Accident Analysis and Prevention 82 (2015) 244–256

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

# Development and evaluation of a finite element model of the THOR for occupant protection of spaceflight crewmembers

Jacob B. Putnam[a], Jeffrey T. Somers[b], Jessica A. Wells[c], Chris E. Perry[d], Costin D. Untaroiu[a,*]

[a] Center for Injury Biomechanics, Department of Biomedical Engineering and Mechanics, Virginia Tech, Blacksburg, VA, USA
[b] Wyle Science, Technology and Engineering Group, Houston, TX, USA
[c] Lockheed Martin, Houston, TX, USA
[d] 711th Human Performance Wing, Wright-Patterson Air Force Base, OH, USA

ARTICLE INFO

*Article history:*
Received 13 July 2014
Received in revised form 2 May 2015
Accepted 4 May 2015
Available online 20 June 2015

*Keywords:*
Crash test dummy
Impact biomechanics
Human-volunteer testing
Biofidelity
Anthropomorphic test device
Human spaceflight

ABSTRACT

New vehicles are currently being developed to transport humans to space. During the landing phases, crewmembers may be exposed to spinal and frontal loading. To reduce the risk of injuries during these common impact scenarios, the National Aeronautics and Space Administration (NASA) is developing new safety standards for spaceflight. The Test Device for Human Occupant Restraint (THOR) advanced multi-directional anthropomorphic test device (ATD), with the National Highway Traffic Safety Administration modification kit, has been chosen to evaluate occupant spacecraft safety because of its improved biofidelity.

NASA tested the THOR ATD at Wright-Patterson Air Force Base (WPAFB) in various impact configurations, including frontal and spinal loading. A computational finite element model (FEM) of the THOR to match these latest modifications was developed in LS-DYNA software. The main goal of this study was to calibrate and validate the THOR FEM for use in future spacecraft safety studies.

An optimization-based method was developed to calibrate the material models of the lumbar joints and pelvic flesh. Compression test data were used to calibrate the quasi-static material properties of the pelvic flesh, while whole body THOR ATD kinematic and kinetic responses under spinal and frontal loading conditions were used for dynamic calibration. The performance of the calibrated THOR FEM was evaluated by simulating separate THOR ATD tests with different crash pulses along both spinal and frontal directions. The model response was compared with test data by calculating its correlation score using the CORrelation and Analysis rating system. The biofidelity of the THOR FEM was then evaluated against tests recorded on human volunteers under 3 different frontal and spinal impact pulses.

The calibrated THOR FEM responded with high similarity to the THOR ATD in all validation tests. The THOR FEM showed good biofidelity relative to human-volunteer data under spinal loading, but limited biofidelity under frontal loading. This may suggest a need for further improvements in both the THOR ATD and FEM. Overall, results presented in this study provide confidence in the THOR FEM for use in predicting THOR ATD responses for conditions, such as those observed in spacecraft landing, and for use in evaluating THOR ATD biofidelity.



## 1. Introduction

With the advent of new space-crew-transport vehicles being developed by the National Aeronautics and Space Administration (NASA) and several commercial companies, the number of spaceflight occupants is expected to increase dramatically. Learning from the trials of the automotive safety field, early development of occupant crash safety standards for these new spaceflight vehicles will be essential in the prevention of injury and preservation of human life. Though the necessity of standards can be learned from the automotive field, the spaceflight standards need to be developed separately due to vast differences between these fields. An automobile impact is a low-occurrence, high-risk event with a crash impact risk of 1 in 1.3 million miles driven and 1 in 3.4 crashes resulting in injury (NHTSA, 2014). Therefore,

* Corresponding author at: Virginia Tech, Department of Biomedical Engineering and Mechanics, Center for Injury Biomechanics, VCOM II Building, 2280 Kraft Drive, Blacksburg, VA 24060, USA. Tel.: +1 540 231 8997; fax: +1 540 231 2953.
*E-mail addresses:* costin@vt.edu, costin.untaroiu@gmail.com (C.D. Untaroiu).

http://dx.doi.org/10.1016/j.aap.2015.05.002

automobile industry standards are focused on mitigating the risk of severe injuries. To achieve spaceflight, the human body is accelerated to over 11,200 m/s to escape Earth's gravity and in turn is decelerated back to 0 m/s during landing (Newby et al., 2013). Though peak accelerations are reduced as much as possible, there is still a large energy transfer into the body during takeoff and landing. Therefore, it is essential to develop spaceflight safety standards with a very conservative total injury risk to ensure the continued health and safety of all human occupants traveling to and from space.

The space-crew-transport vehicles currently being developed for NASA are the Orion, SpaceX Dragon, and Boeing CST-100. All are capsule based and each has a unique landing acceleration environment based on the individual designs (Newby et al., 2013). The Sierra Nevada Corporation Dream Chaser lifting-body space-transport vehicle is not currently under consideration by NASA (Foust 2014; Somers et al., 2014a); however, these designs may be used for commercial space transportation outside of NASA. During takeoff, the crewmembers experience posterior–anterior accelerations. During landing, crewmembers typically experience accelerations in inferior–superior (spinal) and either anterior–posterior (frontal) or posterior–anterior (rear) directions. Though nominal takeoff conditions can be highly controlled, launch aborts may impart a large load on the crewmembers and may include significant off-axis oscillatory accelerations. Capsule landing is usually controlled by parachutes, thus dependent on wind conditions and parachute performance. In addition, wave slope and direction or ground terrain can also greatly influence the landing loads. The variability in landing conditions further adds to the necessity of conservative injury risk standards, requiring thorough crash safety analysis of these conditions.

Crash safety analysis is primarily performed through the testing of anthropometric test devices (ATDs), commonly referred to as crash test dummies. Currently, NASA is investigating the Test Device for Human Occupant Restraint (THOR) ATD for use in the development of new spaceflight safety standards. The THOR ATD, developed by the National Highway Traffic Safety Administration (NHTSA), was chosen for this investigation due to its improved biofidelity over other common ATDs, specifically the industry standard Hybrid III ATD (Shaw et al., 2002).

NASA performed a series of frontal and spinal impact tests on the THOR ATD at the Wright-Patterson Air Force Base (WPAFB) to assess responses in spaceflight-like landing conditions (Newby et al., 2013). The purpose of the testing was twofold: to understand the physical response of the THOR ATD to conditions similar to expected spaceflight impacts, and to provide test data for model calibration and validation. The acceleration pulses were sinusoidal, ranging from 10 to 20-*g* at a 70 ms rise time. In addition, 10-*g* runs were conducted with 40 and 100 ms rise times to assess the frequency response of the THOR ATD. Although these pulses are not the exact anticipated loads for the NASA Orion vehicle, they were selected to cover the range of accelerations and rise-times expected during nominal and off-nominal landing conditions. A subset of these test data was used to calibrate and validate the THOR FEM in frontal and spinal loading.

The increase in computational power over the last decade has enabled the use of a computational component complementary to experimental testing. The development of a finite element model (FEM) in the crash safety field presents many opportunities to increase the efficiency and capabilities of human safety analysis. An accurate and reliable THOR FEM provides a tool to increase testing efficiency, as simulated test setups can easily be adjusted to assess response in a variety of conditions. In addition, these models allow for the optimization of vehicle or restraint system design throughout the manufacturer's design process (Untaroiu et al., 2007; Bose et al., 2010; Adam and Untaroiu, 2011).

The goal of this study was to develop an accurate THOR FEM for spaceflight crash safety analysis. The effectiveness of the THOR FEM was ensured through comparison to physical tests in both frontal and spinal impacts. Once verified against the THOR ATD, the THOR FEM was used to assess biofidelity against human-volunteer test data. Based on these results, recommendations are made on the effectiveness of the THOR to predict human response in the spaceflight loading regimen. The THOR FEM may be used to aid in the development of new spaceflight occupant safety standards, provide an effective tool in the optimization of new vehicle designs without the expense of testing and physical prototyping, and continually improve the THOR ATD biofidelity.

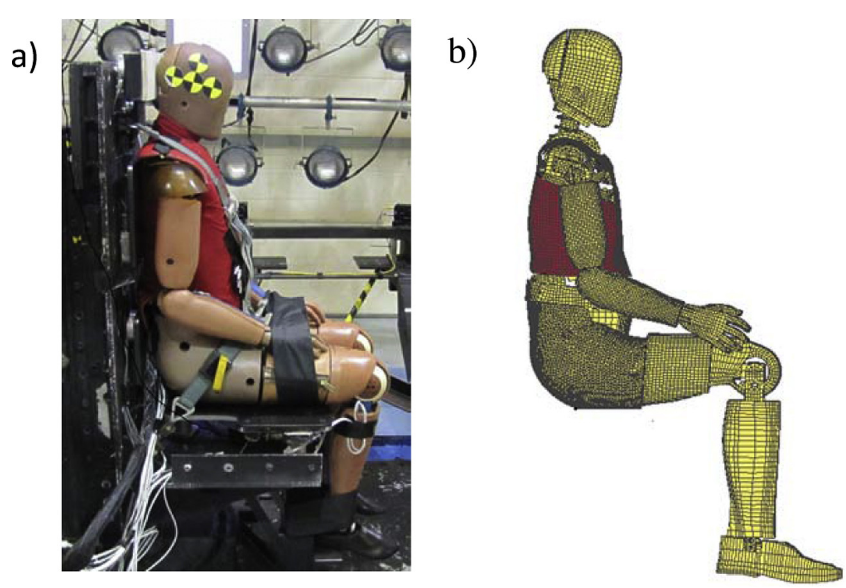


**Fig. 1.** THOR: (a) ATD, (b) FEM.