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Evaluation of Human and Dummy Finite Element Models under Spaceflight Loading Conditions

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ABSTRACT

In an effort to develop occupant protection standards for future crewed spacecraft, the National Aeronautics and Space Administration (NASA) has been investigating the test device for human occupant restraint (THOR) dummy in relevant impact test scenarios. In this study, the biofidelity of THOR and total human model for safety (THUMS) finite element (FE) models were evaluated against a series of human-volunteer tests previously performed by the United States Air Force (USAF). The pre-test human position and sled acceleration pulses measured during testing were used to setup the FE simulations. Predicted responses by both human and dummy models were compared to human test data recorded under the same impact conditions. In addition, dummy injury criteria and human stress/strain data were calculated to evaluate the risk of injury predicted by the dummy and human model, respectively. While some differences were observed in thorax load distribution and neck stiffness, the results show reasonable biofidelity of the dummy/human FE models in terms of kinematic response. In addition predicted dummy injury criteria and human model stress/strain values are shown to positively relate. As a compliment to dummy testing, numerical simulation provide efficient means to assess vehicle safety throughout the design process and further improve the design of physical dummies. The assessment of the THOR and THUMS FE models in spaceflight testing condition is an essential first step to implementing these models in the computational evaluation of space transport vehicle occupant safety. Promising results suggest future use of these models in this field.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) along with several commercial companies (e.g., Boeing, Sierra Nevada, SpaceX, etc.) are currently developing new spacecraft to transport passenger crews to and from space. Simultaneously NASA is working to improve vehicle safety standards to protect occupants during flight. In these spacecraft, the occupants are typically loaded along the frontal and spinal directions during the launch and landing. Due to its improved biofidelity in multidirectional impact loading NASA has chosen the test device for human occupant restraint (THOR) dummy to investigate relevant injury assessment reference values (IARV) for these complex impact scenarios (Somers et al., 2014).

The THOR dummy has been developed and continuously improved by the National Highway Traffic Safety Administration (NHTSA). THOR was developed to provide a test dummy with improved biofidelity over the industry standard Hybrid III, for the automotive field (Parent, Craig, Ridella, & McFadden, 2013; Ridella & Parent, 2011). Improved complexity and flexibility of the THOR spinal structure suggest potential for combined frontal and spinal impact analysis. However, to ensure biofidelity in the spinal direction the response of THOR must be assessed against human data.

A finite element (FE) model of THOR has recently been calibrated and validated in a series of spinal and frontal loading conditions(Putnam, Somers, Wells, Perry, & Untaroiu, 2014; C.D. Untaroiu, Putnam, Somers, & Pelletierre, 2014). This computational model could be used to evaluate the dummy, reducing the cost and time required for conventional testing. In addition the development of human FE models allow evaluation against human kinetic response, which cannot be measured in volunteer testing.

The main goal of this study was to evaluate the biofidelity of the THOR and THUMS FE models in test conditions matching a human-volunteer test series previously performed by the United States Air Force (USAF). Comparisons were made between kinematic response of the FE models and the human volunteers, and additionally between kinetic responses of the models.

METHODS

FE Models

THOR FE Model. A FE model of the latest THOR ATD, matching the specifications of the latest anthropomorphic test device (ATD) with the NHTSA developed modification kit (THOR-K) was used in this study. To ensure model accuracy this finite element model was calibrated and validated on component (Putnam, Somers, & Untaroiu, 2014) and full model levels(Putnam, Somers, Wells, et al., 2014; C.D. Untaroiu et al., 2014) prior to this study. The complete model calibration and validation was done against a series of THOR dummy tests performed at the Wright Patterson Air Force Base (WPAFB) under conditions closely matching the tests (Somers et al., 2014). The THOR-K FE model contained 222,292 nodes and 444,324 elements (286,804 deformable), with a time step of 0.65 µsec.

THUMS FE Model. The THUMS FE model v.4 (JSOL, Tokyo, Japan), designed to match the anatomical characteristics of a 50th percentile human male, was used in this study (Chawla, Mukherjee, Mohan, & Parihar, 2004; Kitagawa, Yasuki, & Hasegawa, 2008; Maeno & Hasegawa, 2001). This human model has been primarily validated against post-mortem human subject (PMHS) tests for use in the automotive field; although, model calibration and validation is limited in the spinal direction. The THUMS FE model consists of 628,366 nodes and 1,755,540 elements (1,744,003 deformable), with a time step of 0.40 µsec.

Test Setup

Simulations were developed based on a series of human-volunteer tests performed to evaluate human response to various spinal impact conditions at the Harry C. Armstrong Aerospace Medical Research Laboratory (AAMRL) horizontal accelerator facility (Shaffer, 1976). In these tests, the subjects were seated within a seat mounted to the accelerator sled (Figure 1a). The seat was mounted in such a manner that gravity was perpendicular to the loading direction. Subjects were restrained to the seat with a 5-point belt system consisting of a double shoulder strap, lap belt, and negative-g strap, each pre-tensioned to 89±22 N. In addition, the subject’s legs were attached to the chair using Velcro™ straps to prevent excessive flailing. All subjects wore a HGU-26/P Air Force helmet (Miller & Mosher, 1989).

A seat model was developed based on the generic test seat used for the THOR testing. The seat dimensions were recorded using a FARO arm system (FARO, Lake Mary, FL), and adjustments were made from this baseline geometry to accurately model the seat used for human testing. Both FE models were positioned within the seat model with appropriate contacts defined between test setup and occupant models (Figure 1 b, c). Material testing was performed on a generic 5-point belt restraint system, similar to that used in testing, through quasi-static tensile tests of each belt part. Then, a material model (LS-DYNA Material Model B01, MAT_SEATBELT(LS-Dyna, 2007)) was used to assign the determined material properties to each belt model part. A second pre-test simulation was run to pretension the belt around the occupant models to 89 N. A generic HGU helmet model was developed to approximate the geometry and inertial properties (mass, center of gravity, and moment of inertia) of the helmets used in testing. In addition, spring models were used to restrain the legs of the occupant models as in testing.

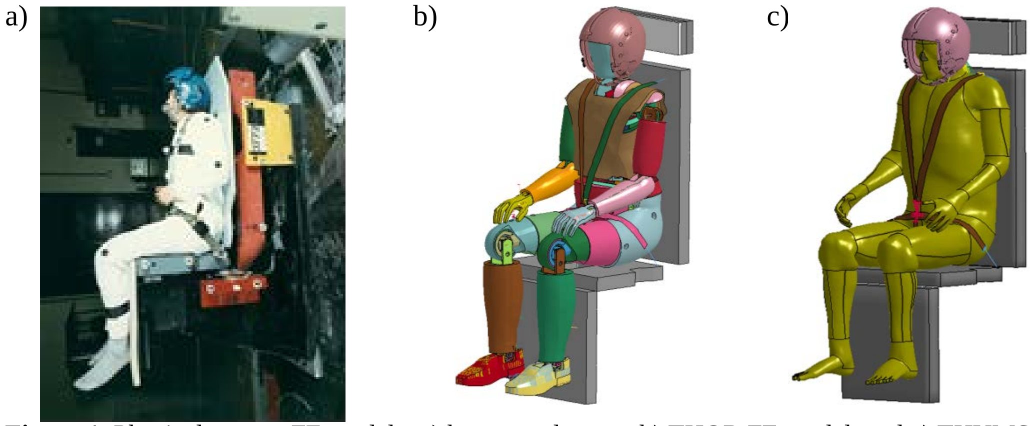

Figure 1. Physical test vs. FE models: a) human volunteer, b) THOR FE model, and c) THUMS FE model.

The dummy/human FE models were evaluated at 1 spinal acceleration pulse in this study. The nominal acceleration pulse was a triangle pulse with a peak acceleration of 10 g at 40 ms. A measured acceleration pulse (Figure 2) was applied, along the spinal direction, to the seat model to drive both occupant simulations. The seat model was constrained in all other directions, to accurately represent the conditions of the acceleration buck used in testing.

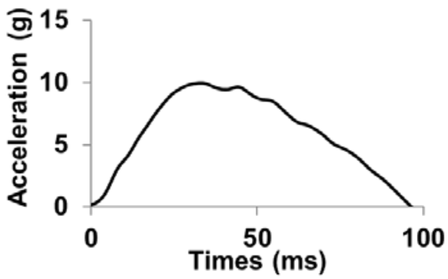

Figure 2. Acceleration pulse used in the occupant simulations.

To evaluate the kinematic response of both human and dummy FE models, head and shoulder displacements were compared to that of the human volunteers. Head and shoulder displacement responses were measured on each human volunteer using photogrammetry to track markers placed on occupants check and shoulder during testing This procedure was done in general accordance to SAE J138 (Miller & Mosher, 1989). In FE simulations, nodal displacements were tracked at representative points on both FE models. In addition, loading between human and dummy FE models was compared at the representative T1 and L1 locations. All data were filtered with an SAE 108 class filter. Lastly, the prediction of lumbar load injury criteria (LLC) by the THOR FE was assessed. LLC is a measure of peak load measured at the lumbar-spine load cell, with respect to a maximum threshold value, originally developed for the H-III 50th dummy. A lumbar load with a peak higher than 6,672 N is considered injurious. This injury prediction of the THOR FE model was compared to L1 injury prediction made by THUMS, calculated as the percentage of maximum yield stress predicted in the L1 cortical bone in the THUMS FE model.

RESULTS

Kinematic Comparison

Both dummy and human FE models predict a larger head displacement than average human-volunteer response (Figure 3). The THUMS human model predicts the largest displacement, although its response is within the range of volunteer data. Human-volunteer shoulder displacement is well predicted by

THUMS, with the majority of its response closely matching average human response. The THOR FE model under predicts human-shoulder displacement. Both head and shoulder displacement predictions by FE models do not rebound as quickly after peak displacement, as that observed in the human-volunteer data.

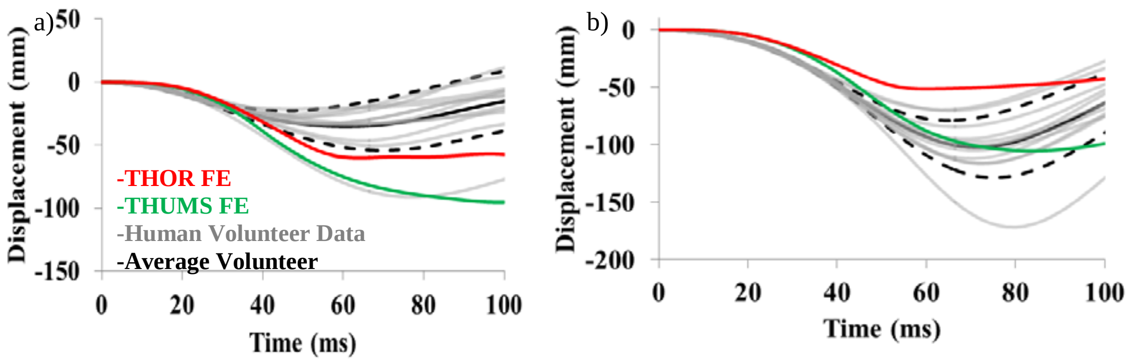

Figure 3. Kinematic Response Comparisons in the spinal direction: a) Head Displacement and b) Shoulder Displacement.

The close prediction of shoulder displacement by the THUMS FE model indicates an accurate transfer of energy through the thorax model in the spinal loading direction. The over prediction of head displacement indicates a softer neck response, than that of the human-volunteers, in both models. This softer response may be due to differences in PMHS and volunteer response in testing. Both the THOR dummy and THUMS were designed to be biofidelic primarily to PMHS standards, thus do not take into account resting muscle tone or bracing by human volunteers (Beeman, Kemper, Madigan, Franck, & Loftus, 2012). Both these effects would stiffen the neck and reduce total head displacement compared to PMHS response. In addition, the under prediction of shoulder displacement by the THOR FE model indicates a stiffer response through the dummy thorax. This may be explained by the rigid nature of the dummy parts, as the dummy shoulder/clavicle region is not flexible in the spinal direction with respect to the spine, which is primarily rigid as well.

Visual comparison of spinal kinematics between THOR and THUMS FE models indicate similar spinal flexion response (Figure 4.) Although, there is slightly increased flexion of the lower thoracic spine in THUMS compared to THOR at the end of simulation. The upper thoracic and neck flexion closely matches throughout simulation. The rigid nature of the THOR spinal column limits biofidelity of spinal curvature, but is shown to provide decent similarity to the THUMS FE model.

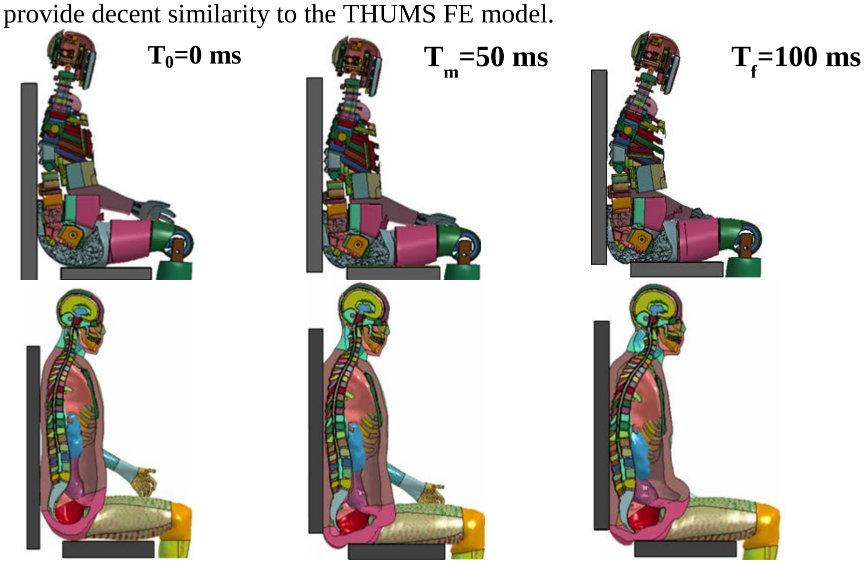

Figure 4. THOR and THUMS FE model response comparison under spinal impact.

Kinetic Comparison

The THOR FE lower neck load cell predicts a slightly lower peak load in T1 than the THUMS FE model (Figure 5a). The lumber-spine load is predicted to be higher by THOR than the L1 load predicted in THUMS (Figure 5b). The load predicted in both regions rises earlier in the THOR FE model. The load time history predicted by THUMS exhibits a much smoother shape than that predicted by THOR.

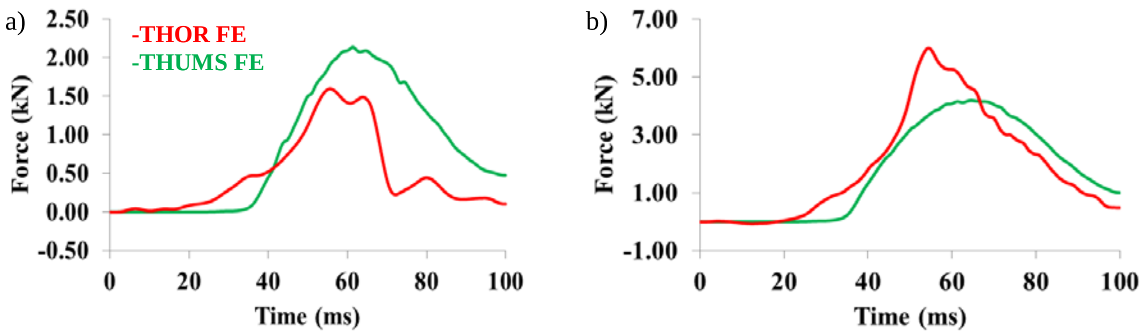

Figure 5. Kinematic response comparisons: a) lower neck – T1 load and b) lumbar spine – L1 load.

The nature of the load predicted by the dummy and human FE models indicates a difference in load transfer through the 2 model structures. Closest to the point of impact, the L1 load in THUMS is smaller than that represented in the THOR model. At the top of the thoracic spine, T1, the THUMS peak load prediction is higher. This is an indication that the impact load may not be as direct through the lumbar spine in the human model as it is in THOR. This could be due to the solid abdominal region of the human model compared to the split abdomen of the THOR, which does not begin offloading the lumbar spine until both abdominal pieces come in contact (Putnam, Untaroiu, Littell, & Annett, 2013).

Risk of Injury Analysis

Peak lumber-spine load gives a similar prediction of lumbar-spine injury as the measured yield stress in the THUMS L1 cortical bone (Table 1.) Peak lumber load predicted by the THOR FE model is 90% of the threshold defined for lumbar injury, while peak stress measured in the THUMS L1 part model was 83% of the defined yield stress value.

Table 1. Lower Spine Injury Analysis

Lower Spine Injury Metrics	
ATD Criteria	**THOR K FE Value**
%LLC threshold	89.96%
Human Criteria	**THUMS Value**
L1% yield stress	83.02%

The similar injury predictions demonstrated by both the THOR and THUMS FE model indicate that peak lumber load measured in THOR may provide an approximate prediction of L1 fracture. In addition, the percent of injury threshold predicted was slightly higher in the THOR FE model, thus providing a more conservative estimate for injury prevention.

CONCLUSIONS

Previously developed ATD (THOR) and human (THUMS) FE models were evaluated against human-volunteer test data, to assess the biofidelity of the THOR ATD and accuracy of the THUMS in spinal impact analysis. Load response of both FE models were used to assess the kinetic response predictions of the THOR ATD against loading of the human body. Results indicate an accurate representation of energy transfer through the thorax of the THUMS FE model, as shoulder displacement closely matched the human-volunteer response. Neck kinematics of both THOR and THUMS FE model indicate a softer neck region compared to human volunteers. A difference of load distribution through the 2 models is indicated by loading discrepancies observed in the T1 and L1 regions; however, lumbar-spine injury predictions are similar between both models.

Based on the results of this study, it is suggested that the stiffness of the THOR neck be increased. Additional flexibility of the THOR shoulder in the spinal direction, may also improve its biofidelity under these loading conditions. Based on comparisons to the THUMS FE model, it is suggested that the mechanics of load distribution through the lower thorax and lumber spine region in THOR should be more thoroughly investigated.

Preliminary injury prediction comparisons indicate a correlation between dummy lumbar load values and stress within lumbar vertebra. Unfortunately this comparison is limited by the peak lumbar load criteria, which was developed for the Hybrid III. Though it should be similar as both dummies are designed to represent the 50th male, it must be re-assessed for the THOR before injury determinations may be made. Secondly, it is unknown if the yield stress assigned to the vertebra material models in THUMS have been validated under compression tests.

Although similar displacement of the shoulder between THUMS and human volunteers indicate a similar kinematic response throughout the thorax, further evaluation is required to validate THUMS in the spinal direction. It is suggested that the pelvis and spine region of THUMS be validated on a component level in the spinal direction as these regions should largely determine response in this direction. Full model kinematics should then be validated under further spinal loading test conditions to ensure confidence in its response.

In the future, with more complete validation, both these models may be used in full scale aeronautic impact simulation and analysis. This would provide a unique insight into human and dummy response in conditions impractical for extensive testing. Such insight could be used for improved dummy testing, new injury criteria development, and vehicle design optimization (Adam & Untaroiu, 2011; C. D. Untaroiu & Adam, 2013). With continued evaluation and validation, it is believed that both THUMS and THOR models have extensive potential to increase occupant safety in the field of aeronautic transportation.

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