A Finite-Element Model of the THOR Mod Kit Dummy for Aerospace Impact Applications

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Abstract

New spaceflight vehicles are currently being developed to transport crews to space by NASA and several commercial companies. During the launch and landing phases, vehicle occupants are typically exposed to spinal and horizontal loading. To reduce the risk of injuries during these common impact scenarios, NASA has begun research to develop new safety standards for spaceflight. The THOR, an advanced multi-directional crash test dummy, was chosen to evaluate occupant spacecraft safety because of its improved biofidelity. Recently, a series of modifications were completed by NHTSA to improve the biofidelity of the THOR dummy. The updated THOR Modification Kit (THOR-k) dummy was tested at Wright-Patterson (WP) Air Force Base in various impact configurations, including frontal and spinal loading. A computational finite-element (FE) model of the THOR was developed in LS-DYNA® software and was recently updated to match the latest dummy modifications. The main goal of this study was to calibrate and validate the FE model of THOR-k dummy that could be used in future spacecraft safety studies. The performance of the calibrated dummy model was evaluated by simulating dummy tests with crash pulses along spinal and frontal directions. The model response was compared with test data by calculating its correlation scores using the CORA rating system. Overall, the calibrated THOR-k dummy model responded with high similarity to the physical dummy in all validation tests, providing confidence in the dummy model for use in predicting response in other similar test conditions such as those observed in the spacecraft landing.

Introduction

The National Aeronautics and Space Administration (NASA) and several commercial companies (including Boeing, Sierra Nevada, and SpaceX) are working to develop new spaceflight vehicles to transport crews to space and return them safely. The majority of these new transportation systems, including the multi-purpose crew vehicle (MPCV, formerly Orion), are capsule-based vehicles. During launch and (especially) landing, the occupants are loaded primarily along the spinal and horizontal directions. The specific loading experienced during landing is highly dependent on parachute performance, wind direction, wind velocity, and the landing site (water or land). Given some uncertainty in spacecraft landing orientation and the desire for low risk of injury, NASA chose the THOR (Test device for Human Occupant

Restraint) dummy to investigate relevant Injury Assessment Reference Values (IARV) because of its improved biofidelity in multi-directional impact loading [1].

The THOR dummy has been developed and continuously improved by the National Highway Traffic Safety Administration (NHTSA) to provide an advanced test dummy for automotive crash safety analysis [2, 3]. Rapid advances in both computational power and crash-simulation technology have enabled the use of a computational component complementary to experimental testing. Finite-element (FE) modeling has increased testing efficiency and is especially useful in the optimization of vehicle components or restraint systems during the manufacturer's design process. However, to provide maximum utility of the dummy computational model, the accuracy of its components should be assessed against the test data recorded from the physical dummy.

The main goal of this study was to calibrate the THOR FE model, which was recently updated to specifications of the latest THOR Mod Kit (THOR-k). To ensure the effectiveness of this update, the model was calibrated using a novel optimization-based approach [4], which utilized a rating score as the objective function [5]. Post-calibration simulations of the dummy under frontal and spinal loading conditions were run to validate the developed model as well as the effectiveness of the optimization-based approach used.

Methods

The THOR-k FE model was developed in LS-DYNA (LSTC, Livermore, CA) from the THOR-NT FE model [6]. The CAD drawings of the THOR-k dummy were reviewed and FE models were developed for the updated parts. Several component calibrations and validations were performed with the models of neck-head complex [7] and lower extremity [8]. Then, the material properties of the updated pelvis FE model were calibrated [9] for vertical loading. Finally, all dummy parts were connected and a positioning tree was developed (Fig. 1) in LS-PrePost® (LSTC, Livermore, CA) to allow easier and faster setup of the dummy posture corresponding to various pre-impact configurations (such as aerospace postures).

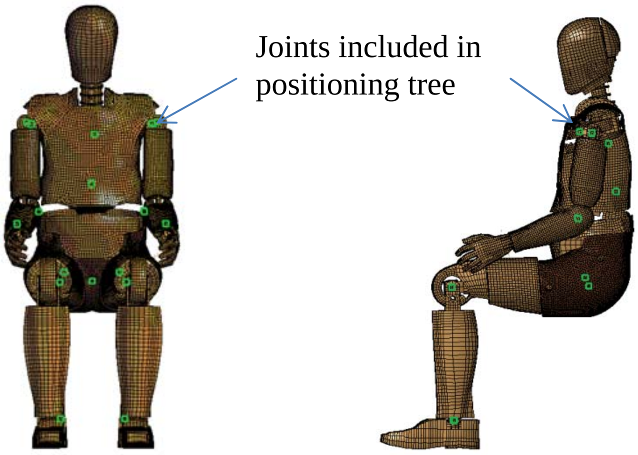

Figure 1. THOR-k FE Model: Positioning tree.

Model Calibration

Traditionally, model evaluations in safety applications have been performed by comparing the peak values of test and simulation data, by qualitatively evaluating the overall curve shapes, or by satisfying several certification guidelines. These methods could be problematic, as they do not provide a quantitative metric for defining the quality of model with respect to its complete time history response. To overcome this, new approaches were proposed to evaluate the response of the model relative to test data based on defined correlation metrics [5, 10, 11]. This quantitative evaluation approach allows model optimization and calibration in terms of kinematic and kinetic response-time histories with respect to available test data.

The THOR-K dummy model was calibrated to optimize the total model rating, developed using CORrelation and Analysis (CORA) signal rating software [12], through the adjustment of FE model parameters. LS-DYNA simulations were run with the model parameters selected iteratively by the optimization algorithm implemented in LS-OPT® software until the value of the total model score, defined as the objective function, was maximized (Fig. 2). A more detailed presentation of the calibration methodology can be found in [4].

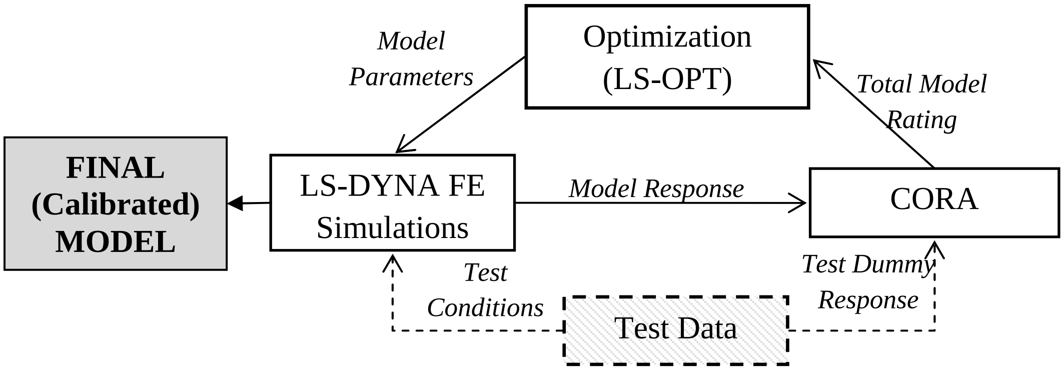

Figure 2. Schematic of the calibration method.

Model Validation

Capsule-vehicles typically land with the crew in a seated position reclined 90° from vertical on their back [1]. Although the specific occupant loading depends greatly on the specific design of the vehicle and landing conditions, all occupants are typically subjected to a combined horizontal and spinal loading. Therefore, the validation of FE model of THOR-k was performed against a subset of WP test data recorded in spinal (vertical) and frontal (horizontal) tests.

The WP impact tests were conducted on the Horizontal Impulse Accelerator (HIA), which has been shown to have ± 5% reproducibility on peak acceleration and velocity profiles. A THOR-k dummy with all of the modifications kit upgrades, excluding the SD-3 shoulder, was used in these tests. The dummy was positioned on a rigid seat with seat pan perpendicular to the seat back and headrest. The dummy was restrained within the seat using a double shoulder strap and lap belt with an optional negative-g strap (crotch strap) (Fig. 3a). A slight pretension was applied to the belts before every test (89±22 N). The dummy hands and feet were additionally restrained to prevent excessive flailing.

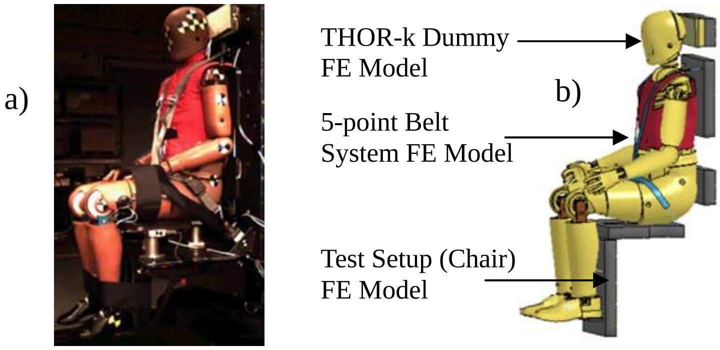

Figure 3. THOR-K dummy and test setup: a) physical, b) FE-Model.

The internal instrumentation of the THOR dummy was used to collect acceleration and load data at different body locations during impacts. Signals were collected at 10,000 samples per second. Data were collected using a 3-kHz antialiasing 5-pole filter. Post-processing filters (SAE J211 compliant) used a 1650-Hz low-pass filter for head accelerations and 1000-Hz low-pass filter for chest accelerations.

The FE Model of THOR-k dummy (with original/THOR-NT shoulder) was positioned on a seat model based on the geometry on the physical seat. A 5-point belt model was developed based on the physical restraint model (Fig. 3b). Hands and feet were constrained using spring models bound to the legs and chair respectively. Dynamic tensile tests were performed on the belts used in WP tests at the Center for Injury Biomechanics (CIB)-Virginia Tech, and the test data were used in defining the material properties of belt models. Appropriate contacts were defined between the dummy parts and dummy-test setup, and then acceleration pulses recorded in testing were applied to the chair model along the spinal (vertical) direction (Fig. 4a) and along the horizontal direction (Fig. 4b).

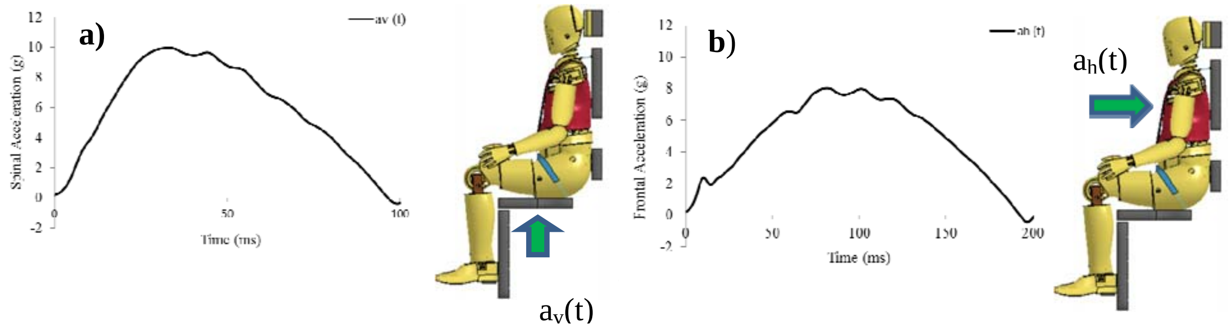

Figure 4. The crash pulses used in the preliminary validation of the whole dummy THOR-k model: a) the spinal (vertical) pulse, b) the frontal (horizontal) pulse.

Results and Discussion

The calibrated THOR-K FE model closely predicted dummy response under spinal loading, receiving a CORA rating of 0.974. Very good kinematics predictability in terms of vertical accelerations is shown at the head CG, chest, and pelvis sites (Fig. 5 a-c). In addition, the time histories of vertical (axial) components calculated at upper and lower load cells followed very well the corresponding test data (Fig. 5 d-e). The time history of the vertical component of lumbar spine load had a shape similar to that of the corresponding test data (fig. 5 f), but the model data showed a higher (about 20%) peak prediction. This difference could be caused by some inaccuracies in the material model of lumbar flex joints, so a further calibration of this dummy region is currently being performed and the results will be provided in a future publication.

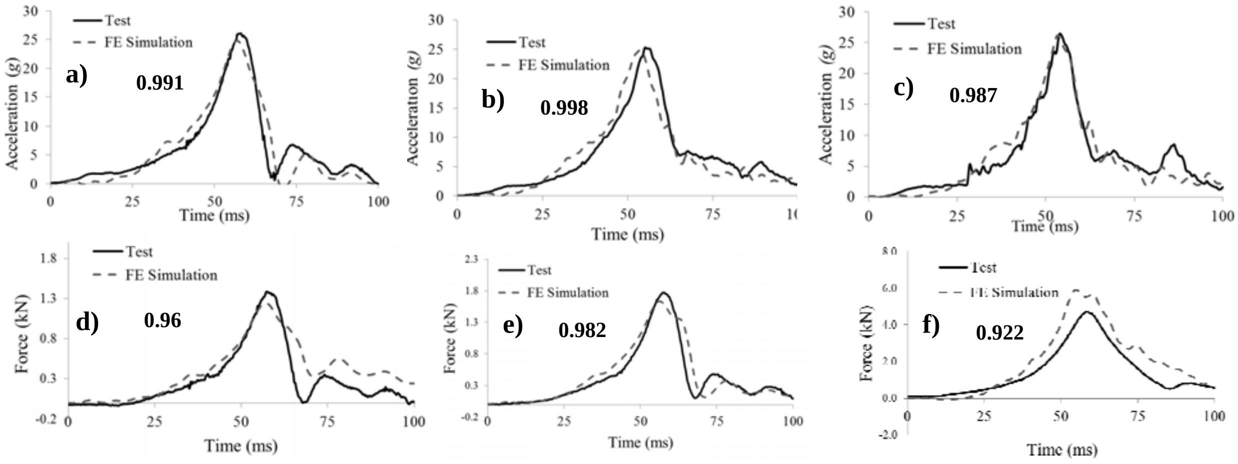

Figure 5. Model validation – the spinal impact time history comparison: a) head CG vertical acceleration, b) chest vertical acceleration, c) pelvis vertical acceleration, d) upper neck vertical force, e) lower neck vertical force, f) lumbar spine vertical force. **Total CORA rating =0.974.**

The dummy model reasonably predicted the response of the test dummy in the frontal loading direction (Fig. 6). The model response received a total CORA score of 0.921 in the frontal simulation. The horizontal acceleration at the head CG and loading at the upper neck load cell (Fig. 6 a, d-e) were predicted very well (CORA scores above 0.99). However, during the start of the deceleration phase (~100 ms), some differences were observed in the lower neck loading (Fig. 6 f), which recorded the lowest score (0.764). These differences were probably associated with the spikes in the chest and pelvis acceleration signals observed at the same time in the model response, but not in the test data (Fig. 6b). Although no improvements were observed in a simulation with the belt force controlled based on test data, this response could be caused by differences in the pre-impact positions of the belts or by a lower biofidelity of the dummy chest model. Future work should include analysis of the belt pre-tensioning and belt position with respect to the dummy model. Additionally the interaction mechanics between the belt and model, such as contact friction, and further thorax calibration should be investigated as well.

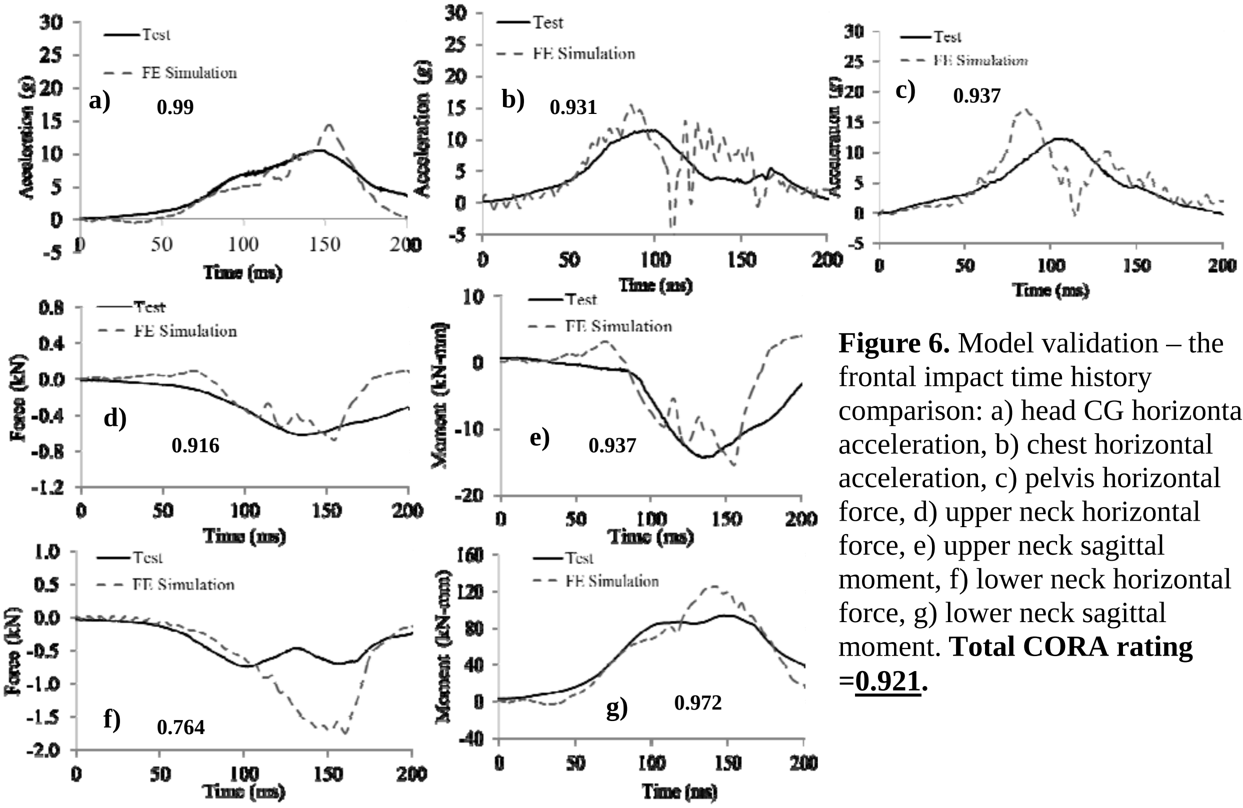

Figure 6. Model validation – the frontal impact time history comparison: a) head CG horizontal acceleration, b) chest horizontal acceleration, c) pelvis horizontal force, d) upper neck horizontal force, e) upper neck sagittal moment, f) lower neck horizontal force, g) lower neck sagittal moment. **Total CORA rating =<u>0.921</u>.**

The recently updated THOR FE model was successfully calibrated to match the response of the THOR Mod Kit crash test dummy. The model was shown to accurately predict dummy response under vertical loading. In addition, the model predictions were shown to be reasonable under frontal loading, indicating its applicability in multi-directional crash test analysis. To further improve the effectiveness of this model, the sensitivity of its response to test conditions, such as positioning and belt interaction, should be more thoroughly investigated. Also, the responses of the THOR FE model should be investigated against additional acceleration pulses to assess the model's robustness in predicting differing acceleration levels. In addition, material testing of the dummy parts may be beneficial in future model calibration. The results provided in this study show a valid response of the developed dummy model under frontal and spinal loading configurations, and suggest that it can be useful in spaceflight loading safety analysis.

Acknowledgements

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