]
	Lateral Flexion (Mini Sled) [4]
Torso	Upper Ribcage Probe Impact [5,6]
Leg	Ankle Eversion [7]

THOR-5F FE MODEL BIOFIDELITY EVALUATION

Head – Forehead Probe Impact

The head of the THOR-5F consist of skull and skin. The skull incorporates a set of accelerometers and angular rate sensors (ARS) to measure the 3D head kinematics. The face of the head comprises of five face load-cells (2 eye, 2 cheek and 1 chin) to measure the compressive loads on face. The mid-sagittal sectional view of the head FE model is shown in Figure 2.

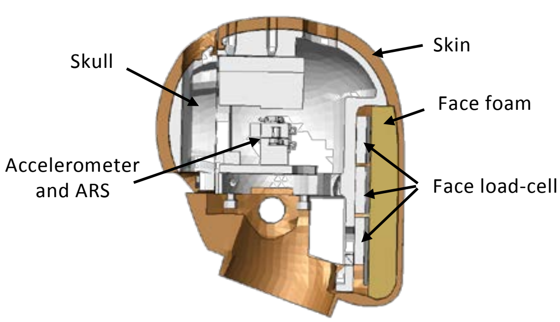


Figure 2. THOR-5F FE head model.

The biofidelilty test data is derived from Melvin and Weber (1985) [2]. The test setup requires torso being maintained straight vertical on a horizontal, flat, rigid surface with unsupported back. The head of the dummy is placed such that the axis of the probe is aimed on the forehead in the mid-sagittal plane, 26 mm above the horizontal line through nasion landmark. The tilt of the dummy head/neck assembly is adjusted so that the impact area on the head is parallel to the face of the probe. The model setup for this loading condition is shown in Figure 3.

The biofidelity response requirement for this load case is a probe force versus time specification as shown in Figure 4. The force in model is measured as contact force between probe and head.

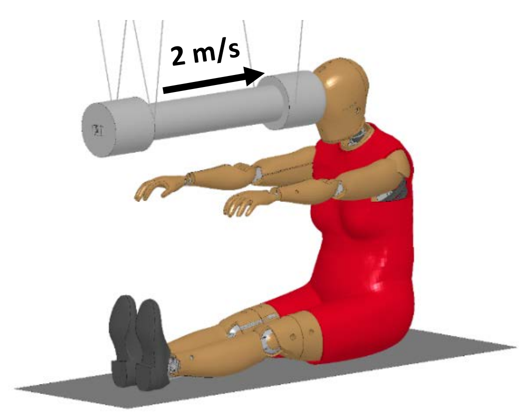


Figure 3. Forehead probe impact model setup.

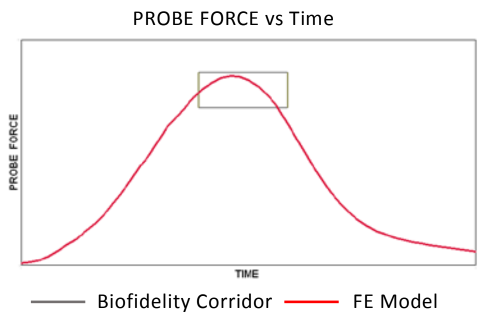


Figure 4. Forehead probe impact model response against biofidelity specification.

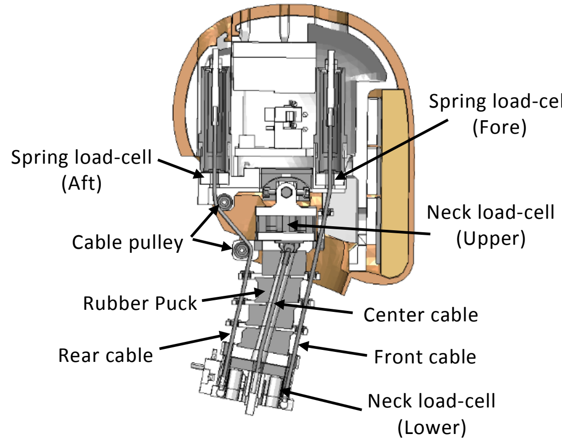


Figure 5. THOR-5F FE neck model.

Neck – Flexion Mini Sled (Frontal and Lateral)
The THOR-5F neck assembly consists of complex structures. The mid sagittal sectional view of the THOR-5F FE neck model assembly is shown in Figure 5. The neck comprises of a series of aluminum disks and rubber pucks. The elliptical rubber pucks along with all the three cables (center, front and rear) provide the desired frontal and lateral bending responses for the neck. Fore and aft springs located in the skull and connected to front and rear cables enhance the biofidelic behavior in the THOR-5F neck. The rubber soft stops (flexion and extension stops) attached at the base of the neck provide desired bending characteristics in both flexion and extension. The instrumentation for the THOR-5F neck assembly includes a pair of spring load cells to measure the compression at the fore and aft locations, the upper and lower neck load cells to measure neck forces and moments, and a rotary potentiometer at the condyle pin to measure the relative rotation between the head and top of the neck.

The THOR-5F neck is validated for the neck flexion in frontal and lateral loading in the mini sled. The setup for the validation is shown in Figure 6. The dummy head and neck assembly is rigidly mounted to the sled at the base of the lower neck load cell. The head and neck assembly is positioned for a frontal flexion test with the front of the head facing the front of the sled. For the lateral loading, the head and neck assembly is rotated 90 degrees and the head front was facing 90 degrees to the direction of the sled. The target input to the sled is the acceleration pulse for frontal loading [3] and lateral loading [4].

Displacement of head CG and T1 landmark in FE model are tracked for displacement time-history. The head and neck rotations are measured as the rotation vector connecting T1 landmark with the head CG in the model. Head and neck angles and trajectory displacements are compared to the available biofidelilty corridors and presented in Figures 7 and 8 for the frontal and lateral loading, respectively.

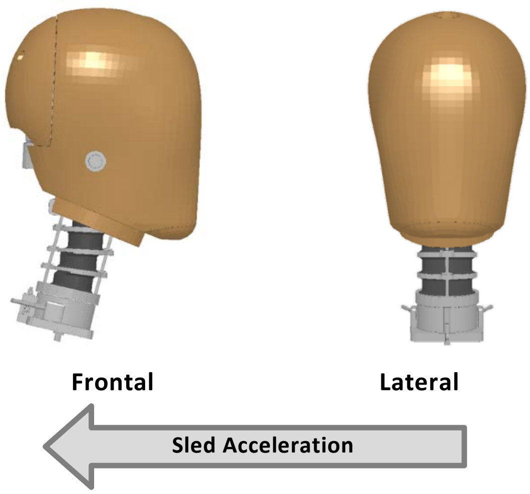


Figure 6. Neck flexion mini-sled model setup.

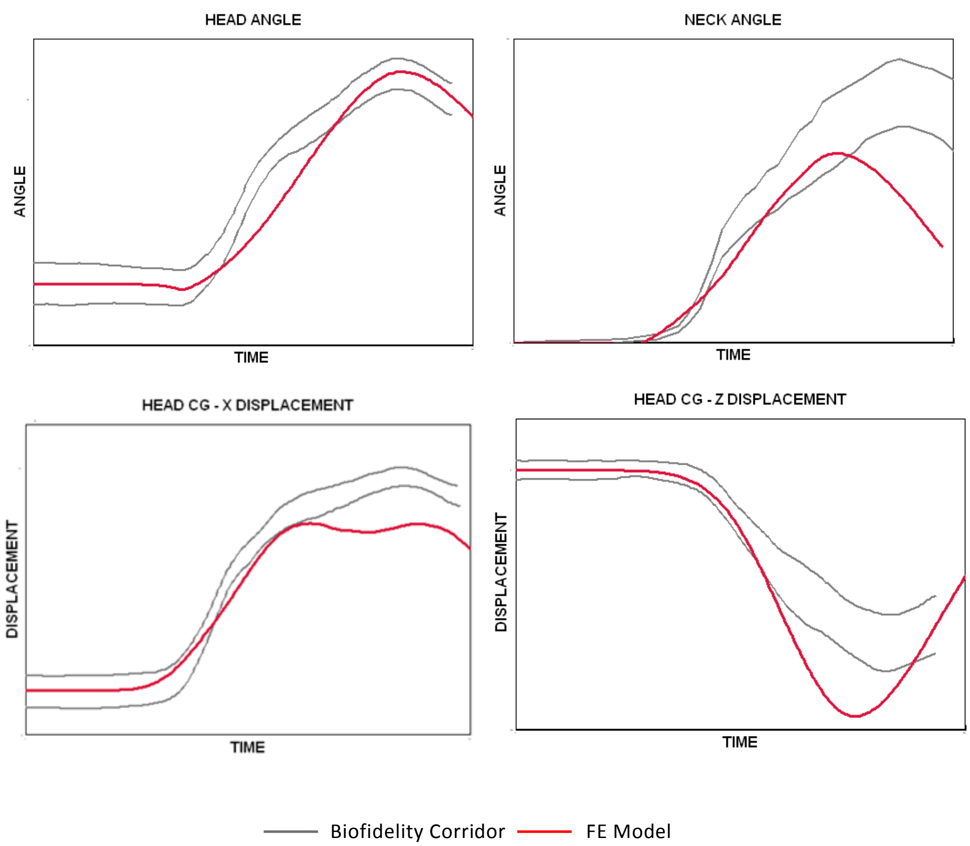


Figure 7. Neck frontal flexion mini-sled response against the biofidelity corridors.

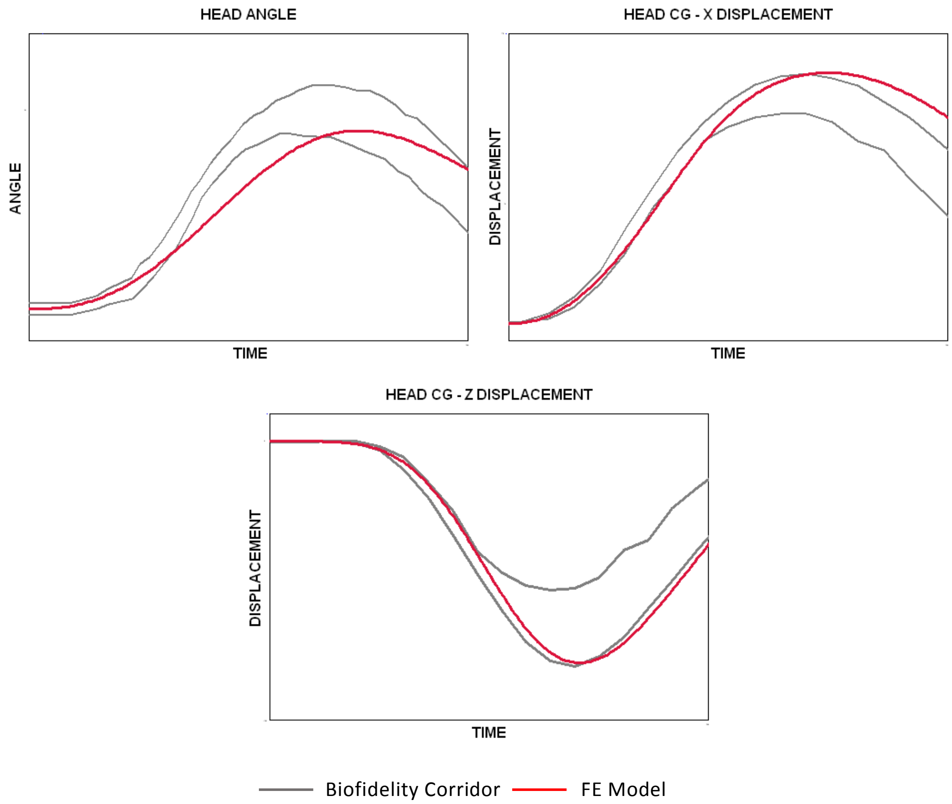


Figure 8. Neck lateral flexion mini-sled response against the biofidelity corridors.

Torso – Upper Ribcage Probe Impact

The THOR-5F torso hardware consists of a complex structural aspect involving ribs, sternum with integrated breasts, spine box shown as sectional view in Figure 9. The torso of the THOR-5F is instrumented with many sensors including accelerometers, ARS, load-cells and two Infra-Red Telescoping Rod for the Assessment of Chest Compression (IRTRACC) in the upper and two IRTRACC in lower ribcage areas. The most important sensor from thorax injury prediction perspective in automotive safety is the chest compression. It is used to measure how much the sternum (front of the chest) compresses relative to the spine box. The THOR-5F model accurately captures all structural, geometric and instrumentation aspects of its hardware counterpart. The materials in THOR-5F model such as foams, rubbers, bib and ribs are modeled using the best available options from the FE material library.

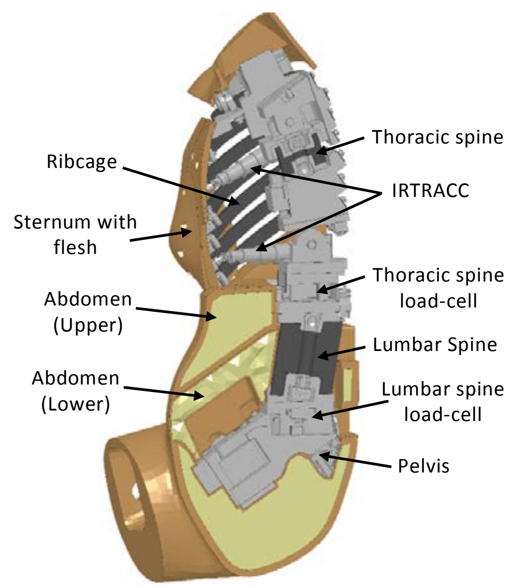


Figure 9. THOR-5F FE torso and pelvis model.

The upper central ribcage probe impact setup is shown in Figure 10. The model is setup in a sitting position without any back support and legs and arms raised to be horizontal to the ground. The probe impacted model such that centerline is at rib #3 level and positioned over the mid-line of the sternum.

Two sets of biofidelity response data are used for model comparison. The external chest compression data are derived from the biofidelity corridors by Lebarbe et al. (2012) [5]. The force is measured as the contact force between the model and the probe and the displacement is measured as the tracked point at the front of sternum along the probe centerline to the spine box.

For the internal chest compression, two upper IRTRACC data from the model are averaged to get the sternum displacement and the forces are measured in the similar way as the contact force between model and the probe. For internal corridors, the response curves are obtained from Neathery et al. (1974) [6].

The results for the model comparison to internal and external biofidelity response corridors are presented in Figure 11.

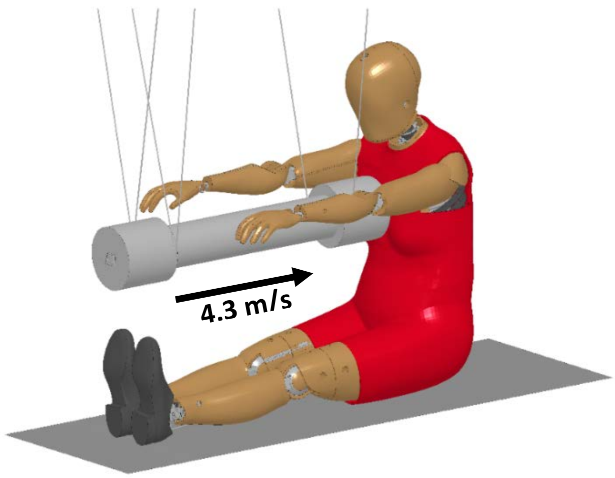


Figure 10. Upper ribcage probe impact model setup.

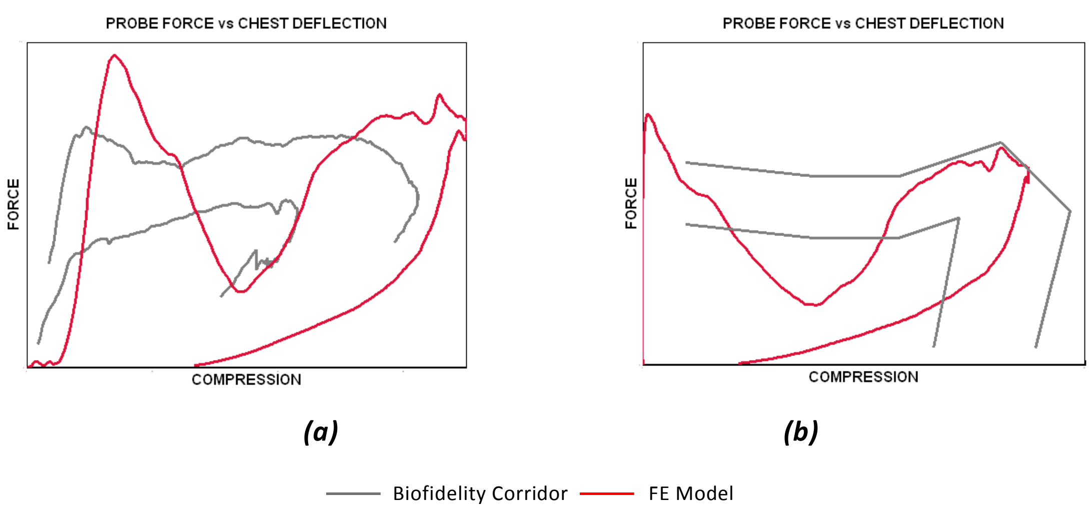


Figure 11. Upper ribcage probe impact response against biofidelity corridors (a) external (b) internal.

Leg – Ankle Eversion and Ankle Design Support

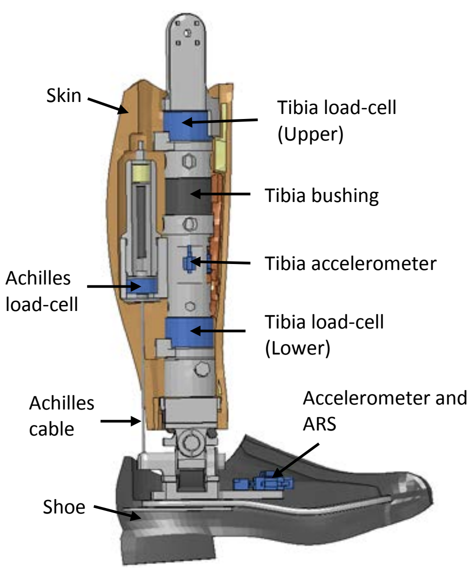
The lower leg of the THOR-5F hardware consists of tibia, molded shoe, Achilles cable. The ankle joint has three rotational degree of freedom with three rotary pots to measure the local rotation of the ankle joint. The lower leg also consist of three load-cells: Achilles load-cell and upper and lower tibia load-cell to measure loads and moments in the tibia. The foot and tibia also have multiple accelerometers and ARS to measure lower leg kinematics. The model is represented very closely to the hardware design and is shown in Figure 12.

The model is evaluated for one of the lower leg (ankle joint) biofidelity test validations derived from Funk et al. (2002) [7]. The model setup is shown in Figure 13. To mimic the hardware setup, the shoe of lower leg were removed and the ankle plate was mounted on the center of an external foot plate. The knee clevis bone was constrained such that only the tibia axial (along Z axis, Figure 13) translation is permitted. Rotation of the ankle joint was achieved by rotation of foot plate as depicted in Figure 13 for the eversion of the ankle. The ankle rotary pot and the lower tibia load-cell moment were recorded in the model for comparison to the biofidelity response corridors.

The initial FE iterations for the ankle eversion loading case revealed that the original design of the ankle as shown in Figure 15 posed unstable deformation of rubber bumpers. The rubber bumper material slid off the wing shape center block instead of compression and hence rubber bumper was not providing any stiffness and support to the ankle joint.

A new hardware design was iterated with the support from FE simulation to optimize the shape of the rubber materials and the center block to better engage rubber bumpers. The original and new ankle design comparison is shown in Figure 14.

The new design showed improved behavior and sensitivity to the rubber bumper material change. The original and new eversion rubber design FE model response comparison against the biofidelity corridor requirements are presented in Figure 15. The new design gave hardware team the possibility to change the composition of the eversion rubber bumper material to achieve the desired stiffness of the ankle joint.



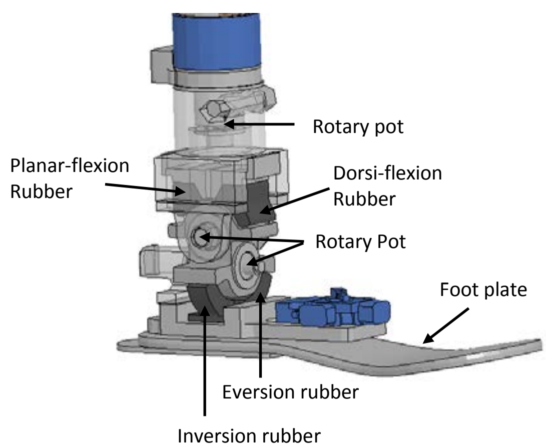


Figure 12. THOR-5F FE lower leg model (left) and details of ankle assembly model (right).

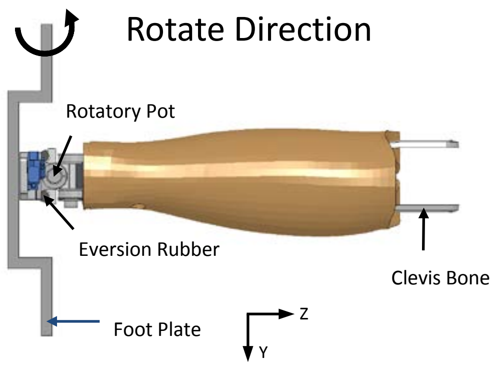


Figure 13. Eversion case FE model setup for the ankle joint.

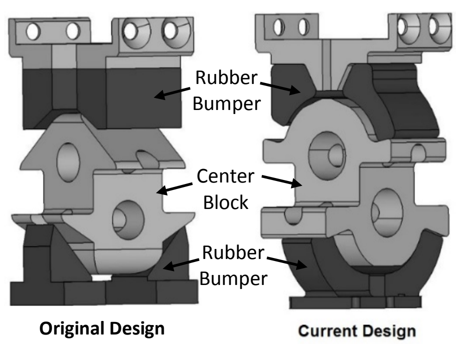


Figure 14. Comparison of the original and new ankle joint design after FE simulations.

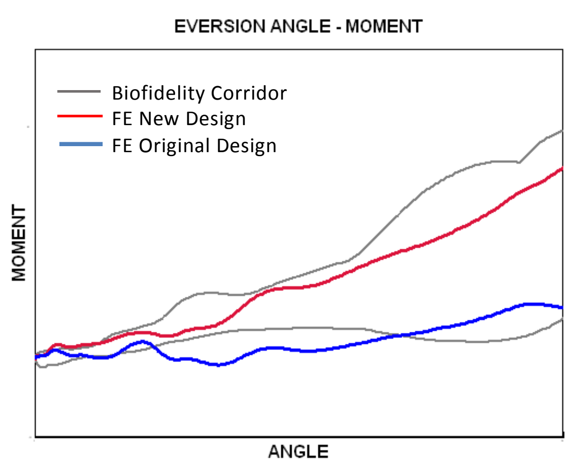


Figure 15. Comparison of the FE model original and new ankle joint design against biofidelity corridors.

DISCUSSION

The limitation for the biofidelity corridors are that they have been derived from scaling down of the cadaver data from the 50th percentile anthropometric representation. The other limiting factor for the current response is the materials from the best possible sources as hardware is currently being developed concurrently. Further material and hardware testing are planned to enhance the model in the most physical way.

CONCLUSIONS

Following conclusions can be drawn from the presented study:

- A very detailed THOR-5F FE model is being developed.
- All the hardware complexities of the structure, material, and instrumentation of the dummies are reasonably captured using the best possible features in the FE solver.
- The model demonstrate promising functionality and performance while computationally being cost-effective.

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