Occupant Protection During Orion Crew Exploration Vehicle Landings

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Introduction  The Constellation Program is evaluating current vehicle design capabilities for nominal water landings and contingency landings of the Orion Crew Exploration Vehicle. The Orion Landing Strategy Tiger Team was formed to lead the technical effort, for which associated activities include the current vehicle design susceptibility to roll control and tip over, reviewing methods for assessing occupant injury during ascent/aborts/landings, developing an alternate seat/attenuation design solution which improves occupant protection and operability, and testing the seat/attenuation system designs to ensure valid results. The EVA Physiology, Systems, and Performance (EPSP) Project is leading the effort under the authority of the Tiger Team Steering Committee to develop, verify, validate and accredit biodynamics models using a variety of crash and injury databases, including NASCAR, Indy Car, and military aircraft. These validated biodynamics models will be used by the Constellation program to evaluate a variety of vehicle, seat, and restraint designs in the context of multiple nominal and off-nominal landing scenarios. These models will be used in conjunction with Acceptable Injury Risk definitions to provide new occupant protection requirements for the Constellation program.

Biodynamics Modeling  Race car and military aircraft occupant protection experience suggests significant benefits can be gained from improved seat and restraint systems. Existing NASA occupant protection requirements are tied to the Brinkley injury risk model, which cannot adequately account for seat/restraint systems and their associated injury responses to a range of landing loads. The EPSP team is coordinating a panel of subject matter experts from auto, racing and military occupant protection backgrounds. The acquisition, processing and modeling of statistical and biodynamic data will be undertaken by the team and reviewed with this expert panel. In addition, the team is responsible for sharing knowledge captured within the project data analysis with the Steering Committee and the Orion project for design and requirements impacts. The team will organize the final project deliverables, validated biodynamics models and report to the Constellation program in time to support critical design review milestones for the Orion project.

Definition of Acceptable Risk  After defining probability of injury associated with critical biodynamic responses, it is necessary to systematically define the highest level of acceptable injury risk during landings consistent with a successful program. This definition is based on key mission drivers such as crew health, safety and performance considerations in the immediate landing environment, long-term crew health considerations including medical policy and future flight status, programmatic success criteria e.g. overall Loss of Crew (LOC) requirement in context of all mission phases, public opinion and ethical considerations, and balancing the risk vs. reward (Utility) for landing environment in context of all mission phases. To put Orion landing risk in perspective, the team is providing a context of injury risk compared with other military and civilian vehicle operations based on overall risk of injury, probability of an off-nominal event, and the risk of injury in an off-nominal event. To accomplish this task, an Operationally Relevant Injury Scale is being defined to allow classification of injuries based on impacts to crew performance and egress.
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The Constellation Program is evaluating current vehicle design capabilities for nominal water landings and contingency land landings of the Orion Crew Exploration Vehicle.

The Orion Landing Steering Committee (LSC) Tiger Team was formed to lead the technical effort, including:

- Evaluating current vehicle design susceptibility to roll control and tip over
- Reviewing methods for assessing occupant injury during ascent/aborts/landings
- Developing an alternate seat/attenuation design solution which improves occupant protection and operability
- Testing the seat/attenuation system designs to ensure valid results

The Occupant Protection Project was formed to develop, verify, validate and accredit biodynamics models using a variety of crash and injury databases that include NASCAR, Indy Car, and military aircraft.
The Brinkley Model is currently used by NASA and the military to determine the risk of injury to vehicle occupants based on seat acceleration. The model calculates a Dynamic Response (DR) using a lumped mass modeled with a spring and damper attached to the seat. An injury classification based on injury probability is then determined using pre-defined DR limits for each axis:

- Very Low: <0.05%
- Low: 0.05 - 0.5%
- Medium: 0.5 – 5%
- High: 5 – 50%
- Very High: >50%

Disadvantages of the Brinkley Model:

- The model assumes a basic seat geometry and so probability of injury is not reduced with seat or safety equipment improvements.
- With the Brinkley model, the only way to reduce injury risk is to attenuate energy.
- Brinkley model only predicts if an injury occurs.
- Brinkley model does not predict injury severity, or anatomical location.
Modeling Road Map

NASCAR
- Validate Model with Sled Tests
  - Run Injury And 100-200 Non-Injury Cases
  - Define Transfer Function
  - Estimate Biodynamic Responses For all cases

IRL
- Run Injury And 100-200 Non-Injury Cases
  - Define Transfer Function
  - Estimate Biodynamic Responses For all cases

Orion
- Run Orion Landing Cases
  - Define Transfer Function
  - Estimate Biodynamic Responses For all cases

Iterate as hardware matures

Estimate P(inj) for each Biodynamic response
Estimate Total Program Risk
Relating Race Car Crash Data to Orion

- How do we relate NASCAR and Indy Racing League (IRL) crash data to Orion?
  - Use numerical models with Hybrid-III manikin
  - Use actual crash data to relate biodynamic responses to injuries
  - Relate NASCAR / IRL biodynamic manikin responses to biodynamic manikin responses from CEV cases
Biodynamic Response Example: Head Acceleration

NASCAR Rear Impact Case (+X)
56.5 g Impact
63.2 mph ΔV
## Definition of Biodynamic Responses

- Using military, passenger vehicle and race car published research and requirements, we worked with industry experts to identify biodynamic responses and determine the limits that would best protect the crew.

<table>
<thead>
<tr>
<th>Parameter (Deconditioned)</th>
<th>0.5% risk</th>
<th>2% risk</th>
<th>5% risk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head Injury Criteria (HIC 15)</td>
<td>300</td>
<td>500</td>
<td>700</td>
</tr>
<tr>
<td>Peak Head Acceleration (g)</td>
<td>119 112 109</td>
<td>151 142 138</td>
<td>166 155 151</td>
</tr>
<tr>
<td><strong>Neck</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Neck (cervical) flexion bending moment (Nm)</td>
<td>42 83 83</td>
<td>57 108 125</td>
<td>89 163 222</td>
</tr>
<tr>
<td>Peak Neck (cervical) lateral bending moment (Nm)</td>
<td>33 65 65</td>
<td>41 82 82</td>
<td>62 123 123</td>
</tr>
<tr>
<td>Peak Neck (cervical) extension bending moment (Nm)</td>
<td>15 34 42</td>
<td>27 49 67</td>
<td>28 56 75</td>
</tr>
<tr>
<td>Peak Neck (cervical) axial tension (N)</td>
<td>631 943 1138</td>
<td>1753 2781 3363</td>
<td>2161 3440 4326</td>
</tr>
<tr>
<td>Peak Neck (cervical) compression (N)</td>
<td>596 946 1142</td>
<td>1067 1694 2046</td>
<td>2167 3440 4154</td>
</tr>
<tr>
<td>Peak Neck (cervical) shear force (N)</td>
<td>593 946 1142</td>
<td>919 1462 1766</td>
<td>1680 2666 3219</td>
</tr>
<tr>
<td><strong>Lumbar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumbar resultant force</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Leg</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Tibial Axial Compression</td>
<td>1914 3000 3690</td>
<td>2490 3900 4800</td>
<td>3825 6000 7380</td>
</tr>
<tr>
<td>Peak Femur Axial Compression</td>
<td>1914 3000 3690</td>
<td>2498 3801 5013</td>
<td>3862 5670 8100</td>
</tr>
<tr>
<td><strong>Chest</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest Sternal to Spine Deflection (mm)</td>
<td>28 31 35</td>
<td>36 44 49</td>
<td>41 50 55</td>
</tr>
</tbody>
</table>

Per CxP 70024 (HSIR revC)
Relating Injury Risk

- Abbreviated Injury Scale (AIS) describes injuries anatomically
  - Standardize injury terminology
  - Rank injuries by severity
  - Facilitate comparisons of injury studies
- Using an operationally relevant injury scale, we can classify AIS injury codes into several categories
- Using these injury severities and anatomical location, we can determine probability of injury occurrence and severity for each region of the body

<table>
<thead>
<tr>
<th>Parameter-Scale</th>
<th>Injury Magnitude</th>
<th>Self-Egress Ability</th>
<th>Flight Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Injury</td>
<td>No Impact</td>
<td>No delay in return</td>
</tr>
<tr>
<td>2</td>
<td>Minor Injury</td>
<td>Minor Impact</td>
<td>Short Delay in Return</td>
</tr>
<tr>
<td>3</td>
<td>Moderate Injury</td>
<td>Major Impact</td>
<td>Long Delay in Return</td>
</tr>
<tr>
<td>4</td>
<td>Severe Injury</td>
<td>Unable</td>
<td>Ended/DQ’d</td>
</tr>
</tbody>
</table>
# Head Injury

Examples of potential Operationally-Relevant Injuries and associated Biodynamics Response Parameters

<table>
<thead>
<tr>
<th>Injury</th>
<th>AIS Score</th>
<th>Operationally Relevant Injury Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild Concussion</td>
<td>161001.1</td>
<td>2</td>
</tr>
<tr>
<td>Severe Concussion</td>
<td>161006.3</td>
<td>3</td>
</tr>
<tr>
<td>Skull Fracture</td>
<td>150000.2</td>
<td>4</td>
</tr>
<tr>
<td>Basilar Skull Fracture</td>
<td>150200.3</td>
<td>4</td>
</tr>
<tr>
<td>Laceration</td>
<td>110604.1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biodynamic Response Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC15</td>
</tr>
<tr>
<td>Head Acceleration</td>
</tr>
<tr>
<td>Head Movement</td>
</tr>
<tr>
<td>Upward Head Movement</td>
</tr>
</tbody>
</table>
NASCAR Injury Distribution

- 4261 Non-Injury Cases
- 16 Class I Injuries
- 15 Class II Injuries
- 4 Class III Injuries
Estimate Results: Brinkley Scores

- Low (0.5%):
  - $P(\text{inj}) = 0.16\%$
- Medium (5%):
  - $P(\text{inj}) = 0.28\%$
- High (50%):
  - $P(\text{inj}) = 0.44\%$
- Very High
  - $P(\text{inj}) = 5.0\%$

- Brinkley Model would predict ~608 injuries vs. 32 observed

<table>
<thead>
<tr>
<th>IRC</th>
<th>No Injury</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
<th>Total</th>
<th>$P(\text{inj})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>2434</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0.16%</td>
</tr>
<tr>
<td>Medium</td>
<td>707</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0.28%</td>
</tr>
<tr>
<td>High</td>
<td>683</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0.44%</td>
</tr>
<tr>
<td>Very High</td>
<td>437</td>
<td>13</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>23</td>
<td>5.0%</td>
</tr>
</tbody>
</table>
Determining Risk of Injury

• Using the NASCAR data set, statistical modeling techniques will be employed to relate injury predictors (biodynamic responses) with the probability of injury by severity.

• Once the each biodynamic response has an associated probability of injury, the Orion landing cases can be assessed to determine the probability of injury.

• Using these data, a team of experts will systematically determine what risk is acceptable in an operationally relevant environment.

• Using landing probabilities, the goal is to lower total risk over all landing conditions.
**Occupant Protection Project Charter**

**TASK DESCRIPTION:**
Determine appropriate methods for modeling and prediction of potential crew injuries. Activities include conducting data mining of injury databases (NASACAR, CIREN, military, etc); assessment of impact simulation and injury prediction methodologies. Recommend techniques / changes to requirements appropriate for Orion including stated limitations.

**Data Mining of Injury Databases**
- Review automobile, NASACAR, military, and other applicable occupant injury databases

**Review limitations and capabilities of analysis tools/techniques**
- Review impact simulation techniques appropriate for Orion
- Review occupant injury prediction techniques

**Recommend analysis techniques and models appropriate for use by Orion**
**Recommend appropriate human mass properties data for use by Orion**
**Provide the necessary mass properties data**
**Recommend appropriate impact acceleration/occupant injury criteria**

**Given driving load cases, assess current 606C baseline and alternate designs and recommend potential modifications, if required**

**PRODUCTS**
- Periodic Briefings to Steering Committee/CEV Project Office
- Given driving load cases (from Orion Project Office)

**Analyze Orion baseline design (606C) as well as alternate configurations developed by Task #2 team**
- Final report to include:
  - Recommendations for standard analysis techniques and models
  - Recommendations for impact acceleration/occupant injury criteria appropriate for use by Orion
Occupant Protection Modeling Forward Plan

**Model Development, Verification, Validations and Accreditation**

- **Model Development**
  - Definition of appropriate injury response parameters

- **Model Verification**
  - Pool crash injury data and classify in an operationally relevant classifications
  - Perform logistic regression between injury response parameters and injury outcome in pooled database

- **Model Validation**
  - Define Validation criteria

- **Validate Model**
  - Definition of acceptable injury criteria

**Definition of Acceptable Risk**

- **Start with Baseline HSIR requirements**
  - Define operationally relevant injury scale
  - Reclassify & pool injury data into operationally relevant injury scale

- **Define medical and operational drivers and mission success criteria**
  - Definition of medical injury disposition policy (Bound long-term health risk)

- **Iterate until we meet acceptable injury criteria**

**Design, Development and Verification of seat/restraint/attenuation system**

- **Use evolving Biodynamics model to define restraint/attenuation**
  - Refine Seat/restraint/stroking design

- **Determine the axis and degree of stroke required**

- **Determine design tolerance failure cases (stacked failures)**

- **Feed seat/restraint attenuation models into Biodynamics model**

- **Iterate until we meet acceptable injury criteria**

**Integrated Test Plan**

- **Model Verification Test Series**
- **Hardware Test Series (Contractor/Program)**
- **Suit-Ring Occupant Interactions Test Series with THUMS Model support**

- **Develop Consensus Recommendations for acceptable injury risk vs landing probability distributions**