UPDATES OF THE LOWER EXTREMITY OF THOR-NT 50th FINITE ELEMENT DUMMY TO MOD-KIT SPECIFICATION

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ABSTRACT

This manuscript describes updates made to the lower extremity (knee-thigh (KT) and leg) of the THOR-NT 50th percentile finite element (FE) dummy, based on the geometry and mechanical characteristics of the THOR Mod Kit (MK) revision.

The geometry and mass of the FE KT region were updated to the same specifications as the THOR-MK design. The FE model knee-thigh compression and knee stretch responses were within the experimental test corridors and met the certification and biofidelity requirements of the THOR-MK. The model response from the knee pendulum impact test matched the dummy certification test data and was within the two first priority corridors of the knee slider certification requirements. An FE model of the molded shoe was developed using a three-dimensional scanning tool. The shoe model was validated using heel and ball-of-foot impact tests, and the simulated responses matched the experimental data. Three load cell modeling approaches were investigated and the locking joint method was the best approach considered for modeling load cells as rigid bodies.

Model updates to the THOR lower extremity and associated instrumentation were integrated into the THOR-NT FE dummy. The updated THOR-NT FE dummy model with the Mod Kit specifications in the lower extremity has the potential of providing improved responses in the frontal sled simulation and other applications.

INTRODUCTION

The Test Device for Human Occupant Restraint (THOR) anthropometric test device (ATD) was developed by National Highway Traffic Safety Administration (NHTSA) to improve upon the performance of the Hybrid III ATD (Haffner et al., 2001). Recently, Untaroiu et al. (2011) have performed the sensitivity analysis to assess the occupant injury risk using the THOR-NT finite element (FE) model undertaken by NHTSA. Choi et al., (2005) conducted the FE modeling effort of the THOR lower extremity and model verifications under different loading conditions and showed good agreement with the quasi-static and dynamic experimental results. Numerical simulations of a 40 % offset frontal crash with a small sedan and FE dummy models were performed and improved capabilities of the THOR lower extremity FE model were presented to assess the lower limb injury risk (Choi et al., 2005).

Recently, a hardware update to the THOR ATD (known as the THOR Mod-Kit) was developed to improve the durability, usability, and biofidelity of the THOR-NT ATD (Ridella and Parent, 2011). Included in this update were modifications to the lower extremity. The deformable length of the assembled femur was increased by 57% to match the biomechanical response of the human femur subjected to an axial impact at the intact knee (Rupp et al., 2003). The knee slider certification procedure and the newly-developed biofidelity requirement were adopted as the THOR-MK requirements to validate the knee slider biomechanical responses (Ridella and Parent, 2011; Balasabrarian et al., 2004). The softening of the rubber shear section of the knee slider and larger bumper stop were also implemented to improve the stiffness response. Finally, a one-piece molded shoe was developed to replace a military-specified (MIL-spec) shoe and a molded rubber foot, and improve the repeatability of the ATD response (Ridella and Parent, 2011).

Similarly, the FE model of the THOR-NT dummy was modified to incorporate the updates of the MK version of THOR. The objective of this paper is to describe the updates to the lower extremity of the THOR-NT FE dummy model and to validate the model based on the specifications for the THOR-MK ATD. Model validation was based on certification tests to the femoral shaft, knee slider, ankle joint, and molded shoe. The updated and validated lower extremity model of the THOR-MK was integrated into the whole THOR-NT FE model.

METHODS

Model Update and Validation of the Femoral Shaft

Modifications to the FE model were made to the new femur puck, guide system, load cell, and the interior rigid bar based on the updated geometry of the THOR-MK femoral shaft provided by NHTSA (Figure 1a). The densities of femoral guide system and thigh flesh were changed from 3.06 g/cm^3 to 2.63 g/cm^3 and from 0.44 g/cm^3 to 0.369 g/cm^3 respectively to meet the mass and inertial properties of the updated femur mechanical assembly (2.51 kg) and thigh flesh (1.05 kg). The geometry of the femoral puck (a compliant component to provide the compressive stiffness along the longitudinal direction of the femoral shaft) was revised to match the dimensions of the new puck design. Femoral puck response was based on the compression tests conducted by Humanetics Innovative Solutions, Inc during the development of the mod kit. Simulations of the femur puck compression consisted of a flat rigid plate compressing the femoral puck up to 15 mm at a rate of 1 m/s (Figure 1b). Compression force and displacement were recorded during the simulation, and parameters for a linear viscoelastic constitutive model were calibrated through a parametric study to match the experimental stiffness data.

The knee-thigh (KT) impact simulations were performed using the updated femur puck model to validate the computational response of femur shaft against the test data reported by Rupp et al. (2003). The femoral head was restraint from translational movement and the longitudinal axis of the femoral shaft was aligned with the impact direction. The knee had a flexion angle of 90°. The molded impactor (impactor with a molded face same as knee flesh) was controlled using a prescribed displacement time history and the impact force was recorded for comparison with the experimental test data (Figure 2).

a)

b)

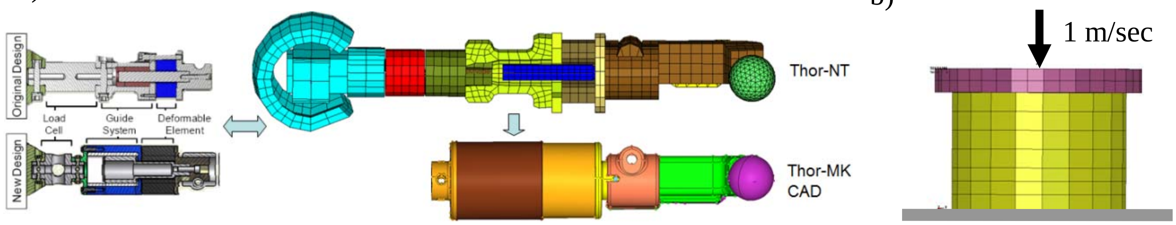

Figure 1. a) Femur shaft model update based on THOR-MK CAD data provided by NHTSA and b) compression test setup of THOR-MK femur puck model.

a)

b)

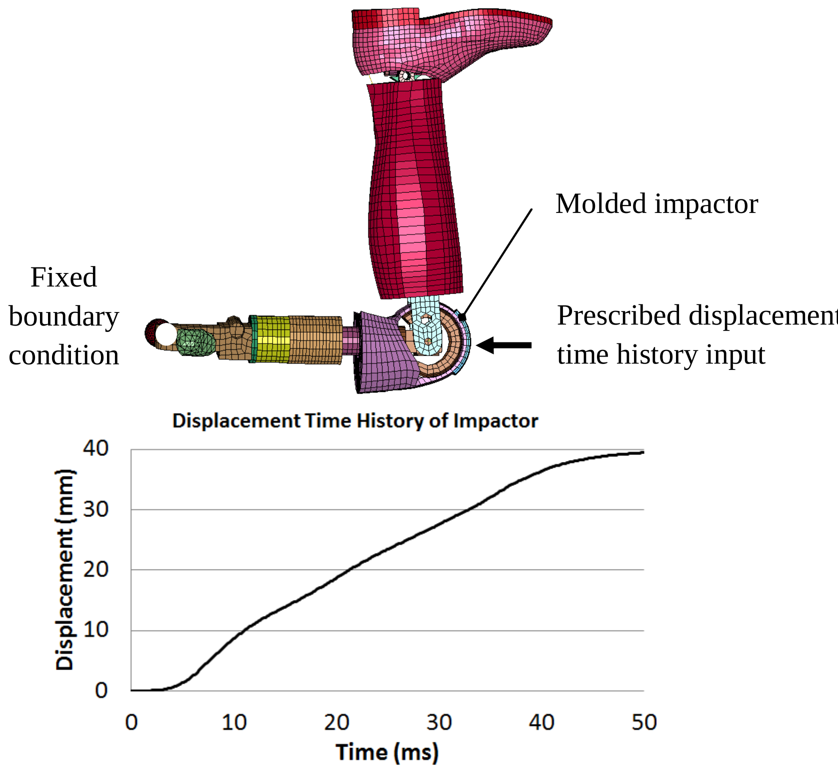

Figure 2. a) KT impact test setup (Rupp et al., 2003) for THOR-MK femur shaft FE validation and b) imposed displacement time history of impactor.

Model Update and Validation of the Knee Slider

The THOR-NT knee slider was modified to meet the newly-defined biomechanical response requirements for knee impact (Ridella and Parent, 2011). The previous THOR-NT FE dummy model did not include the knee slider and was limited in its ability to represent loading to the upper tibia. Therefore, a new FE knee slider model was integrated into the lower extremity model to simulate the response of the updated physical knee slider.

The knee slider consists of two articulating pieces connected by a sliding joint interface. The body of the knee slider (shown in green in Figure 3b) can rotate freely within the rigid knee assembly (shown in orange in Figure 3b), while the outermost component of the slider (shown in blue in Figure 3b) can translate relative to the knee slider body. Translation between the outermost and knee slider body components is resisted by the shear deformation of the rubber connecting the two pieces. The outermost component is connected to the leg clevis, allowing the translational joint to rotate with the lower leg relative to the knee. Computationally, these joints were modeled as kinematic joints, with free rotation of the knee slider body relative to the knee and restrained translation of the outermost component of the slider relative to the knee slider body. The translational joint restraint was defined based on certification test data from tests on the physical ATD (Figure 11a). A stopper was modeled in front of the knee translational joint to prevent movement in the opposite direction.

a) b)

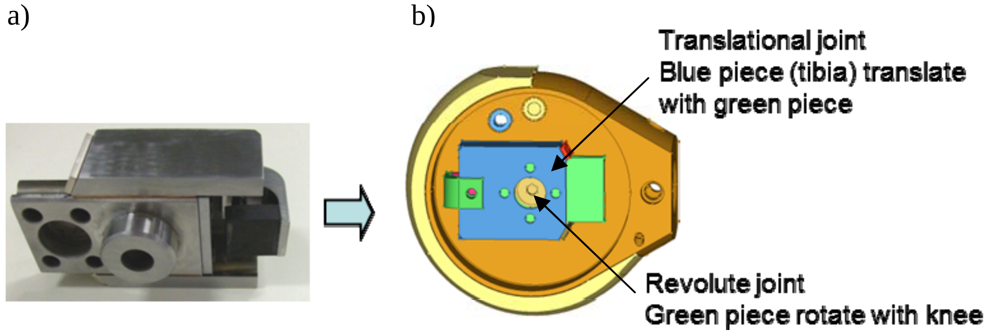

Figure 3. a) Physical knee slider of THOR-MK and b) three dimensional drawing of knee slider.

The stiffness response of the newly designed knee slider model was verified using the pendulum impact certification test on the physical THOR-MK ATD. This test mirrors the Hybrid III knee slider certification test, with a pendulum weight of 12 kg and impact surface diameter of 76.2 mm (Figure 4a). A 14.5 mm thick piece of low-density foam was placed between the knee clevis and the impactor. The knee clevis model was connected to the knee translational joints with two rigid beam models to ensure the force transmission to the knee rotational center. The knee translational joint was aligned with the impact direction and the pendulum model impacted the knee clevis with an initial velocity of 2.75 m/s. The displacement time history of the knee clevis and the reaction force at the femur shaft were recorded for response comparison with experimental data (Figure 4b).

Furthermore, the updated knee slider FE model was validated against the knee shear response of post mortem human subjects (PMHS) provided by Balasubramanian et al. (2004) for biofidelity check. The knee and leg model was set up with a 90° angle relative to the femur shaft and a constant velocity of 1.8 m/s along the anterior-posterior (A-P) direction was imposed to the tibia shaft. The reaction force at the femur shaft was processed using a SAE low-pass filter of 600 Hz (as done in the experimental test) to compare the model to the test data (Figure 4c).

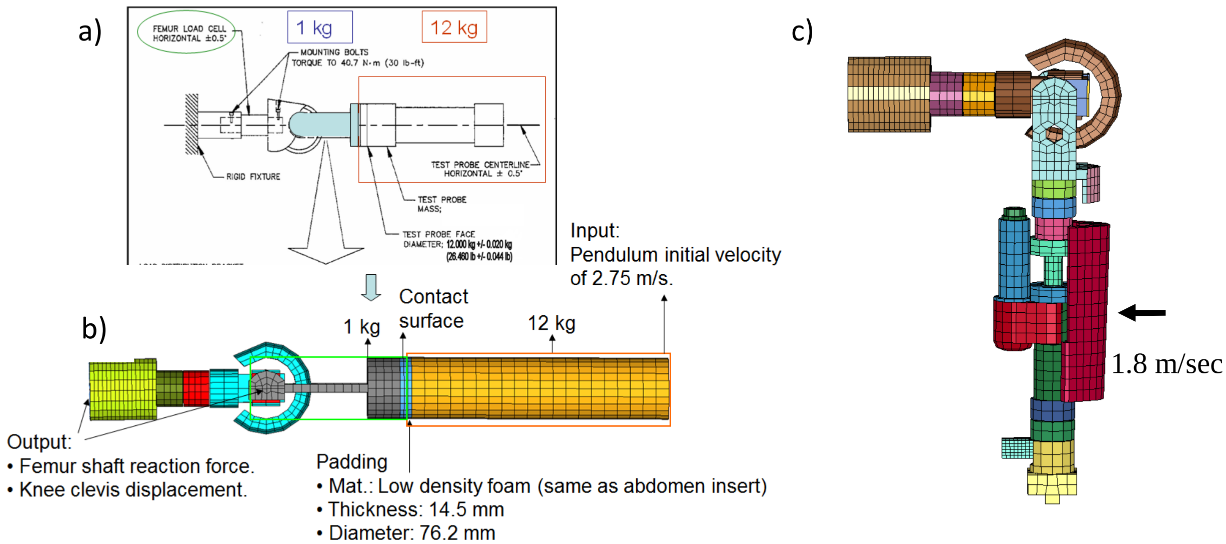

Figure 4. Certification validation setup of THOR-MK knee slider; a) physical certification test setup, b) FE simulation setup, and c) biofidelity validation setup based on the experiment performed by Balasubramanian et al. (2004).

Development of Molded Shoe Model

Because the three-dimensional geometry data for the THOR-MK molded shoe was unavailable, shoe geometry was obtained by scanning the surface of the molded shoe using a high speed laser scanning coordinate measurement machine (Focus 3D, FARO Technologies, Lake Mary, FL). The shoe was prepared by taping the outer surface for better scanning quality, and multiple scans were taken to ensure clean and complete surface data of the shoe. The FARO Scene software package was used to align all scans into a single point cloud (2.4 million points) and filter the data to eliminate outliers and noise (Figure 5).

A three-dimensional solid mesh of the molded shoe volume was generated in Hypermesh (Altair Engineering, Troy, MI) using the final point cloud dataset. The molded shoe FE model consisted of 2072 nodes and 1481 elements (Figure 5). Most elements in the shoe model (approximately 90%) were hexahedral elements with good mesh quality (minimum Jacobian of 0.57). The shoe material was modeled using a linear viscoelastic constitutive model with the material parameters calibrated using the dynamic heel impact test data (refer to next section). The total mass of the FE shoe model (1.38 kg) was close to the mass of the physical molded shoe (1.32 kg). The one-piece molded shoe FE model has replaced a military-specified (MIL-spec) shoe and a molded foot rubber of the THOR-NT FE model.

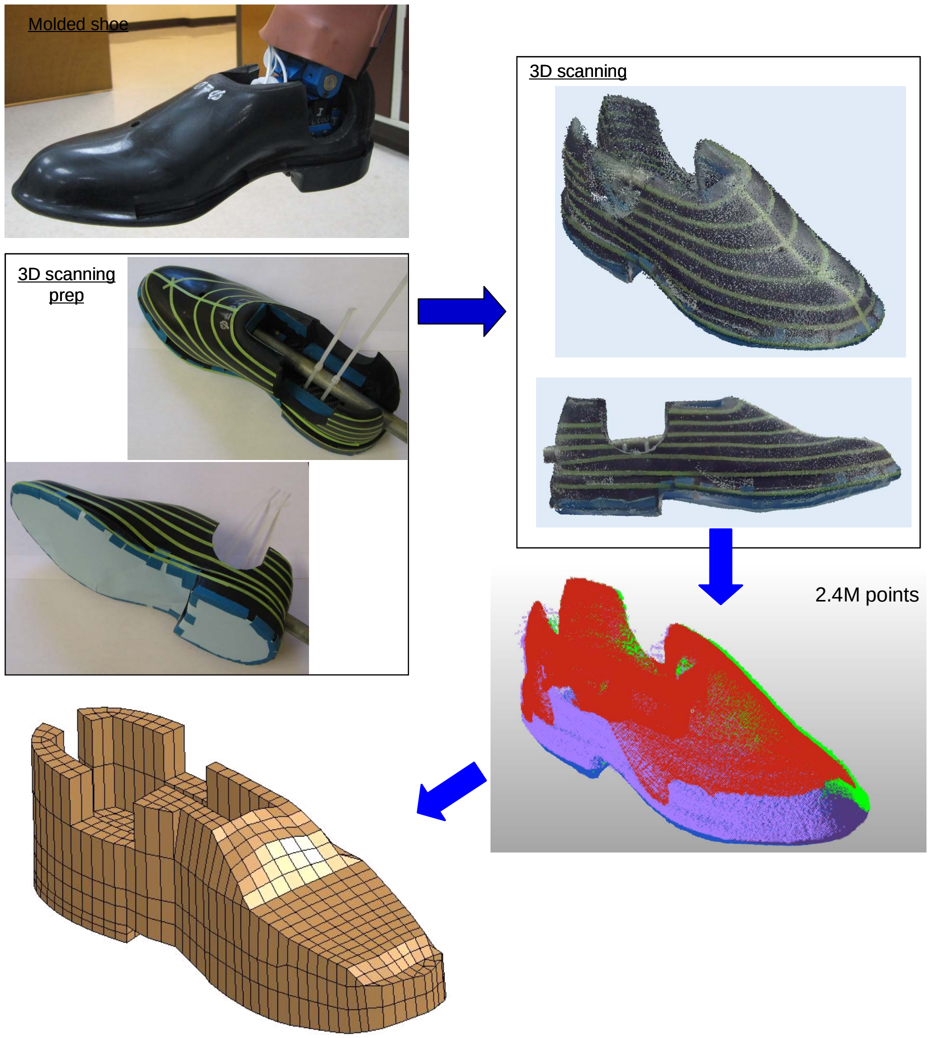

Figure 5. Development process of molded shoe FE model using the 3D laser scanning tool.

Heel and Ball-of-Foot Impact Tests and Simulations

The dynamic heel and ball-of-foot impact tests specified in the certification procedures for the THOR-LX were performed to validate the performance of the ankle and the compliant elements in the foot and tibia (NHTSA, 2004). There are two certification tests that specify impact with the 5.0 kg NHTSA dynamic impactor (cylinder shape with 63.5 mm diameter, NHTSA, 2004) to the molded foot: a heel impact at 4.0 m/s and a ball-of-foot impact at 5.0 m/s. These tests were conducted using the updated molded shoe of the THOR-MK hardware. The pendulum arm was mounted to a rigid shaft that pivoted on a low friction ball bearing. The proximal tibia was fixed rigidly with the Achilles cable and the toe pointing upward (0° flexion for heel impact and 15° plantar flexion for ball-of-foot impact, Figure 6). The impact point was aligned with the longitudinal axis of the tibia for heel impact tests, and 102.5 mm anterior of the dorsi-plantar joint for the ball-of-foot impact tests. The compressive force was measured in heel impact tests, while the force and moment time histories at the lower tibia load cell were recorded to calculate the ankle resistive moment and rotational displacement time histories were recorded. Six tests were run for each impact condition, and all data was processed using CFC600 filters.

To verify the updated THOR-MK molded shoe model, foot, and ankle response, heel and ball-of-foot impact simulations were performed. The heel impact simulations were performed with the FE shoe in the horizontal position, while the shoe FE model was rotated from 15° of plantarflexion to the neutral position and the Achilles cable was adjusted to match the ball-of-foot impact test configuration. The translational joint model and load cell model at the upper tibia were removed to mimic the certification test configuration (Figure 6). A linear viscoelastic material model was used for the molded shoe and the material parameters were iteratively tuned until the tibia force time history from the heel impact simulation reasonably represented those from the experiments.

The center of the impactor was aligned with the center of the dorsi-plantar joint for the heel impact simulation, and the impactor was set 102.5 mm anterior of the ankle joint for the ball-of-foot impact simulation. The impact speeds were 4 m/s (heel impact simulation) and 5 m/s (ball-of-foot impact simulation). The mass of the impactor was 5 kg in both simulations. The force time history of the lower tibia load cell was calculated in the heel impact simulation, while the ankle moment time history was determined in the ball-of-foot impact simulation.

a) b)

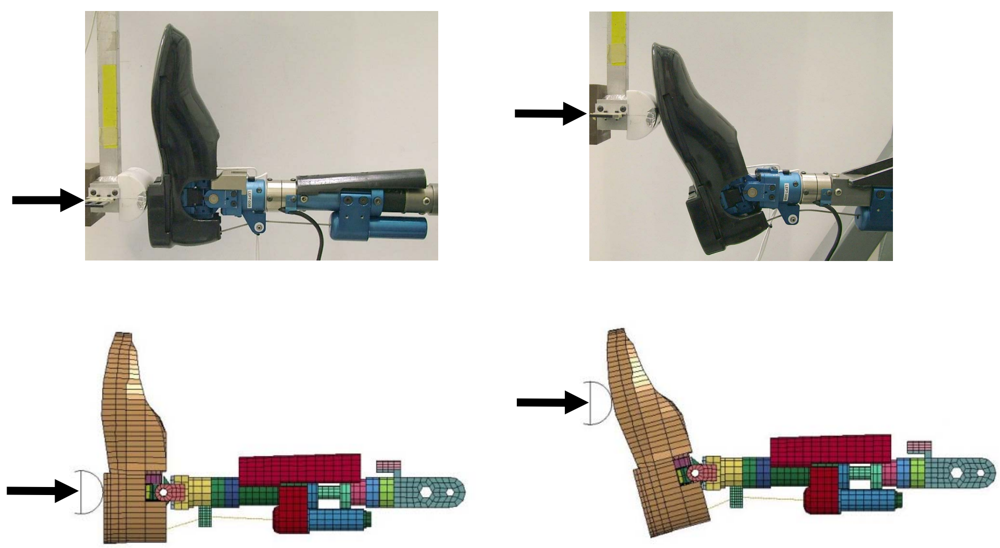

Figure 6. THOR-MK impact test and simulation setups of a) dynamic heel impact and b) dynamic ball-of-foot impact.

Investigation of Load Cell Modeling

To evaluate the force and moment output capabilities of the THOR-MK model, three modeling approaches were considered for modeling the load cells: the locking joint, the cross-section definition, and the beam element output. The simplified load cell was modeled as two pieces (Figure 7a), and the three different types of load cell models were setup connecting two pieces. The locking joint approach connected both pieces by fully constraining their relative motion, and forces were calculated as the reaction force to satisfy this constraint. The beam element approach connected both pieces by a zero-length beam with high stiffness for all six degrees of freedom, and forces were calculated from the small deflections of the beam. The cross-section approach connected the pieces with shared nodes, and the sum of forces was calculated at this interface.

The local coordinate system was defined at the simplified load cell model to apply input loadings and calculate output data. A known force or moment was applied to one piece of the simplified load cell model and each model output was compared with the given input for modeling compatibilities. For the force input, the load (Figure 7b) was applied along the longitudinal axis of load cell defined as the z-axis of the local coordinate system, and a vertical load was applied along the x-axis of the local coordinate system to impose the y-axis moment. The calculated force and moment outputs were compared with the given inputs to check the modeling accuracy according to three different modeling concepts.

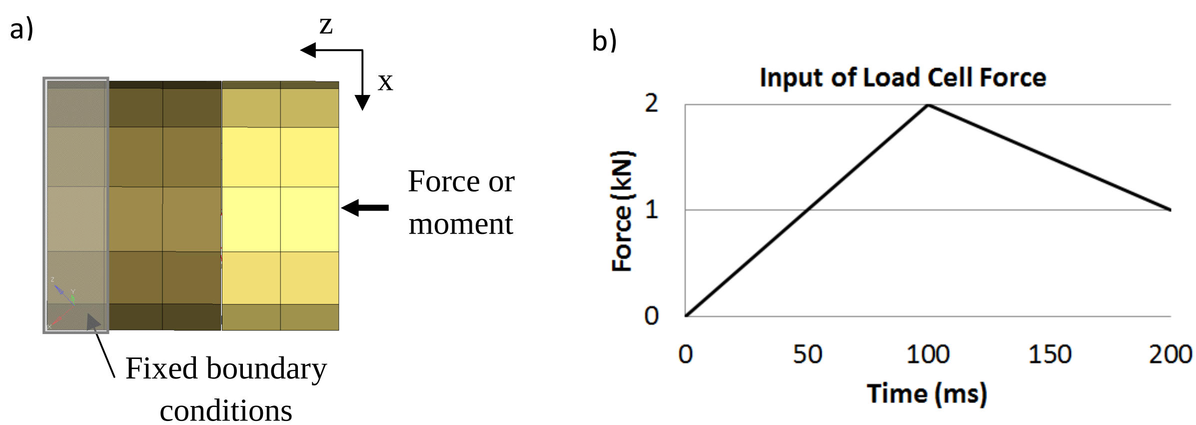

Figure 7. Conceptual modeling approach for load cell FE model; a) load cell components and simulation setup and b) input data of force time history for the model verification.

RESULTS

Model Update and Validation of the Femoral Shaft

The compression response for the updated femoral shaft model and femur puck (Figure 8a) was verified. The simulated compression force reached 4.8 kN at 15 mm of displacement, and matched the averaged experimental test data of 4.84 kN (Figure 8b). The viscoelastic material properties of the femoral puck calibrated to match the compression tests were applied to the updated FE model of the THOR-MK femoral puck (Table 1). Based on the viscoelastic constitutive models, the femur puck material in the THOR-MK design was softer than the puck material in the THOR-NT.

The stiffness characteristics of the THOR-MK femur model were validated using direct axial impact simulations. The model response was slightly stiffer than the experimental response of the physical THOR-MK (Figure 9). However, the THOR-MK femur model response showed good agreement with the biomechanical corridors developed by Rupp et al., (2003). The THOR-MK femur shaft showed a significantly decreased stiffness response than that of the previous THOR-NT model.

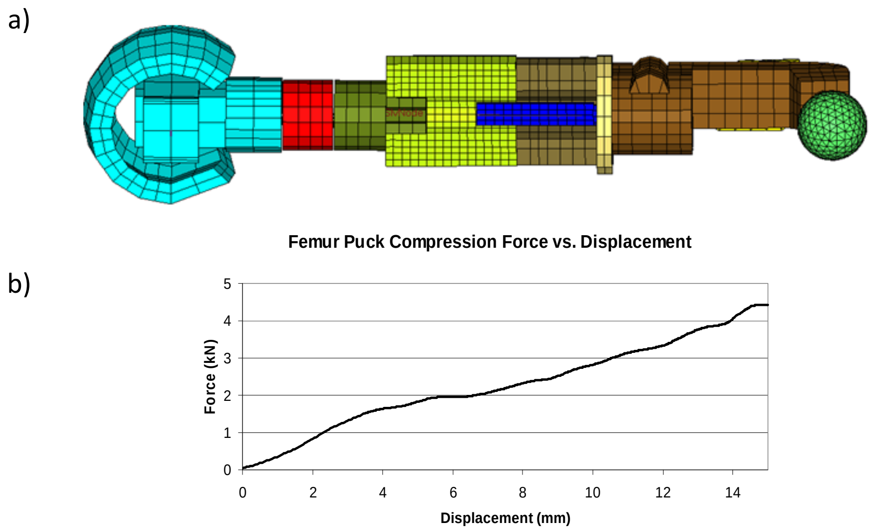

Figure 8. a) Updated femur shaft FE model based on THOR-MK CAD data provided by NHTSA and b) Force-displacement response of THOR-MK femoral puck model

Table 1. Material properties of femoral puck determined from iterative simulations

Material Model	*Viscoelastic*			
Properties	K (GPa)	G0 (GPa)	GI (GPa)	B (1/s)
Previous Values	7.0E-2	3.0E-3	1.0E-3	0.32
Updated Values	1.0E-2	2.5E-3	8.0E-4	0.32

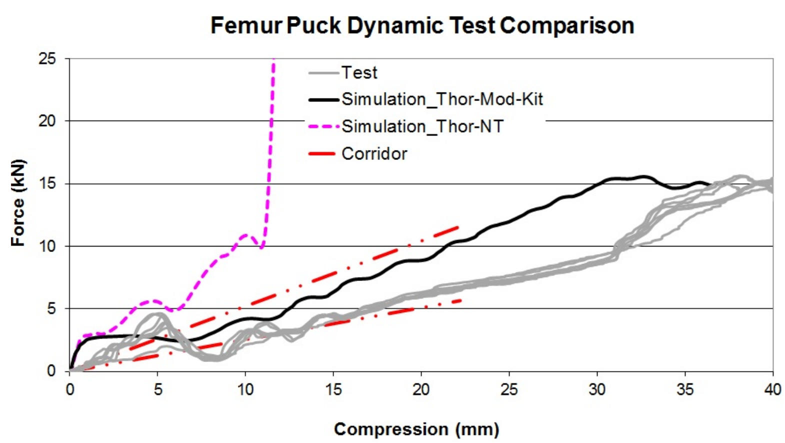

Figure 9. Comparison of force-displacement responses in KT impact among experiments and FE simulations.

Model Update and Validation of the Knee Slider

The force displacement response of the knee slider certification validation showed good agreement between the experiment and simulation (Figure 11a). For the knee slider biofidelity validation, the calculated stiffness response was in good agreement with the experimental results from Balasubramanian et al. (2004), although slightly less stiff (Figure 11b).

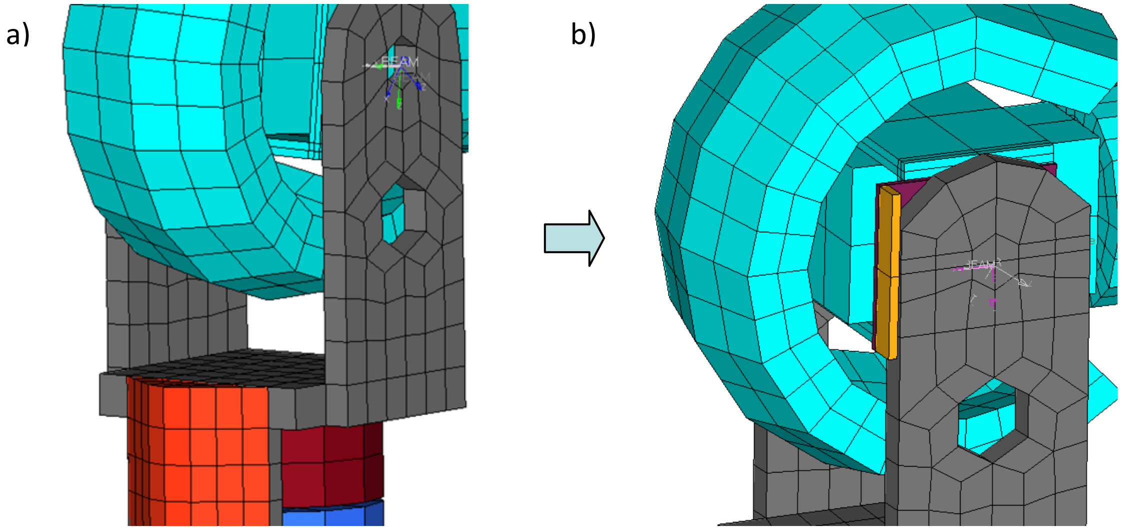

Figure 10. Knee slider designs of FE models, a) THOR-NT FE knee model and b) updated THOR-MK FE knee slider model.

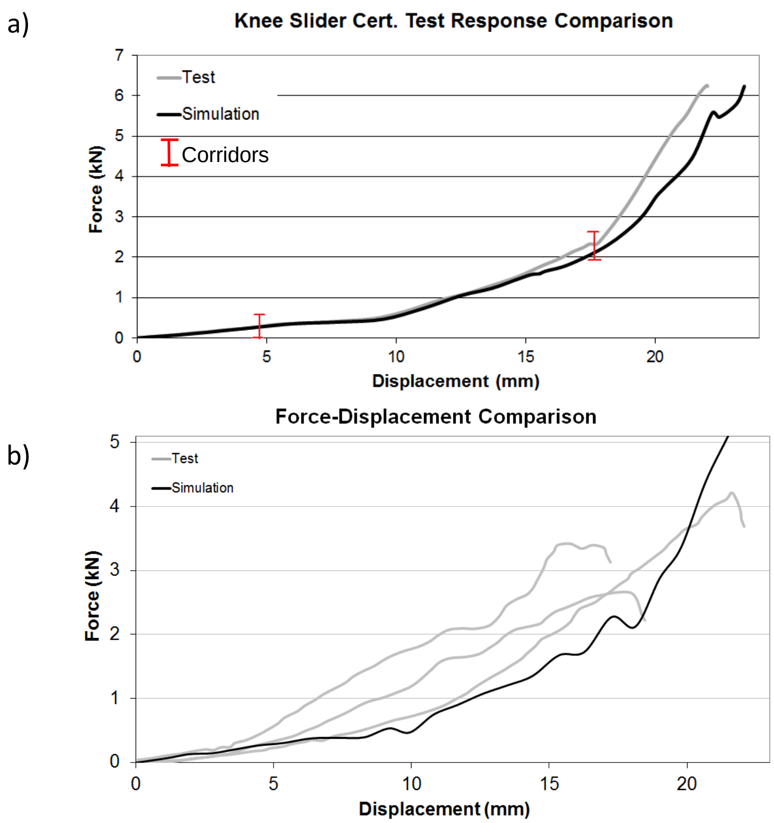

Figure 11. a) Force-displacement comparison of THOR-MK knee slider certification and b) force-displacement response of biofidelity validation according to Balasubramanian et al.'s experimental setup (2004).

Heel and Toe Impact Tests and Simulations

The heel and ball-of-foot impact tests specified in the certification procedures for the THOR-LX were conducted on the physical molded shoe and simulated using the updated THOR-MK lower extremity model. The six dynamic heel impact tests were showed good repeatability over the force time history of the impact (Figure 12). The peak compressive forces measured by the lower tibia load cell ranged between 2722 N and 2817 N at 10 ms. Subsequently, the corresponding heel impact simulation was performed and the force time history of lower tibia was calculated. The maximum peak force predicted by the model was 2769 N at 10 ms (Figure 12a). The results showed good correlation (the same level of peak forces at the same occurrence time) between the physical test and simulation responses, peak force levels, peak force occurrence times, and overall shape of the response curves.

The six dynamic ball-of-foot impact tests were conducted and used to validate the performance of the ankle and the compliant elements in the load path (molded shoe and ankle stopper) under dorsiflexion loading. The force and moment time histories at the lower tibia load cell were recorded. The peak ankle resistive moment calculated by the lower tibia force and moment were ranged between 44.0 Nm and 53.0 Nm, and the test responses showed good repeatability. Subsequently, the ball-of-foot impact simulation was performed using the same test configuration. The time history of ankle resistive moment was observed to have a peak of 49.9 Nm at 36 ms (Figure 12b). Good overall agreement was observed between the experimental and computational data for the loading phase, since the maximum moment calculated in the simulation is in the peak moment range obtained in the six tests.

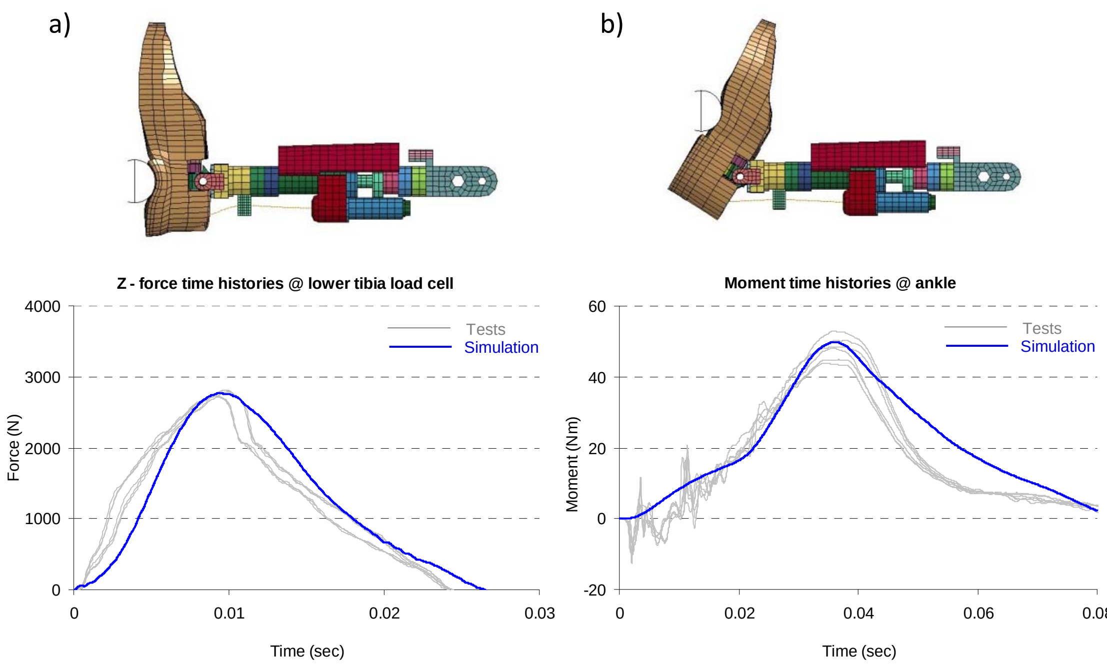

Figure 12. Comparison of FE model response under heel and ball impact loadings.

Investigation of Load Cell Modeling

Three types of load cell modeling methods were evaluated: the locking joint, the cross-section, and the beam element (Table 2). When representing axial force, all three approaches accurately measured the corresponding input profile. Thus, these three different load cell modeling concepts were all capable of recording forces in local coordinate systems. The moment output profiles of the locking joint and the cross-section were the same as the given input data, but the moment time histories of the beam element were not calculated. The locking joint and the cross section approaches are suitable for only rigid body and deformable body modeling, respectively (LSTC, 2007). Since the load cells in the THOR FE model were considered rigid for computational efficiency, the locking joint method was the recommended implementation strategy for load cells.

Table 2. Comparison of load cell modeling approaches

Approach	**Force Output**	**Moment Output**	**Note**
Locking joint	*Yes*	*Yes*	*For rigid body*
Cross-section	*Yes*	*Yes*	For deformable body
Beam element	*Yes*	No	

Integration into the THOR-NT Model

All FE model updates of the THOR-MK lower extremity, including the modified design of femur shaft, translational joint for knee slider, molded shoe, and foot modification, were incorporated into the whole dummy FE model (Figure 13).

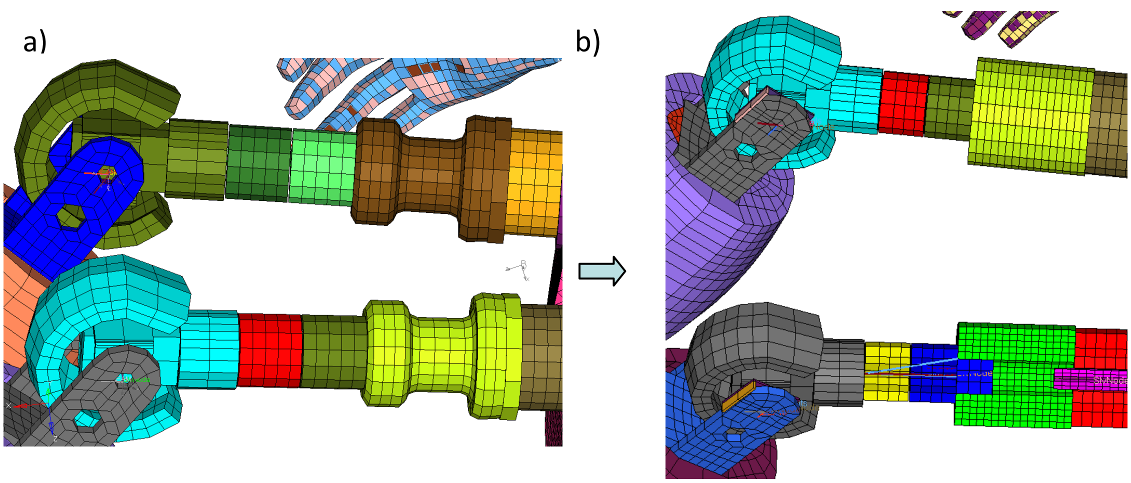

Figure 13. THOR-MK updates in the femur shaft and knee slider regions; a) THOR-NT knee-thigh region and b) THOR-MK knee-thigh region.

DISCUSSION

THOR lower extremity FE model consists of approximately 17000 nodes and 12000 elements based on the three-dimensional drawings of the physical hardware. While most parts in the actual THOR dummy were represented, some parts were simplified to increase the model stability and reduce the total calculation time during FE simulations. While the skin of the THOR lower extremity was modeled as an elastic material, the femur puck, tibia compliance bushing and foot padding were represented by linear viscoelastic materials. The deformable seatbelt model was used for the Achilles cable, and components made of steel or aluminum were modeled as rigid bodies for FE simulation efficiency.

One limitation of the current THOR model is that only the lower extremity part of the current dummy model was updated to the THOR-MK version. The hardware discrepancy in other body regions might introduce the different response when comparing the current updated THOR-NT FE model with the physical THOR-MK dummy. The head and neck, shoulder, and pelvis of the THOR-NT FE model will be updated in the near future to match the MK specifications. Once all body regions are assembled to the global model, several full body validations will be conducted to assess its responses against the test data. The THOR-MK model will have the potential of better predicting the driver kinematics and injury responses than its predecessors under various applications, such as the small overlap oblique impact scenarios.

The molded shoe FE model of THOR-MK was developed using the three dimensional scanning tool in this study. The three-dimensional geometry data of the molded shoe was obtained by a high speed laser scanning coordinate measurement tool. While millions of points (x, y, and z coordinates) were collected covering the surface of the molded shoe, the point cloud data should be carefully checked and filtered to remove some noisy data. The point data was transferred to the pre-processing software for constructing FE models. Finally, this procedure from the three dimensional scanning data to the FE model was better for accurately modeling the complex geometry.

CONCLUSIONS

The lower extremity of THOR-NT FE dummy was updated to the THOR-MK specification by improving the certification and biofidelity capabilities of the femoral shaft, including the knee slider (translational joint), updating the load cell modeling approach, and developing the molded shoe model. The heel and ball-of-foot impact simulations were performed with the developed molded shoe FE model. The calculated responses of both impact simulations showed good agreement with the experimental responses. Additional updates to the other body regions of the current dummy model are necessary to better understand the dummy response during vehicle crash tests and develop advanced restraint systems.

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