STAPP CAR CRASH CONFERENCE
SHORT COMMUNICATION

SC17-05

Multi Directional THOR Testing Comparison to an Updated FE THOR Model

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ABSTRACT – The use of anthropomorphic test devices (ATDs) for calculating injury risk of occupants in spaceflight scenarios is crucial for ensuring the safety of crewmembers. Finite element (FE) modeling of ATDs has the benefit of reducing cost and time in the design process. The objective of this study was to examine the effects of optimized material properties on an FE THOR and evaluate its efficacy for spaceflight configuration testing using a multi-direction test matrix. 11 physical tests were simulated using the NHTSA FE THOR v2.1 as well as an updated version of model with optimized material properties for spaceflight loading directions, combining for 22 total simulations. Simulation responses were compared to physical testing using the CORrelaiton and Analysis (CORA) method (Gehre, 2009). The updates to the model increased fidelity by 18.8%, and the model was determined to be sufficiently validated for spaceflight configuration modeling and simulation.

INTRODUCTION

Crewmembers are subjected to dynamic forces in both the launch phase of spaceflight and also upon landing after re-entry. While previous methods to reduce injury risk were based on seat acceleration response, more recent methods are based on anthropomorphic test device (ATD) response (Somers, et al., 2014). NASA has chosen the test device for human occupant response (THOR) 50th percentile ATD for injury risk assessment in spaceflight loading due to its biofidelity in multi-axis performance (Somers, et al., 2014).

Harnessing the application of finite element (FE) modeling of ATDs in the field of injury biomechanics has the benefits of cost and time-effectiveness over physical testing, especially in the iterative design phase. The 50th percentile male FE model of the THOR distributed by the University of Virginia and NHTSA has been validated at the component level and full body level for car crash simulation, but the response in vertical and lateral loading has not been studied in detail (Panzer, et al., 2015). Furthermore, the validation of the model in a spaceflight configuration restraint system is incomplete. Previous work has been demonstrated the benefits of optimizing material properties of the THOR model for spaceflight loading, but only two test conditions were simulated for comparison (Putnam, et al., 2014, Putnam, et al., 2015).

Therefore, the goal of this study was to examine the output response of the FE NHTSA THOR v2.1 and compare the kinematic and kinetic response to an updated version of the model with previously optimized material properties using an expanded test matrix.

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METHODS

Physical Experiments

The Wright Patterson Air Force Base (WPAFB) Aerospace Biodynamics and Performance Group test database was queried for physical experiments conducted with the THOR ATD in a simple seat and belt set up. Twenty six physical experiments were identified, which fit within the search parameters. These tests were conducted in three directions using the Horizontal Impulse Accelerator (HIA) and a 90-90-90° rigid seat, fitted with a 5-point belt system (Perry, et al., 2013, Somers, et al., 2014). Using a sign convention in which the x-axis points anteriorly, the y-axis points left, and the z-axis points superiorly, the sled impulses were applied in the –X (frontal, eyeballs in), +Y (lateral, eyeballs right), and +Z (vertical, eyeballs down) orientations. The sled accelerations were half-sine pulses, which can be described by a combination of peak acceleration, and the rise time to the peak and is presented in Table 1.

Table 1: THOR physical test matrix

Dir	Acc (G)	Rise Time (ms)	Physical Tests (N)
-X	8	100	2
-X	10	70	2
-X	20	70	2
+Z	10	40	4
+Z	10	70	2
+Z	10	100	3
+Z	20	70	2
Y	10	40	2
Y	10	70	2
Y	10	100	2
Y	20	70	3

THOR Model Updates

In order to fulfill the purpose of validation of a finite element THOR model in multiple directions, the NHTSA THOR v2.1 was used as the starting model (Panzer, et al., 2015). Material properties from the literature were used to update the NHTSA THOR v2.1 including changes to the pelvis material properties, the upper thoracic flex joint (UFJ), the lower thoracic flex joint (LFJ), head springs, and the removal of the Thorax Cables (PIDs 700151,700153) (Putnam, et al., 2014, Putnam, et al., 2015). Finally, the UFJ was re-meshed to incorporate a finer mesh. The updated THOR model is referred to henceforth as the NASA THOR.

Simulation

The THOR FE models were positioned into an upright position by using the dummy positioner in LS-PrePost, and the node locations were exported for use as the starting position for later simulations. The FE ATDs were then positioned slightly above the seat model, and gravity settling was applied for 150 ms. Concurrently, the belt system was pre-tensioned to 20 lbf at each anchor location. Immediately following the 150 ms settling portion of the simulation, the belt retractors were locked ensuring no pullout in the belt system was allowed, and the acceleration pulse was applied to the seat.

Post-Processing

The kinematics of the simulated ATDs were qualitatively compared to the test videos from the physical experiments as a prerequisite for quantitative data analysis. Simulation ATD and belt system signals were compared against the average curve from the matched physical tests. Since the number of tests in each condition was small, and variation between tests was low, only the cross correlation portion of CORrelation and Analysis (CORA) was used for comparison between physical and simulation environment (Gehre, et al., 2009).

The cross correlation score for the resultant linear head acceleration (C_{Head}), resultant linear T6 acceleration (C_{T6}), resultant linear pelvis acceleration (C_{Pelvis}) were calculated. The cross correlation score for each belt force-time curve was computed and averaged (C_{Belts}). The simulation was then scored using Eq. 1.

$$C_{Overall} = \frac{1}{A}\sqrt{{C_{Head}}^2 + {C_{T6}}^2 + {C_{Pelvis}}^2 + B \times {C_{Belts}}^2} \qquad \text{Eq. 1}$$

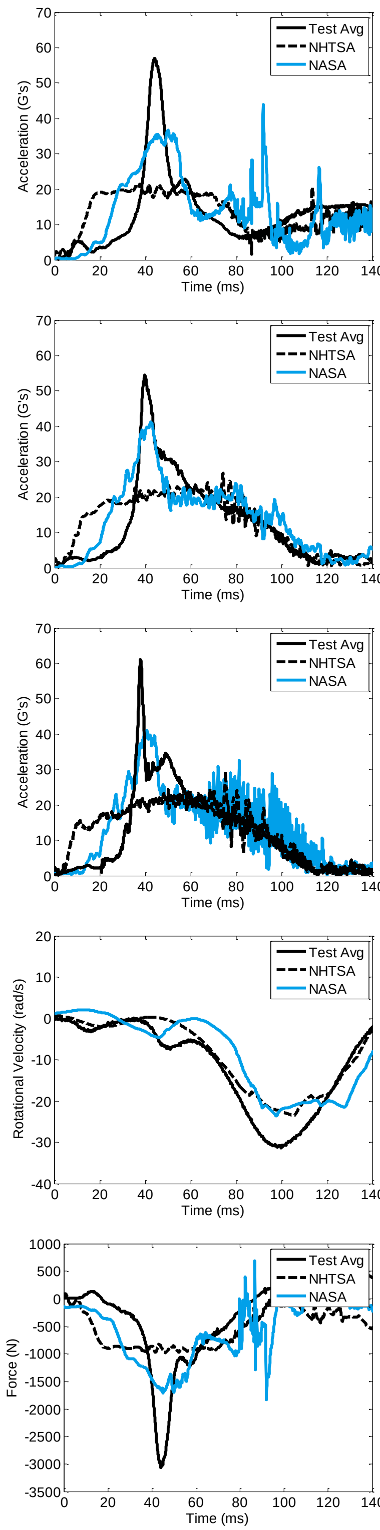
Here, if the simulation was conducted in the –X (frontal) direction, $A = 2$ and $B = 1$. In lateral, or vertical loading scenarios, $A = \sqrt{3}$ and $B = 0$. This effectively removes the belt scores for directions in which the restraints are not acting in opposition of ATD movement. $C_{Overall}$ ranged from 0 to 1, with unity indicating a perfect match.

RESULTS

Both the unmodified NHTSA THOR v2.1 and the NASA THOR model were subjected to the 11 sled pulse accelerations, resulting in 22 total simulations. In general, the NASA THOR performed better in both the qualitative and quantitative portion of the comparison analysis. Figure 1 demonstrates the difference between selected kinematic and kinetic responses of the two models in a +Z (vertical) loading scenario with 20 G peak acceleration and 70 ms rise time.

The shape of the acceleration curves is markedly closer to the physical response with the updated model, demonstrating a local peak at the appropriate time, as opposed to a prolonged acceleration plateau in the NHTSA model.

The NASA THOR model performed better than the NHTSA THOR v2.1 in 10/11 simulations, earning on average a 18.8% increase in $C_{Overall}$, indicating higher fidelity. $C_{Overall}$ scores above 0.9 were considered excellent, those above 0.8 were considered very good. A $C_{Overall}$ score below 0.6 was determined to be a poor response. The average overall score for the NASA THOR model was 0.848±0.070. Best average response by direction for the updated THOR was –X (0.880±0.021), Y (0.870±0.076), and +Z (0.801±0.076).



a)
b)
c)
d)
e)

Figure 1: Comparison of NHTSA THOR v2.1 to the NASA THOR results from a +Z (vertical) Impulse with 20G peak acceleration and 70 ms rise time. Resultant linear acceleration of the head (a), T6 (b), and pelvis (c). Rotational velocity of the head in the local y-axis (d). Upper neck load cell axial force (e).

DISCUSSION

The updated material properties effectively introduced more deformability into the FE THOR model. The change was most notable in the pelvis flesh response. Specifically, the NHTSA THOR v2.1 deformed 2 mm during the gravity settling phase, compared to 15 mm deformation by the NASA THOR. This phenomenon affected the propagation of load into the spine. The NHTSA THOR acceleration response was highly coupled to the sled acceleration, while the NASA THOR more closely resembled the experimental test video and signal response. The change in modeling of the UFJ–thorax cable combination increased the stability of the model, which had previously tended to produce a high frequency vibration response as the simulation length increased.

CONCLUSION

22 THOR simulations were completed, 11 with the NASA THOR, and 11 with the NHTSA THOR v2.1. The results were compared to physical experiment data conducted at WPAFB on the HIA. The NASA THOR model performed better in both qualitative and quantitative comparisons to the physical counterpart in the 5-point restraint and rigid seat set up modeled in this study.

It can be concluded that the NASA THOR model response is closer to the physical response from the tests conducted by WPAFB. Furthermore, the NASA THOR model is sufficiently validated for spaceflight configuration testing against the physical counterpart.

ACKNOWLEDGMENTS

This study was supported by NASA Human Health and Performance Contract (HHPC) through KBRwyle. Views expressed are those of the authors and do not represent the views of NASA or KBRwyle. Simulations were performed on the Wake Forest University DEAC cluster, a centrally managed resource with support provided in part by the university.

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