NASA RVLT: Human Body Models for Crashworthiness Research Overview

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Introduction – NASA Revolutionary Vertical Lift Technology (RVLT) Project Impact Dynamics / Crash Safety Task

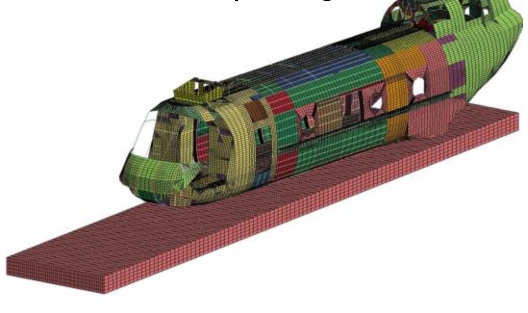
- **Task Objective:** *"To improve the crashworthiness and impact safety of urban air mobility (UAM) vehicles and provide data to simplify the certification process. Efforts will include development of validated computational models of these vehicles, as well as other impacting bodies such as birds and drones. Efforts will also focus on developing and evaluating energy absorbing and crush properties of emerging and non-traditional composite materials and processes. Finally, occupant protection will be addressed using computational models and physical assets as it pertains to all rotorcraft environments."*
- **Problem Statement:** "*There currently is a lack of data for requirements regarding the crashworthy performance of UAM vehicles and impact loads generated by a bird strike. To address this technology gap, NASA will develop test guidelines,* ***<u>adopt modeling methodologies demonstrating capability for 'certification by analysis',</u>*** *acquire vehicle and occupant data on full-scale representative vehicles, and provide data/guidance to consensus standards organizations and the UAM community."*

- 4 Main focus points
  - The investigation of occupant injury using physical and computational assets
  - The development of energy absorbing technology
  - The generation of data from sub- and full-scale crash test data
  - **The execution of advanced finite element (FE) modelling techniques**

RVLT Historical Testing / Research Examples

- RVLT (and predecessors) have been conducting crash research for 20+ years at Langley Research Center (LaRC)
  - Dynamic performance of composites
    - ACAP – large composite rotorcraft prototype
    - SARAP – composite fuselage prototype
  - Occupant protection
    - F28 vertical and full-scale crash testing
    - Transport Rotorcraft Aircraft Crash Testbed (TRACT 1&2)
    - Anthropomorphic Test Device (ATD) vertical drop testing
    - Advanced ATD research
  - Energy absorbing concepts development
    - MD-500 with Deployable Energy Absorber concept
    - TRACT 2 crushable “conusoid” subfloor
  - Advanced computational simulation efforts
    - Full-scale aircraft development
    - Terrain replication
    - ATD evaluations

TRACT FEM impacting soil

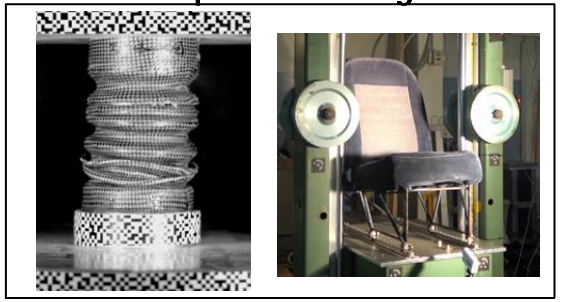


TRACT “conusoid” subfloor

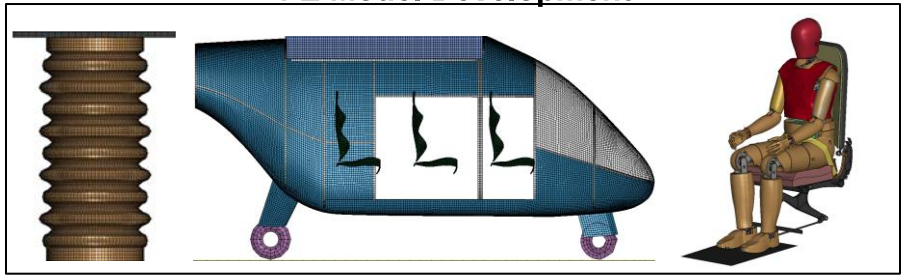
Current Research in Crashworthiness Analysis Methodologies

- Goal 1. Determine predictive accuracy of component, vehicle, and occupant FE models within dynamic impact environments

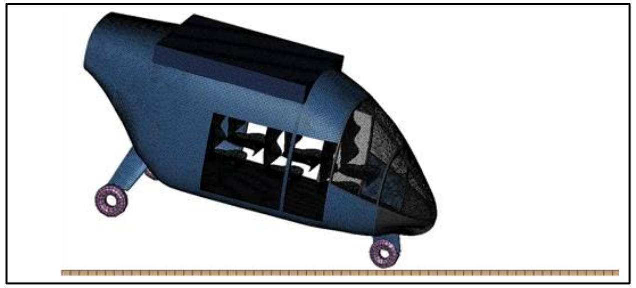
Component testing



FE Model Development

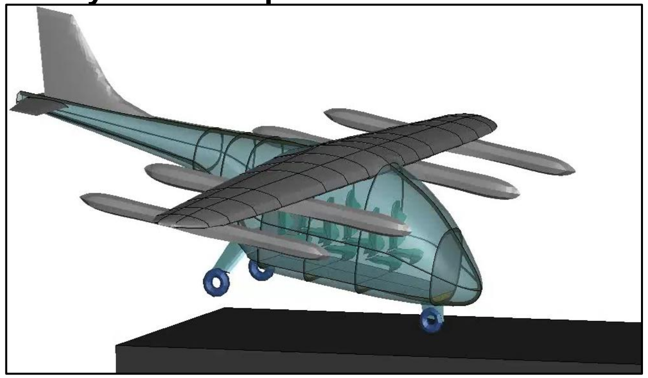


Full-Scale Test Verification

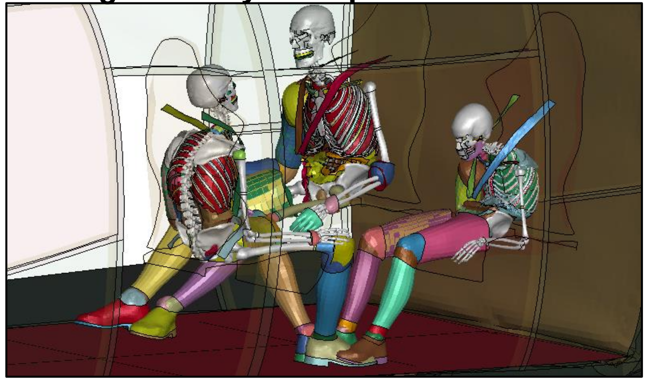


- Goal 2. Develop methodologies to improve quantification of vehicle crashworthiness through FE analysis

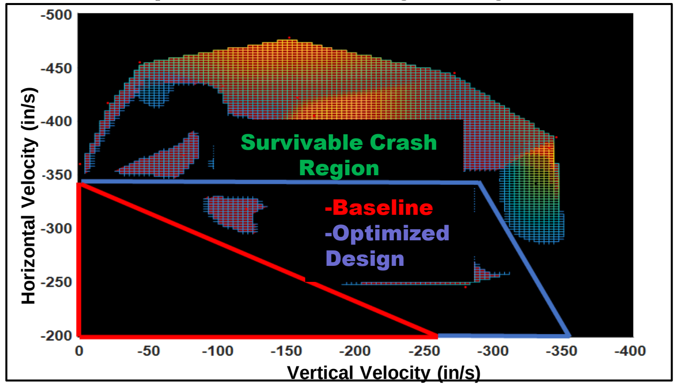
Analysis of complete crash environment



High Fidelity Occupant Simulation

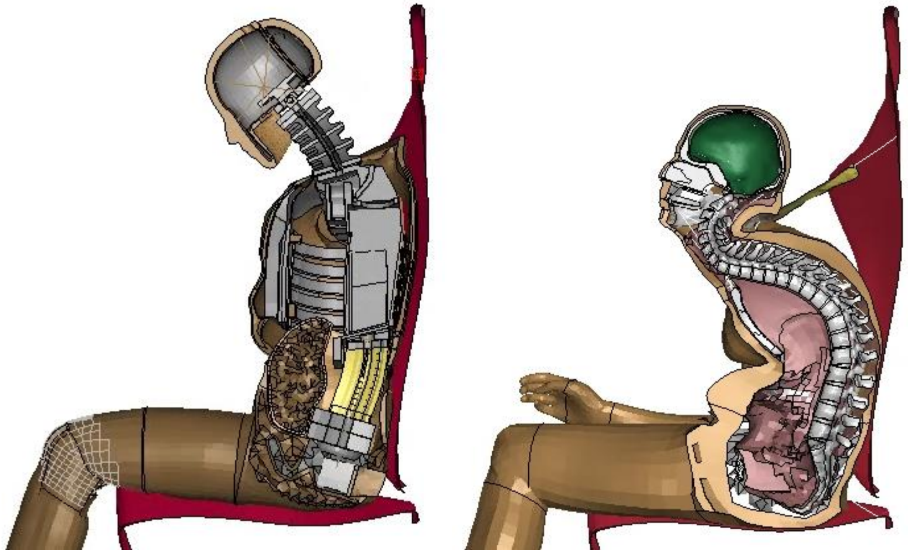


Impact Survivability Analysis

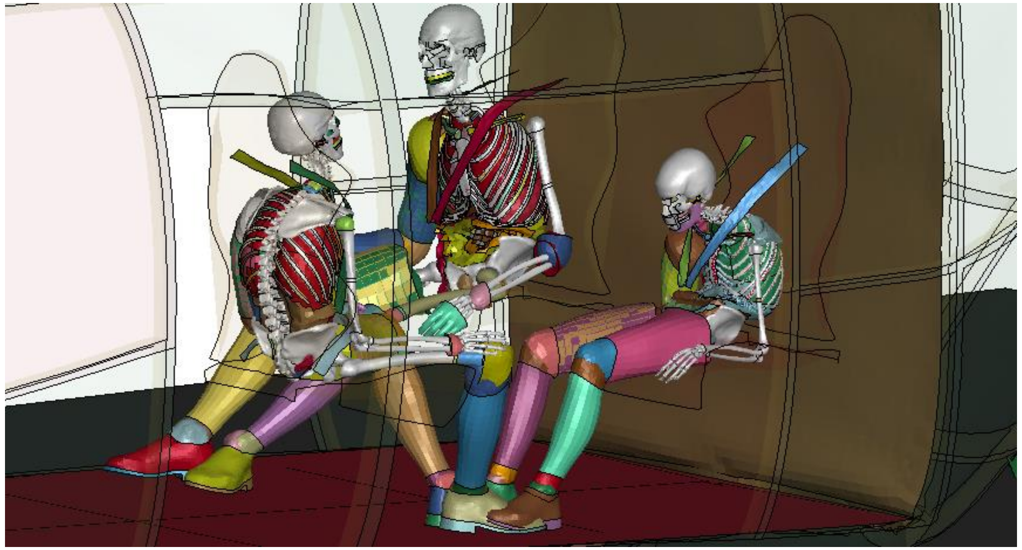


Improve Quantification of Crashworthiness - Human Body Models

- Evaluate capability of human body models (HBMs) to supplement limitations of ATDs within aerospace loading environments
  - Characterize differences in predicted occupant kinematics under multi-axis loading
  - Compare injury risk predictions



- Demonstrate use of human body models to better characterize injury risk mechanisms within vehicle design
  - Verify low injury risk across “survivable” crash space (5^{th} – 95^{th} anthropometry)
  - Identify potential injury sources not captured under current ATD criteria
  - Study effects of positioning/bracing



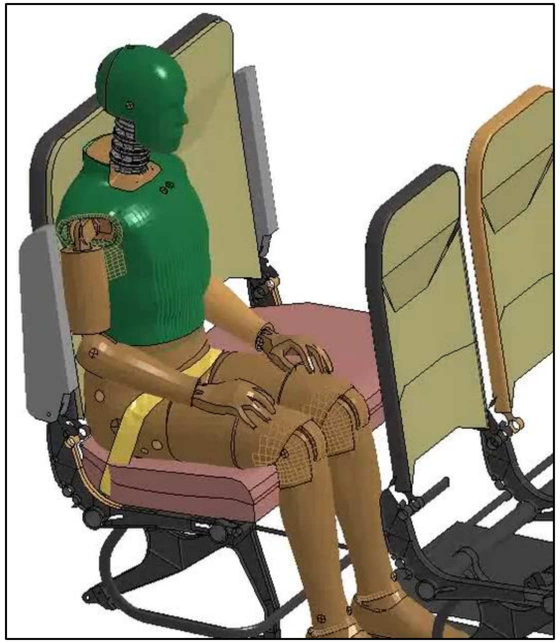
ATD/HBM Capability Evaluation – Traditional Aircraft (Fokker F28)

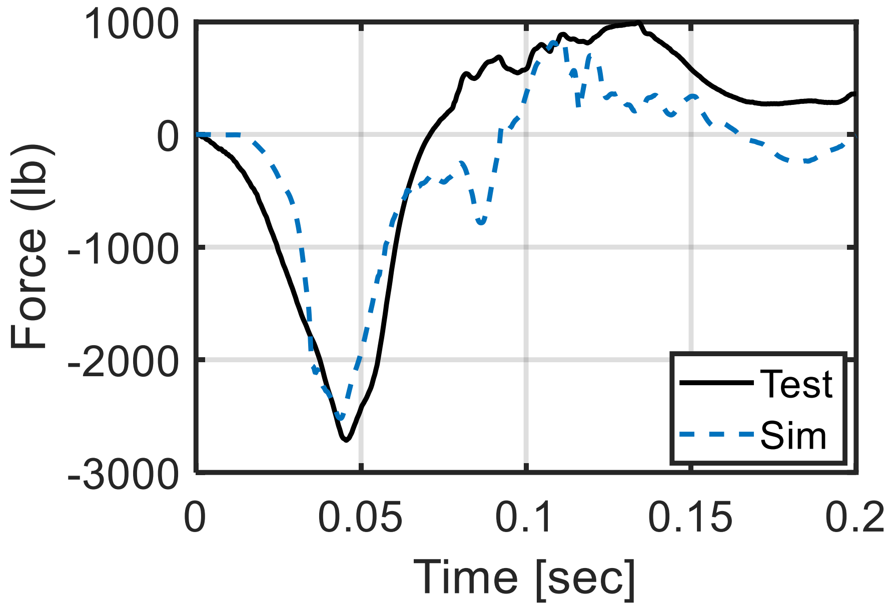
Vehicle Specifications: 33,306 lb, 3+2 Seating, 85p capacity
Test Conditions: 32 ft/s Vertical & 65 ft/s Horizontal Velocity

ATD/HBM Capability Evaluation – Traditional Aircraft (Fokker F28)

ATD/HBM Capability Evaluation – Occupant Model Validation

- Prior to simulating HBMs in the F28 test condition, the occupant models (seat, belts, boundary conditions) were validated using ATD test data

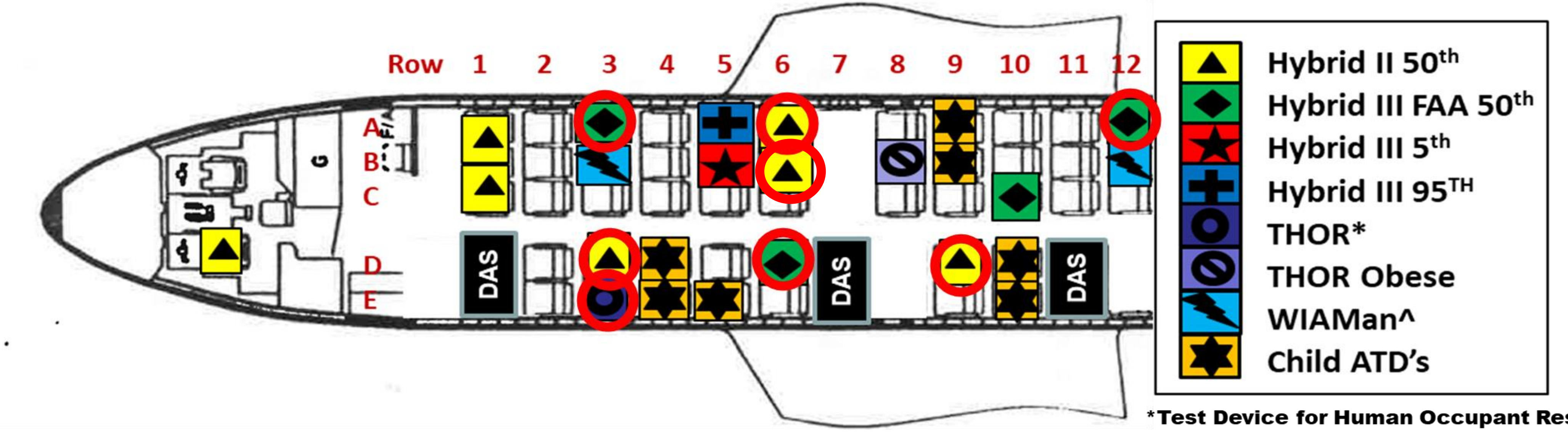




ATD/HBM Capability Evaluation – HBM Simulated Conditions

- Currently available HBM models (paid and free), Global Human Body Model Consortium (GHBMC) and Total Human Model for Safety (THUMS), were simulated in conditions representative of the mid-size male occupant ATDs tested
- Eight seated locations were simulated with each HBM model

[1]

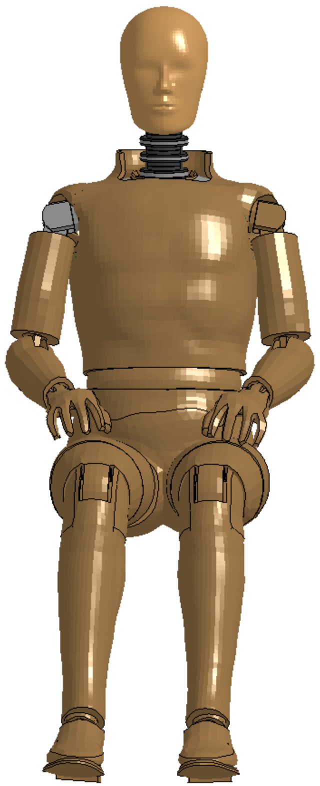


*Test Device for Human Occupant Restraint
^Warrior Injury Assessment Manikin

ATD/HBM Capability Evaluation – Tool Comparison

ATD

Hybrid III



Biofidelity: Inherently not Biofidelic

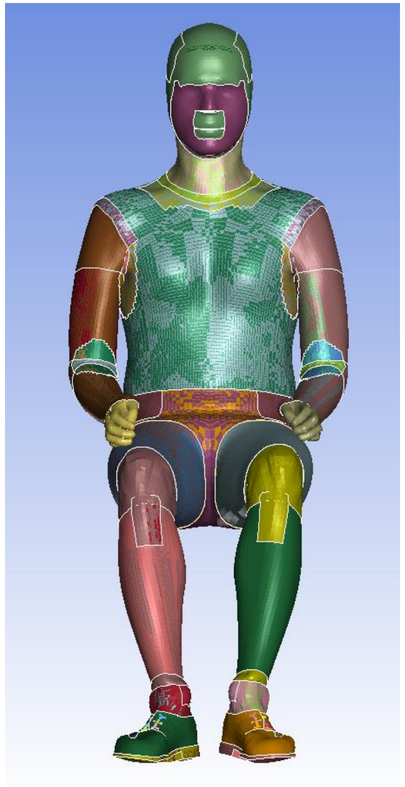
Injury Prediction: Finite - location/mechanism limited - validated within specific loading environments - well defined/agreed upon

Cost: 0 - $$

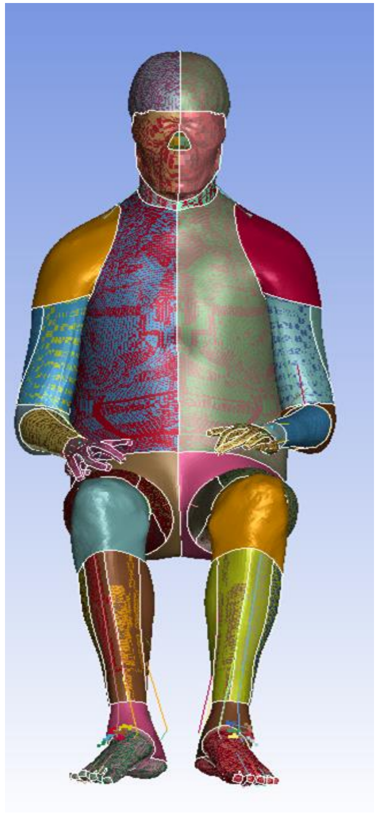
Analytical Cost: Fast

HBM

GHBMC



THUMS



Biofidelity: Potentially biofidelic - aspects validated for automotive - not well characterized in aerospace

Injury Prediction: Full body – currently limited by validation data - not well defined/agreed upon

Cost: 0 - $$$

Analytical Cost: Medium - Slow

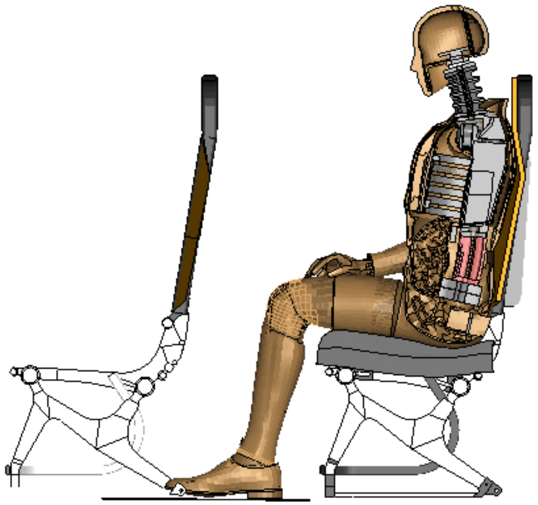
ATD/HBM Capability Evaluation – Kinematic Comparison

Seat 3D/E – Hybrid II 50th and THOR

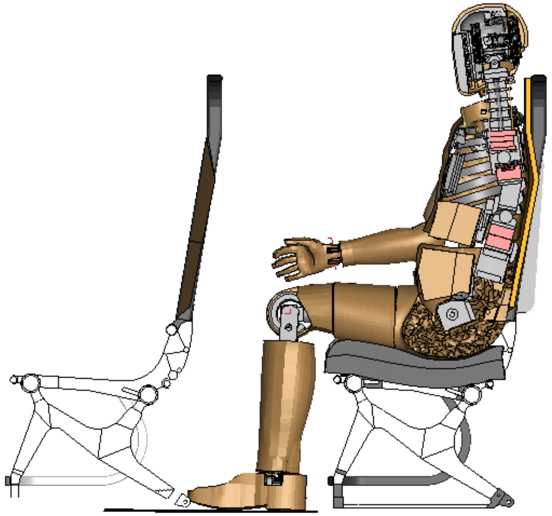
ATD/HBM Capability Evaluation – Kinematic Comparison

Initial Position

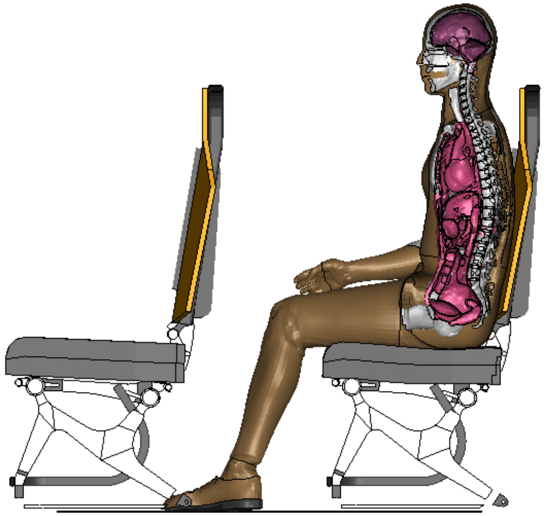
Hybrid III ATD



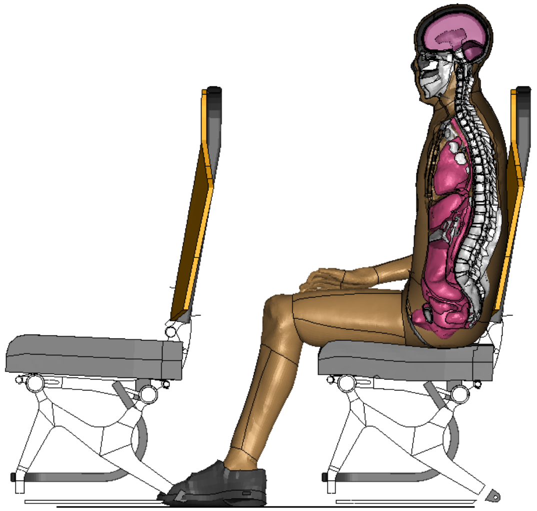
THOR ATD



GHBMC HBM



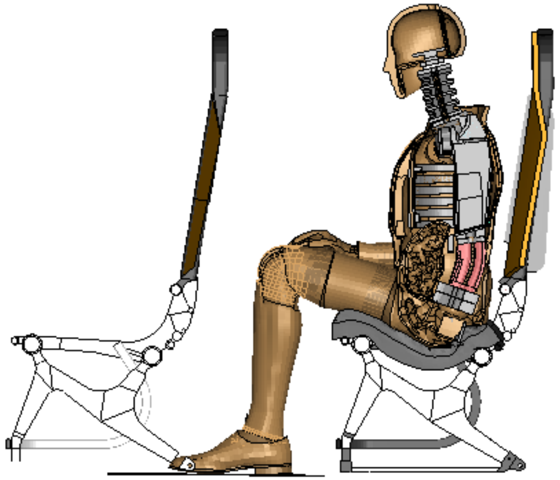
THUMS HBM



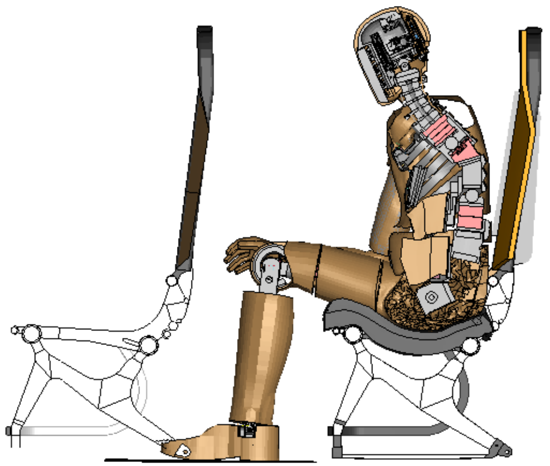
ATD/HBM Capability Evaluation – Kinematic Comparison

Peak Vertical Compression

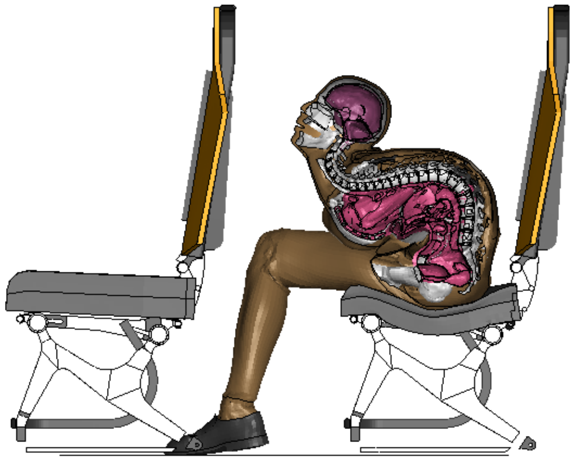
Hybrid III ATD



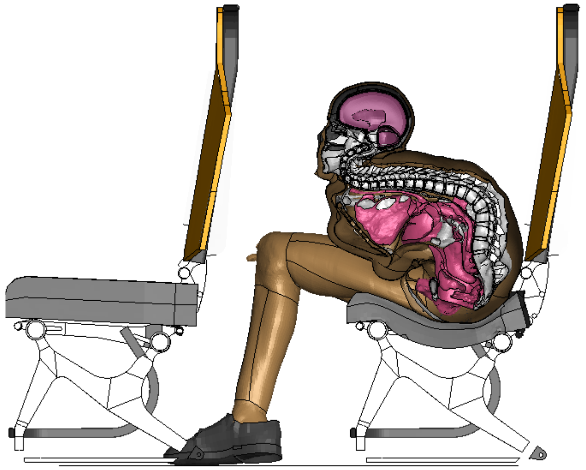
THOR ATD



GHBMC HBM



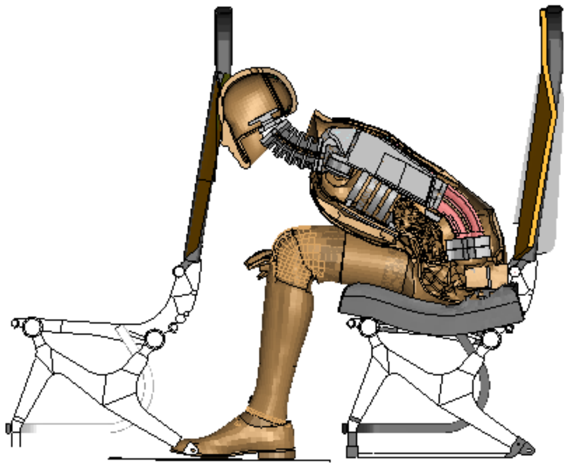
THUMS HBM



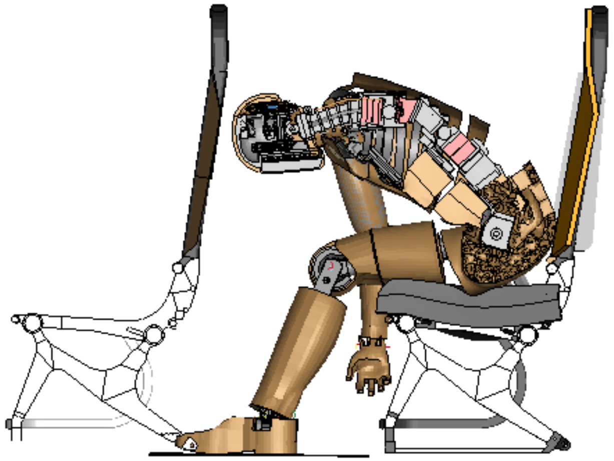
ATD/HBM Capability Evaluation – Kinematic Comparison

Peak Horizontal Displacement

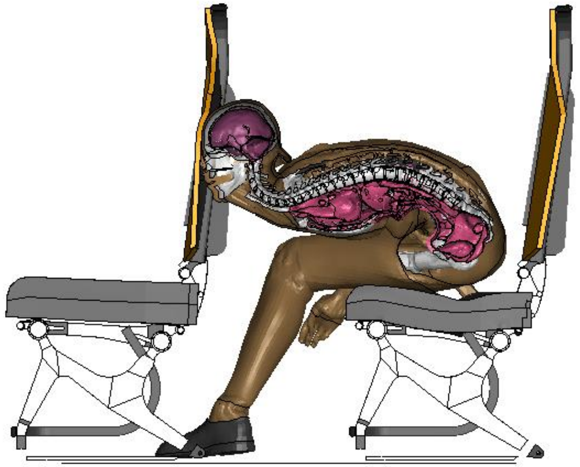
Hybrid III ATD



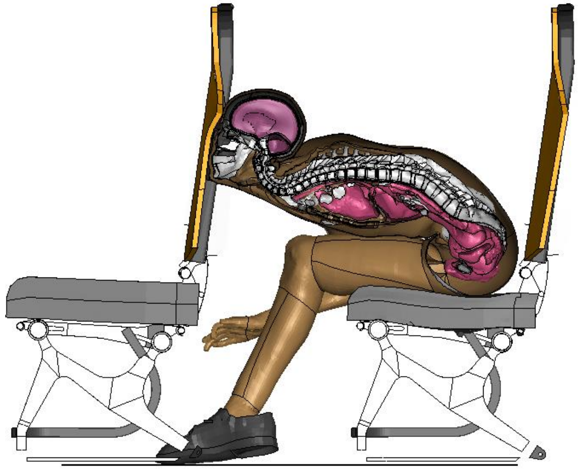
THOR ATD



GHBMC HBM



THUMS HBM



ATD/HBM Capability Evaluation – Injury Risk Comparison

Injury Metrics Compared Between ATD and HBM

Body Component	Injury Equation
Head [1]	$P(AIS\ 3+) = \Phi\left(\frac{\ln(HIC_{15}) - 7.45231}{0.73998}\right)$
Brain [2]	$P(AIS\ 3+) = 1 - e^{-\left(\frac{BrIC - 0.523}{0.531}\right)^{1.8}}$
Neck [3]	$P(AIS\ 3+) = \frac{1}{1+e^{(3.227 - 1.969 * N_{ij})}}$
Lumbar Vertebra [4]	$P(Single\ Fracture) = 1 - e^{-\left(\frac{F}{0.16}\right)^{2.52}}$

[1] Eppinger, R., et al., Supplement: development of improved injury criteria for the assessment of advanced automotive restraint systems - II, D.o.T.N.H.T.S. Administration, Editor. 2000.
[2] Takhounts, E., et al., Development of brain injury criteria (BrIC). Stapp car crash journal, 2013. 57: p. 243-66.
[3] Eppinger, R., et al., Development of improved injury criteria for the assessment of advanced automotive restraint systems - II, N.H.T.S. Administration, Editor. 1999.
[4] Yoganandan N., et al., Human lumbar spinal column injury criteria from vertical loading at the base: Applications to military environments. J Mech Behav Biomed Mater. 2020

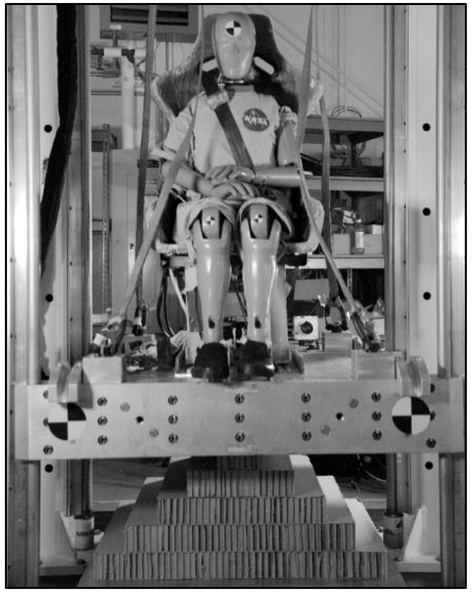
Injury Risk Predictions Averaged Across Seat Location

Body Component	GHBMC	THUMS	ATD
Head	33.94%	3.41%	24.51%
Brain	83.54%	60%	Not Calculated
Neck	1.85%	6.66%	36.88%
Lumbar Vertebra	100%	100%	100%

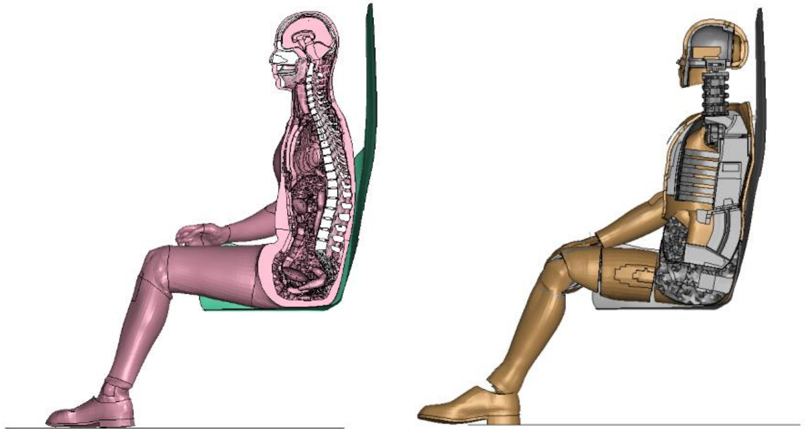
ATD/HBM Capability Evaluation – Preliminary Conclusions

- HBMs predict significant differences in torso kinematics compared to ATD’s in vertical loading environments
  - Driven by spinal flexibility compared to rigid ATD spine boxes
- Although differences in spinal kinematics were observed, aspects of response driving standard injury metric responses evaluated by ATDs were consistent with HBMs
  - Lumbar loading and torso flexion kinematics which drove head strike
- The THUMS and GHBMC models generally predicted similar kinematic response within the evaluated aerospace loading environment
- The THUMS model was limited by high computation cost and instrumentation issues

Current HBM Work – Drop Tower Testing/Analysis



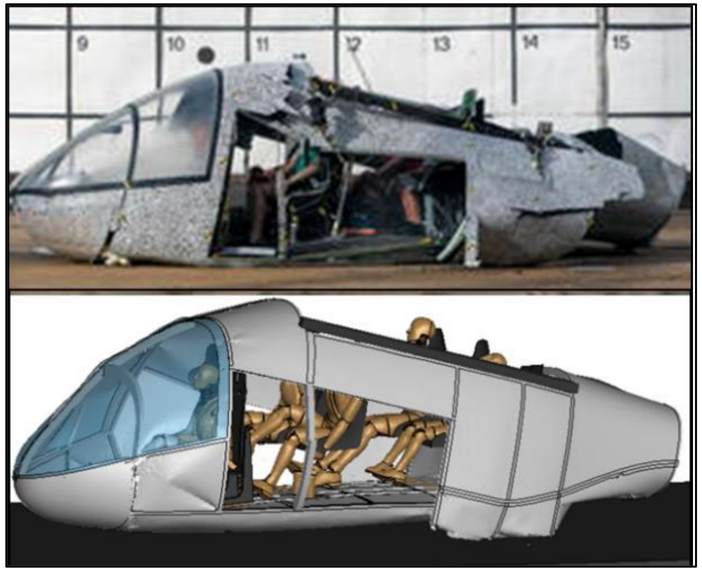
- Seat level vertical impact tests have been conducted using 30 ft drop tower facility at NASA LaRC to study effects of seated environment on occupant loading response
  - Seats: combination of generic, commercial, and NASA developed
  - Conditions: 10 g – 45 g peak impact acceleration
  - ATDs: Hybrid III 5th, 50th, 95th , WIAMAN (planned), THOR (simulated)



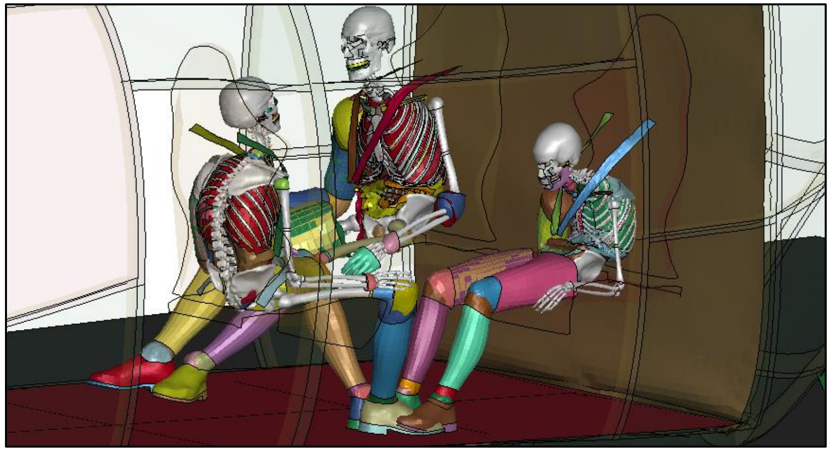
- GHBMC currently being simulated in tested conditions
  - Goal 1: Determine whether HBM models predict similar sensitivities between seat environment /loading conditions and injury risk as measured by ATDs
  - Goal 2: Evaluate effects of occupant posture changes on predicted response

Next Steps – Characterization of HBM Response in eVTOL Representative Vehicle Environment

- HBMs to be simulated in representative eVTOL vehicle test environment
  - Vehicle and ATD occupant FEMs validated against full-scale test data
  - HBMs and advanced ATD models to be simulated in tested environment as well as distribution of crash-landing cases

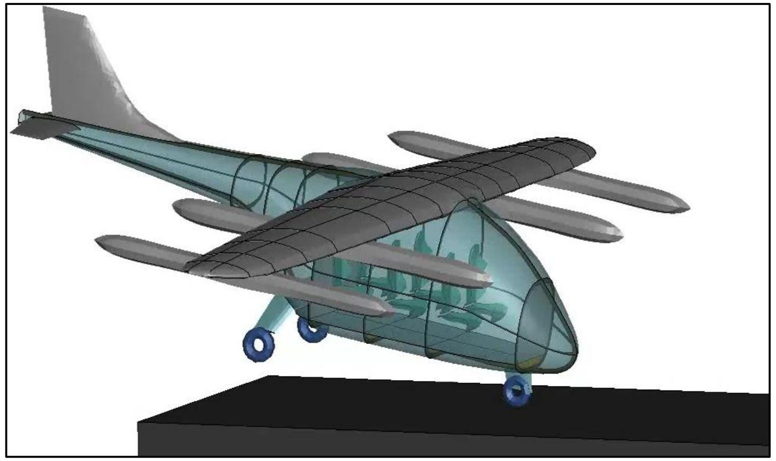


- Goal: Evaluate capability of HBMs to identify injury risk within relevant eVTOL crash environments
  - Identify potential benefits over standard ATD analysis for unique/complex loading environments

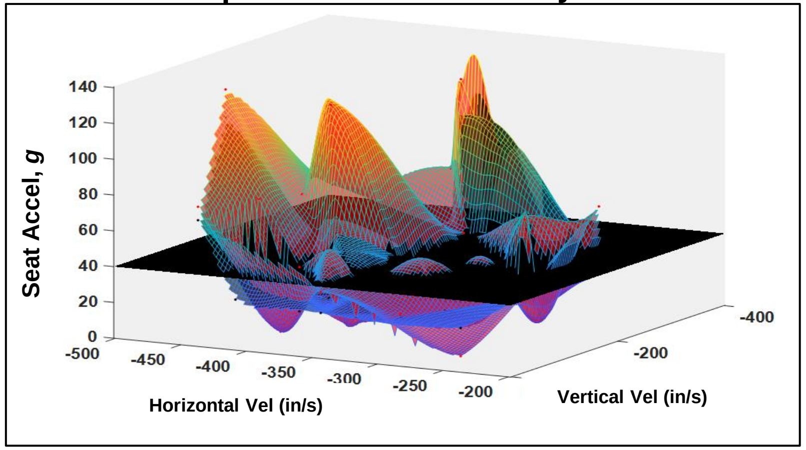


Future Vision: Improved Quantification of Crashworthiness Through Analysis

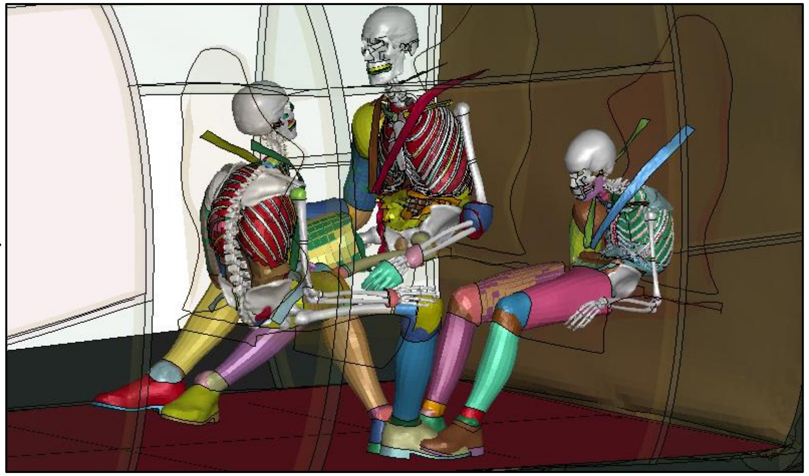
Vehicle Impact Simulation



Impact Monte Carlo Analysis



High Fidelity Human Simulation - Injury Risk Analysis



Vehicle Impact Survivability Envelope