Validation Methodology for Passenger Safety

Development of a Verified and Validated, Parametric Cervical Spine Injury Model

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Motivation and Support

- Project sponsored by the Naval Air Warfare Center - Aircraft Division, Dr. Barry Shender, PM
- Assess probability of injury for military pilots in severe situations
  - Ejections and carrier landings
    - Female aviators in cockpit systems designed for males
  - Added mass in helmet systems
  - Long-term high-g exposures
Program Goals

▪ Develop a predictive model of the musculoskeletal system
▪ Employ hierarchical model validation methodology
▪ Investigate sex and weight effects on probability of cervical spine injury
▪ Develop a tool to assist with designing new helmet systems, seats, etc.
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▪ **Employ hierarchical model validation methodology**

▪ Investigate sex and weight effects on probability of cervical spine injury

▪ Develop a tool to assist with designing new helmet systems, seats, etc.
Multidisciplinary Team Approach
US Navy/NAVAIR

Voluntary Neck Strength & Endurance

Forces & Moments

Hard/Soft Tissue Properties (Mechanical Testing/ QCT/BMD)

Hard/Soft Tissue Geometry Ligaments, Discs Muscles (QCT, MRI, Cryomicrotome)

Manikin & PMHS, Human (NBDL) Sled Testing

Behavior, Pain Surveys

Fill Gaps in Basic Knowledge and Injury Tolerance

Develop, Verify & Validate a Predictive Spinal Injury Model

Design Criteria

Injury Mitigation

Training

SwRI®

Multidisciplinary Team Approach
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SwRI®
Computational Modeling for Biomechanical Analysis

- Relatively easy to construct high fidelity models from high quality 3D image data
  - powerful geometry modeling and meshing software
  - high performance computational resources
  - Resulting models “looks” almost identical to the actual biological system
- Non-linear material constitutive models with properties either derived from experimental data or reported in the literature
- Large deformation, and motion defined by sliding contact between complex, deformable articulating surfaces

Result: High Fidelity Computational Models
Model Verification and Validation (V&V)

- High fidelity should not be confused with model credibility
- High fidelity is necessary but not sufficient
  - Fidelity is the result of modeling tools (pre-processor, FE code, etc.) computational speed, etc.
- Model credibility is the result of specific and rigorous model V&V

Fidelity ≠ Accuracy
Introduction

Why Model Verification and Validation (V&V)

- Fidelity does not mean accuracy
- Decision makers want to know:
  - What is the error between the model and tests?
  - How much confidence do we have in the model predictions?
  - Can we use these models to predict occupant injury?
  - Can we design safer systems using these models?
  - How accurate are these models for decision making?
- Model Verification and Validation can help answer these questions

Fidelity ≠ Accuracy
Model Validation Example

Traditional Approach

• Construct FE model of target system
• Use material property data from the literature
• Apply boundary conditions to simulate experiment found in the literature
• Compare (overlay plot) of model predicted response with experiment results
• Validation:
  • model is valid if prediction falls within experimental corridors
Model Validation

Issues with Traditional Approach

- Details of the experiment are often not well known or understood by the modeling team
  - Experiment boundary conditions
  - Size and shape of exp. specimen
  - Can the experiment be modeled?

- Material properties often “tuned” or selected to match high level structural response
  - Range of values in the literature – let’s pick the values that give us a good match
  - Right answer for the wrong reason

- Corridor limits are arbitrary (±1 SD)

- Reducing the quality of the experimental data improves the chance that the model is valid (not good!)

- Mismatch not quantified

- How credible are these models for decision making?
The validation process has the goal of assessing the predictive capability of the model by quantitatively comparing the predictive results of the model with validation experiments.

Three key elements of Validation:
- Validation Experiments
  - Defined by validation hierarchy
- Uncertainty Quantification
  - Experiment
  - Model
- Validation Metrics
  - Quantification of error

Hierarchical Model V&V Approach

ASME V&V-10 Guidelines

- Customer/stakeholder establishes intended use and top-level validation requirement
- Validation hierarchy
  - Breaks the problem into smaller parts
  - Validation process employed for every element in the hierarchy (ideally)
  - Allows the model to be challenged (and proven) step by step
  - Dramatically increases likelihood of right answer for the right reason
- Validation team constructs hierarchy, establishes sub-level metrics and validation requirements
  - Modeling and experiment teams work closely together to define hierarchy and experiments/simulations
  - Experiments are designed expressly for model validation
- In general, validation requirements will be increasingly more stringent in lower levels
- Single physics and components used to identify material parameters
- Material models “locked-in” at more complex system levels
- Full system (un-validated) sensitivity analysis can provide guidance
Hierarchical Model V&V Approach

- **Levels 1 & 2**: Material model parameter identification - fit to experimental data
- **Levels 3 & 4**: No model fitting/tweaking/calibrating
  - Model performance validated against independent set of experiments
- Supporting experiments performed at:
  - Medical College of Wisconsin – Pintar and Yoganandan
  - University of Virginia/Duke University – Bass and Lucas
Hierarchical Model V&V

Single Physics: Material Model Parameter Identification

Experimental setup
- Isolate individual intervertebral disc lamellae
- Loaded in tension until failure
- Resulting stress-strain relationship recorded
- 67 experiments performed
- Experiments performed by Stemper, Yoganandan, Pintar

Simulation optimization
- Isolated annulus tissue model
- Replicated experiment boundary conditions
- LS-DYNA transversely isotropic quasi-linear viscoelastic constitutive model
- Non-linear least squares optimization for each experiment
- Target is force-time history
- Statistical distribution of parameters determined

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>StDev</th>
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<tbody>
<tr>
<td>c1</td>
<td>2.97e5</td>
<td>2.92e5</td>
</tr>
<tr>
<td>c3</td>
<td>3.13e4</td>
<td>2.60e4</td>
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<tr>
<td>c4</td>
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</tr>
<tr>
<td>λ</td>
<td>1.14</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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Hierarchical Model V&V

Single Physics: Material Model Parameter Identification

- **Experimental Setup**
  - Dynamic relaxation experiments on isolated ligaments from 6 male and 6 female cadavers (ALL, PLL)
  - 25% strain input
  - Held for 1 minute - force relaxation recorded
  - Scott Lucas and Dale Bass – UVa

- **Simulation**
  - Isolated ligament model
  - Replicated experiment boundary conditions
  - LS-DYNA transversely isotropic quasi-linear viscoelastic constitutive model
  - Non-linear least squares optimization
  - Target is force-time history
  - Statistical distribution of material model parameters determined

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Accounting for Anatomic Variability

Statistical Shape and Trait Analysis

QCT Scans of 100 Individuals
Individual Models

Average Model

Parametric SSM Model

\[ p_i = (v_{1x}, v_{1y}, v_{1z}, \ldots, v_{jx}, v_{jy}, v_{jz})^T \]

\[ \bar{p} = \frac{1}{n} \sum_{i=1}^{n} p_i \]

\[ p_v = \bar{p} + \sum_{j=1}^{n} c_j \sqrt{\lambda_j} q_j \]

- Parametric Model = Average Model + weighting factors x Principal Components
- Weighting factors contain all variability within the population of interest
- Compact and efficient representation of complex anatomy
- Represent >95% of population anatomic variability with less than 10 variables

i=1...50 – males
i=1...50 - females

Nicolella and Bredbenner, 2012
Bredbenner et al., 2014
Characterizing Uncertainties

Probabilistic Computational Model

Aleatory uncertainty
Operational Conditions
Population Group

Finite Element Model

Predicted Probabilistic Response

Material Property
COV's~100%

Forces
unknown & variable

Boundary Conditions
unknown & variable

Geometry
COV's~20%

Model Response
Forces, Stress, Strain, Deflections, etc.
Hierarchical Model V&V Approach

- Levels 1 & 2: Material model parameter identification - fit to experimental data
- Levels 3 & 4: No model fitting/tweaking/calibrating
  - Model performance *validated* against independent set of experiments
Validation Metrics
How do you define valid?

- A metric is the quantitative *measure* of the mismatch between model predictions and experimental data.

- Typically some type of a difference measure in system response quantities (statistics, probability distributions, etc.)

- Desired features of a validation metric
  - Consider uncertainties in both the model and the experiment – *implies a statistical comparison*
  - Reflect only the comparison (not the adequacy)
Probabilistic Validation - Area Metric

- Calculates the area between the experimental CDF and predicted model CDF
  - Compares mean response and variability between prediction and experiment
  - Gives quantitative measure of model performance
  - Requires expert opinion to determine what is good enough
  - Model = experiment
    - $A=0$
Probabilistic Validation - Error Metric

- Absolute error between a model prediction and an experimental response quantity
  - Model prediction and experimental measurement are uncertain
  - Normalized by the experimental mean value (to simplify solution)

\[ Z = \frac{\gamma_{\text{mod}} - \gamma_{\text{exp}}}{E[Y_{\text{exp}}]} \]

\[ p = P(|Z| \leq z) \]  Probability that the error will not be exceeded

- Validation Requirement

\[ p < p_r, \text{ or } z < z_r \]

Probabilistic Validation - Error Metric Interpretation

- CDF (integration of PDF) of $Z$
  - X-axis is error - $Z$
  - Y-axis is probability level - $p$
- 90% probability that the error will not be greater than 15.6%
- 61% probability that the error will not be greater than 10%
- The error between the model and the experiment is fully defined
- The benchmark level of error is the error of the experiment compared to itself at a 90% probability level

$Z = \text{error between model and experiment}$
Experimental setup

- Isolated vertebra-disc-vertebra specimens
- Loaded with 100 N tension in sine function

Simulation

- Perform probabilistic analysis incorporating variability of material properties and viscoelastic properties
- Calculate area metric and z-metric

<table>
<thead>
<tr>
<th>Time</th>
<th>Benchmark Error</th>
<th>Sim Validation</th>
<th>Area Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>84%</td>
<td>82%</td>
<td>0.137</td>
</tr>
<tr>
<td>5</td>
<td>89%</td>
<td>88%</td>
<td>0.180</td>
</tr>
</tbody>
</table>
Example Component Level Validation

Experimental set-up
- Pure moment loading of complete motion segment to 2 N-m
- Rotation of superior vertebrae recorded

Simulation
- Perform probabilistic analysis incorporating variability of material properties (Disc and all ligaments)
- Calculate area metric and z-metric

<table>
<thead>
<tr>
<th>Load</th>
<th>Benchmark Error</th>
<th>Sim Validation</th>
<th>Area Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 N-m</td>
<td>34%</td>
<td>93%</td>
<td>0.103</td>
</tr>
</tbody>
</table>

![](image.png)
Example Component Level Validation

Experimental set-up
- Pure moment loading of complete motion segment to 6 N-m
- Rotation of superior vertebrae recorded

Simulation
- Perform probabilistic analysis incorporating variability of material properties (Disc and all ligaments)
- Calculate area metric and probabilistic error metric

Qualitative Validation

![Graph showing range of motion for different loading directions: Flexion, Extension, Lateral Rotation, Axial Rotation, Lateral Bending, Axial Bending. The graph compares experimental data (blue bars) and finite element model data (red bars).]
Example Component Level Validation

Probabilistic error metric

| Motion          | $e_{\text{benchmark}}$ | FEM $p = P[|Z| \leq e_{\text{benchmark}}]$ |
|-----------------|------------------------|---------------------------------------------|
| Flexion         | 48%                    | 98%                                         |
| Extension       | 222%                   | 97%                                         |
| R Axial Rotation| 172%                   | 81%                                         |
| L Axial Rotation| 260%                   | 91%                                         |
| R Lateral Bending| 45%                   | 61%                                         |
| L Lateral Bending| 48%                   | 77%                                         |

Area metric

<table>
<thead>
<tr>
<th>Motion</th>
<th>Area Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>0.11</td>
</tr>
<tr>
<td>Extension</td>
<td>0.60</td>
</tr>
<tr>
<td>R Axial Rotation</td>
<td>0.61</td>
</tr>
<tr>
<td>L Axial Rotation</td>
<td>0.67</td>
</tr>
<tr>
<td>R Lateral Bending</td>
<td>0.54</td>
</tr>
<tr>
<td>L Lateral Bending</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Example Subsystem Level Validation

similar results for axial rotation, flexion, and extension
Model Verification and Validation

System Level V&V: Dynamic Lateral Impact

- **Experimental Setup**
  - Three PMHS specimens potted at T1 and mounted to lateral impact loading sled
  - Sled was accelerated using a pendulum impacter at 1, 2, and 3 m/s impact velocities
  - Head and vertebral kinematics were recorded using a Vicon motion capture system
  - Accelerometer used to record sled accelerations

- **Simulation**
  - Full Cervical spine + head
  - Accelerations applied to T1
  - Probabilistic analysis performed
  - Head kinematics validated using area metric
Model Validation Example

Sensitivity of Error to Model and Experiment Uncertainties

Model vs. Experiment

Validation metric

Error metric sensitivity analysis

Global Sensitivity

Variable

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Summary

• Modeling tools allows the development of complex, high fidelity models
  • Model fidelity ≠ model validity
• Hierarchical approach (ASME V&V-10 Committee)
  • Breaks the problem into smaller parts
  • Validation process employed for every element in the hierarchy (ideally)
  • Allows the model to be challenged (and proven) step by step
  • Dramatically increases likelihood of right answer for the right reason
• Modeling and experiment teams need to work together
  • Experiments should be designed for model validation
• Account for uncertainty in both model and experiment
• Validation metric is the measure of the mismatch between model and experiment – Quantitative
• Sensitivity analysis can provide some insight into source of mismatch
Thank You

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