A Finite Element Model of the THOR-K Dummy for Aerospace and Aircraft Impact Simulations

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Motivation

**Improve Safety Analysis**
- Spaceflight Safety Standards
- Restraint Systems & Seat Technology

**Dummy Testing**
- Test Device for Human Occupant Restraint (THOR)
- Potential in Aerospace Field
- Limited Multidirectional Evaluation

**Dummy/ Human FE modeling**
- Reduced Cost and Time
- Sensitivity and Design Optimization
- Human Kinetic Analysis

Multipurpose Crewed Vehicle (MPCV) - Water Landing

Pilot Ejection

http://i88.photobucket.com/albums/k188/trademarq/ejection-seat.jpg
Goals

1) Update and Improve the THOR Finite Element (FE) model to specifications of the latest mod kit (THOR-K)

2) Evaluate the kinematic and kinetic response of the FE model in frontal, spinal, and lateral impact loading conditions
The latest version of THOR

**Head/Neck:** Re-designed (head parts, OC-Joint, cable guides)

**Thorax:** Implemented IR-TRACC thoracic displacement measurement

**Pelvis:** Re-designed

**Lower Limb:** Re-designed (knee joint, femur, foot)

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**FE Model Updates**

- **VT-Head/Neck**
  - Re modeled head parts
  - Simplified OC-Joint

- **NHTSA Collaborators**
  - Thorax, Pelvis, Lower Limb

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424 parts
~ 221k nodes / 443k elements
~ 290k deformable elements
~ 0.063 μs
Development, Calibration and Validation of Head-Neck THOR-K FE Model

Part Updates

- Head ballast
- Front face distribution plate

Head/Neck Springs

- Front spring
- Rear spring

Instrumentation

- Head Skin
- Cable Friction
- Head/Neck Springs
- Neck Pucks

Model calibration

- Developed THOR-K head-neck model
  - NBDL lateral
    - Calibrated neck-puck stiffness
    - Pendulum extension
    - Pendulum flexion
    - Calibrated front spring material
    - Calibrated rear spring material
    - Calibrated cable friction
    - Head impact
  - Calibrated head-skin material

Model validation

- NBDL frontal
- Pendulum lateral
Model Development: Head-Neck THOR-K FEM

Part Updates
- Modeled CAD part geometries
- Simplification of OC-Joint

Head CG & Mass Validation
- Ballast Adjustment
- Spec. Tolerance

Instrumentation
- Head CG accelerometer
- Front spring
- Rear spring
- Head ballast
- Head casting
- Face foam
- Upper-neck load cell (cross-section)
- Lower-neck load cell (locked joint)
- OC Joint
Model Calibration: Head-Neck THOR-K FEM

- Head impact
- Calibrated head-skin material
- NBDL lateral
- Calibrated neck-puck stiffness
  - Pendulum extension
  - Calibrated front spring material
  - Pendulum flexion
  - Calibrated rear spring material
- Calibrated cable friction
- Head impact
- Calibrated head-skin material
**CORA (CORrelation and Analysis) Rating Score**

- Multi-aspect curve rating system
- Proposed SAE ISO Standard
- Developed by PDB

Signal Score $S_{\text{CORA}}$

- Corridor Method $S_{\text{co}}$
- Cross Correlation Method $S_{\text{cc}}$

Phase Shift $S_{\text{p}}$
- Size $S_{\text{s}}$
- Progression $S_{\text{sh}}$

$C = 1$

$0 < C < 1$

$T_{\text{min}}$ / $T_{\text{max}}$
Model Calibration (example)

- **Upper neck lat. force**
  - Orig.: 0.826 | Cal.: 0.948

- **Upper neck vert. force**
  - 0.902 | 0.996

- **Lower neck lat. force**
  - 0.985 | 0.975

- **Lower neck vert. force**
  - 0.864 | 0.94

- **Head Lat. displ.**
  - 0.901 | 0.974

- **Head vert. displ.**
  - 0.716 | 0.985

- **NBDL lateral Bending Score**
  - Original: 0.845 | Calibrated: 0.971

- **Model Parameters**
  - Optimization Algorithm (Isight)
  - LS-Dyna FE Simulation
  - CORA Analysis

- **Model Response**
  - Test Conditions
  - Test Data
  - Total Model Rating
Model Validation: Head-Neck THOR-K FEM

Model validation

NBDL frontal

Upper neck horiz. force

Upper neck sagittal mom.

Head CG sagittal rotation

Cora Score: 0.948
Model Validation: Head-Neck THOR-K FEM

Model validation

NBDL frontal

Pendulum lateral

Upper Neck Lat. Force

Upper Neck Vert. Force

Upper Neck cor. moment

Cora Score: 0.936
Full THOR-K Dummy Testing

Performed at WPAFB
- Based on Historic Volunteer Tests
- THOR-K ATD
- Hybrid III ATD
- Horizontal impulse accelerator

Test Directions
- Frontal
- Spinal
- Lateral
Simulation Setup

Chair Model

Belt Model
Belt Material Characterization

**Testing**
- Uniaxial Loading
- 250-lb load @ 1 mm/s

**Results**
- Developed Force/Strain Curve
  - Belt material
- Estimated Elastic Modulus
  - Fabric Material

![Force-Strain Curve](image_url)

- \( E = 0.17 \text{ kN/mm}^2 \)
- \( E = 0.083 \text{ kN/mm}^2 \)
- \( E = 0.068 \text{ kN/mm}^2 \)
Simulation Conditions

- **Boundary Conditions**
  - Sled Acceleration
  - Gravity Applied to all Parts
  - Stress Initialization
  - Belt Constraints

- **Acceleration Pulse**
Instrumentation

- Head Accelerometer
- Chest Accelerometer
- Pelvis Accelerometer
- Upper Neck Load Cell
- Lower Neck Load Cell
- L1-Lumbar Spine Load Cell
Frontal Results - Overview

CORA Rating: .906
Frontal Results – Frontal Acceleration

Kinematics
- High CORA Rating
- Similar Peaks
- Faster rise time in head and pelvis
Frontal Results – Frontal Force

Kinetics
- Similar response in lower neck
- Upper Neck & Lumbar Spine
  - Faster Rise
  - Larger Peak

C = 0.888

THOR ATD
- Upper Neck

C = 0.921

THOR FE
- Lower Neck

C = 0.721

Lumbar Spine
Spinal Results - Overview

LS-DYNA keyword deck by LS-PrePost
Time = 114

CORA Rating: .874
Spinal Results – Anterior Acceleration

Kinematics
- Similar Peaks
- Similar Rise in head and chest
- “Bouncing” Pelvis
Spinal Results- Anterior Force

Kinetics
- Similar upper body
- High lumbar over prediction

Upper Neck
- THOR ATD
- THOR FE
- C=0.868

Lower Neck
- C=0.928

Lumbar Spine
- C=0.815
Lateral Results - Overview

LS-DYNA keyword deck by LS-PrePost
Time = 152

CORA Rating: .838
Lateral Results – Lateral Acceleration

Kinematics
- Similar timing
- Large peaks in head & pelvis
- Largely dependent on positioning of impact plates

THOR ATD | THOR FE

Head CG: C=.867
Chest: C=.877
Pelvis: C=.912
Lateral Results – Lateral Force

Kinetics
- “Bouncing” response
- Larger secondary impact

THOR ATD  THOR FE

Upper Neck
C=0.918

Lower Neck
C=0.857

Lumbar Spine
C=0.597
Conclusions

The THOR-K FE Head/Neck model validated.

The THOR FE model accurately represents the THOR-K dummy in frontal, lateral, and spinal tests.

Significant differences are observed in spinal flexibility and pelvis stiffness between models.
Next Steps: Full Calibration

Model calibration

Calibrated THOR-K model

Model validation

Lateral Impact
Pelvis Calibration – Quasi Static

Pelvis Compression Test
- Performed by Denton (Humanetics)
- Pelvis Skin & Flesh
- 30-mm Compression @ 250 mm/min

Material Model Optimization
- Objective: Force/Displacement
- Variables: Stiffness Scale Factor

Results
- Decreased Stiffness

![Graph showing force vs. displacement for simulation and test, with optimized results highlighted.](image-url)
Pelvis Calibration - Dynamic

**Simulation**
- Spinal WPAFB Test
- 10 g @ 40 ms

**Procedure**

1. **Model Parameters**
2. **Optimization Algorithm (LS-Opt)**
3. **Total Model Rating**
4. **Model Response**
5. **CORA Analysis**
6. **LS-Dyna FE Simulation Response**
7. **Test Conditions**

- **Test Data**
- **Variable Pelvis Foam Stiffness**
  - *SF1
  - *SF2
  - *SF3
  - *SF4

- Stress (GPa)
- Strain (%)
Next Steps: Human Model Comparison
Human Model Comparison: Simulation ex.
Human Model Comparison: Kinematics ex.

Head CG Vertical Displacement

Displacement (mm)

Time (ms)
Limitations & Future Work

Limitations
- Lack of material dynamic part testing for THOR-K material model characterization.

Future Work
- Calibration and Validation of the full THOR-K FE model
- Simulate the same tests with Human FE Models (THUMS and GHBMC)
- Compare Human FE model data against historic volunteer test data recorded at Wright Patterson Air Force Base.
- Simulate Full Scale Aerospace Crashes
- Use Dummy and Human FE Models to Optimize Seat Designs in Aerospace Safety Applications
Questions?
# Head/Neck CG calculations

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<tr>
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<th>FE-Model</th>
<th>THOR-K Head</th>
<th>Difference</th>
<th>Tolerance</th>
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<td>X-CG (mm)</td>
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