Validation Methodology for Passenger Safety

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

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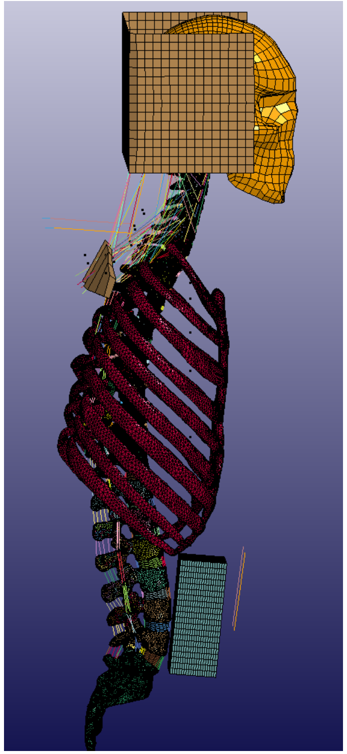
Motivation and Support

- 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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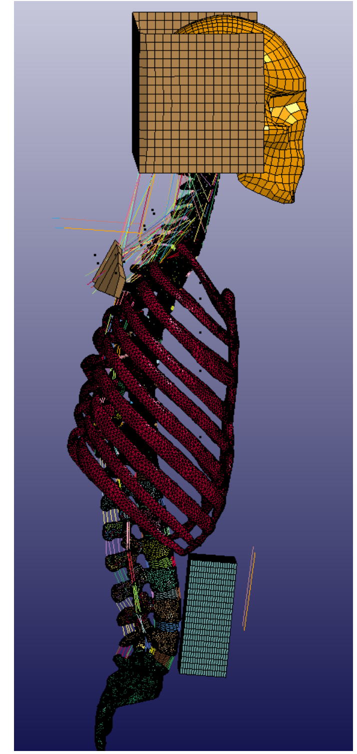


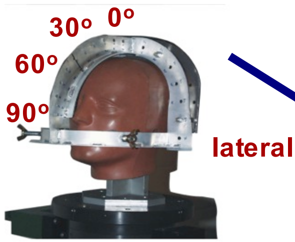
Multidisciplinary Team Approach

US Navy/NAVAIR

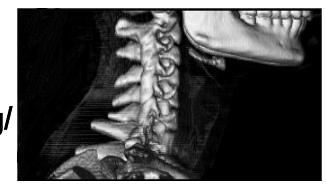
Voluntary Neck Strength & Endurance

Behavior, Pain Surveys

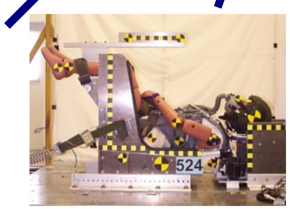
Forces & Moments



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



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



Manikin & PMHS, Human (NBDL) Sled Testing

Fill Gaps in Basic Knowledge and Injury Tolerance

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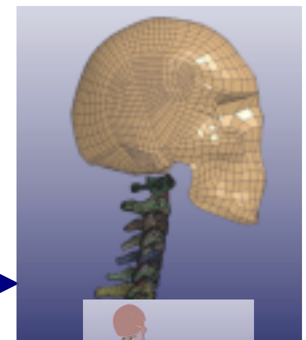
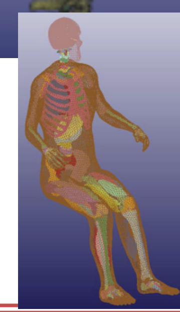




Develop, Verify & Validate a Predictive Spinal Injury Model

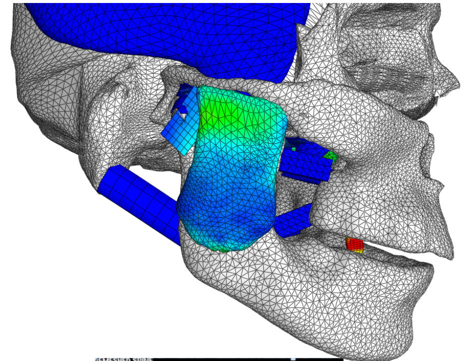
Design Criteria

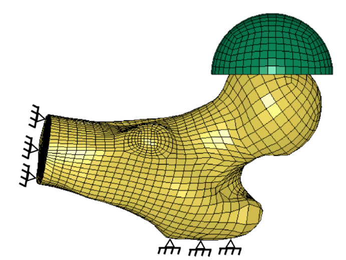
Injury Mitigation

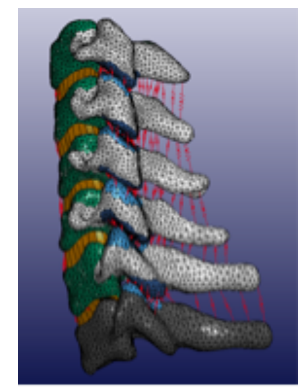
Training

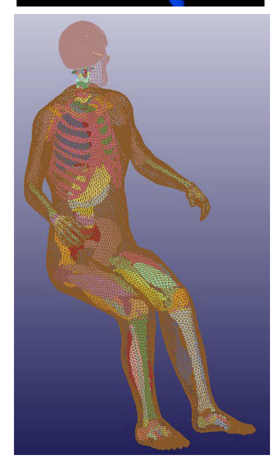
Computational Modeling for Biomechanical Analysis

- 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



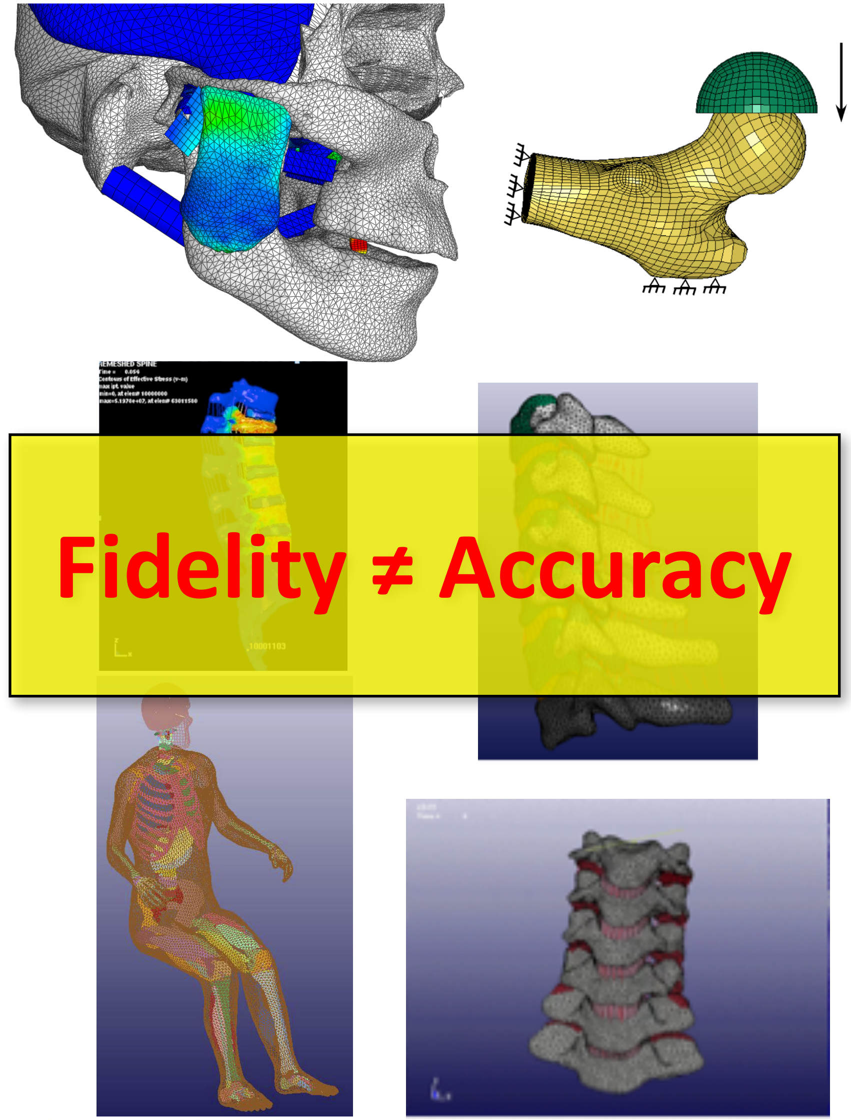






Model Verification and Validation (V&V)

- 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

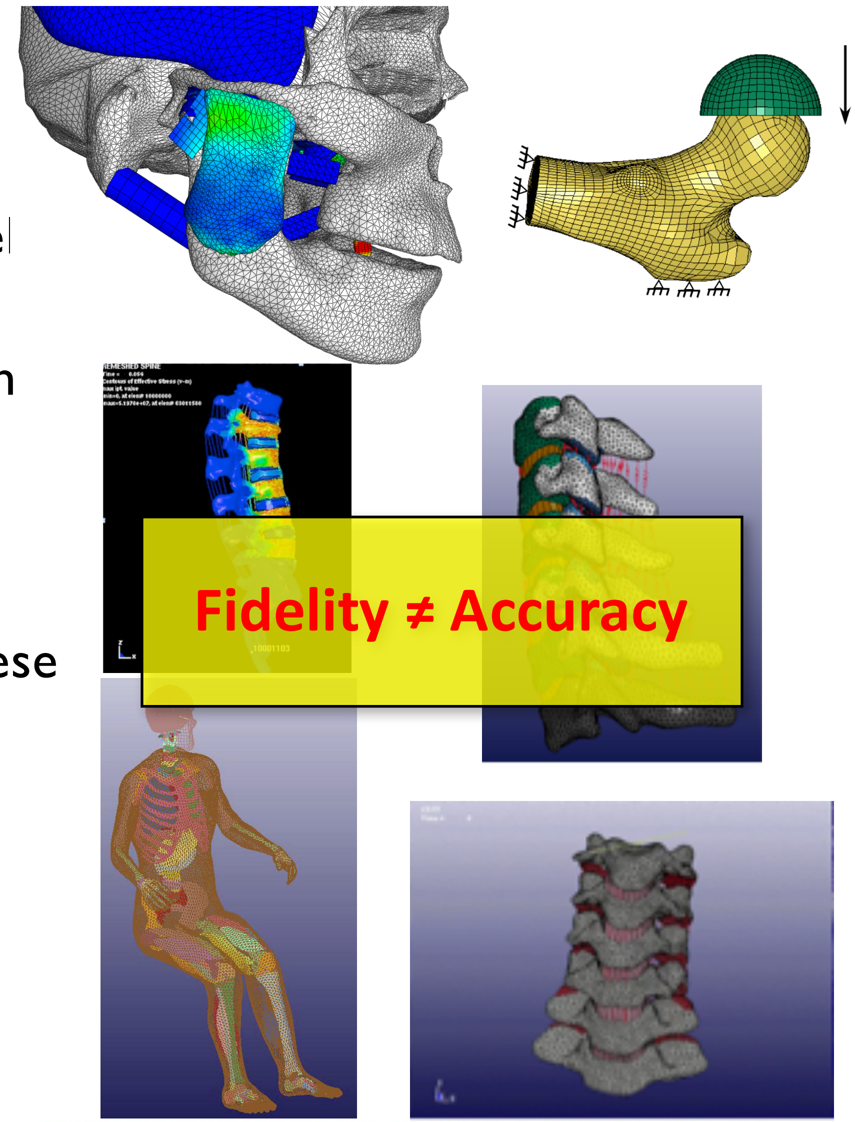


Fidelity ≠ Accuracy

Introduction

Why Model Verification and Validation (V&V)

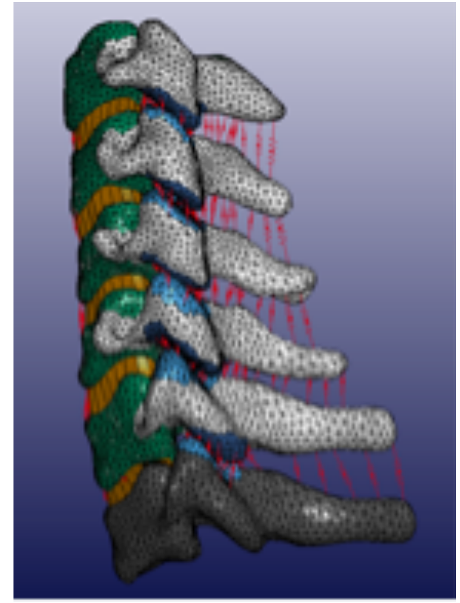
- <u>Fidelity does not mean accuracy</u>
- Decision makers want to know:
  - What is the **error** between the model and tests?
  - How much **confidence** do we have in the model predictions?
  - Can we use these models to predict occupant injury?
  - Can we design safer systems using these models?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

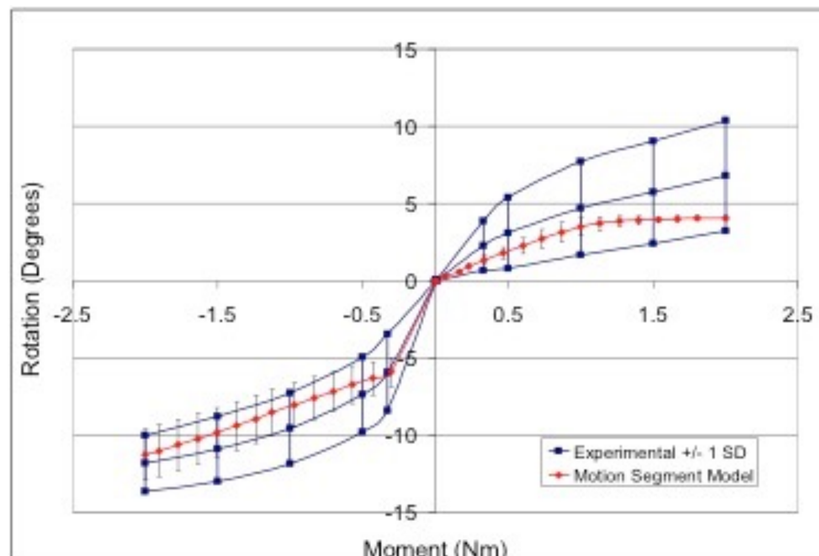


Model Validation Example

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

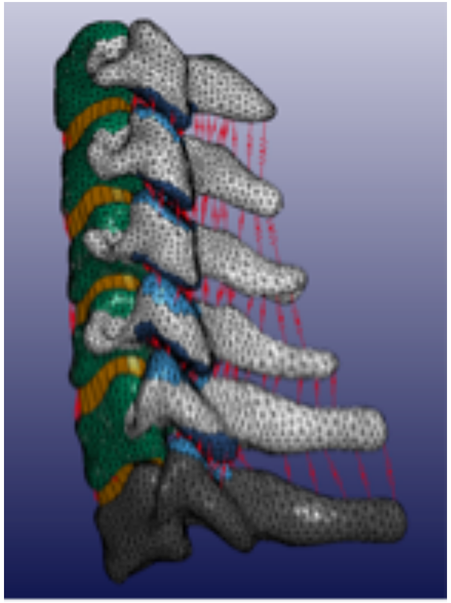


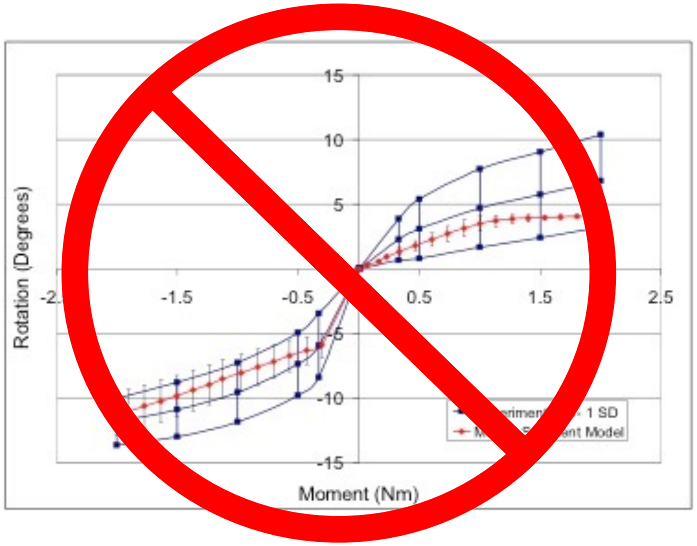


Model Validation

Issues with Traditional Approach

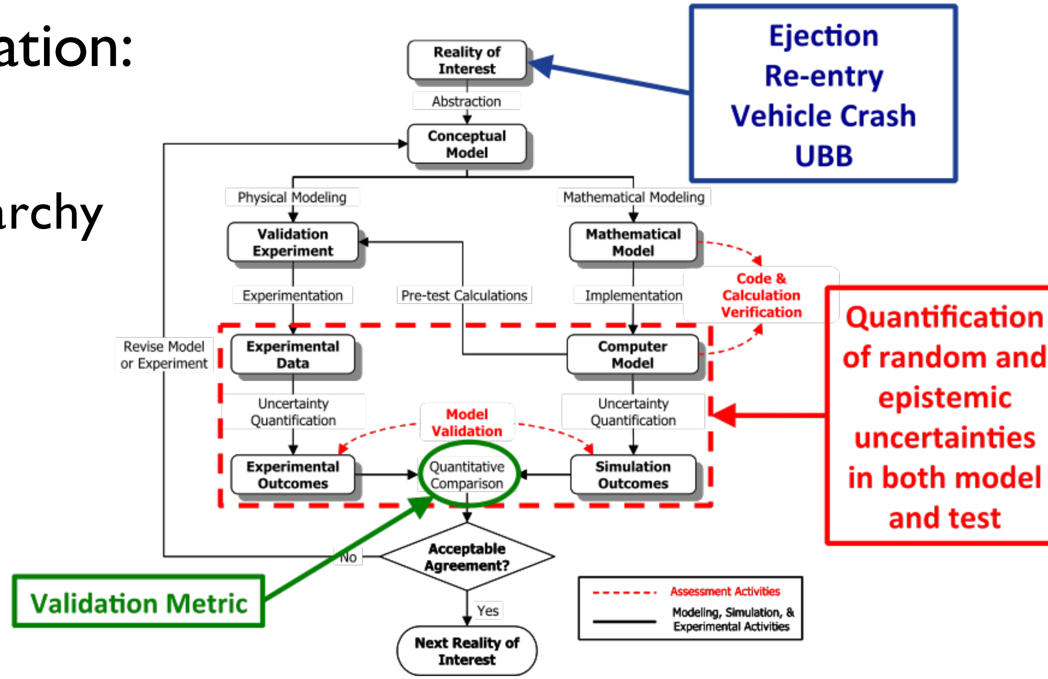
- Details of the experiment are often not well known or understood by the modeling team
  - Experiment boundary conditions
  - Size and shape of exp. specimen
  - Can the experiment be modeled?
- Material properties often "tuned" or selected to match high level structural response
  - Range of values 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?**





Validation Process

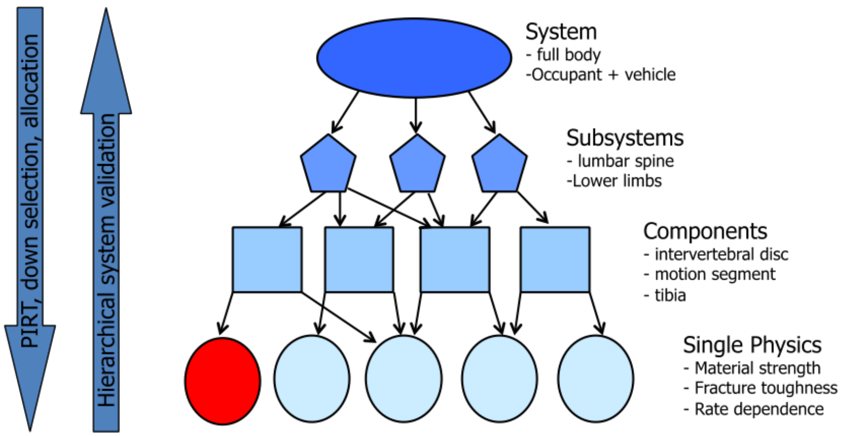
- The validation process has the goal of assessing the predictive capability of the model by quantitatively comparing the predictive results of the model with validation experiments.
- Three key elements of Validation:
  - Validation Experiments
    - Defined by validation hierarchy
  - Uncertainty Quantification
    - Experiment
    - Model
  - Validation Metrics
    - Quantification of error



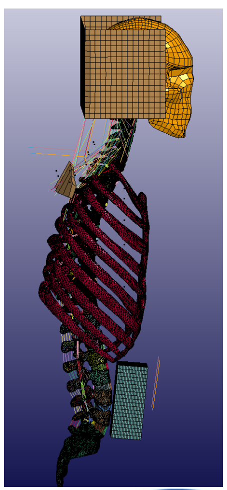
Approach based on ASME V&V 10-2006 "Guide for V&V in Computational Solid Mechanics"

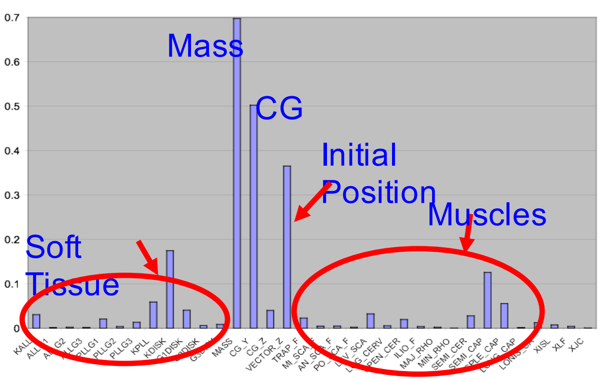
Hierarchical Model V&V Approach

ASME V&V-10 Guidelines



Approach: Bottoms up guided by sensitivity analysis of (un-validated) full system model

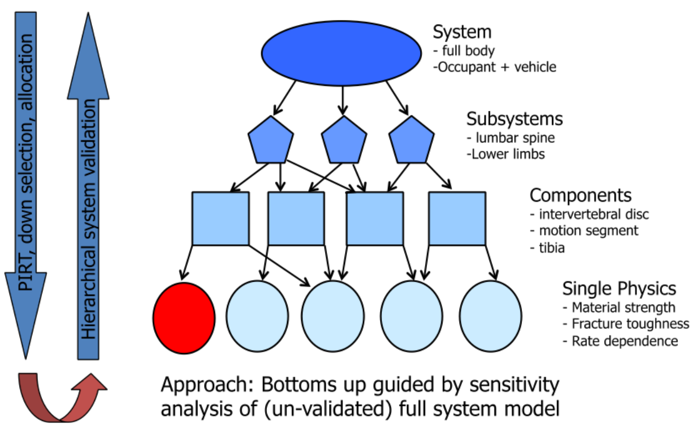


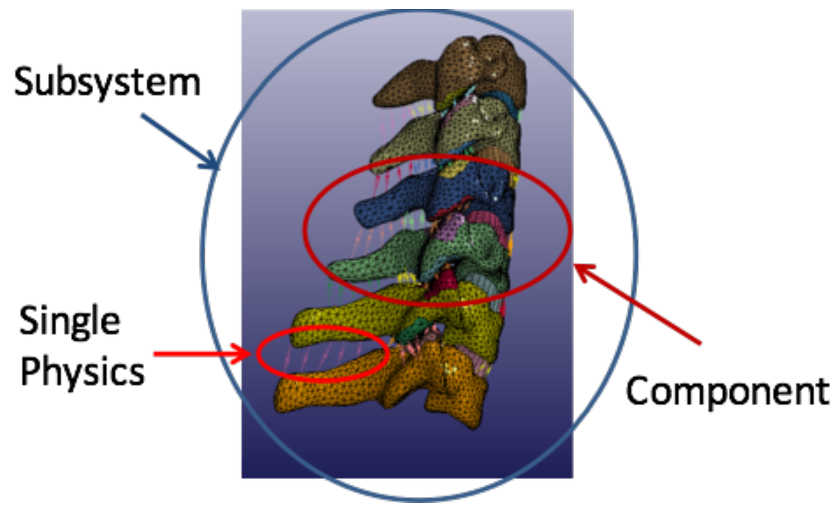


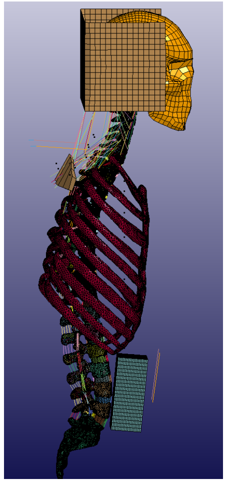
- Customer/stakeholder establishes intended use and top-level validation requirement
- Validation hierarchy
  - Breaks the problem into smaller parts
  - Validation process employed for every element in the hierarchy (ideally)
  - Allows the model to be challenged (and proven) step by step
  - Dramatically increases likelihood of <u>right answer for the right reason</u>
- 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

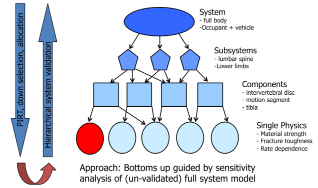






system

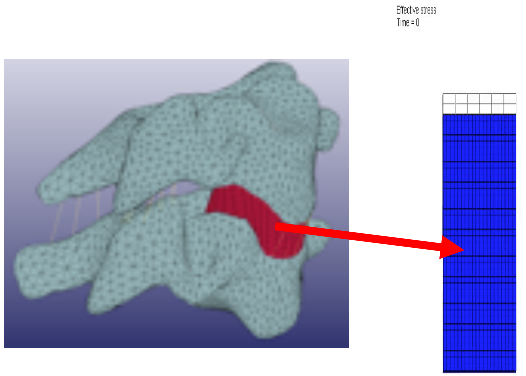
Hierarchical Model V&V



Single Physics: Material Model Parameter Identification

Experimental setup

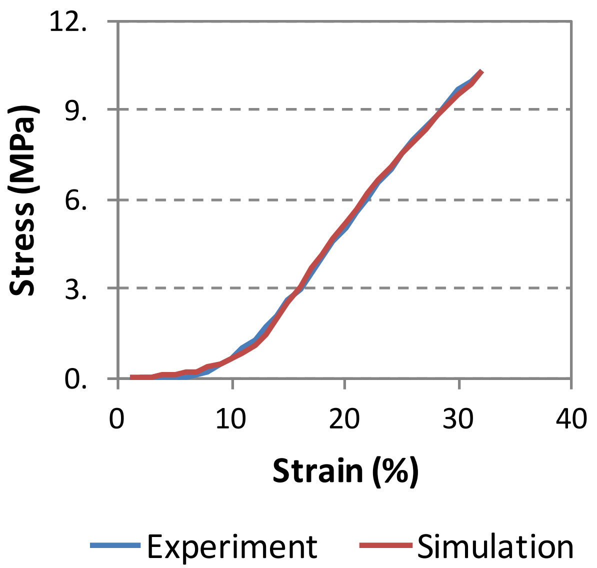
- Isolate individual intervertebral disc lamellae
- Loaded in tension until failure
- Resulting stress-strain relationship recorded
- 67 experiments performed
- Experiments performed by Stemper, Yoganandan, Pintar



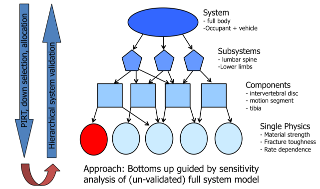
Simulation optimization

- 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

Parameter	Average	StDev
c1	2.97e5	2.92e5
c3	3.13e4	2.60e4
c4	25.7	8.1
c5	1.80e7	1.16e7
λ	1.14	0.05

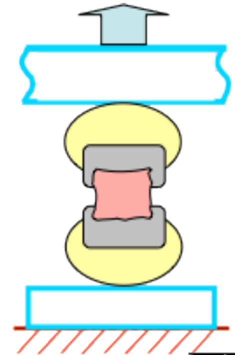


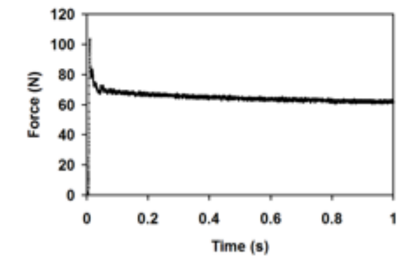
Hierarchical Model V&V

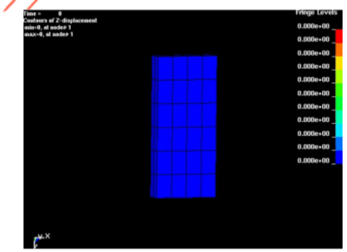


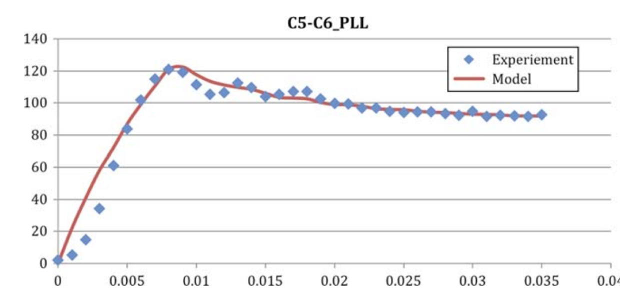
Single Physics: Material Model Parameter Identification

- **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





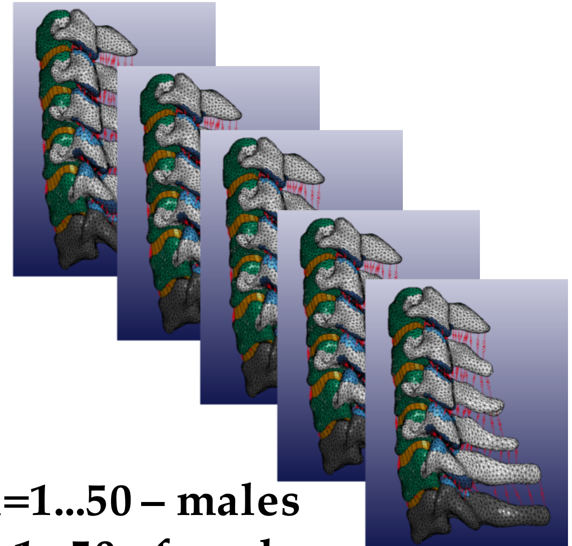




[1] W. L. Francis, T. D. Eliason, Ben H Thacker, G. R. Paskoff, B. S. Shender, and D. P. Nicolella, "Implementation and validation of probabilistic models of the anterior longitudinal ligament and posterior longitudinal ligament of the cervical spine.," *Comput Methods Biomech Biomed Engin*, pp. –, Oct. 2012.

Accounting for Anatomic Variability

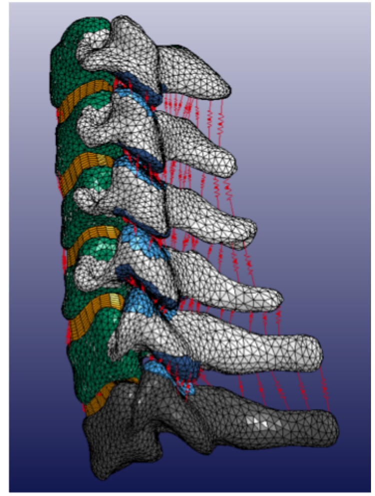
Statistical Shape and Trait Analysis



i=1…50 – males
i=1…50 - females

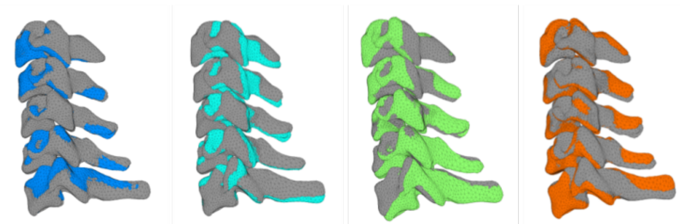
$$p_i = (v_{1x}, v_{1y}, v_{1z}, \ldots, v_{jx}, v_{jy}, v_{jz})^T$$

QCT Scans of 100 Individuals
Individual Models



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

Average Model



$$p_v = \bar{p} + \sum_{j=1}^{m} c_j \sqrt{\lambda_j}\, q_j$$

Parametric SSM Model

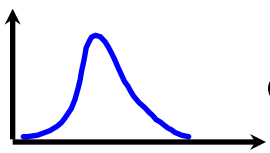
- **Parametric Model = Average Model + *weighting factors* x Principal Components**
- **Weighting factors contain all variability within the population of interest**
- **Compact and efficient representation of complex anatomy**
- **Represent >95% of population anatomic variability with less than 10 variables**

Nicolella and Bredbenner, 2012
Bredbenner et al., 2014

Characterizing Uncertainties

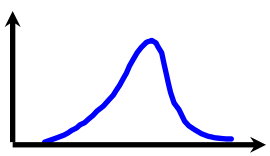
Probabilistic Computational Model

Aleatory uncertainty Operational Conditions Population Group



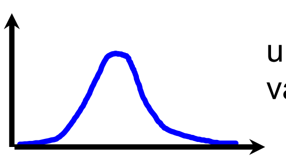
COV's~100%

Material Property



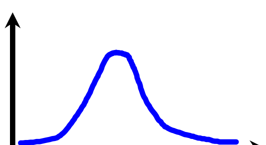
unknown & variable

Forces



unknown & variable

Boundary Conditions



COV's~20%

Geometry

Finite Element Model

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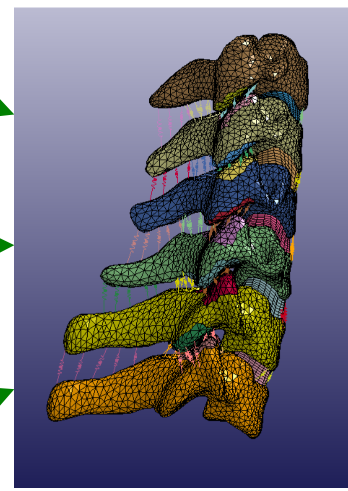
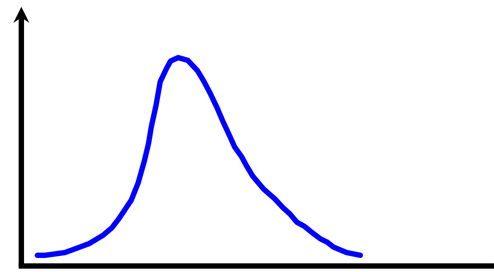


Predicted Probabilistic Response



Model Response
Forces, Stress, Strain, Deflections, etc.

Hierarchical Model V&V Approach

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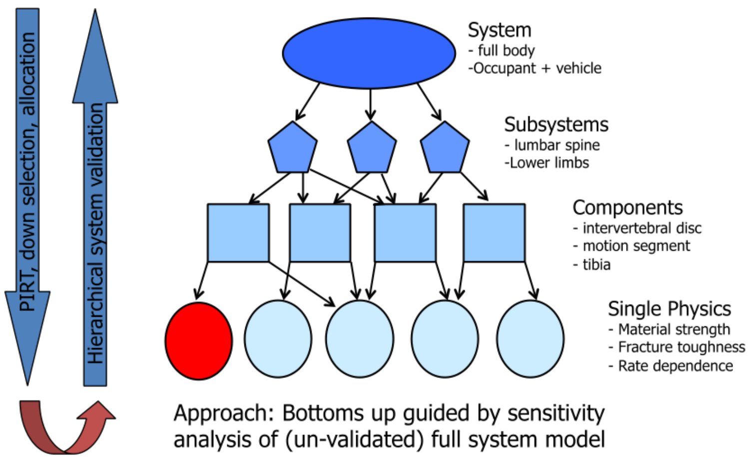
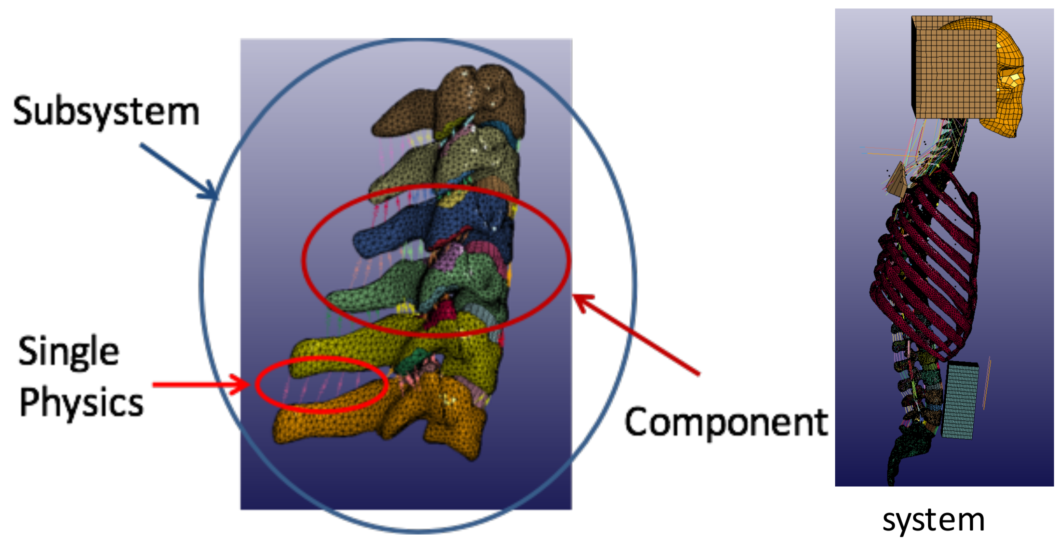
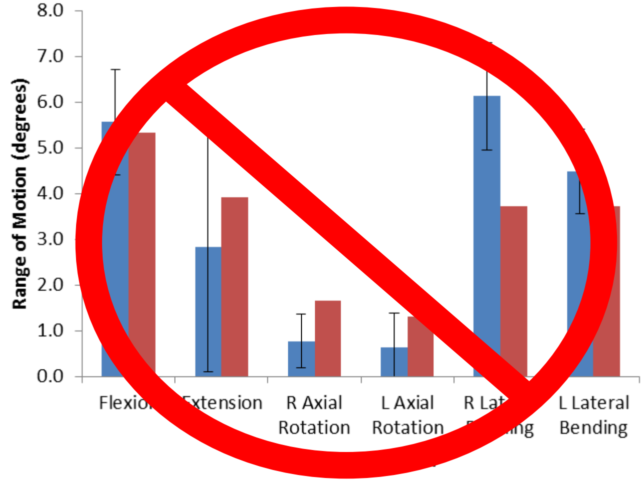
- **Levels 3 & 4: No model fitting/tweaking/calibrating**
  - **Model performance validated against independent set of experiments**

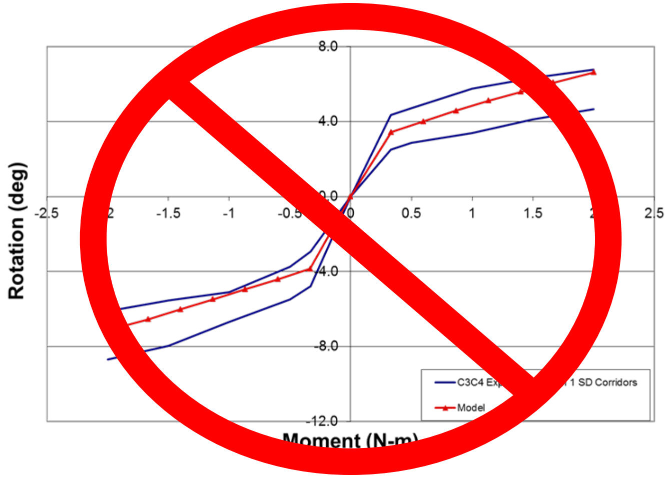




Validation Metrics
How do you define valid?

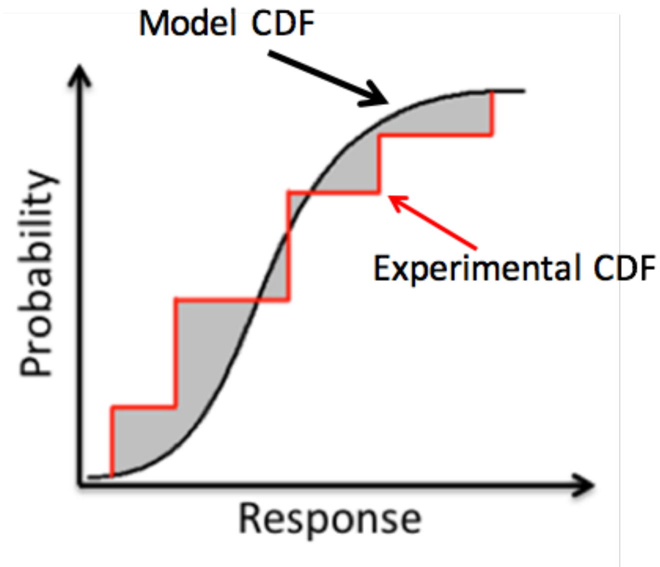
- A metric is the quantitative *measure* of the mismatch between model predictions and experimental data
- Typically some type of a difference measure in system response quantities (statistics, probability distributions, etc.)
- Desired features of a validation metric
  - **Consider uncertainties in 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

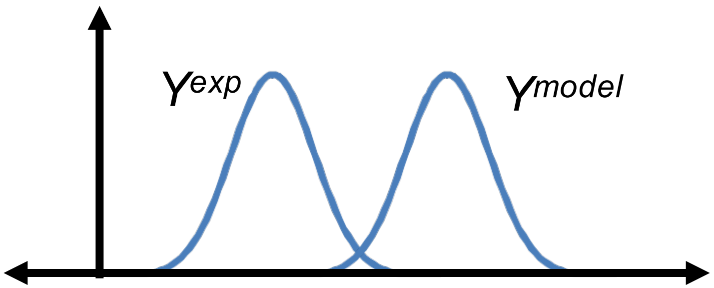
- Absolute error between a model prediction and an experimental response quantity
  - Model prediction and experimental measurement are uncertain
  - Normalized by the experimental mean value (to simplify solution)

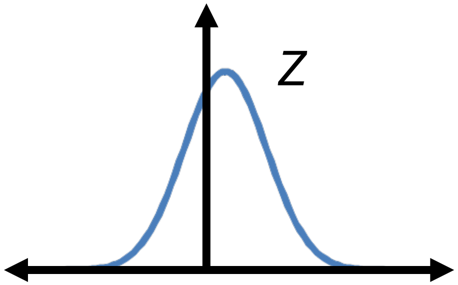
$$Z = \frac{Y^{mod} - Y^{exp}}{E[Y^{exp}]}$$

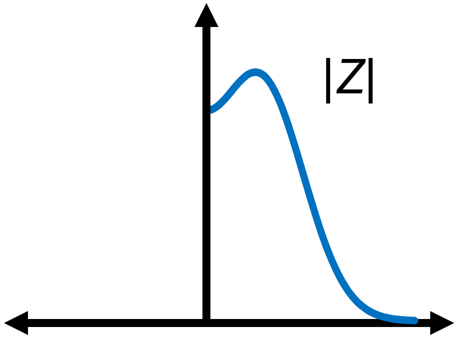
$$p = P\left(|Z| \le z\right)$$ Probability that the error will not be exceeded

  - Validation Requirement

$$p < p_r, \text{ or } z < z_r$$



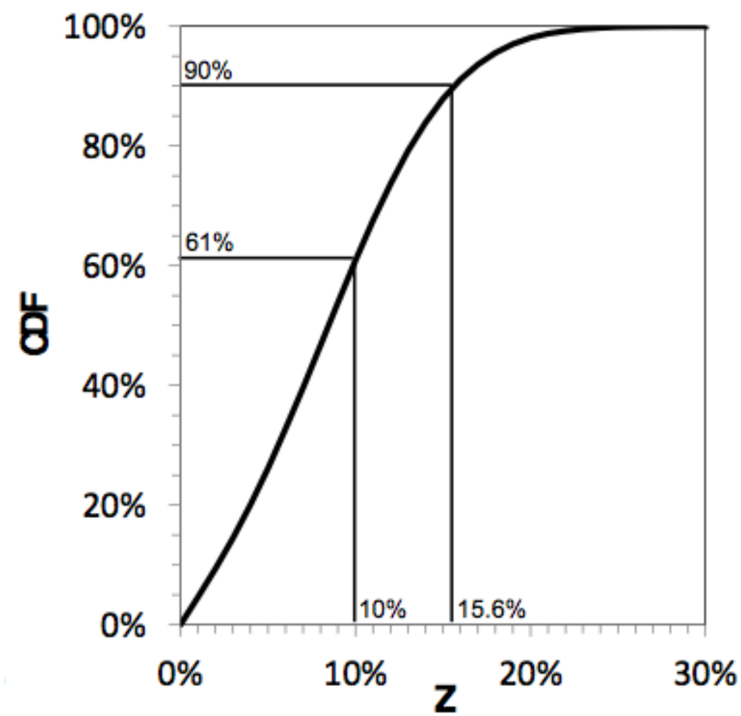




Thacker, B.H. and T.L. Paez, “A Simple Probabilistic Validation Metric for the Comparison of Uncertain Model and Test Results,” AIAA SciTech, 16th AIAA Non-Deterministic Approaches Conference, National Harbor, Maryland, 13-17 January 2014.

Probabilistic Validation - Error Metric
Interpretation

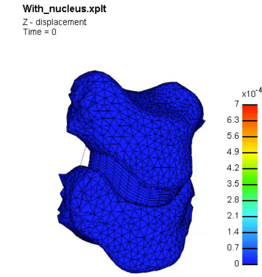
- CDF (integration of PDF) of Z
  - X-axis is error - Z
  - Y-axis is probability level - p
- 90% probability that the error will not be greater than 15.6%
- 61% probability that the error will not be greater than 10%
- The error between the model and the experiment is fully defined
- The benchmark level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



Z = error between model and experiment

Hierarchical Model V&V

Component Validation



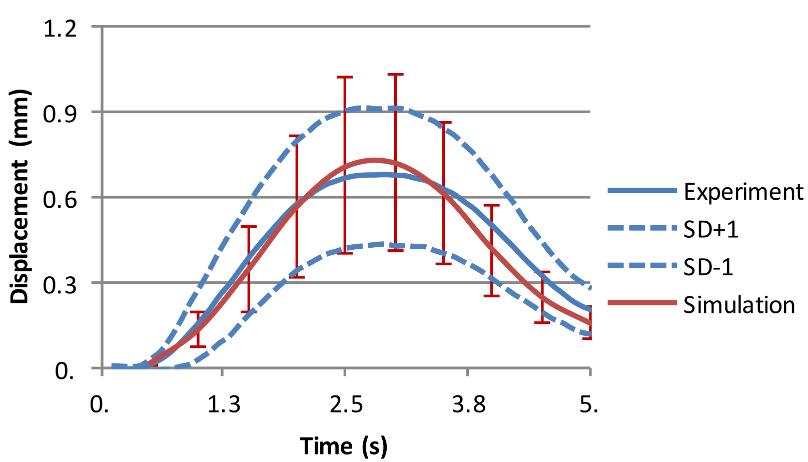
Experimental setup

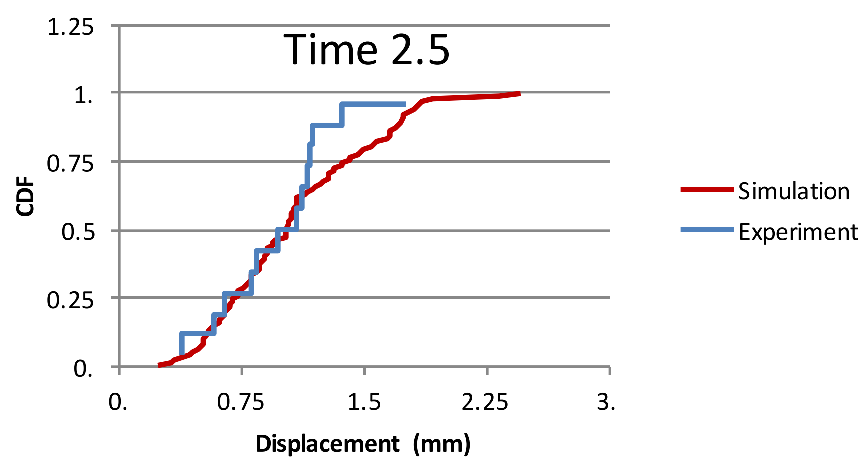
- Isolated vertebra-disc-vertebra specimens
- Loaded with 100 N tension in sine function

Simulation

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

Time	Benchmark Error	Sim Validation	Area Metric
2.5	84%	82%	0.137
5	89%	88%	0.180





Example Component Level Validation

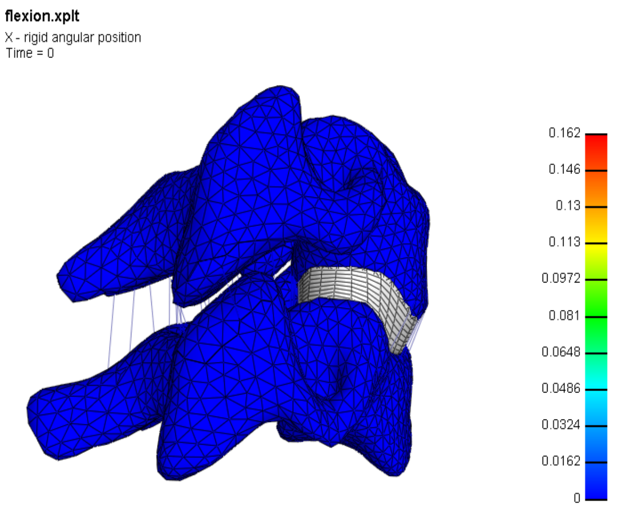
Experimental set-up

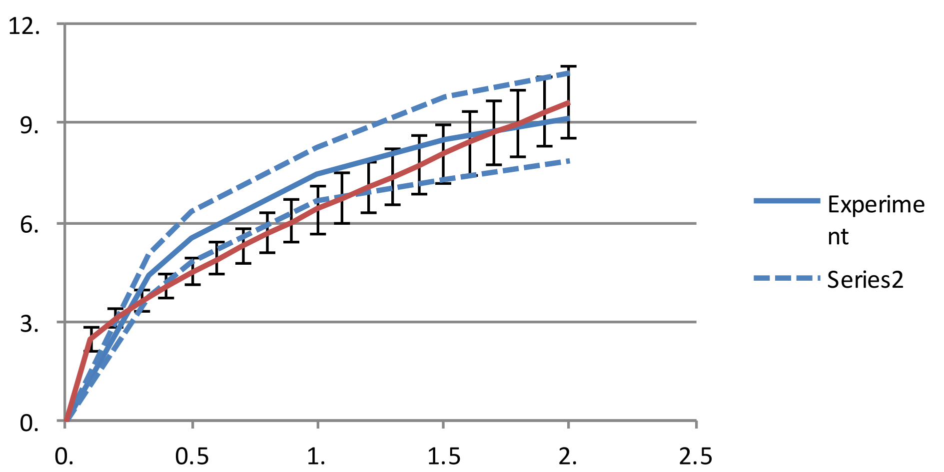
- Pure moment loading of complete motion segment to 2 N-m
- Rotation of superior vertebrae recorded

Simulation

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

Load	Benchmark Error	Sim Validation	Area Metric
2 N-m	34%	93%	0.103





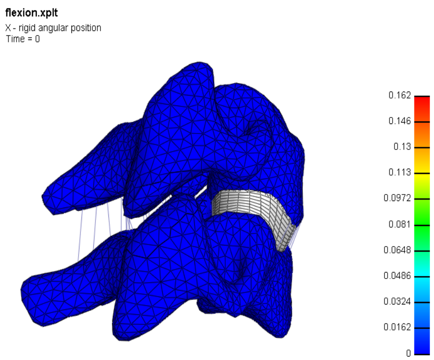
Example Component Level Validation

Experimental set-up

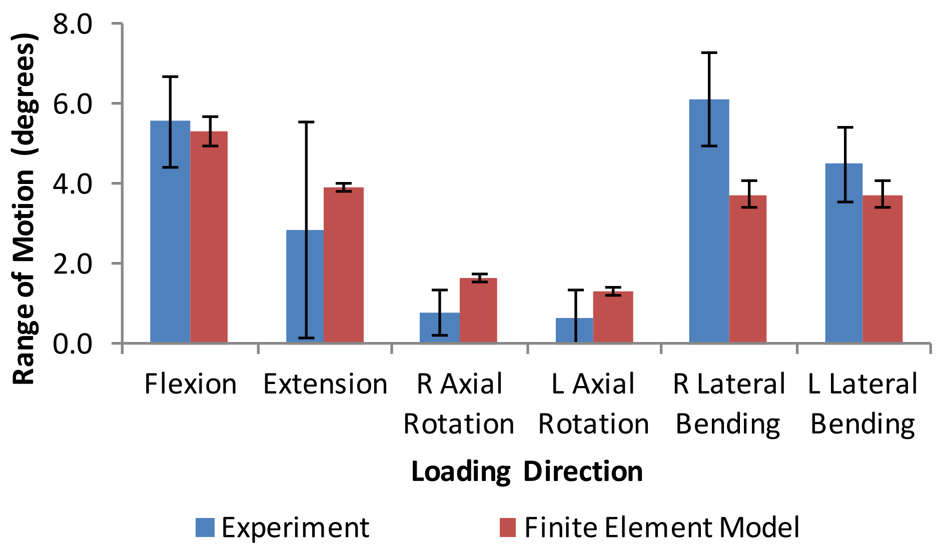
- Pure moment loading of complete motion segment to 6 N-m
- Rotation of superior vertebrae recorded

Simulation

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

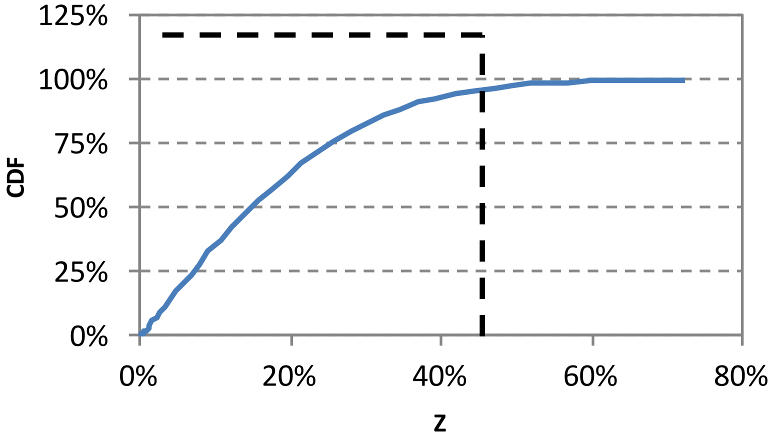


Qualitative Validation

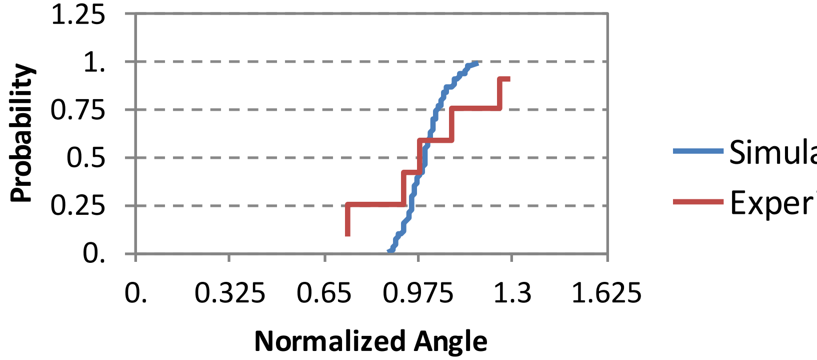


Example Component Level Validation

Probabilistic error metric



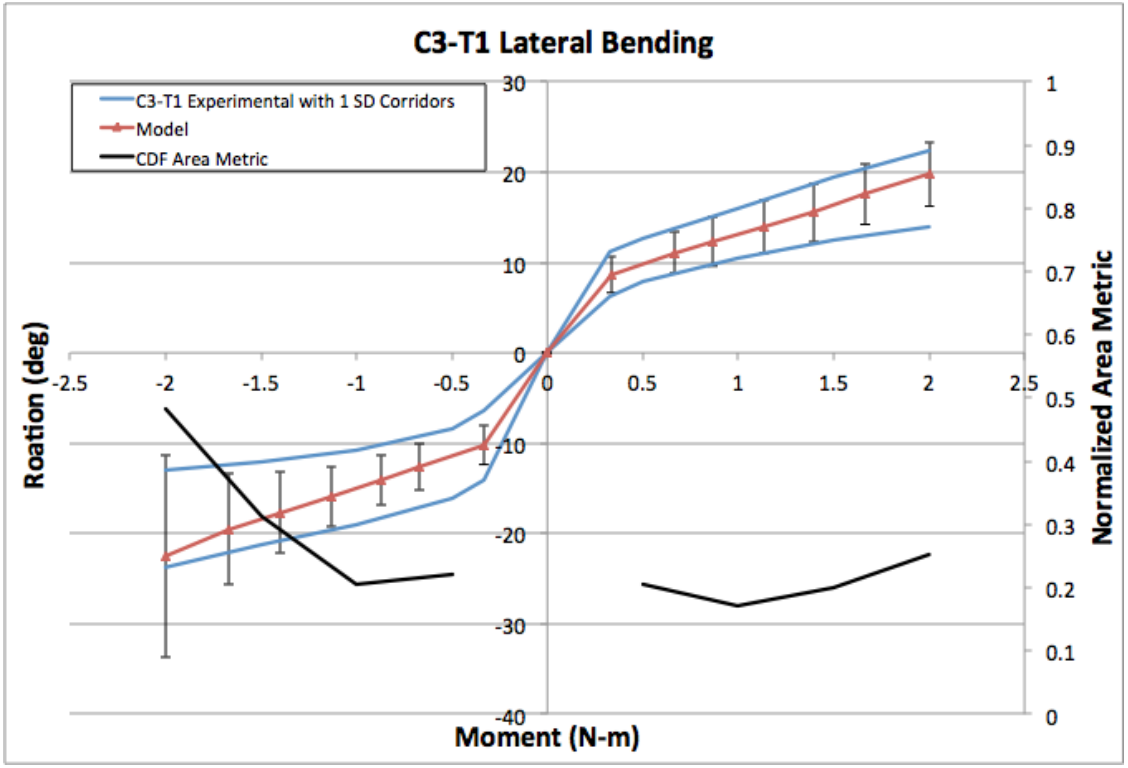
Area metric

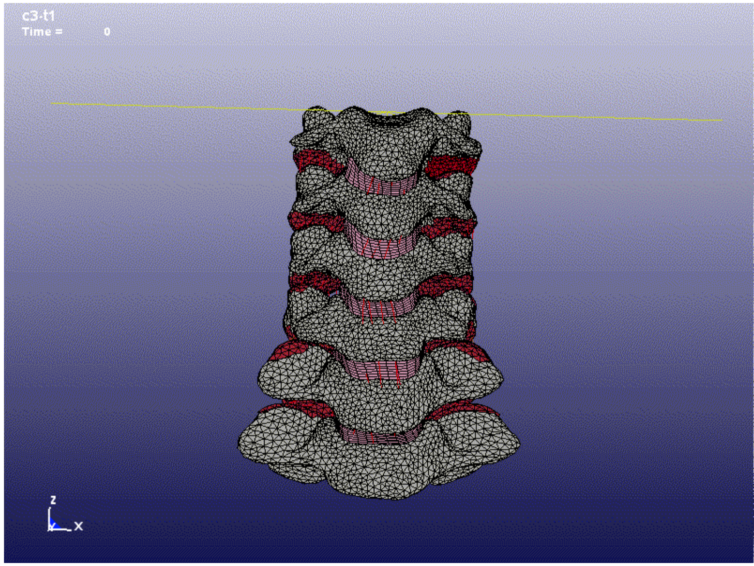


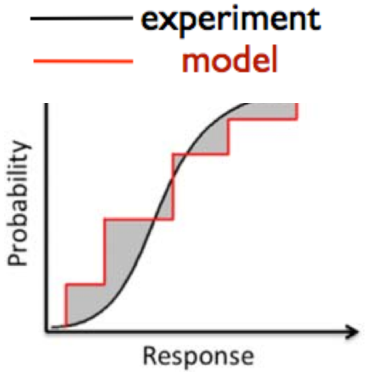
Motion	$e_{benchmark}$	FEM $p = P[\|Z\| \leq e_{benchmark}]$
Flexion	48%	98%
Extension	222%	97%
R Axial Rotation	172%	81%
L Axial Rotation	260%	91%
R Lateral Bending	45%	61%
L Lateral Bending	48%	77%

Motion	Area Metric
Flexion	0.11
Extension	0.60
R Axial Rotation	0.61
L Axial Rotation	0.67
R Lateral Bending	0.54
L Lateral Bending	0.17

Example Subsystem Level Validation





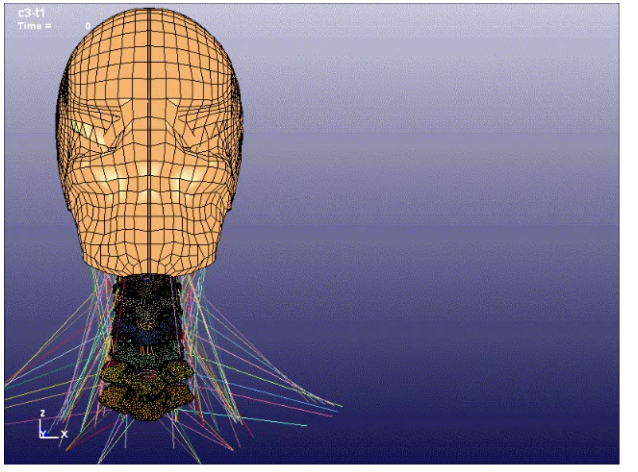


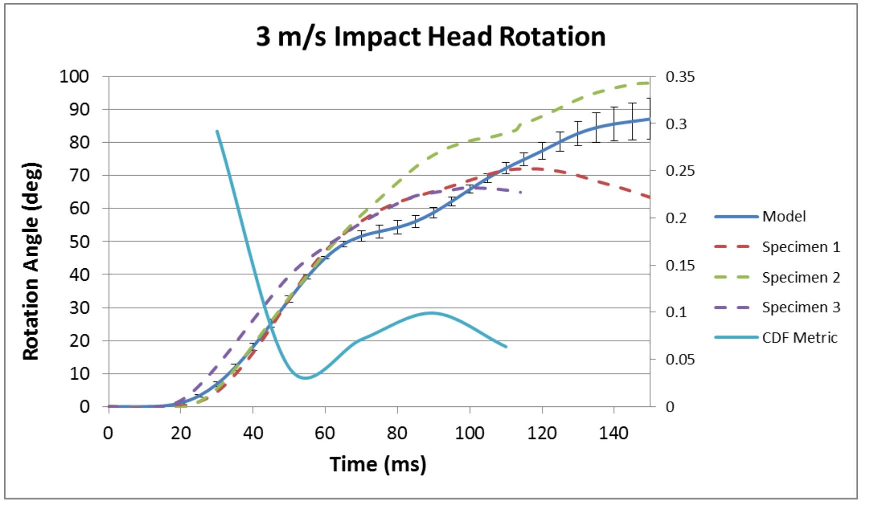
similar results for axial rotation, flexion, and extension

Model Verification and Validation

System Level V&V: Dynamic Lateral Impact

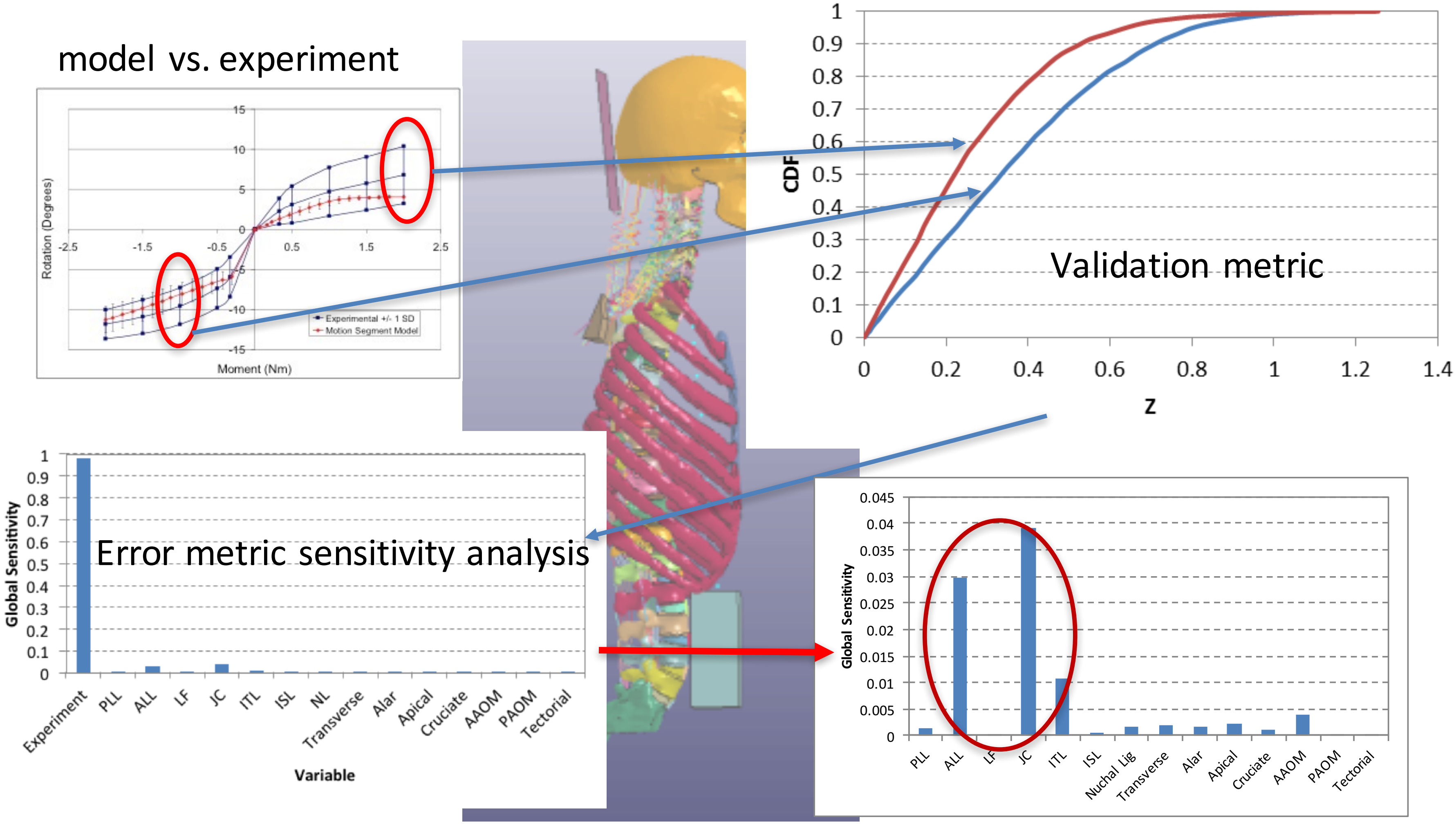
- **Experimental Setup**
  - Three PMHS specimens potted at T1 and mounted to lateral impact loading sled
  - Sled was accelerated using a pendulum impacter at 1, 2, and 3 m/s impact velocities
  - Head and vertebral kinematics were recorded using a Vicon motion capture system
  - Accelerometer used to record sled accelerations
- **Simulation**
  - Full Cervical spine + head
  - Accelerations applied to T1
  - Probabilistic analysis performed
  - Head kinematics validated using area metric





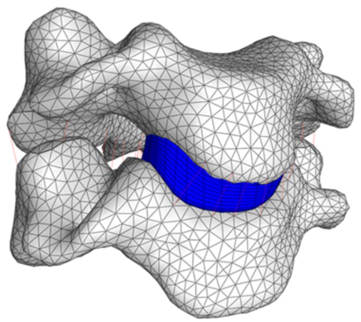
Model Validation Example

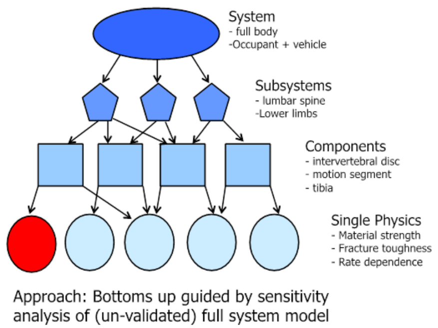
Sensitivity of Error to Model and Experiment Uncertainties

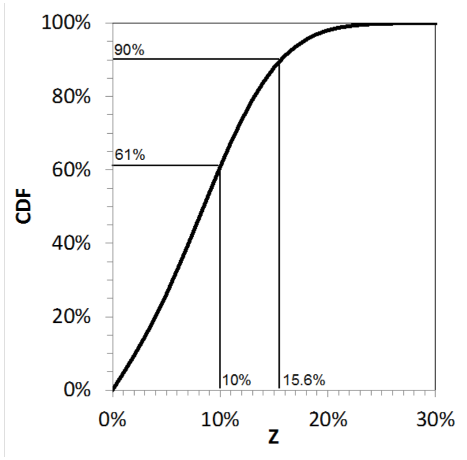


Summary

- 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 <u>right answer for the right reason</u>
- 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 *<u>measure</u>* of the mismatch between model and experiment – Quantitative
- Sensitivity analysis can provide some insight into source of mismatch





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