EVALUTION OF A FINITE ELEMENT MODEL OF THE THOR-NT DUMMY IN FRONTAL CRASH ENVIRONMENT

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ABSTRACT

The THOR-NT dummy has been developed and continuously improved by NHTSA to provide manufactures an advanced tool that can be used to asses injury risk in crash tests. With the recent improvements of finite element (FE) technology and the increase of computational power, a validated FE model of the THOR-NT provides an efficient tool for design optimization of vehicles and their restraint systems. The main goal of this study is to assess the current version of THOR-NT FE dummy model in the frontal crash environment. A three-dimensional (3D) FE model of the dummy was developed in LS-Dyna based on the drawings of the THOR-NT dummy. The material properties of the deformable parts and the properties of joints connecting rigid components were derived from the impact test data. To provide validation data for the assembled dummy model, two 40 km/h sled tests were conducted with the dummy restrained by a standard belt system and positioned in a rigid seat with the legs constrained at the knees. The upper body kinematics of the dummy was recorded by means of a 3D motion capture system that tracked the movement of retro-reflective markers attached to the dummy and to the buck. The dummy model fidelity was quantitatively assessed by comparing the displacement time histories of upper body and the reaction forces from the crash simulation with the corresponding data from the sled test. While the relatively low score of the model (0.55 -on a scale from 0 to 1) suggests the need of additional model improvements and validations under different test conditions (e.g., different shapes of deceleration pulses, and initial velocities), its reasonable performance in the direction of sled deceleration during 40 km/h frontal crash event would recommend it for use in impact simulations intended to improve the design of new vehicles and their restraint systems.

INTRODUCTION

Anthropometric test devices (dummies) are frequently used in crash testing to evaluate injury risk for vehicle occupants. The THOR (Test device for Human Occupant Restraint) dummy has been developed and continuously improved by the NHTSA (National Highway Traffic Safety Administration), and has shown improved biofidelity in impact tests relative to the Hybrid III, the dummy used in the current regulations (Shaw et al. 2002). While experiment testing is the current basis of crashworthiness evaluation for new car models, rapid advances in both computational power and crash simulation technology enables the use of a complementary computational component during the manufacturer's design process, especially in the optimization of vehicle components or restraint systems (Untaroiu et al. 2007). In order to provide maximal utility of the dummy model, its kinematical and dynamical predictions must be extensively verified under various crash scenarios before use in the vehicle design process.

The main goal of this study was to evaluate a FE model of THOR-NT Dummy in a frontal impact environment. A crash simulation with the deceleration pulse of a sled test was performed with the THOR-NT FE dummy model and the three-point restraint system positioned in a test setup model developed in LS-Dyna software (vers. 971, Livermore, CA, US). The displacement time histories of several characteristic nodes on the dummy surface (corresponding to the markers used in testing), and dummy interaction loads with the belt and the sled obtained from the simulation, were compared with test data using objective rating criteria developed in previous studies (Jacob et al. 2000, Hovenga et al. 2004 and 2005). It is believed that the rating methodology and the associated 'objective' values can help identify priorities for further improvements in the THOR-NT dummy model.

METHODOLOGY

The Finite Element Model of the THOR-NT

A three-dimensional finite element model was developed to represent the THOR-NT dummy using the LS-Dyna software package (vers. 971). CAD drawings of the THOR-NT physical dummy were used to construct the geometry of the model. Most head-neck elements (Figure 1) were modeled as rigid bodies except the elastomers (neck pucks and neck bumpers, OC joint stops), the non-linear springs (front and rear spring subassemblies), the foam material (face padding and head skin), and the steel neck cables. The rigid bodies that articulated relative to each other were connected with joint elements. The head-neck FE model was constructed to output equivalent measurements as those recorded in the physical THOR-NT Head-Neck: an upper and lower neck load cell; force in the front and rear spring assemblies; face load cells, and rotation of the OC joint. The completed FE model was correlated with the physical THOR-NT Head-Neck by simulating a head drop test and a frontal flexion test (Malone et al. 2007a).

In the thorax FE model (Figure 2), deformable materials have been used in the following components: elastomer (shoulder and neck bumpers, flex joints, jacket and bib), foam material (upper abdomen and mid-sternum), and the steel (ribs). Joint elements were defined between the articulating rigid bodies and a variety of contact definitions were used to define the interaction between rigid bodies and deformable materials. The thorax FE model outputs the same measurements as the THOR-X CRUX (Compact Rotary Unit), that is deflection units in four locations and one accelerometer located on the Mid-Sternum. The thorax FE model was correlated with the physical THOR-X by simulating two Kroell impact tests, one at 4.3 m/sec and the other at 6.7 m/sec, and comparing to the experimental results. The force deflection curves for impactor force vs. chest deflection derived from the simulation were well correlated with those obtained from experimental data. It was concluded that the FE model can be used to accurately predict the results of physical tests performed with the THOR-X (Malone et al. 2007b).

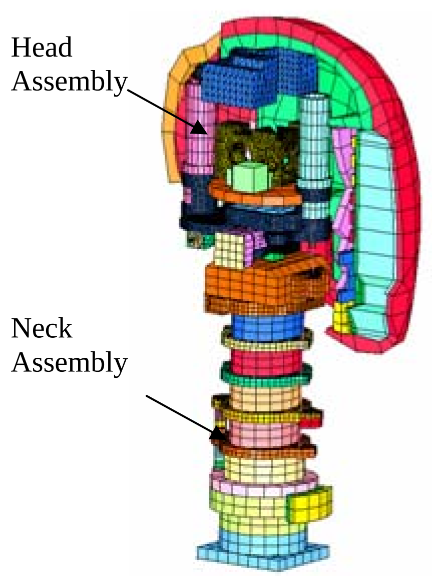

Figure 1. The Thor-NT Head-Neck Assembly

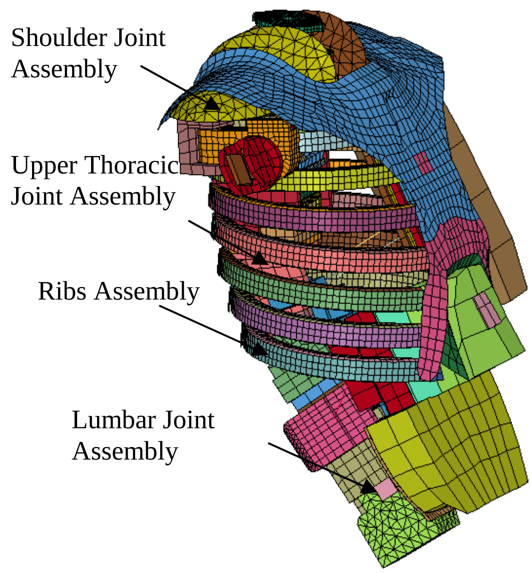

Figure 2. The Thor-NT Thorax FEM

In the lower extremity FE model (Figure 3), the parts defined as deformable were the following: the tibia skin, foot skin, tibia compliance spring, the heel padding/shoe, and the Achilles'cable. To account for the movement of the leg and ankle, one translational joint was created for compression of the tibia and three revolute joints were created to allow movement of the ankle. Stiffness and damping properties were assigned to each of the joints to represent the mechanical properties in the physical THOR-LX. The finite element model outputs the same measurements as the THOR-LX dummy: two six-axis load cells, two accelerometers, and rotation angles of the ankle. The completed finite element model was correlated with the physical THOR-LX by simulating ten physical experiments and comparing the results (Varellis et al. 2004). Three impacts to the forefoot were conducted to evaluate the dorsi joint performance. Two heel impacts were performed to evaluate the tibia compliance. Three Achilles' tests were conducted to assess the Achilles' cable forces. Two skin tests were performed to determine the effect of the skin on the tibia forces. The time histories of impactor deceleration, load cell forces, joint angles and moments calculated for these tests all compared well to the experimental data. Therefore, it is concluded that the finite element model can be used to accurately predict the results of physical tests performed with the THOR-LX

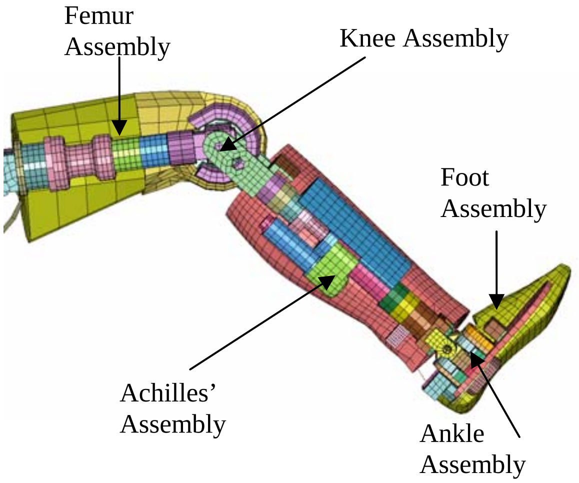

Figure 3. The Thor-NT lower extremity FEM

The THOR-NT FE model (Figure 4) has 329 parts (components) and almost 340,000 elements, majority of them (93%) defined as rigid. The material models and joint definitions used in the FE model can be find in the THOR-NT manuals (Malone et al. 2007a, 2007b, Varellis et al. 2004).

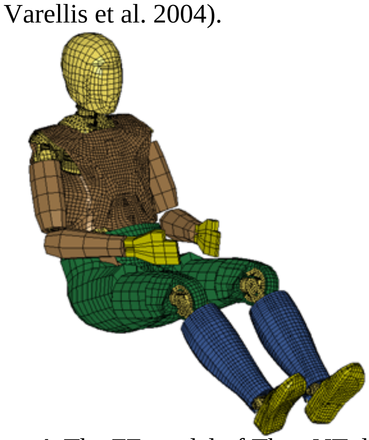

Figure 4. The FE model of Thor-NT dummy

The THOR-NT dummy in frontal crash environment

The THOR-NT dummy was subjected to two 40 km/h frontal sled tests in order to provide test data for the validation of THOR-NT FE model. The dummy was positioned on a rigid planar seat and its torso was restrained by a standard 3-point shoulder and lap belt system (without pre-tensioner an/or load limiter systems). Since the primary goal of this test was the response evaluation of the dummy upper body regions (thorax, neck, and head), additional restraints for the lower regions of the dummy were applied (Untaroiu et al. 2009). A rigid knee bolster was used to restrain the motion of the pelvis and lower extremities, and ankle straps were applied to constrain the feet on a footrest. The dummy was positioned on the seat in a specified posture that approximated the posture of a front seat passenger (Figure 5a). The linear and angular dimensions, that characterize the dummy and belt initial position (e.g. H-point position, lower extremity angles, belt angles) with respect to the sled system, were recorded prior to testing (Table 1). Dummy kinematics were recorded by means of a 3D motion capture system that consisted of 16 cameras (Vicon MX13) arrayed to track the movement of retro-reflective markers attached to the dummy and to the sled buck during the impact event (Figure 5). In addition, load cells were used to record the interaction forces between the dummy and the sled or belt system.

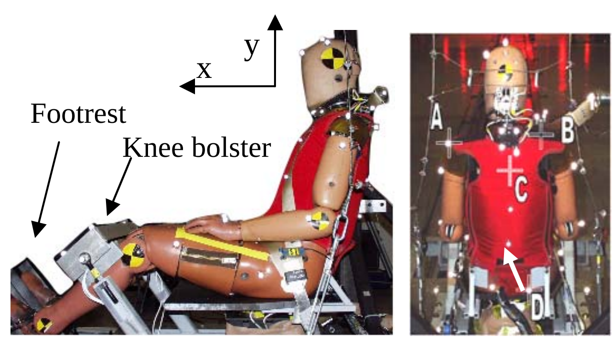

Figure 5. The Thor-NT dummy test setup. The Vicon marker positions A) Left shoulder, B) Right shoulder, C) Upper spine, and D) Lower spine.

Table 1. Initial posture setup

Measurement	Test	FE
Belt angle (deg)	24.9-25.2	25.7
Sternal angle (deg)	66.2-67.6	68.9
Femur angle (deg)	6.4 -7.1	6.6
Tibia angle (deg)	34.7	40.6

The frontal crash test was simulated in the LS-Dyna software (ver. 917, Livermore, CA, USA) using THOR-NT dummy FE model and the FE model of the test setup developed using the sled CAD design (Figure 5b). The dummy and the finite element (FE) belts were positioned based on the corresponding data recorded prior to the test. FE belts were modeled with quadrilateral elements which have been assigned a material model with tensile force-deflection characteristics determined from testing (6-8% elongation, 6000 lbf minimum tensile strength). A set of the nodes corresponding to locations of Vicon markers used in testing was defined, and their trajectories were calculated during the crash simulation. Since the dummy feet were tied to the footrest using straps during the tests, a tied contact was defined between the nodes corresponding to the FE models of shoes and the foot rest in the FE simulation. Surface-to-surface contacts were defined between each leg and the knee bolsters, and between the seat belts and thorax. The time histories corresponding to these contacts were calculated during the impact simulation.

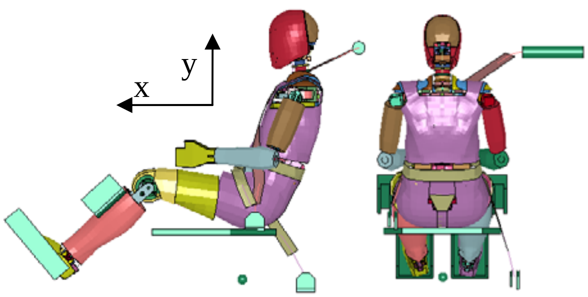

Figure 6. The Thor-NT FE model in pre-impact position

The crash was simulated by applying the time history of linear buck acceleration recorded in Test 1 to the sled model along the x-direction (Figure 7) and constraining the sled motion in all other directions.

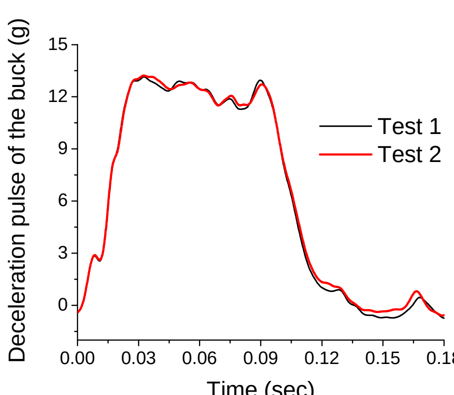

Figure 7. Deceleration pulses of the sled tests

The evaluation of THOR-NT FE model response in frontal crash environment using objective rating methods (ORM)

Continuous development of crash simulation technology considerably increases the utility of virtual testing for the development of restraint systems. However, a dummy model must be evaluated relative to test data before using in crash applications.

Traditionally, model evaluations have been performed by comparing the peak values of the test and simulation data, by evaluating the overall curve shapes qualitatively, or by satisfying several certification guidelines. Recently, there have been several efforts (Jacob et al. 2000, Hovenga et al. 2004, and 2005) focused on developing systematic methodologies for model evaluations, especially in a crash event where a large number of channels must be compared. Based on the characteristics of the data channel to be evaluated, Jacob et al 2000 developed four different methods: the Global Evaluation Method (GEM)- for "normal" channels, the Threshold Evaluation Method (TEM) – for "poor interest" channels, the Criterion Evaluation Method (CEM) – for "criterion" channels. and Limit Evaluation Method(LEM) – for corridor data. In each of these methods, specific criteria were defined based on the local and global characteristics of the test curves. Hovenga et al. 2004 suggested three criteria for evaluating the similarity of the two curves: the peak criterion, the peak-timing criterion, and the Weighted Integrated Factor (WIFac). The first two are the methods in which scalar values, simply the peak values or the times to the peak values from both the simulation and test, are compared. The similarity of overall shapes from two curves is compared by WIFac, defined as:

$$C_{WIFAC} = 1 - \sqrt{\frac{\int \max\left(\left|f(t)\right|, \left|f^*(t)\right|\right)\left[1 - \frac{\max\left(0, f(t) f^*(t)\right)}{\max\left(f^2(t) f^{*2}(t)\right)}\right]^2 dt}{\int \max\left(\left|f(t)\right|, \left|f^*(t)\right|\right) dt}} \quad (1)$$

where $f(t)$ and $f^*(t)$ are the time histories of the experimental signal and the simulation signal, respectively.

In our study, the load signals and the displacement signals that recorded peaks values exceeding 40 mm (in absolute value) in testing were considered as "high interest" channels and were calculated as a linear combination of the peak criterion C_p, the peak to time criterion C_{p_time}, and the WIFac.

$$C_{channel}^{high} = w_p C_p + w_{pt} C_{p\_time} + w_{wh} C_{WIFAC} \quad (2)$$

where the peak criterion C_p and the peak to time criterion C_{p_time} were defined as in Jacob et al. 2000.

$$C_p = 1 - \frac{\left| f_p - f_p^* \right|}{f_p} \qquad (3)$$

$$C_{p\_time} = 1 - \frac{\left| t_p - t_p^* \right|}{\Delta t_{ref}} \qquad (4)$$

where $\Delta t_{ref} = 0.4 \cdot \Delta t_{eval}$ (Jacob et al.2000)

The peak criteria was considered the most important followed by the peak time criteria and WIFac and have been assigned the following weighting factors: $w_p = 0.5;\ w_{pt} = 0.3;\ w_{wh} = 0.2;$

The TEM ((Jacob et al. 2000) was used for the displacement signals that recorded low peak displacements in testing (under 40 mm in absolute value). The channels included in this category were the following: z-displacement of upper spine marker, and y and z displacements of pelvis and lower spine. This method just evaluates how much the signal of the model stays within a prescribed corridor defined based on its maximum values (Figure 8). First criteria of this method was defined based on maximum value of the signal with respect to the threshold

$$C_{v\_th} = 1 - \frac{\max\left(\left|\Delta V_j\right|\right)}{\max\left(\left|Threshold\right|\right)} \qquad (5)$$

where $Threshold = 1.5V_m$ ((Jacob et al. 2000)

The second criterion used by this method is defined based on the time the signal remains in the corridor as:

$$C_{t\_th} = 1 - \frac{\sum \Delta T_i}{\Delta t_{ref}} \qquad (6)$$

where $\Delta t_{ref} = 0.4 \Delta t_{eval}$ (Jacob et al. 2000)

The total score of the "low interest" channels was calculated as a linear combination of both criteria

$$C_{channel}^{low} = w_{v\_th} C_{v\_th} + w_{t\_th} C_{t\_th} \qquad (7)$$

The total score of the displacement of each marker was computed as a weighted average of all cartesian displacements as:

$$C_{ch} = w_x C_{ch\_x} + w_y C_{ch\_y} + w_z C_{ch\_z} \qquad (8)$$

The score in the direction of deceleration was considered the most important with a weighting factor $w_x = 0.7;$ the weighting factors of other two cartesian scores were defined as $w_y = w_z = 0.15;$. The kinematic and load scores of the model were defined as the average of markers scores and the load scores, respectively.

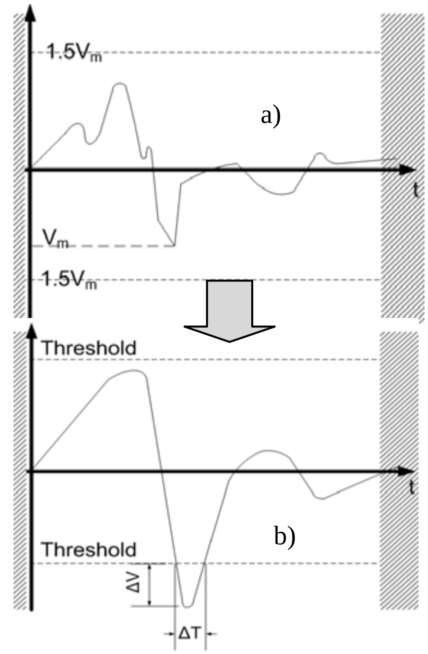

Figure 8. Schematic diagram of TEM criterion a) threshold line setting from the test results and b) procedure of TEM scoring

RESULTS

Since a good repeatability was observed between tests in term of the time histories of buck pulse deceleration (Figure 7) and the dummy kinematics (Figure 9), the simulation results were compared with data from only one test (Test 1). A qualitative comparison between the relative motion of the dummy with respect to the buck and corresponding data predicted using the THOR-NT FE model was performed at different time steps (Figure 10). The time histories of marker displacements along each coordinate axis obtained from the analysis of the Vicon data were compared to the similar data obtained from tracking a set of dummy nodes located at the positions of photo-target markers (Figure 11).

Two significant time intervals can be observed in the dummy motion during the frontal crash test. First, the dummy has an almost translational motion under the inertia forces generated by the deceleration pulse until about 60 ms. In this phase, the thorax rotates slightly in the sagittal plane and the dummy spine becomes almost vertical at the end of 60 ms. In the second phase, the dummy thorax begins to rotate in the transverse plane toward the right side in addition to continued anterior motion (along to the deceleration direction). The neck-head and upper extremities assemblies begin to move forward relative to the thorax (restrained by the shoulder and lap belts) to almost horizontal positions at the end of the simulation (120 ms).

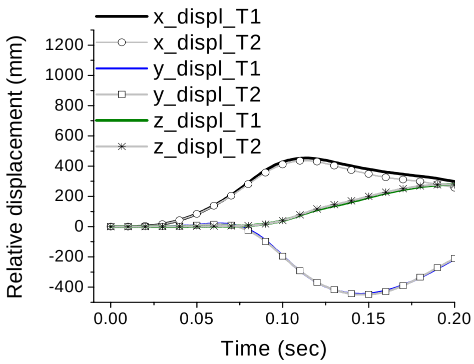

Figure 9. Comparison between the dummy head displacements relative to the buck recorded in testing

In the frontal crash FE simulation, two specific time intervals can be delimitated in the motion of THOR-NT FE relative to the buck as well. As in testing, the model demonstrates a translational motion until 60 ms. The time histories of displacements along the direction of deceleration (x-axis) predicted by the THOR-NT FE model were almost identical to the corresponding data recorded in testing (Figure 11 a-b). However, several differences start to occur in the time histories of the right shoulder and the pelvis x-axis displacements (Figure 11 c, f) which are lower and respectively higher than the corresponding test data due to the sagittal rotation observed in testing, but not in the FE simulation. Time histories of contact forces at the knee bolster and footrest predicted by the FE model are in good agreement with test data, except a region around 40 ms when high force spikes occur in the knee bolster force and a drop in footrest force (Figure 12 d-f). In the second part of the crash (after 60 ms), all time histories of the x-displacement predicted by the model show similar trends to the test data, but differences occur in the peak levels of this data, due to the inability of the THOR-NT model to replicate the sagittal rotation of the dummy spine observed in testing. The Thorax model exhibits mostly translational motion, as observed in the low levels of maxima (20 mm) of time histories of y and z displacements of thorax and pelvis markers, except for the right shoulder where the attached marker showed displacements similar to the test data along the z-direction, but generated much lower values in the y-direction (Figure 11 c).

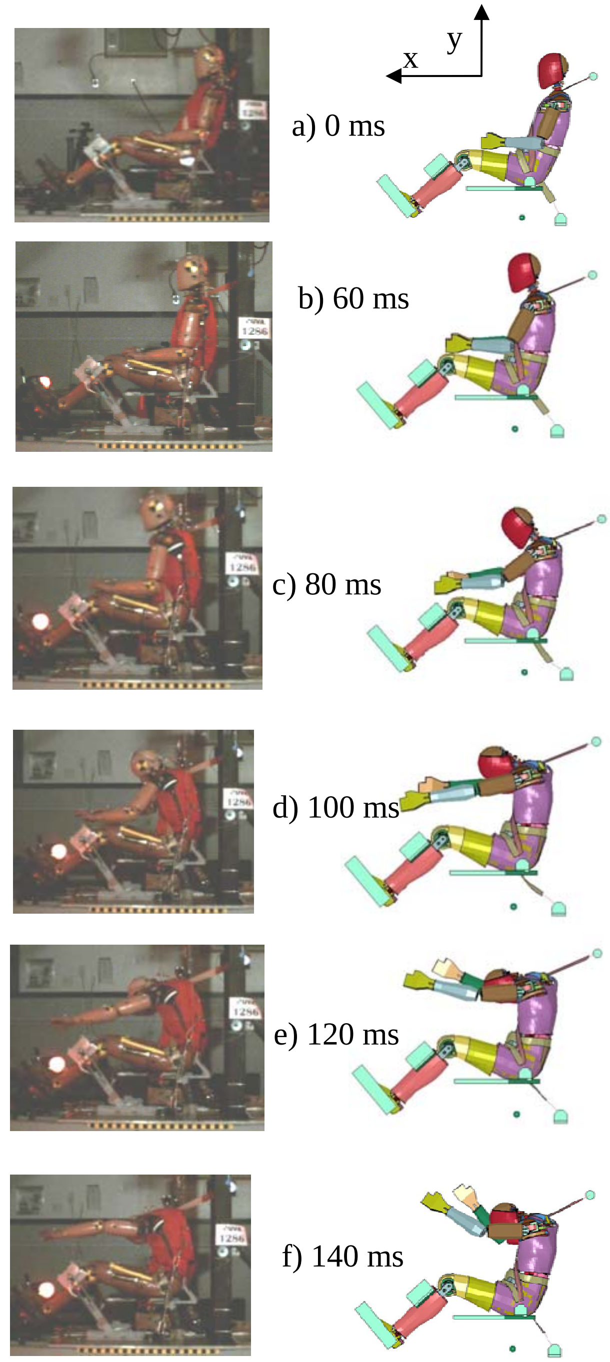

Figure 10. The overall dummy kinematics in frontal sled test. Comparison between test and FE simulation

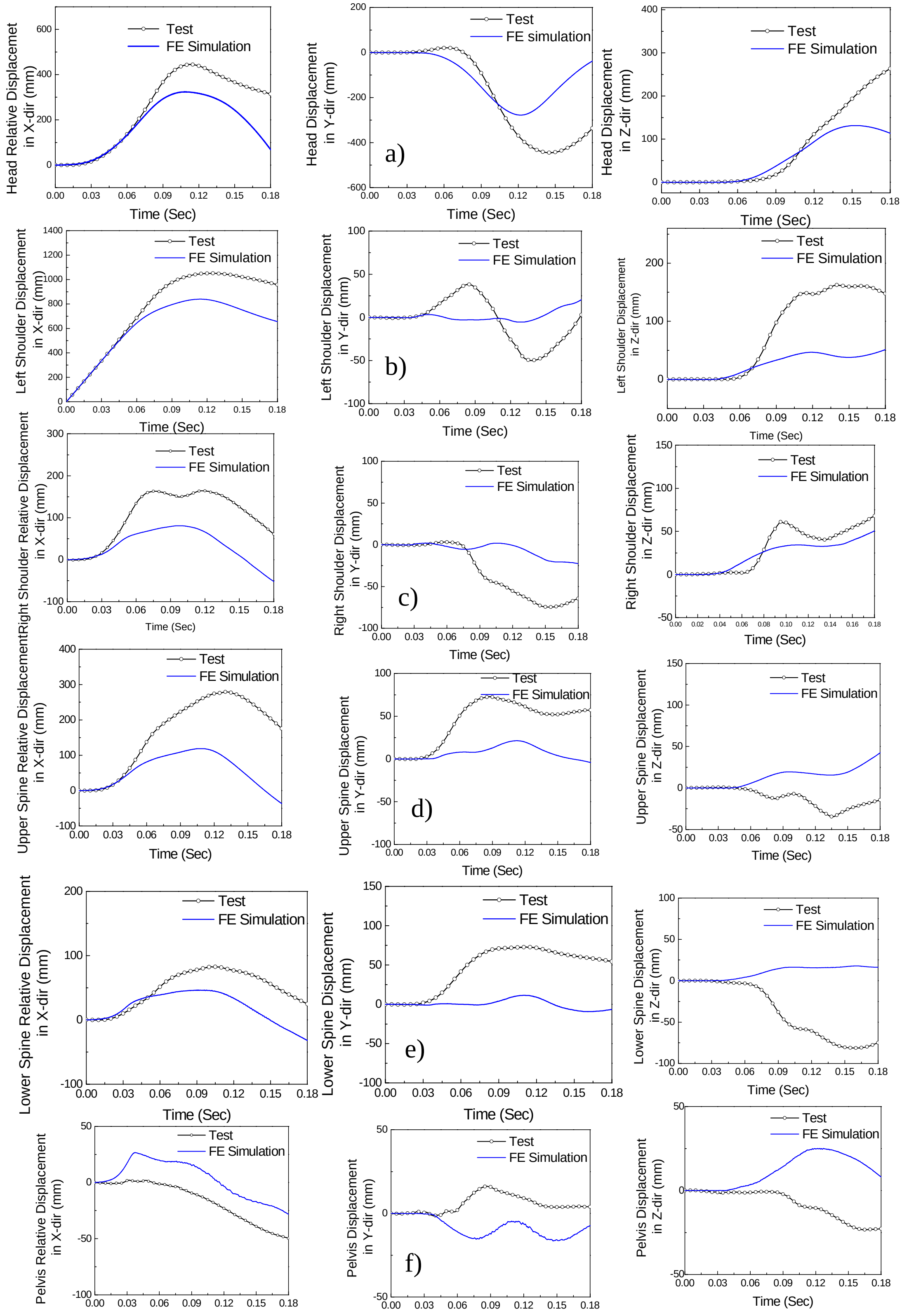

Figure 11. The time histories of marker displacements a) head, b) left shoulder c) right shoulder d) upper spine e) lower spine and f) pelvis

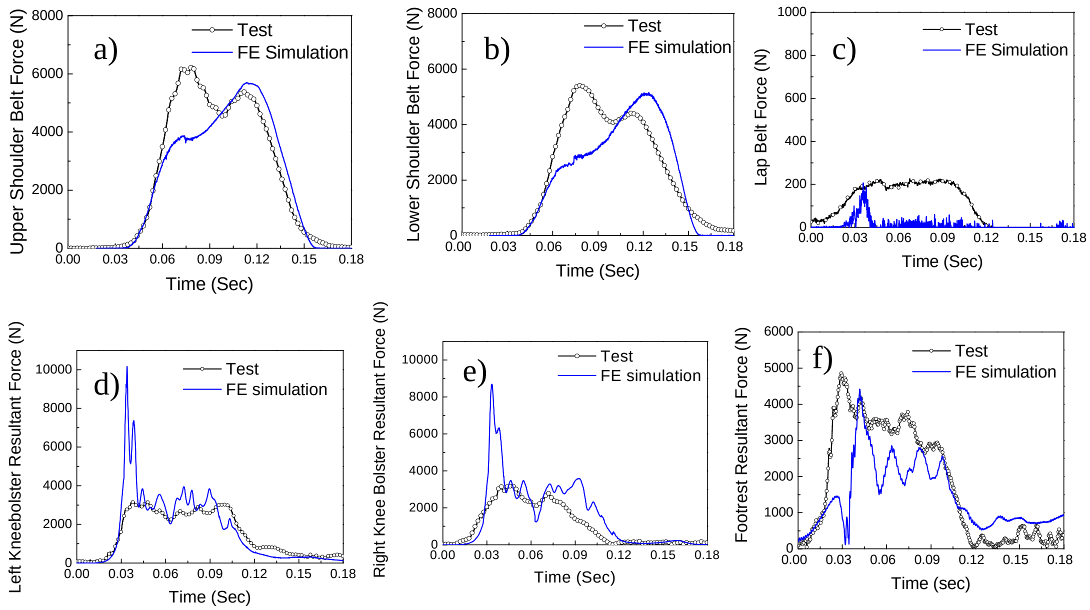

Figure 12. The time histories of resultant force in a)upper shoulder belt, b) lower shoulder belt c) lap belt d) left knee bolster e) right knee bolster f) footrest

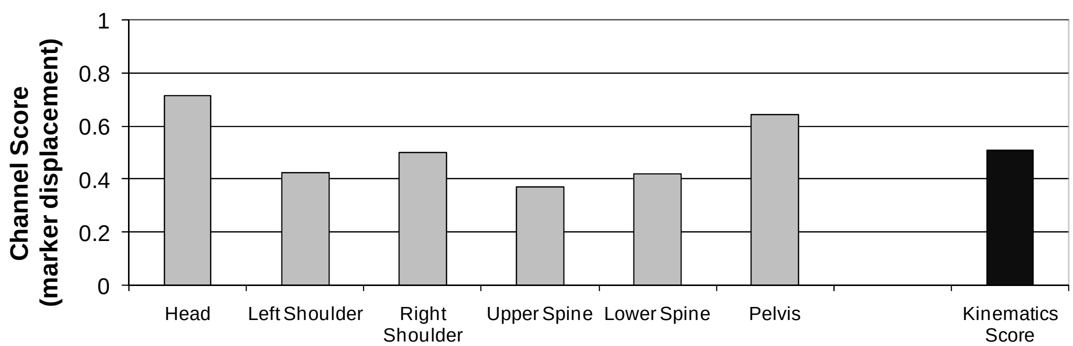

Figure 13. The channel scores of the time histories of marker displacements

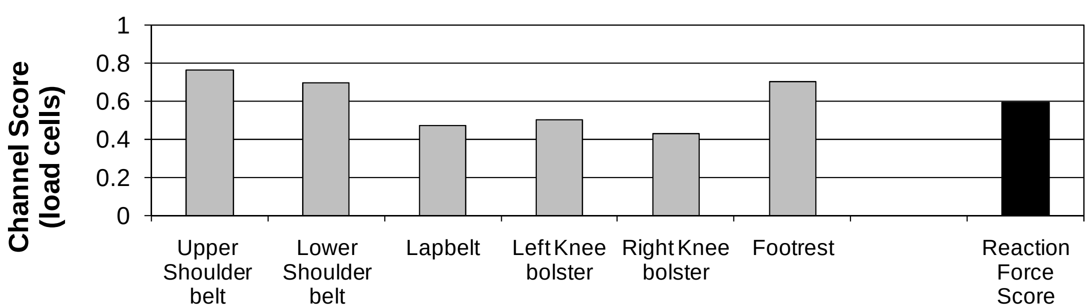

Figure 14. The channel scores of the time histories of reaction forces

The time histories of the shoulder belt loads recorded during testing showed a bi-modal trend with maximum values around 6.2 kN and 5.6 kN at the upper location and lower location, respectively. A diminished bi-modal trend was observed in the shoulder belt forces predicted by the model, and the maximum values were recorded on the second peaks instead of the first ones as in testing (Figure 12 a-b). While an almost constant load (0.2 kN) was recorded in the lapbelt in testing, the load belt was almost negligible in the simulation after a 0.2 kN peak at about 35 ms. (Figure 12 c). Reasonable correlation between test and simulation was observed in the time histories of resultant force in the dummy contacts with knee bolsters and the footrest during the second part of the crash simulation (Figure 12 d-f).

The rating scores of each marker displacement (Figure 13) and loadcell channels (Figure 14) were calculated using the procedure explained in the previous section. The displacement of head marker recorded the highest kinematic score (0.71) and the upper spine the lowest (0.37). The highest loadcell score was calculated in upper shoulder belt (0.76) and the lowest in right knee bolster (0.43). The average kinematics and loadcell scores were 0.51 and 0.59, respectively.

DISCUSSION

This study presents a multifaceted assessment of a FE model of THOR-NT dummy in a frontal crash environment. In addition, to visual comparison of dummy kinematics used mainly in all previous validation studies (e.g. Dsouza and Bertocci 2009), a new quantitative kinematics comparison was introduced. This new approach employed the displacement time histories of retro-reflective markers attached to specific dummy body regions, which were recorded during a frontal crash event by an array of 16 Vicon cameras. These tri-dimensional measurements recorded with a high measurement precision (under 1 mm) help to better understand the complex interaction of the dummy with the restraint systems and test setup and allow a quantitative comparison with similar data calculated easily by computer models. In addition, to the kinematics component, load time histories in belts (shoulder and lapbelt) and in the lower limb contacts with the test setup were measured and compared with the FE model predictions.

Although the numerical simulation showed a reasonable qualitative correlation with testing in terms of overall motion of the dummy relative to the test setup, some discrepancies were observed in the time histories of marker displacements and the external loads (belts and test setup). In addition to the forward translation along the direction of deceleration pulse, the thorax of THOR-NT dummy recorded two significant rotations in sagittal and transverse planes. The FE simulation predicts well the forward motion of the dummy, but not the levels of thorax rotations. While the causes of these un-correlations are still unknown, it is obvious that these causes are internal, due to the THOR-NT dummy FE model, or external, due to a poor replication of the dummy-test setup interaction.

The dummy Thorax FE model was developed according to CAD drawings of the THOR-NT physical dummy and its components were assumed either deformable or rigid. While deformable parts require to be assigned material properties, the rigid parts are connected by defined joints which required structural properties (e.g. moment vs. angle). Both material and structural properties are generally strain rate dependent. The deformable parts (e.g. foam and rubber) were usually defined based on force vs. deflection curves recorded in tension and compression at discrete strain rates (using Mat 181 in Ls-Dyna). More material characterization tests, in different loading conditions (e.g. shear tests, more strain rates) and then material parameter identifications using optimization techniques (Untaroiu et al. 2007) would improve the accuracy material properties of deformable parts. In addition, validations of the upper thoracic and lumbar joints, and then of the whole thorax against tests more appropriate to the frontal crash test than the Kroell tests (e.g. dynamic belt tests – Kent et al. 2004) would certainly increase the capability of Thorax FEM to replicate the dummy response.

The external causes of test-simulation un-correlations include the pre-impact position of the dummy relative to the test setup and the inaccurate characterization of dummy-test setup interfaces. The dummy was positioned in the test setup according to angular (e.g. sternal angle, belt angle, femur angle, tibia angle etc.) and linear (e.g. neck to medial belt edge etc) positioning data recorded prior the impact test. Although this test data was generally matched well in the model, some inherent differences occurred in a few parameters (e,g. tibia angle). While the influence of these positioning parameters on the overall behavior of the model is unknown, a sensitivity study based on FE simulations is recommended. It is believed that the results of this study would help both future tests and simulations in giving a greater importance to the measurement or matching to test data of the most sensitive positioning geometrical parameters. Although the level of lapbelt force (max. 0.2 kN) was much lower than the level of shoulder belt (max. around 6 kN), a special attention should be allowed in future tests and simulations of pre-impact positioning of this belt. The definition of dummy-buck contacts may have also a significant influence on the dummy kinematics, especially through the friction force between seat and dummy. Therefore, in the future tests it would be recommended the measurement of the time histories of seat–to-dummy contact forces, and verification of this data in FE simulations.

A model of the dummy is considered to be good if it can replicate accurately the dummy kinematics and reaction forces with the test setup recorded in testing. A quantitative comparison between physical dummy and its model is difficult to obtain, especially when the number of channels is high, as in the current test. The objective rating methods, recently developed and used in other previous study, can be a promising tool for model assessment. The THOR-NT dummy FE model obtained relatively closed scores in the kinematic and kinetics assessment (0.51 and 0.59, respectively). If the average of these scores is calculated, the total score of the model will be 0.55 which place it in a poor quality range according to Jacob et al 2000's classification (1 is the best score, and 0 is the worst). However, it should be mentioned that the quality values used in these rating methods are heavily dependent on the criteria and weighting factors applied. Therefore, these methods are especially useful for comparing models that use the same rating conditions.

Although it is obvious that the THOR-NT FE dummy model requires additional improvements and validations under additional test conditions (e.g., pulses of different shapes, and directions), its relatively reasonable performance in 40 km/h sled tests would recommend it for use in impact simulations intended to improve the design of new vehicles and their restraint systems.

CONCLUSIONS

This study presents a multifaceted assessment of a finite element model of THOR-NT dummy in a frontal crash environment. First, the three-dimensional kinematics of certain points on the dummy and the interaction forces between the dummy and the test setup were accurately recorded in a 40 km/h sled test with an advanced optical system and load cells. The FE of the dummy, developed and validated at the component level in previous studies, was positioned with respect to a FE model of the test setup according to the test configuration recorded prior to the test. The load and displacement signals (especially along the deceleration direction) show a similar trend with the test data, but some discrepancies were observed: their peak values and in sagittal and transversal motion of the dummy. While the main causes of the low capability of the model to predict the torso rotations observed in testing are unknown, several ideas for model improvement were suggested for the future development and validation of the model. Objective rating techniques, which quantify the similarity of peak level, peak time, and overall shape of two curves, were employed to compare the results of simulations with the test data. Although, the rating values calculated are greatly dependent on the criteria and the weighing factors used in their definition, it is believed that the rating approach would be useful for comparing different versions of the dummy model which will use the same rating condition. In addition to further refinements of current THOR-NT model, the numerical approach presented in this study, which try to determine an overall score from comparison of numerous time histories curves, can be applied in the process of verification/validation of other dummy or human models used in crash simulations.

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