IRCOBI 2018 Workshop Series

IRCOBI

International Research Council on Biomechanics of Injury

Human Body Modeling and Validation with Biomechanics Experiments

Duane Cronin
Matthew Panzer
Philippe Vezin
Narayan Yoganandan
Karin Brolin
Matthew Reed
Philippe Beillas
Scott Gayzik

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University of Virginia
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Medical College of Wisconsin
Chalmers University of Technology
UMTRI Transportation Research Institute University of Michigan
Wake Forest School of Medicine
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Human Body Modeling and Validation with Biomechanics Experiments

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University Research Chair in Impact Mechanics and Material Characterization
Professor, Department of Mechanical and Mechatronics Engineering
Cross-Appointed to Applied Health Sciences
Board Member and Council Member, International Research Council on Biomechanics of Injury
Director, Impact Mechanics and Material Characterization Group

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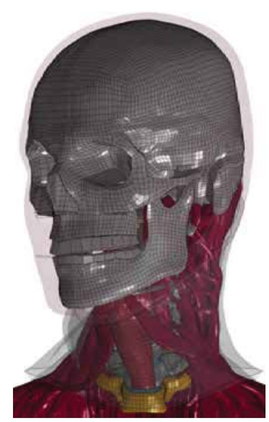
Weclome!

Human body models (HBM) have become widespread in recent years, owing to:

- Increased computing power
- Enhanced model detail and fidelity
- Improved boundary conditions
- Mechanical properties of materials
- Constitutive models



Goal
To present and discuss the development and validation of detailed finite element HBM in the context of experimental data.

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Agenda

Agenda [Morning]	
09:00	Introduction and overview Historical summary and current models Finite Element Codes, Model inputs/outputs [Dr. Duane Cronin]
09:30	Introduction to the FE method [Dr. Matthew Panzer]
10:00	Biomechanical experiments with the intent of validating HBM: from tissues to whole body [Dr. Philippe Vezin]
10:30	Coffee break and Discussion
11:00	Experimental testing and measurements in biomechanics… with the intent of validating HBM [Dr. Narayan Yoganandan]
11:30	Body region modeling and validation [Dr. Matthew Panzer]
12:00	Lunch (provided)
Agenda [Afternoon]	
13:00	Active musculature in HBM [Dr. Karin Brolin]
13:30	Addressing population heterogeneities (age, sex, stature) [Dr. Matthew Reed]
14:00	HBM Repositioning [Dr. Philippe Beillas]
10:30	Coffee break and Discussion
15:00	Model Integration, Verification and Validation (V&V) [Dr. Scott Gayzik]
15:30	Summary and wrap-up [Dr. Duane Cronin]

Why Modeling?

- How can we improve safety and mitigate injury in high-risk events?
- Experimentally we image and measure at high speed, but there are limitations…

Why Modeling?

- The test that cannot be done – live human subject, injurious condition
- The test that will not be done *again* - historic data


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Some thoughts on models

- Essentially, all models are wrong,
  but some are useful. [George Box 1976]

[We need to develop a model with intent]

[What is the question we are trying to answer?]

[A computational model must be designed with **balance**]

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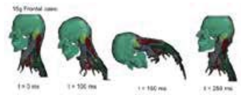
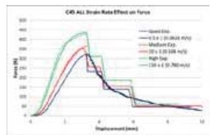
A balanced approach is required.

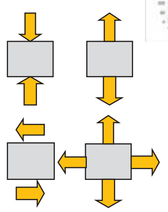
Model Requirements



Model Scale

- Material properties
- Constitutive models





Response
Kinetic/Kinematic

Potential for Injury

Material Properties

Geometry/ Anatomy

Loading (BC's)

- Model refinement
- Relevant anatomical structures

- Force, Deformation or related quantities
- Representative
- Coupling

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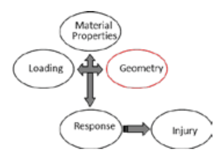
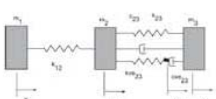
Impact Mechanics and Material Characterization Group

Model Requirements - Geometry



- Model design must be reasonable, and meet requirements:
  - Prediction goals
  - Relevant material properties
  - Continuum-based approach
  - Computation cost

Mathematical Model

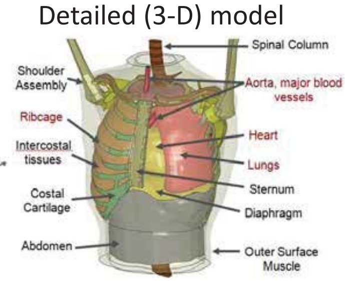


Lobdell lumped mass model

Multibody model

Detailed 2-D blast model

Detailed (3-D) model



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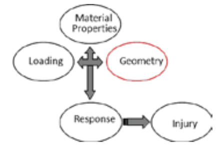
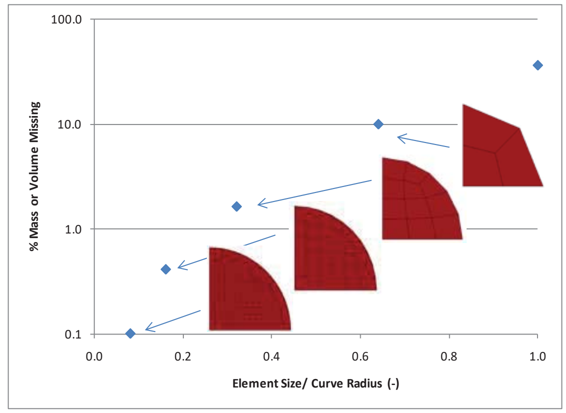
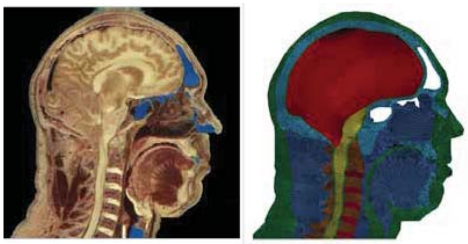


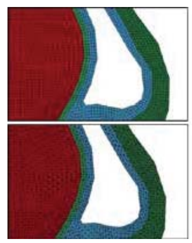
Model Requirements - Geometry

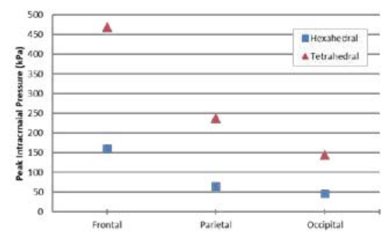
<u>Meshing</u>

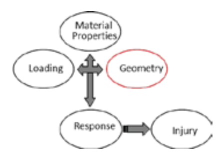
- Discretization:
  - 1D, 2D shell, 3D solid
- Element formulation







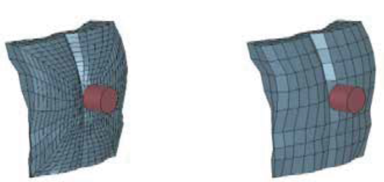


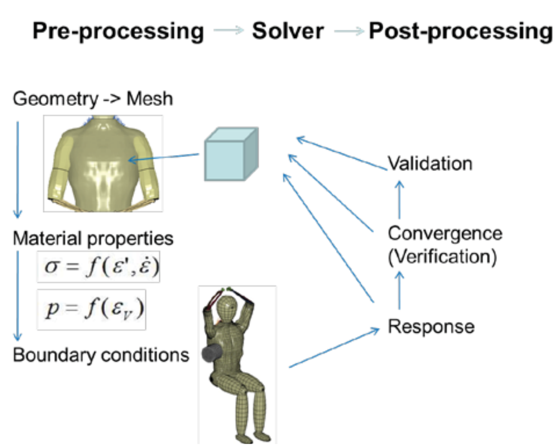


Model Requirements - Geometry

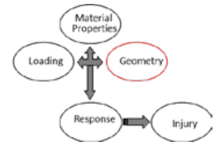
<u>Meshing</u>

- Element size and quality
- Strain $\varepsilon = \frac{\Delta l}{l_0}$
- Strain rate $\dot{\varepsilon} = \frac{V}{l_0}$





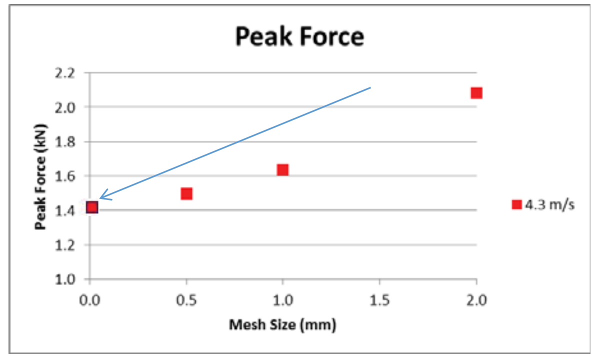
Model Requirements - Geometry



Mesh Convergence (Verification)

- Richardson extrapolation (Roache)
- Grid Convergence Index

Grid Refinement Ratio, r	2
Order of Convergence, p	1.66
Factor of Safety, F_s	1.5
GCI_{12}	0.07
GCI_{23}	0.19
r^pGCI_{12}	0.21

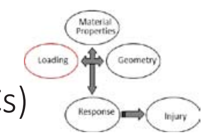


Coarse mesh: 26,142 elements

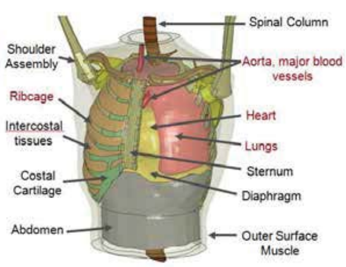
Intermediate mesh: 209,108 elements

Fine mesh: 1,672,836 elements

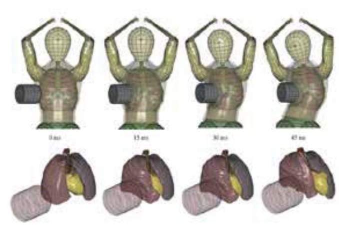
Model Requirements – Loading (BCs)



- Model requirements – Progressive complexity



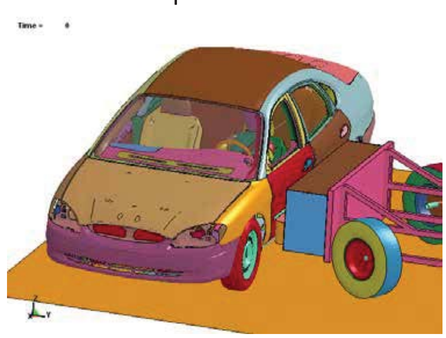
Watson, IJCR 2011
Yuen, WCB 2010
Campbell, ESV 2009
Yuen, IRCOBI 2008
Forbes, IJC 2006
Forbes, WCB 2006
Forbes, IUTAM 2005



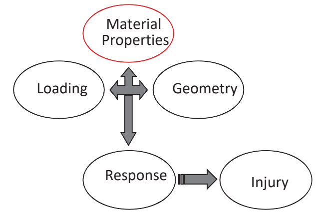
Pendulum impact

Side sled test

Side impact vehicle test

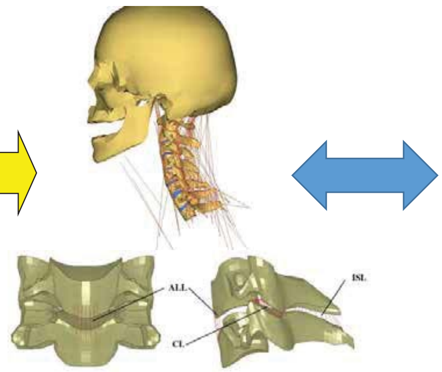


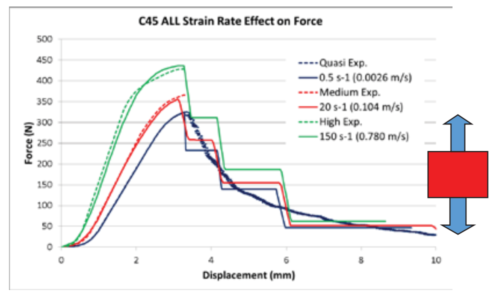
Material Properties



- Generally regarded as the most challenging area with a high degree of uncertainty.
- Most biological materials exhibit non-linear response and are sensitive to strain rate.

** Need to bracket the expected strain and strain rate

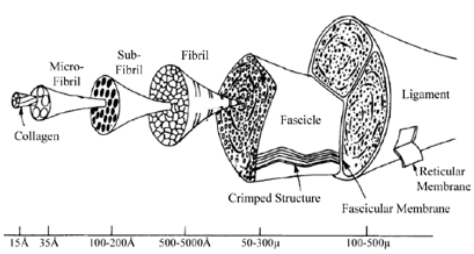


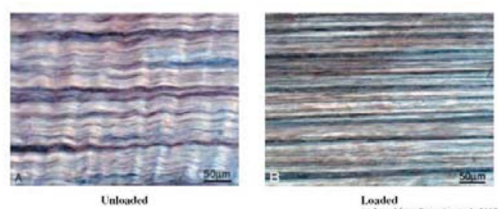


[Mattucci 2011]

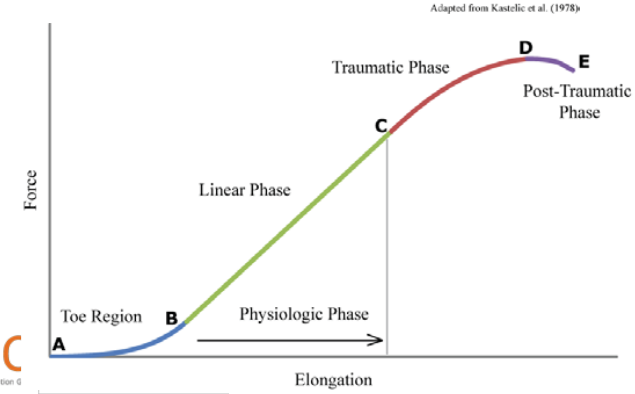
Material Characterization

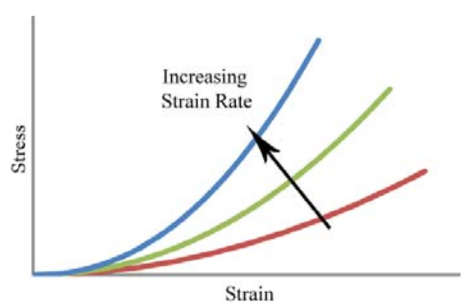
Ligament Structure





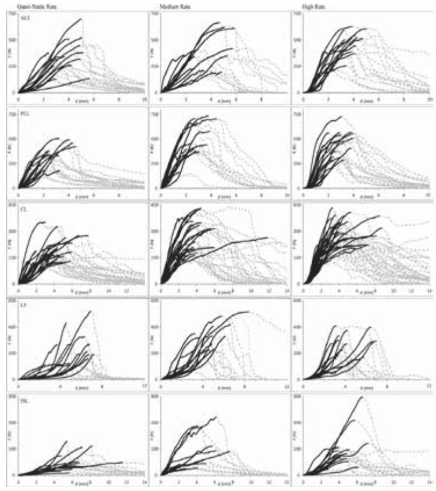
Toe region: "un-crimping" of the collagen fibrils
Linear region: stretching of the collagen fibrils
Yield: failure of the individual collagen fibrils.

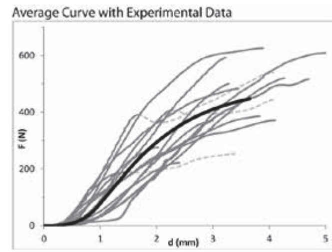




Material Characterization

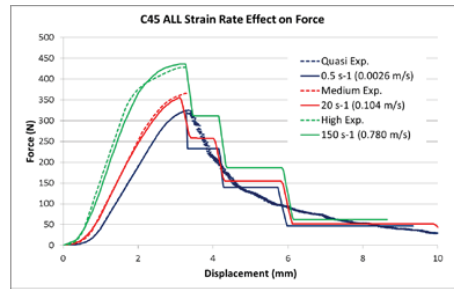
LF @ 150 1/s





Mattucci, JMBBM 2015

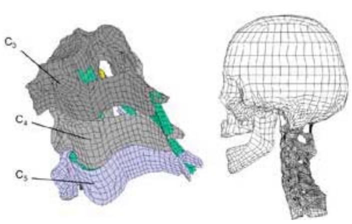
Numerical implementation



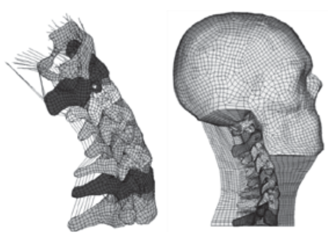
Ligament: multiple axial elements
Force-Displacement curves with
Progressive element failure.

Evolution of neck models…

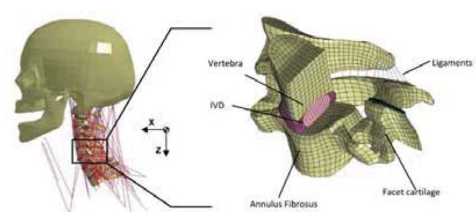
WSU NM
Yang (1998)



Deng (1999)

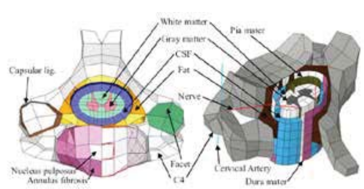


Meyer(2004)

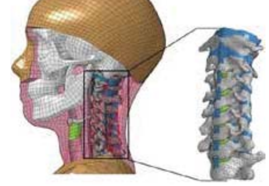


Panzer (2011)

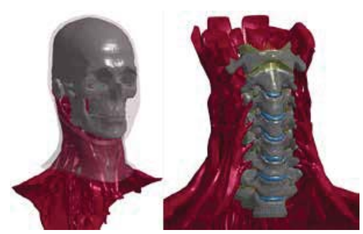
Duke NM
Nightingale (2016)



THUMS
Kimpara (2006)



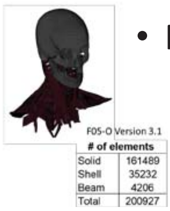
Osth (2016)



GHBMC V4.5

GHBMC Neck Model

- Model goal/intent
  - Prediction of kinematic response
  - Prediction of Crash Induced Injuries
    - Vertebral fracture
    - Ligament distraction/failure
    - Disc avulsion
  - Requirements
    - Element size/computation time
    - Mesh quality (aspect ratio, Jacobian, skew etc.)
    - Validation at multiple scales (tissue, segment, full neck, full body).



Validation Level	# of Cases	List of Cases
Lower cervical segments (C2-C3 to C7-T1)	48 quasi static 10 dynamic	Quasi static: four modes of bending, three shear directions, tension Dynamic: Nightingale flexion/extension
Upper cervical segment (C0-C2)	8 quasi static	4 ROM and 4 traumatic flexion, extension, axial rotation, tension
Ligamentous cervical spine	2 quasi static 2 dynamic	Quasi static: axial rotation, tension Dynamic: 8g frontal and 8g rear
Full musculature neck model	4 dynamic	NBDL: 15g and 8g frontal, 7g lateral Deng: 7g rear
Total:	**74 cases**	

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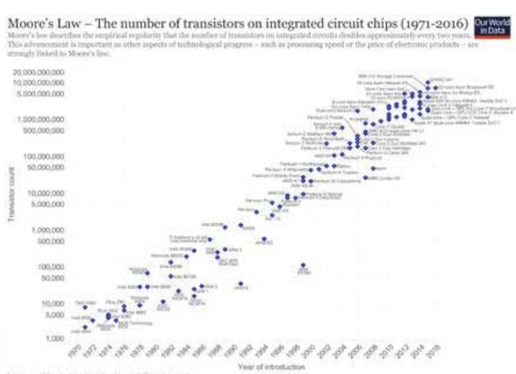
Compute power

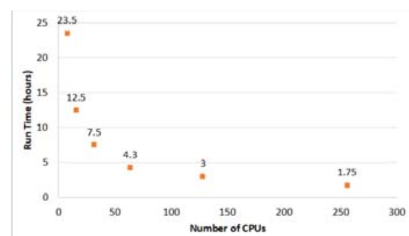
- SMP – Symmetric Multiprocessing
- MPP – Massively Parallel Processing (Cluster)

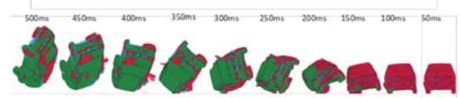
Moore's Law – the number of transistors in an integrated circuit doubles approximately every two years [1965]
-> Projected to end ~2025!

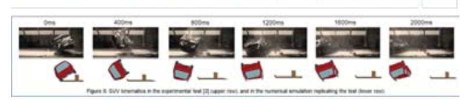
'Red Room' @ UW
1967 IBM 360/75
1 MB memory

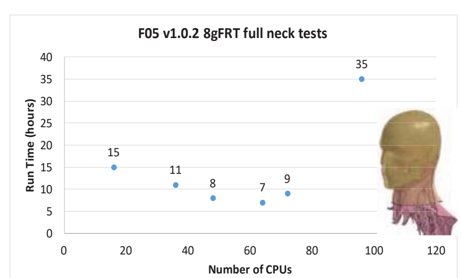
'Graham' @ UW
2017
33,000 cores
5 petabyte parallel storage











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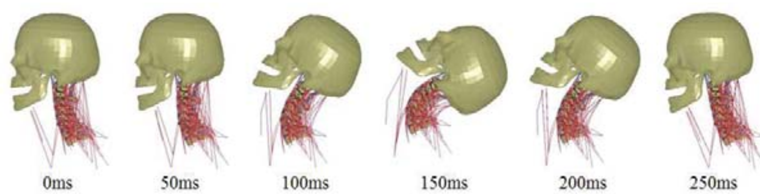
Why pursue modeling?

- Models can allow us to:
  - Interpret experimental results
  - Investigate response to impact (sensitivity studies)
  - Consider new designs for protection and safety

- **Models must be developed with a specific intent or hypothesis.**
  - Models are an approximate representation of a physical phenomenon, bounded by their assumptions and have a finite life.



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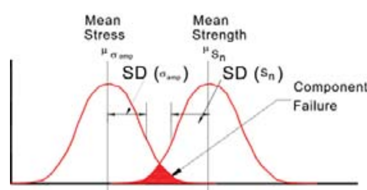
Good enough?



- Verification, Validation and Uncertainty Quantification (VV&UQ)

- The goal of V&V is to build confidence (TRUST) in the predictive capability of the model.
- **Verification:** accurate representation of the underlying problem and mathematical implementation
- **Validation:** determination of the model ability to represent real-world impact scenarios
- **Calibration:** Adjusting properties (material, failure) and model parameters (mesh, boundary conditions) to achieve a desired outcome.
- **Uncertainty Quantification** involves quantifying (and reducing) uncertainty in models
  To determine the possibility of an outcome, given uncertainty in many aspects of the model

- All simple test cases, and V&V cases must be repeated when moving to a new code, or a new version of the current code.

ASME V&V 10-2006, "Guide for Verification and Validation in Computational Solid Mechanics"

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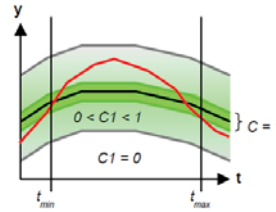
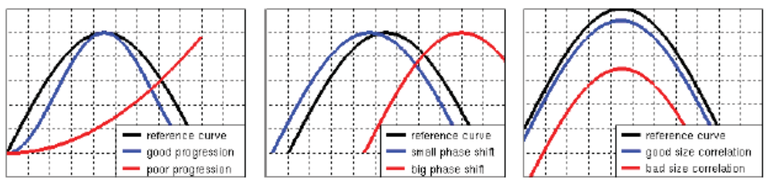
Verification & Validation

- **COR**relation and **A**nalysis (CORA) Partnership for Dummy Technology and Biomechanics, Ingolstadt, Germany http://www.pdb-org.com/en/information/18-cora-download.html
- Corridor rating
  - User defined or generated response corridors
- Cross Correlation ratings
  - Progression (shape), Phase Shift, Size





- Two methods - intended to compensate for limitations in the individual methods and provide an objective rating. (Rating between 0 and 1)

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Agenda

IRCOBI International Research Council on Biomechanics of Injury

Agenda [Morning]	
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Introduction to the Finite Element Method
-An extremely brief overview-

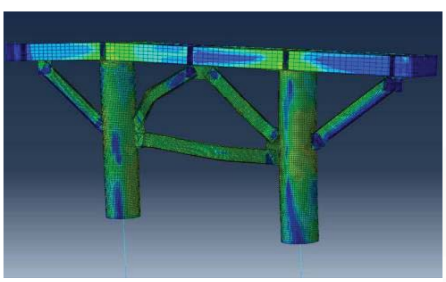
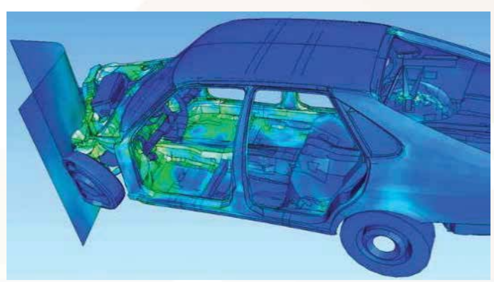
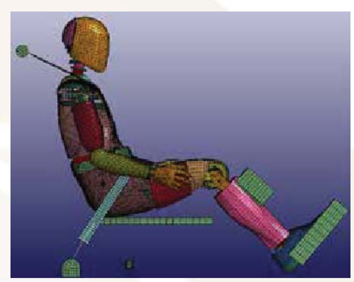
Matthew B. Panzer, PhD

Center for Applied Biomechanics
University of Virginia

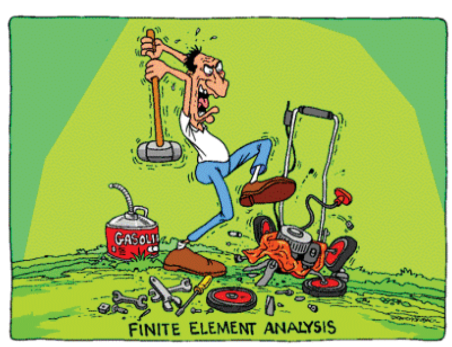
Pre-IRCOBI Workshop on Human Body Modeling
September 11, 2018
Athens, Greece

The Finite Element Method: Overview

- The world is full of very complex engineering problems

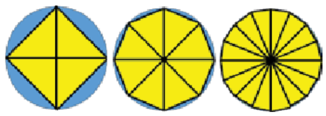




No exact solution is possible, but it can be approximated using numerical methods!



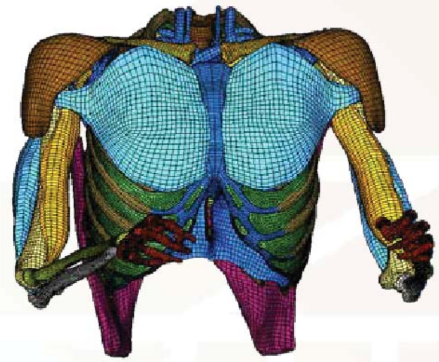
The Finite Element Method: Overview

- Discretization

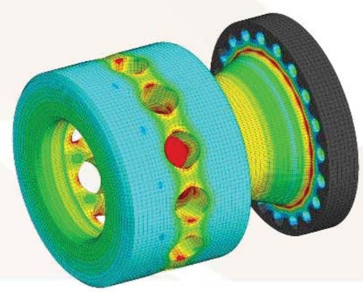


# of triangles	Error
4	36%
8	10%
32	1%

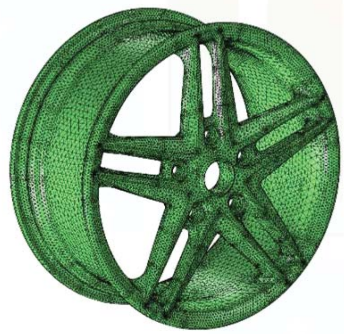
Solve many small problems instead of one large one.

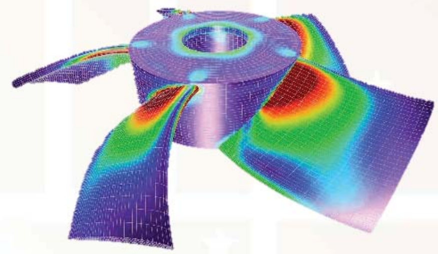


Model complex shapes and materials



Estimate mechanical behaviors prior to physical prototype.

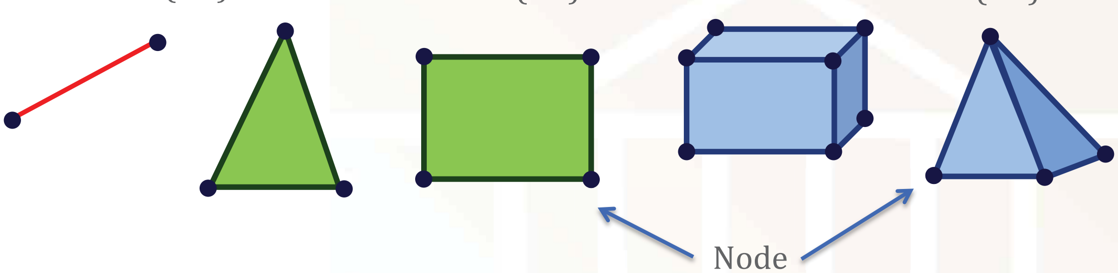




The Finite Element Method: Overview

- The basic structure of finite elements
  - Dividing the domain, structure, or continuum into sub-regions called *finite elements.* Elements are of simple shapes:

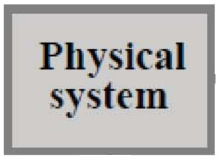
Beam element (1D) Shell element (2D) Solid element (3D)



  - *Nodes* are defined for each element and are discrete points that unknown variables *(field variables)* are to be determined. Field variables may be displacement, temperature, or velocity
  - A collection of elements connected at the nodes is called a *mesh*.

The Finite Element Method: Overview

- Sources of error
  - Approximation = error



The Finite Element Method: Overview

- Words to live by as a modeler

"All models are wrong, but some are useful"

- *George E.P. Box, 1976*

"Everything should be made as simple as possible, but not simpler"

- *Albert Einstein*

“Garbage in, garbage out”

- *George Fuechsel*

What is finite element modeling?

The Finite Element Method: Basics

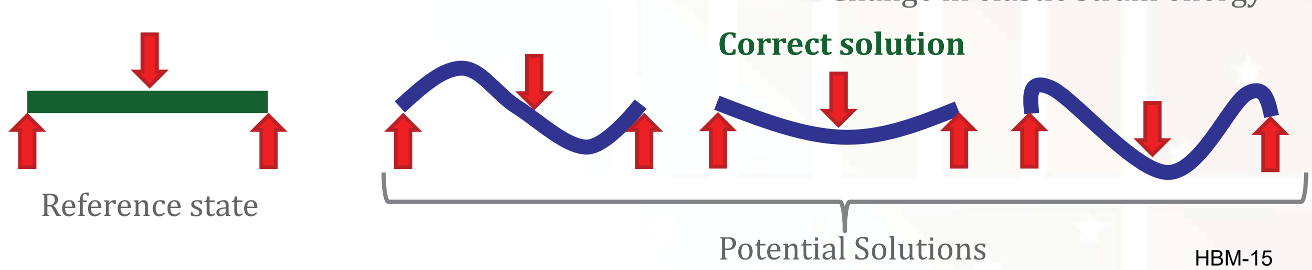
- Numerical method for structural analysis
- Guiding theory: Principle of Minimum Potential Energy (PMPE)
  - *A structure or body shall deform or displace to a position that minimizes the total potential energy*

$$\Pi = U + V$$

Total potential energy (Π); Elastic strain energy (U); Potential energy (V)

$$\delta\Pi = \delta U - \delta W = 0$$

Minimum potential energy ($\delta\Pi$); Change in elastic strain energy (δU); External work (δV = -δW)



HBM-15

The Finite Element Method: Basics

- External work

$$\delta W / \delta u = \{F\}$$

- Elastic strain energy

$$U = \frac{1}{2}\int_V \{\varepsilon\}^T \{\sigma\}\, dV$$

Strain vector → $\{\varepsilon\}$; Stress vector → $\{\sigma\}$

  - Applying basic concepts from continuum mechanics:

$$\{\varepsilon\} = \frac{du}{dx} = [B]\{u\} \qquad \{\sigma\} = E\varepsilon = [E][B]\{u\}$$

Strain-Displacement Matrix → $[B]$; Displacement Vector → $\{u\}$; Material Tensor → $[E]$

$$U = \frac{1}{2}\int_V \{[B]\{u\}\}^T \{[E][B]\{u\}\}\, dV$$

$$U = \frac{1}{2}\{u\}^T \left(\int_V [B]^T[E][B]\, dV\right)\{u\}$$

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The Finite Element Method: Basics

- Elastic strain energy

$$U = \frac{1}{2}\{u\}^T \left(\int_V [B]^T[E][B]\, dV\right)\{u\}$$

$$\delta U / \delta u = \left(\int_V [B]^T[E][B]\, dV\right)\{u\}$$

Stiffness Matrix →

$$[K] = \int_V [B]^T[E][B]\, dV$$

- System of equations for static equilibrium

$$\delta\Pi = \delta U - \delta W = 0$$

$$[K]\{u\} - \{F\} = 0$$

$$\boxed{[K]\{u\} = \{F\}}$$

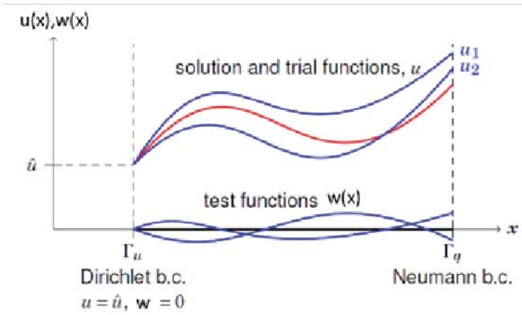
← SOLVE THIS!

The Finite Element Method: Basics

- The potential energy in a structure is mathematically a *weak-formulation* boundary value problem (BVP)

$$\Pi = \frac{1}{2}\{u\}^T\left(\int_V [B]^T[E][B]\,dV\right)\{u\} - \{F\}\{u\}^T$$

- *Calculus of Variations* is a framework that minimizes the functional in a weak-formulation →goal of PMPE



- *Method of Galerkin* is the concept that we can use piecewise solutions of *u* to satisfy the weak-form BVP

The Finite Element Method: Basics

- The procedure for FEA follows a general framework

1. Discretization
2. Develop the element stiffness matrix
3. Assembly of matrices to form global or system equations
4. Apply kinematic boundary conditions
5. Solve the global or system equations
6. Calculate secondary quantities

- Step 2 is the most interesting part of this whole process

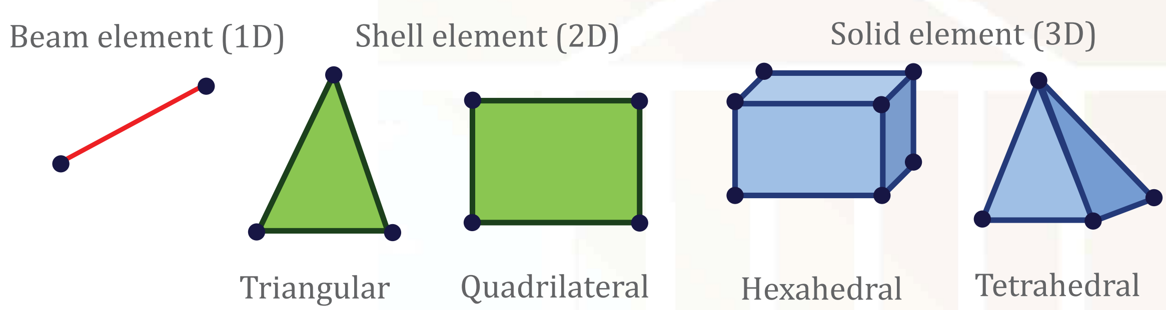
What is the element stiffness matrix?

The Finite Element Method: Stiffness Matrix

- The fun part of FEM is how the stiffness matrix is formulated

$$[K] = \int_V [B]^T [E][B]\, dV$$

- It is dependent on element type and topology…



- And *interpolation function!*

The Finite Element Method: Stiffness Matrix

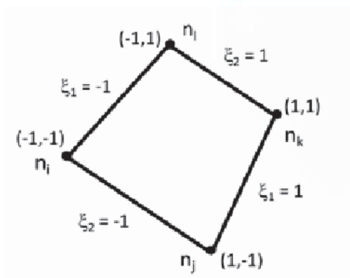
- Interpolation function (or *shape function*) of an *isoparametric* element relates any position within the element as a function of the nodal position (x) using a natural coordinate system

Interpolated position → $\{X(\zeta)\} = [N]\{x\}$ ← Nodal position

- It also applies to displacement

Interpolated displacement → $\{q(\xi)\} = [N]\{u\}$ ← Nodal Displacement; ← Shape Function

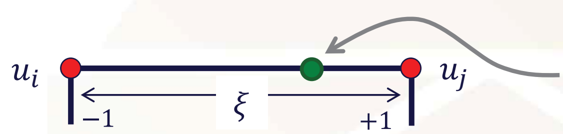
- Example: *Linear Quadrilateral*



$$[N] = \frac{1}{4}\begin{bmatrix} (1-\xi_1)(1-\xi_2) & 0 \\ 0 & (1-\xi_1)(1-\xi_2) \\ (1+\xi_1)(1-\xi_2) & 0 \\ 0 & (1+\xi_1)(1-\xi_2) \\ (1+\xi_1)(1+\xi_2) & 0 \\ 0 & (1+\xi_1)(1+\xi_2) \\ (1-\xi_1)(1+\xi_2) & 0 \\ 0 & (1-\xi_1)(1+\xi_2) \end{bmatrix}^T$$

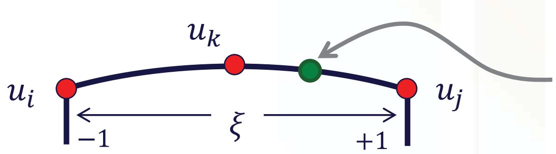
The Finite Element Method: Stiffness Matrix

- *Linear* elements use a linear interpolation function



$$q = \frac{1}{2}(1-\xi)u_i + \frac{1}{2}(1+\xi)u_j$$

- *Quadratic* elements use a quadratic interpolation function, requiring a node on the edge or nodal rotations



$$q = \frac{1}{2}(1-\xi)\xi u_i + \frac{1}{2}(1+\xi)\xi u_j + (1+\xi^2)u_k$$

- The form of these function differ depending on the topology of the element (e.g., triangular, quadrilateral)

The Finite Element Method: Stiffness Matrix

- From the compatibility equations for strain $\{\varepsilon\} = \frac{du}{dx} = \frac{dq}{dx}$

we can use the interpolated displacement to calculate strain within the element

$$\{\varepsilon\} = \frac{d([N]\{u\})}{dx} = \left[\frac{\delta N}{\delta x}\right]\{u\}$$

- Recall that the shape function is in natural coordinates ξ, so we need to convert the derivative using the Jacobian

$$J_{ij} = \frac{\delta x_i}{\delta \xi_j} \qquad \frac{\delta f}{\delta x} = J^{-1}\frac{\delta f}{\delta \xi}$$

- Applying this we get a formula for [B]

$$\{\varepsilon\} = \left[\frac{\delta N}{\delta x}\right]\{u\} = \underbrace{J^{-1}\left[\frac{\delta N}{\delta \xi}\right]}_{[B]}\{u\}$$

Strain-displacement matrix $[B] \longrightarrow [K] = \int_V [B]^T[E][B]\, dV$

The Finite Element Method: Stiffness Matrix

- The shape function [N], and therefore the strain-displacement matrix [B], is unique for each type of element formulation

Element strain → $\{\varepsilon\} = [B]\{u\}$ ← Nodal Displacement

- Most element types have a [B] that is a function of the natural elemental coordinate system ξ. This implies that strain {ε} varies throughout the element.
  - The exception to this the linear triangular element, which is also called the *constant strain triangle* because [B] is constant

The Finite Element Method: Stiffness Matrix

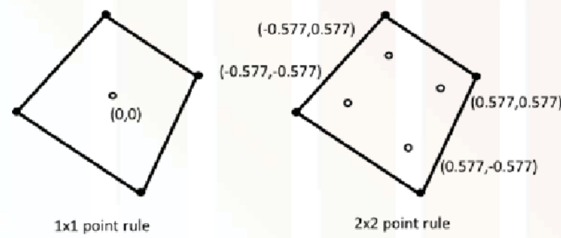
- A non-constant [B] means we need a way to integrate for [K]

$$[K] = \int_V [B]^T [E][B]\, dV$$

- Gauss-quadrature is used to approximate the integral

$$\int_a^b f(x)dx \simeq w_1 f(x_1) + w_2 f(x_2)$$

Example for 2D quad



The Finite Element Method: Stiffness Matrix

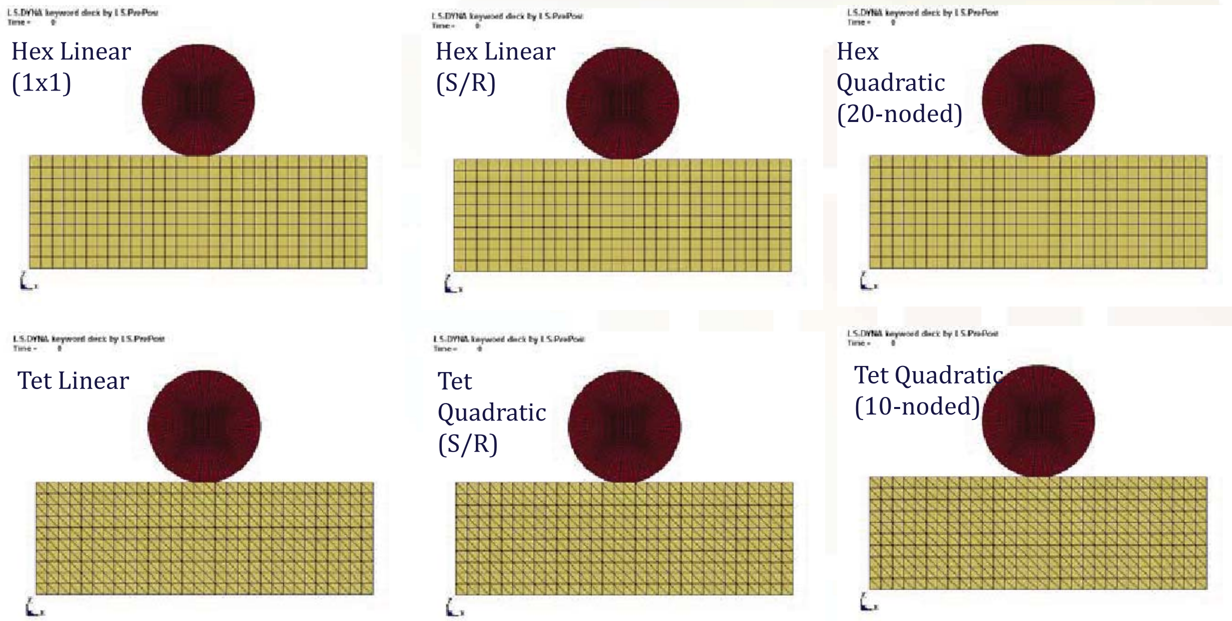
- The integration scheme will affect how [K] is calculated
- There are also inherent characteristics to the element resulting form choice of integration scheme

Type	Pros	Cons
Single point	•Efficient •Good with poor quality elements	•Hourglassing •Too soft when mesh is coarse Slower to converge
Multi point	•No hourglassing •Good rate of convergence	•Shear lock with poor elements •More expensive than single point •Too stiff when mesh is coarse

- Hybrid techniques (such as selectively reduced elements) can alleviate some limitations (hourglassing) but not all (shear lock)

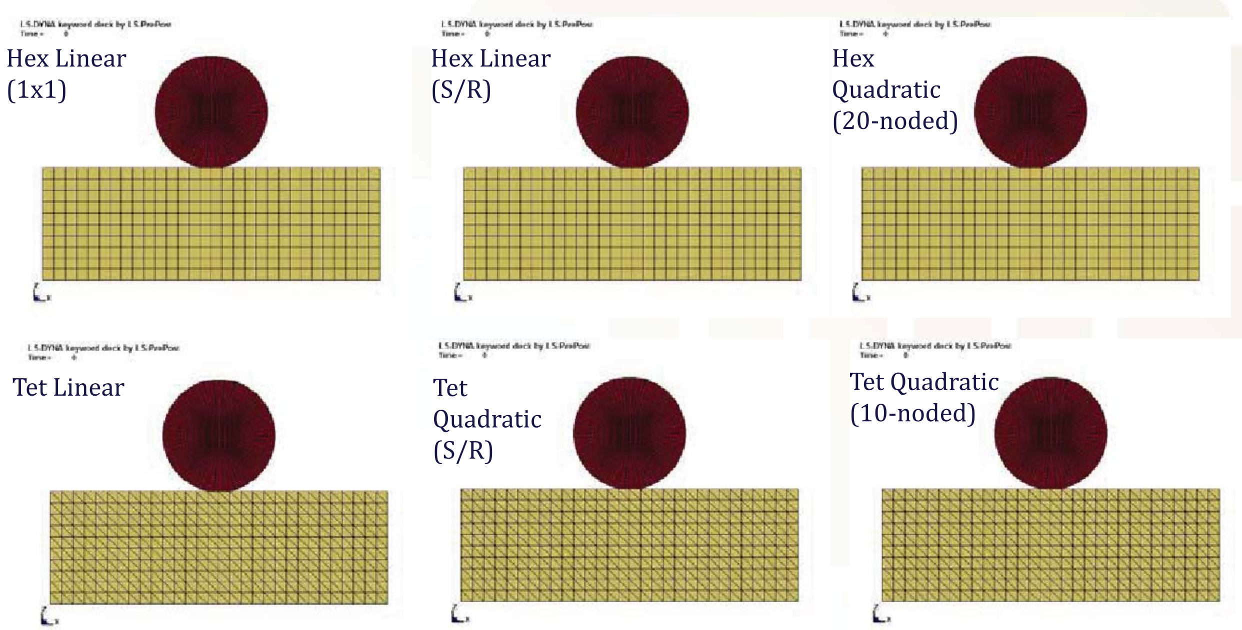
The Finite Element Method: Comparison

- Example: Comparison of element types in LS-Dyna
  - Foam (highly compressible)



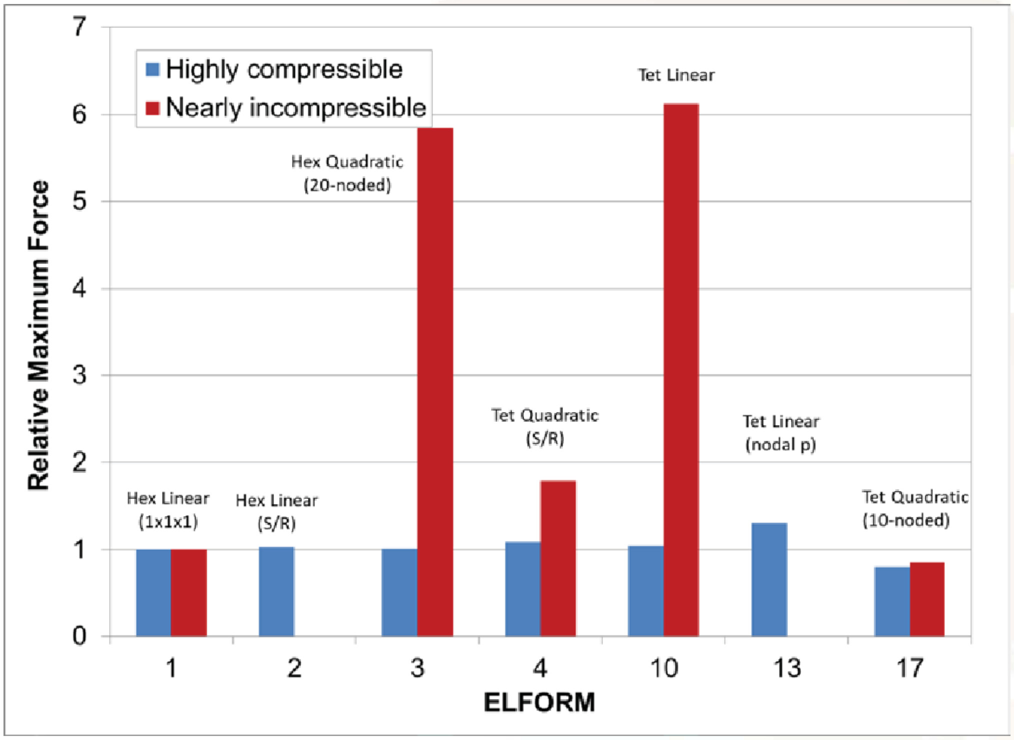
The Finite Element Method: Comparison

- Example: Comparison of element types in LS-Dyna
  - Brain (nearly incompressible)



The Finite Element Method: Comparison

- Maximum relative force



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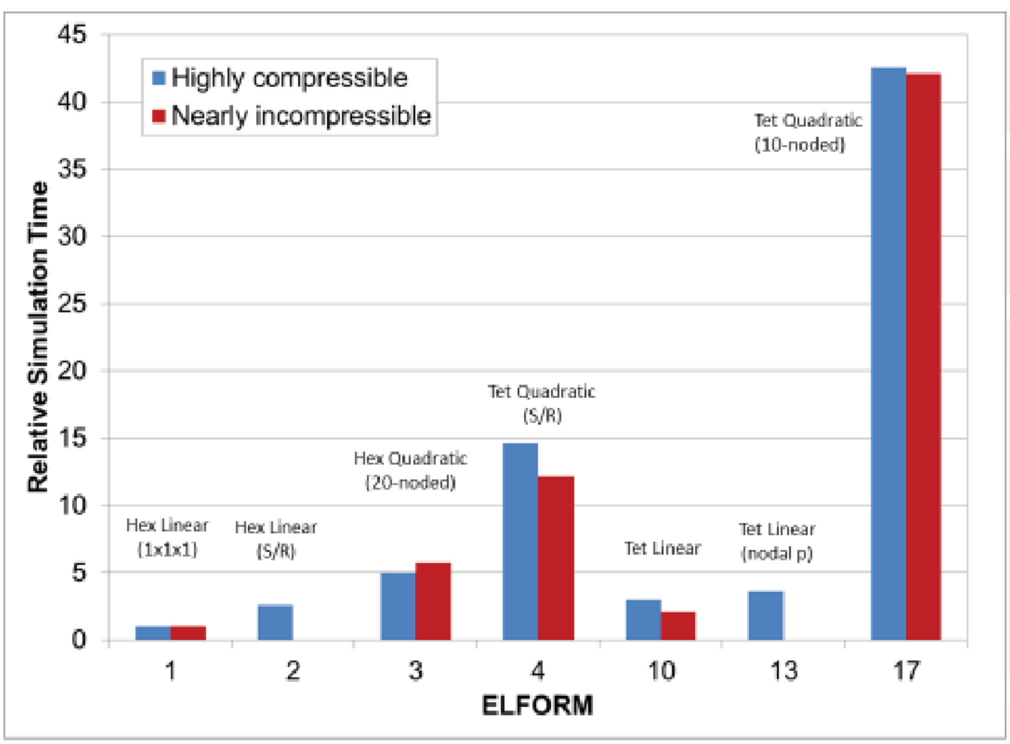
The Finite Element Method: Comparison

- Simulation time



HBM-23

The Finite Element Method: Comparison

- Common 2D element types

Type	Pros	Cons
Tri (CST)	•Computationally cheap •No hourglassing •Trivial to mesh	•Volumetric locking •Very stiff with coarse mesh •Slower to converge
Quad {1x1}	•Computationally cheap •Good with poor elements	•Hourglass control needed •Soft with coarse mesh •Can be difficult to mesh
Quad {2x2}	•No hourglassing •Good rate of convergence	•Shear lock with poor elements •Stiff with coarse mesh •Computationally expensive •Can be difficult to mesh

The Finite Element Method: Comparison

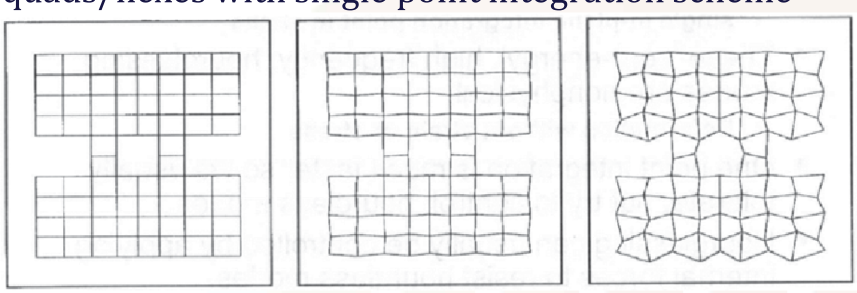
- Common 3D element types

Type	Pros	Cons
Tet (4-noded)	•Computationally cheap •No hourglassing •Easy to mesh	•Very stiff, volumetric locking with incompressible materials •5x more elements need relative to hex
Tet (10-noded)	•No hourglassing •Easy to mesh •Good performance for most materials	•Very computationally expensive •5x more elements need relative to hex
Hex (underintegrated)	•Computationally cheap •Good performance for all materials	•Hourglass control needed •Difficult to mesh
Hex (fully integrated)		•Stiff, shear locking with incompressible materials •Computationally expensive •Difficult to mesh

What's the deal with hourglassing?

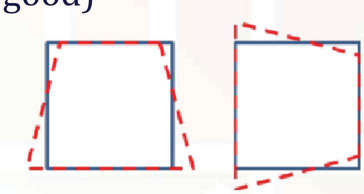
The Finite Element Method: Hourglassing

- Hourglassing occurs in elements with rank deficiency
  - Linear quads/hexes with single point integration scheme



Undeformed mesh   Slight hourglass   Extreme hourglass

- Missing eigenvalues represent zero-energy deformation modes
  - Modes associated with rigid body motion (this is good)
  - Modes associated with deformation (this is not good)
- Hourglass modes must be controlled or solution will be unstable

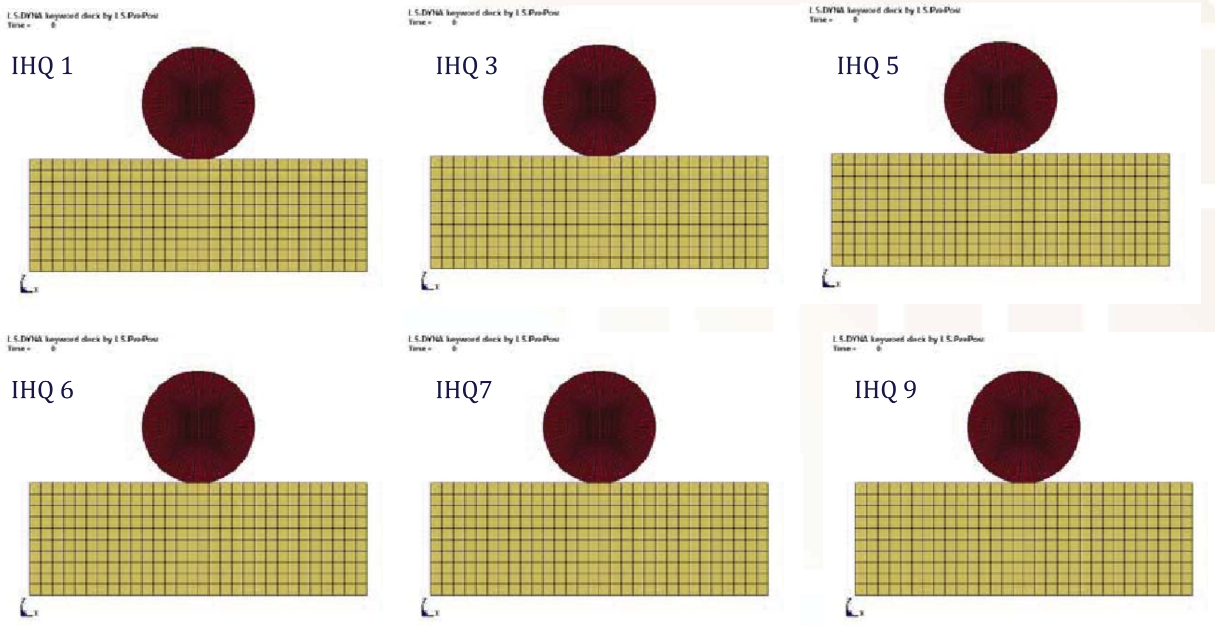


HG modes in linear quad

HBM-25

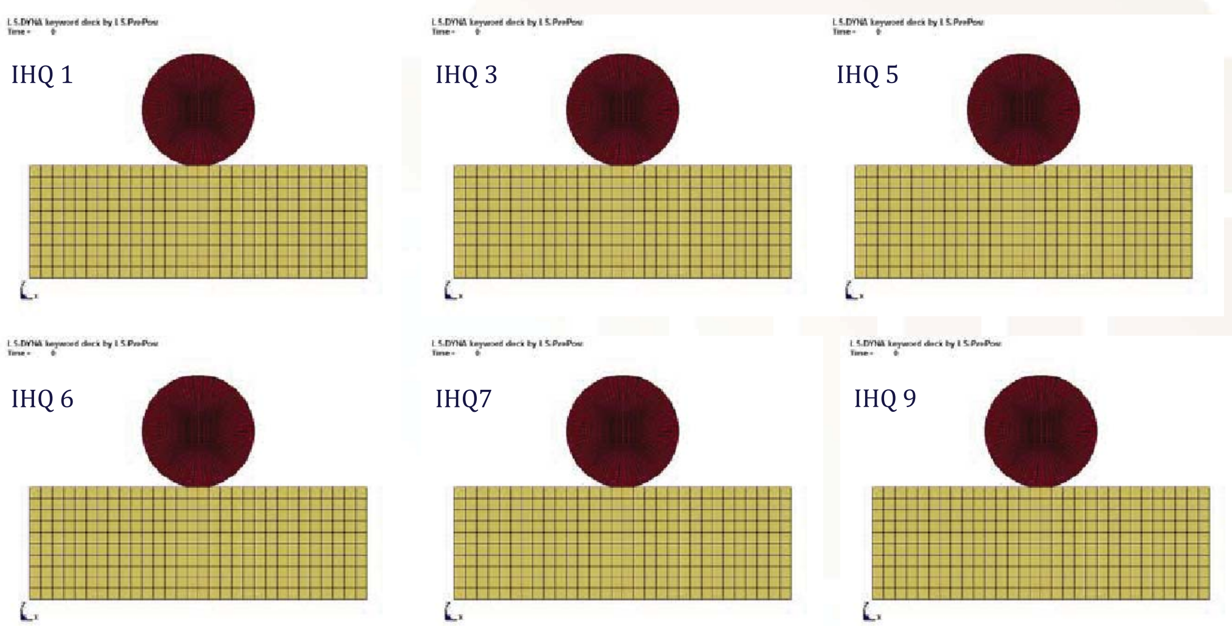
The Finite Element Method: Hourglassing

- Example: Comparison of hourglass control types in LS-Dyna
  - Foam (highly compressible)



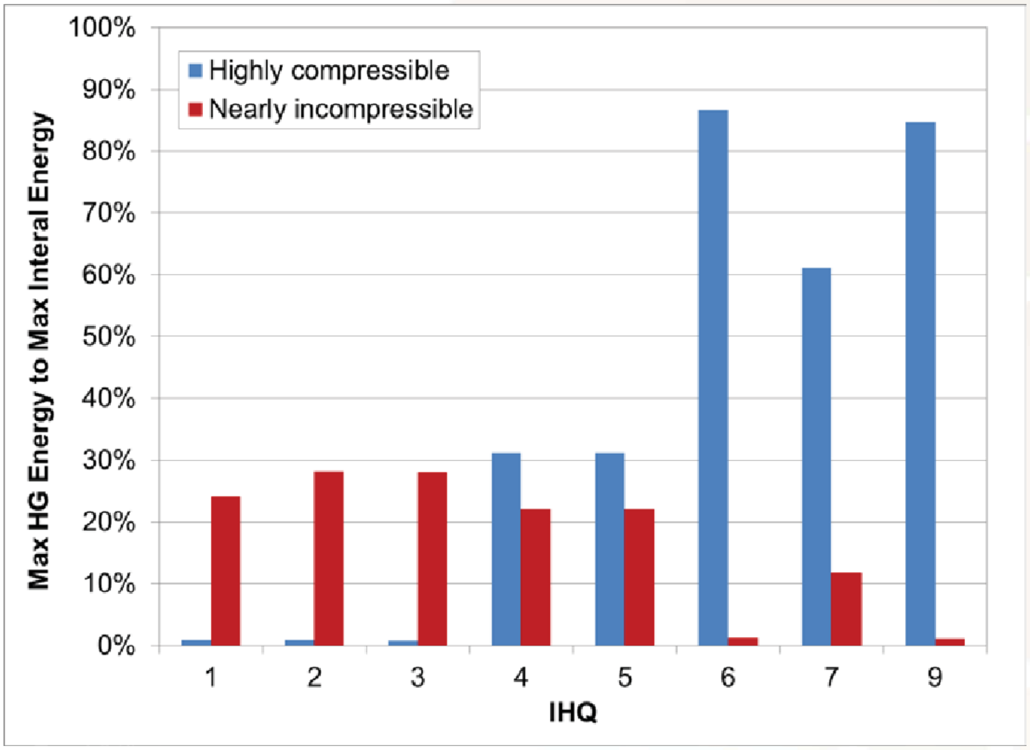
The Finite Element Method: Hourglassing

- Example: Comparison of hourglass control types in LS-Dyna
  - Brain (nearly incompressible)



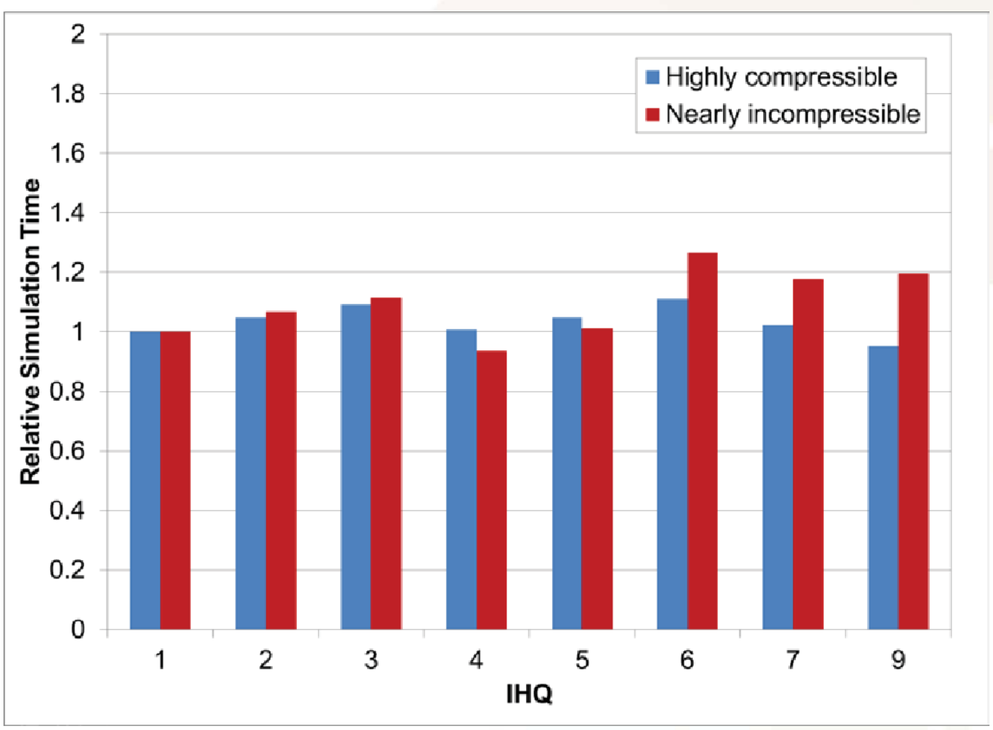
The Finite Element Method: Comparison

- Hourglass energy



The Finite Element Method: Comparison

- Simulation time



This is a conference on impact, why are you talking about dynamics?

The Finite Element Method: Dynamics

- Dynamics are solved using the equations of motion

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\}$$

Mass matrix → $[M]$; Damping matrix → $[C]$; Stiffness matrix → $[K]$; Force vector → $\{F\}$

- Time needs to be discretized (time steps), and there are two approaches to integrating over time: Explicit and Implicit

- Explicit
  - Nodal accelerations are solved based on the displacements and velocities of the previous time step, and new velocity and displacement are updated
  - "March through time" approach
  - Easy math, cost effective
  - Time step must satisfy the CFL criterion for stability

$$\Delta t < \frac{2}{\omega_{max}}\left(\sqrt{1+\xi^2} - \xi\right)$$

$$\{\ddot{u}\}^i = [M]^{-1}\left(\{F\}^i - [C]\{\dot{u}\}^i - [K]\{u\}^i\right)$$

$$\{\dot{u}\}^{i+1/2} = \{\dot{u}\}^{i-1/2} + \{\ddot{u}\}^i \Delta t^i$$

$$\{u\}^{i+1} = \{u\}^i + \{\dot{u}\}^{i+1/2}\frac{\Delta t^i + \Delta t^{i+1}}{2}$$

HBM-28

The Finite Element Method: Dynamics

- Implicit
  - Nodal displacements, velocities, and accelerations are solved together using a method of creating an effective stiffness matrix and force vector
  - More complicated math, costly
  - Unconditionally stable

$$[\hat{K}] = [K] + \frac{4}{\Delta t^2}[M] + \frac{2}{\Delta t}[C]$$

$$\{\hat{F}\}^{i+1} = \{F\}^{i+1} + [M]\left(\frac{4}{\Delta t^2}\{u\}^i + \frac{4}{\Delta t}\{\dot{u}\}^i + \{\ddot{u}\}^i\right) + [C]\left(\frac{2}{\Delta t}\{u\}^i + \{\dot{u}\}^i\right)$$

$$[\hat{K}]\{u\}^{i+1} = \{\hat{F}\}^{i+1}$$

- Explicit vs Implicit

	Explicit	Implicit
Pro	• Cheap cost per time step	• Large time steps possible
Con	• Many small time steps required	• **Expensive cost per time step**
Uses	• Large models • Dynamic or quasi-static analysis (linear or nonlinear) • Nonlinear models, and with contacts • Impact and short duration events	• Small and medium models • Linear static analysis • Limited nonlinear static analysis (no contact) • Long duration events

Introduction to the Finite Element Method

-An extremely brief overview-

Matthew B. Panzer, PhD

Center for Applied Biomechanics
University of Virginia

Pre-IRCOBI Workshop on Human Body Modeling
September 11, 2018
Athens, Greece

Experimental testing and measurements in biomechanics… with the intent of validating HBM

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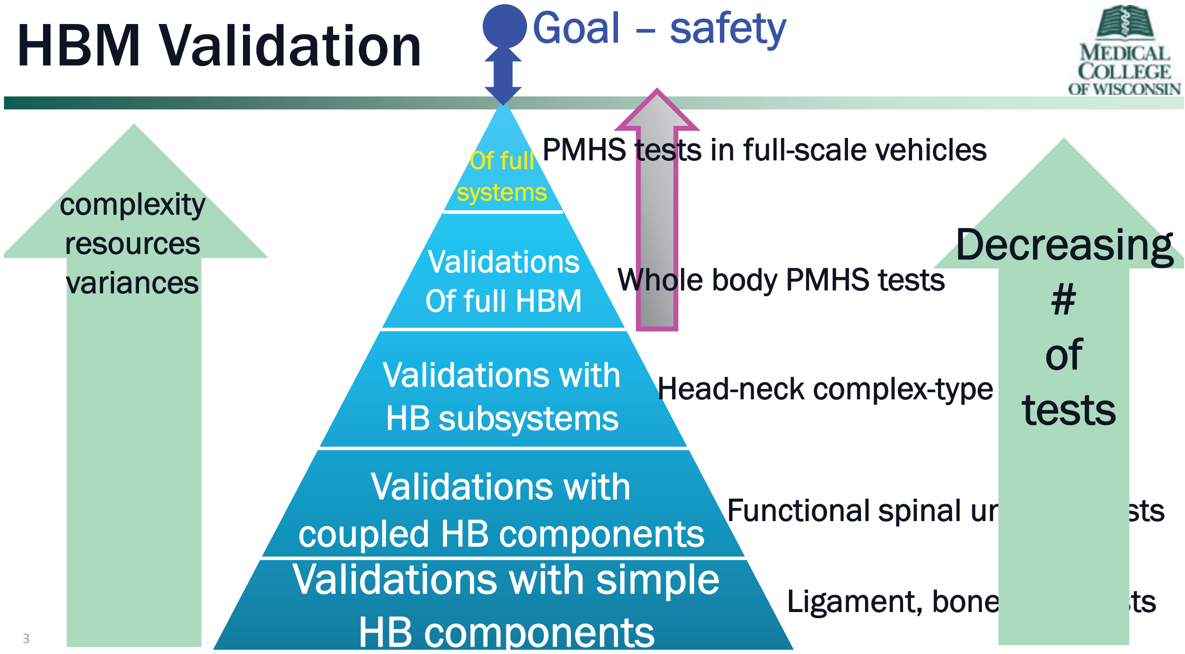
Validation

- Assessment of accuracy of a computational model by comparing with experimental data
  - Physics associated with the model
  - Solving the right equations
- Showing that the developed HBM is capable of making "appropriate" predictions for the intended purpose

HBM Validation



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3

Workshop Focus Should Address

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1. Existing data,
2. What we can measure, and
3. How we can use this to assess HBM

4

1. Existing Data: PMHS Sled Tests (USA)

University and abbreviation		Primary PI
Medical College of Wisconsin	MCW	Yoganandan
University of Virginia	UVa	Crandall
Ohio State University	OSU	Bolte
Wayne State University	WSU	King
University of Michigan	UMRTI	Schneider*

US DOT-NHTSA main sponsor and Industry

5

1. Existing Data: MCW PMHS Sled Tests

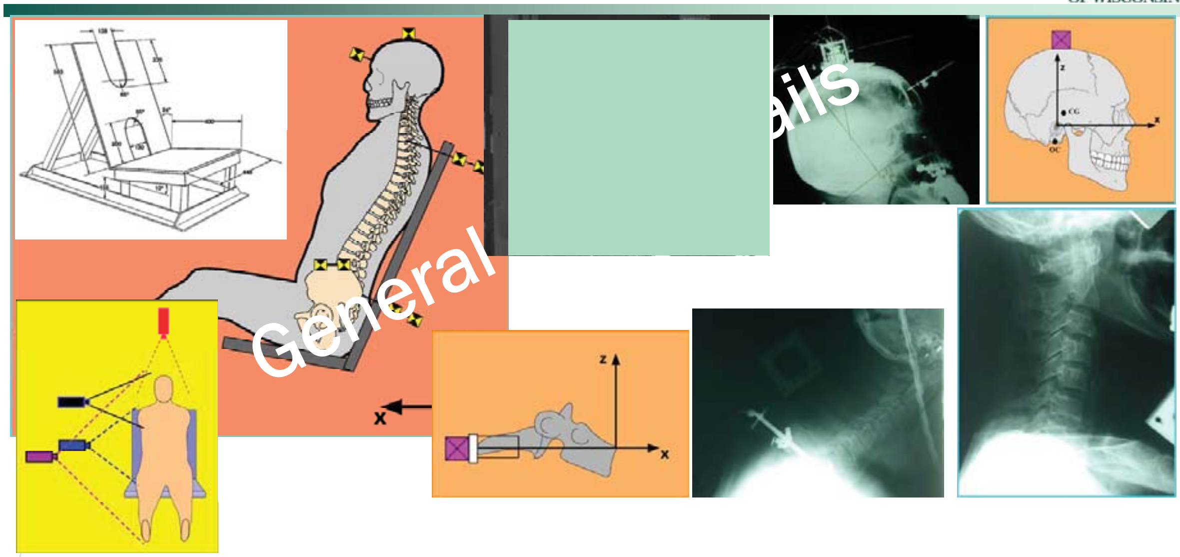
Impact	Main Authors	Publication Years
Front	Yoganandan, Morgan	1990's
Rear	Yoganandan, Philippens, Wismans	Late 1990s-2000
Nearside	Pintar, Maltese, Yoganandan, Martin	Mid 1990s-2000
Far-side	Pintar, Fildes, Yoganandan	2003-2010
Side oblique	Yoganandan, Humm, Rudd	2000s to date
Front oblique	Humm, Yoganandan	2016 to date

Data from >100 PMHS sled tests are published

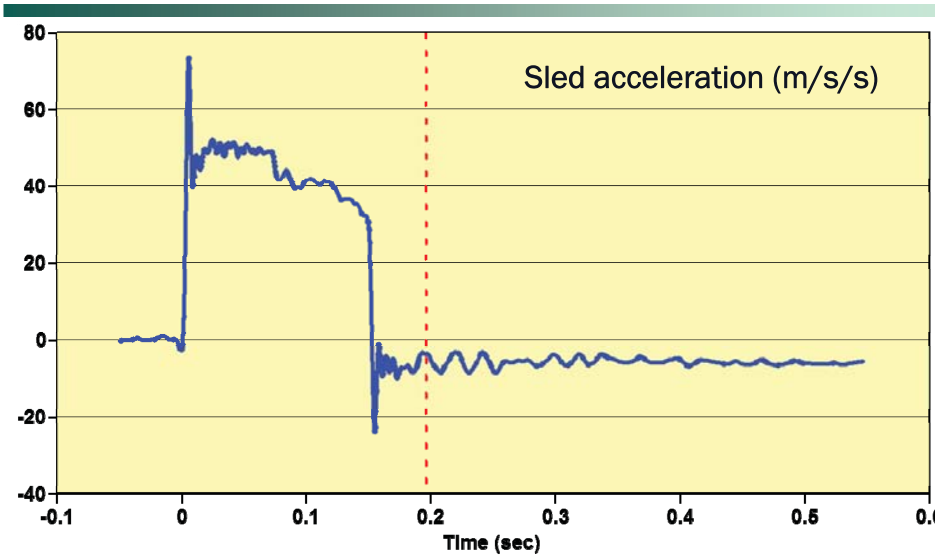
6

US DOT-NHTSA main sponsor

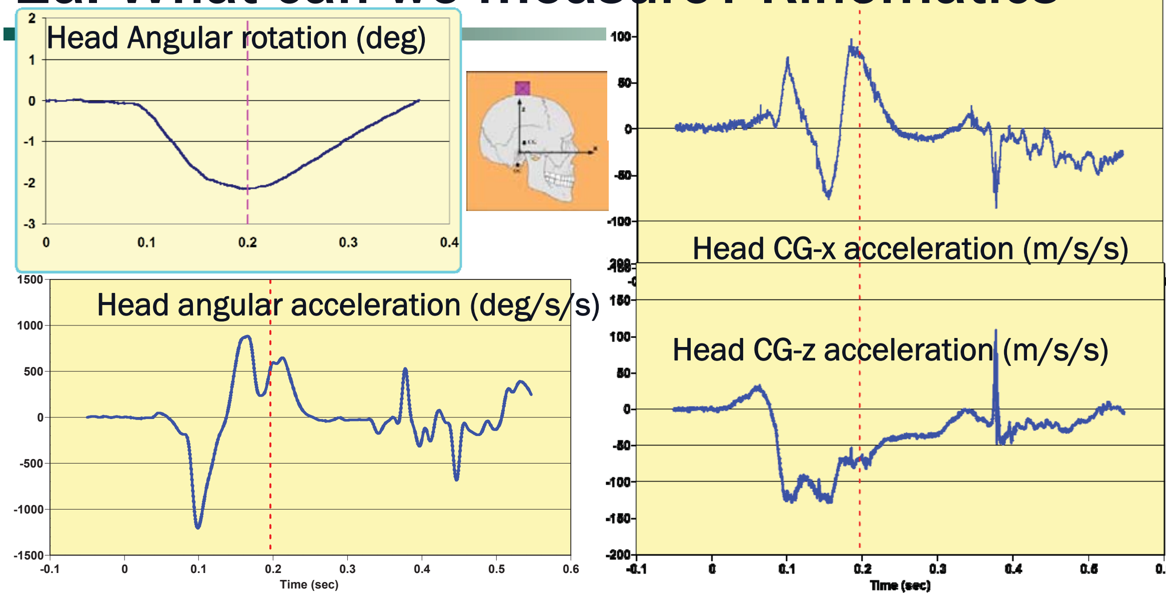
2a. What can we measure? Rear Impact



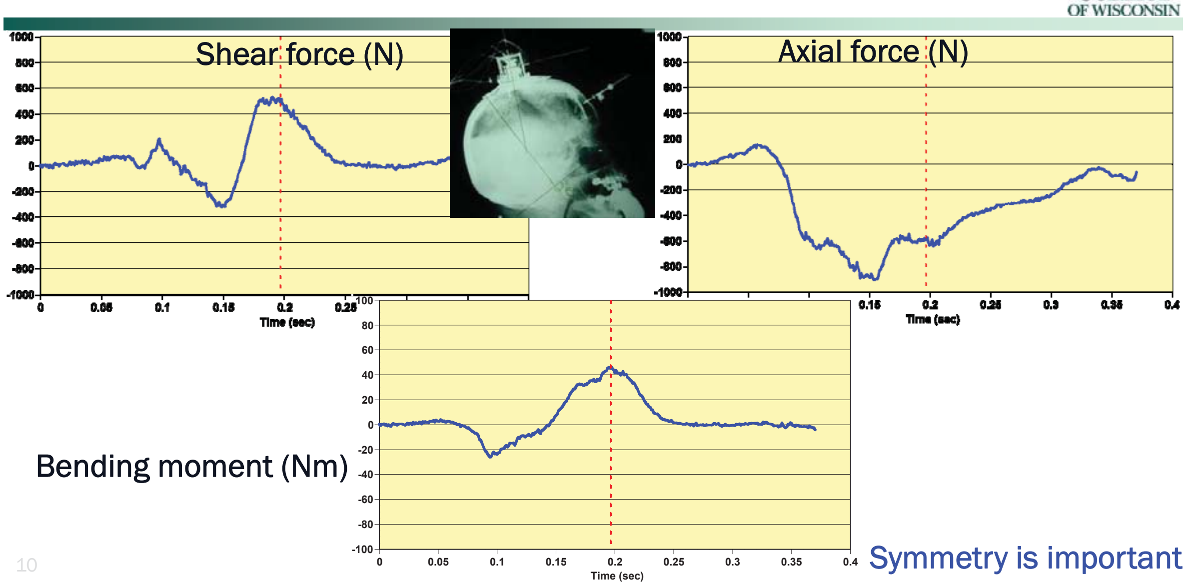
2. What can we measure? Rear Impact



2a. What can we measure? Kinematics



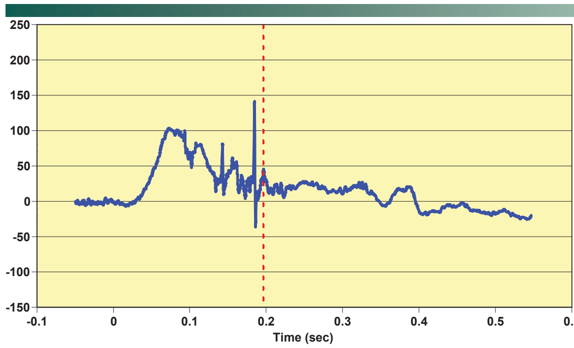
2a. What can we measure? OC Loads



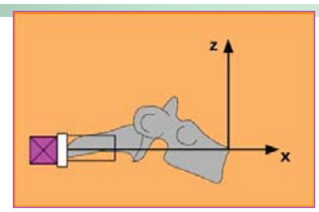
Symmetry is important

10

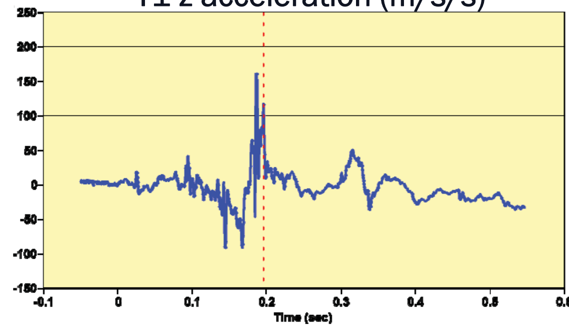
2a. What can we measure? T1 Kinematics



T1-x acceleration (m/s/s)

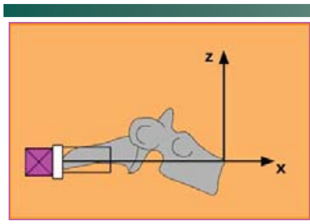


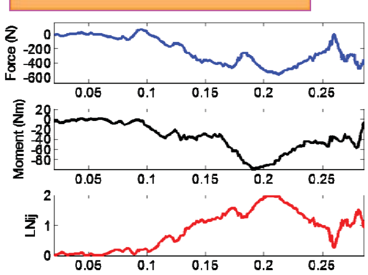
T1-z acceleration (m/s/s)

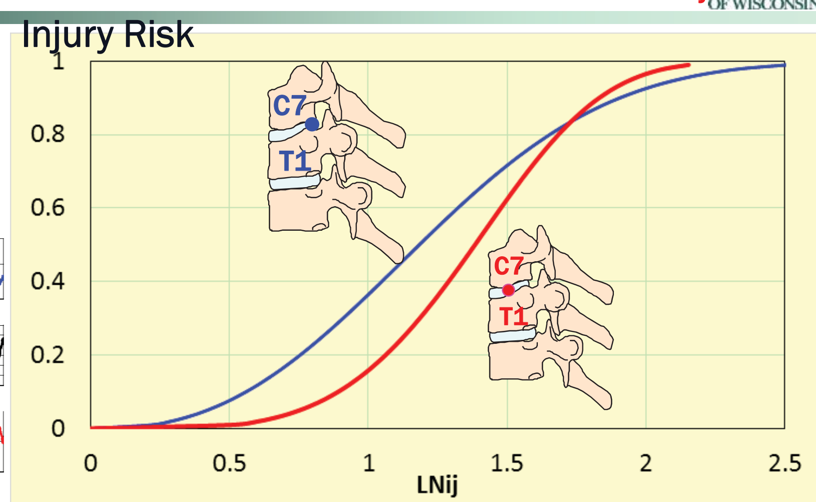


11

2a. What can we measure? Lower Neck LN_{ij}







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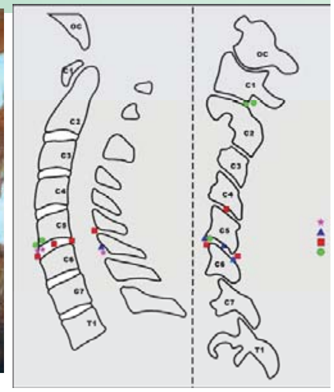
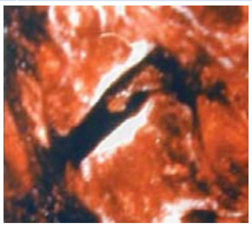
2a. What can we measure? Injuries

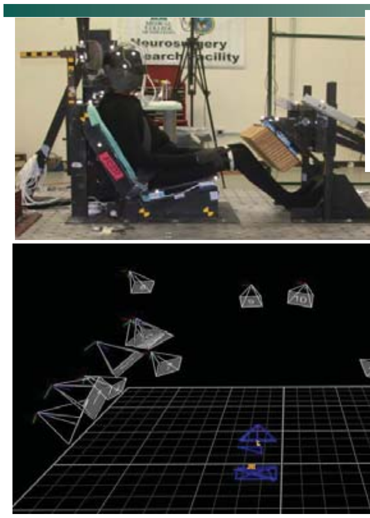
ID	Soft tissue injury
1	C5-6 disc, C6-7 flavum
2	None
3	C5-6 facet, C6-7 flavum
4	C4-5, C5-6 facet, C5-6 disc
5	C5-6, C1-2 facet

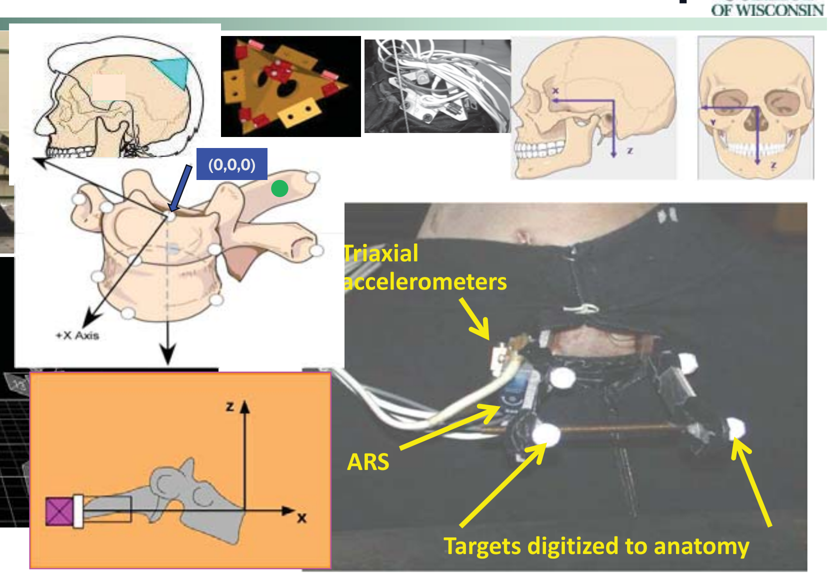




- HBM fidelity to validate
  - Bony fractures/severities: cortical and cancellous
  - Joints and soft tissue (ligaments) disruptions
  - Solid and hollow organs injuries
- Field data helps focus the HBM

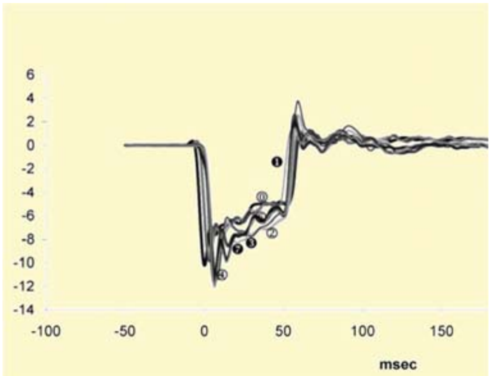
2b. What can we measure? Frontal Impact



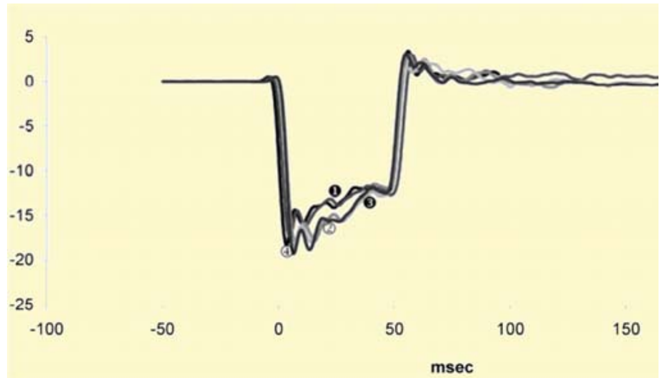


2b. What can we measure? T1 Kinematics

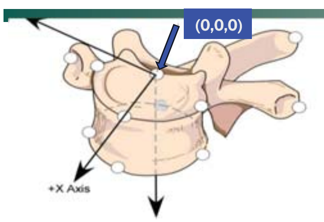
Input sled pulse (g) – low velocity



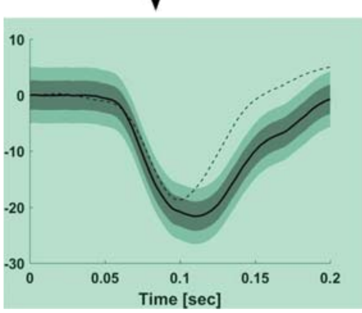
Input sled pulse (g) – high velocity



3. How can we assess HBM? T1 Kinematics

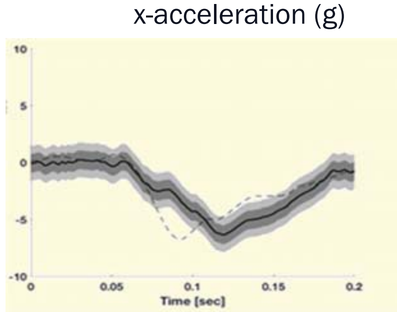


- Validation along the entire curve?
- Validation in the loading phase only?
- How many SD away from the mean corridor?
- CORA/rankings for how many regions/components?

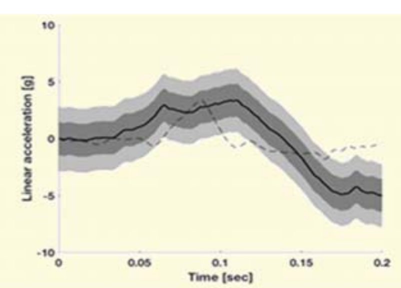


Angular velocity (rad/sec)

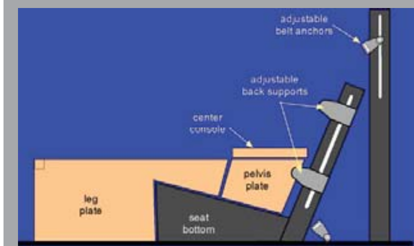
x-acceleration (g)

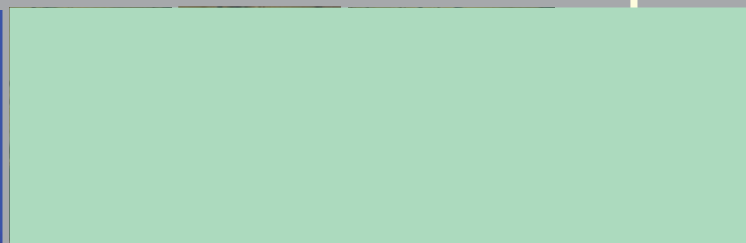


z-acceleration (g)

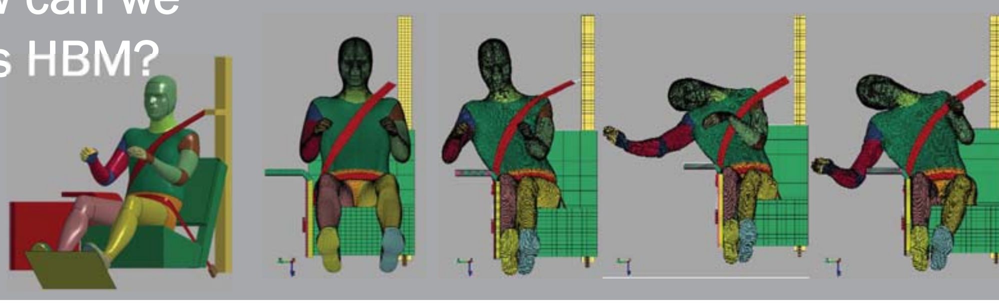


2c. What can we measure? Far-side Impact

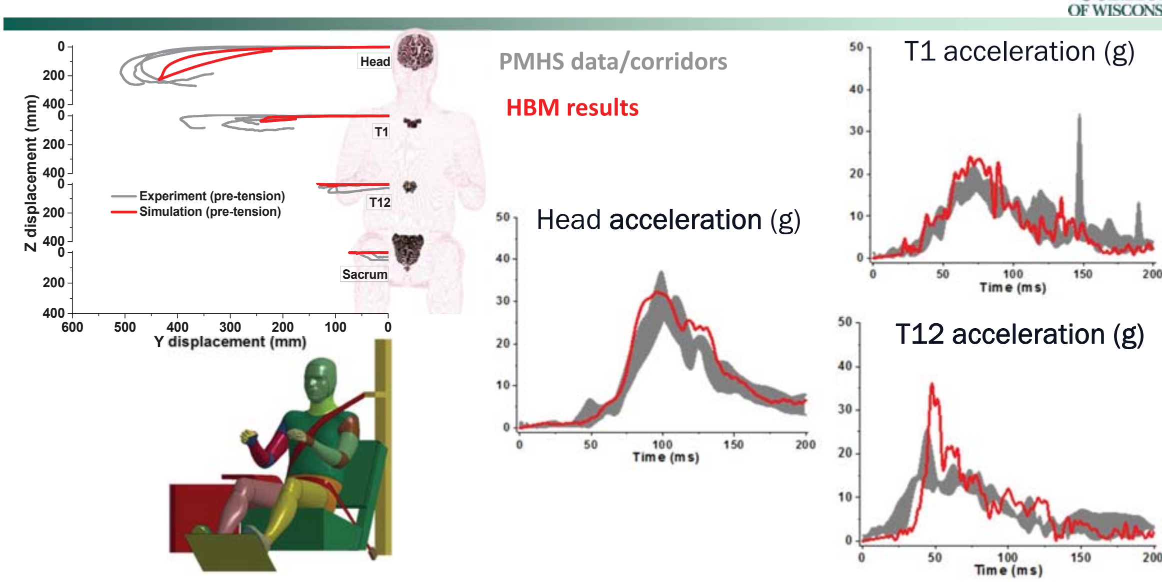




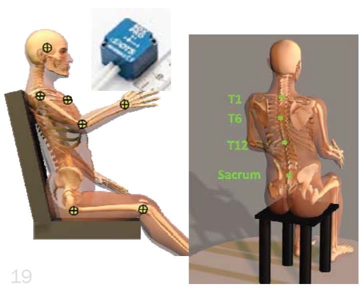
3. How can we assess HBM?



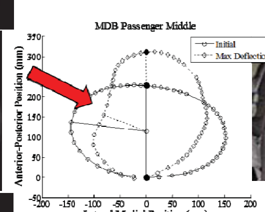
3. How can we assess HBM? Far-side Impact



2d. PMHS in Full-scale Vehicle Tests



2d. PMHS in Full-scale Vehicle Tests



- HBM needs vehicle modeling
- More complex and more resources
- One of the ultimate tests in the HBM validation process
- Small size limits robustness, but field data can be used

Hierarchical Validation: Whole Body PMHS

- More realistic, from sled to full-scale vehicle
- Includes interactions between subsystems
- Extract external biomechanical metrics
- Evaluate injuries with those metrics
- Risk curves may serve as assessors
- >complex to simulate in the HBMs
- >variance: full-scale vehicle tests
- Validation depends on test robustness

Summary: Workshop Focus Should Address

1. Existing data: Principal modes: front, rear, near and far-side, and oblique
2. What we can measure: getting > comprehensive
   - pre- and posttest images, (x-rays, CT, BMD, …)
   - G-pulses, loads, accelerations, deflections, …
   - Sometimes, fracture times available (AS/SG)
   - Risk curve (IRC) techniques have advanced
3. How we can use this to assess HBM: Validation is > complex
   - Regional validation cannot be assumed to be equally valid for others
   - Need to know experimental details: publications not always adequate
   - Experimentalists and modelers need to work together to advance HBMs
   - Needed new tests should be designed in concert with modelers, robustness issue
   - Validation with injury criteria & IRCs needed to have confidence in the HBM outputs

Body region modeling and validation

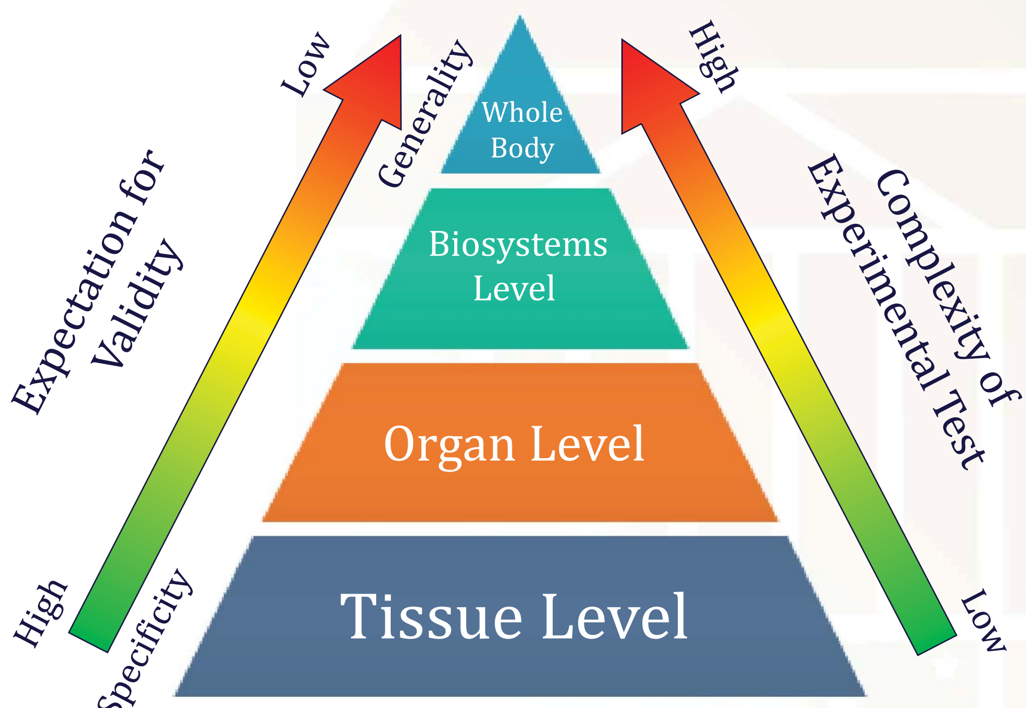
Matthew B. Panzer, PhD

Center for Applied Biomechanics
University of Virginia

Pre-IRCOBI Workshop on Human Body Modeling
September 11, 2018
Athens, Greece

Human Body Model Validation

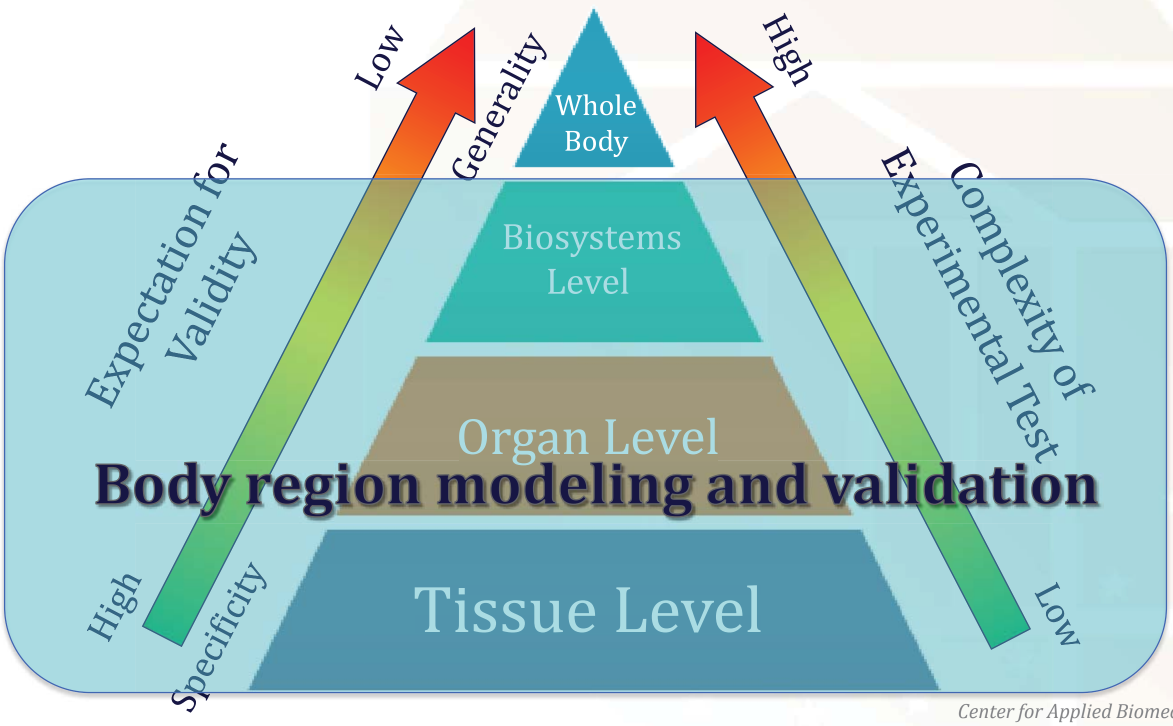
- The state-of-the-art human body model is validated at multiple levels within the body, but developed from the *ground up*



HBM-41

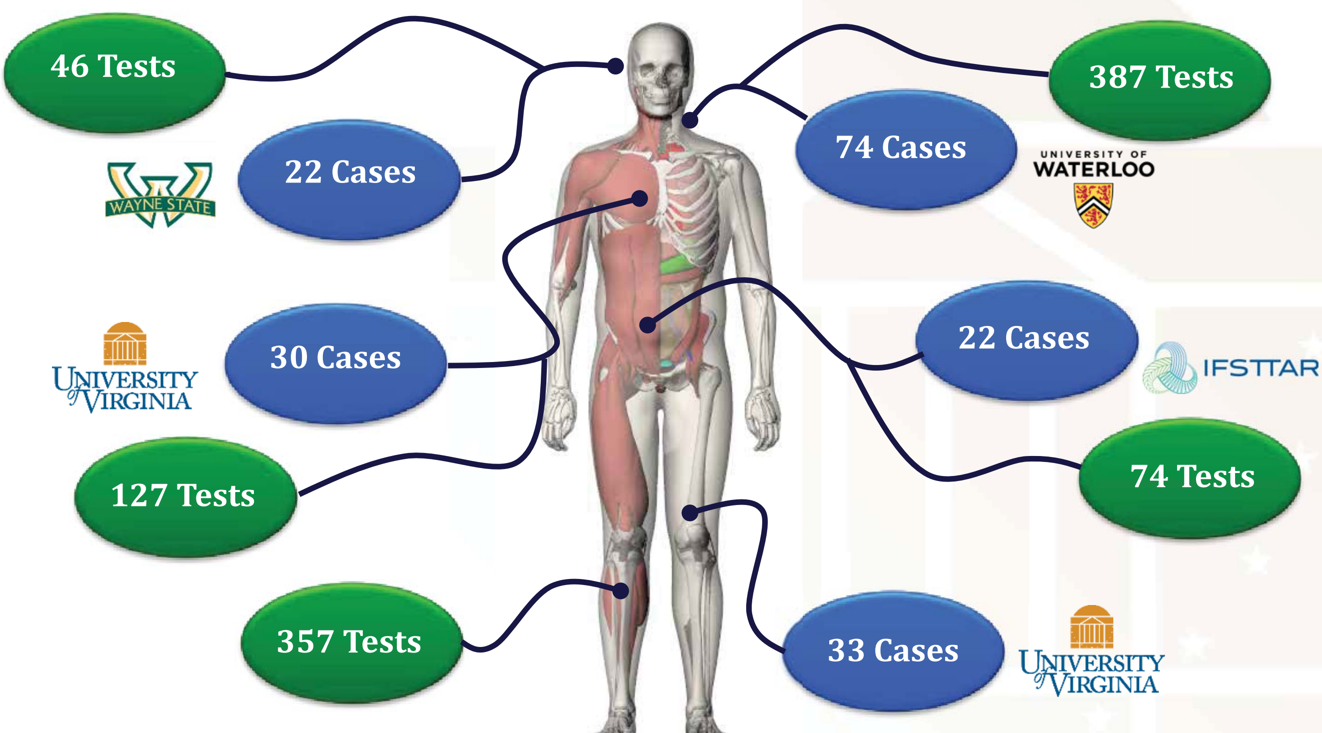
Human Body Model Validation

- The state-of-the-art human body model is validated at multiple levels within the body, but developed from the *ground up*



Body Region Validation

- GHBMC M50 body region validation cases and test data

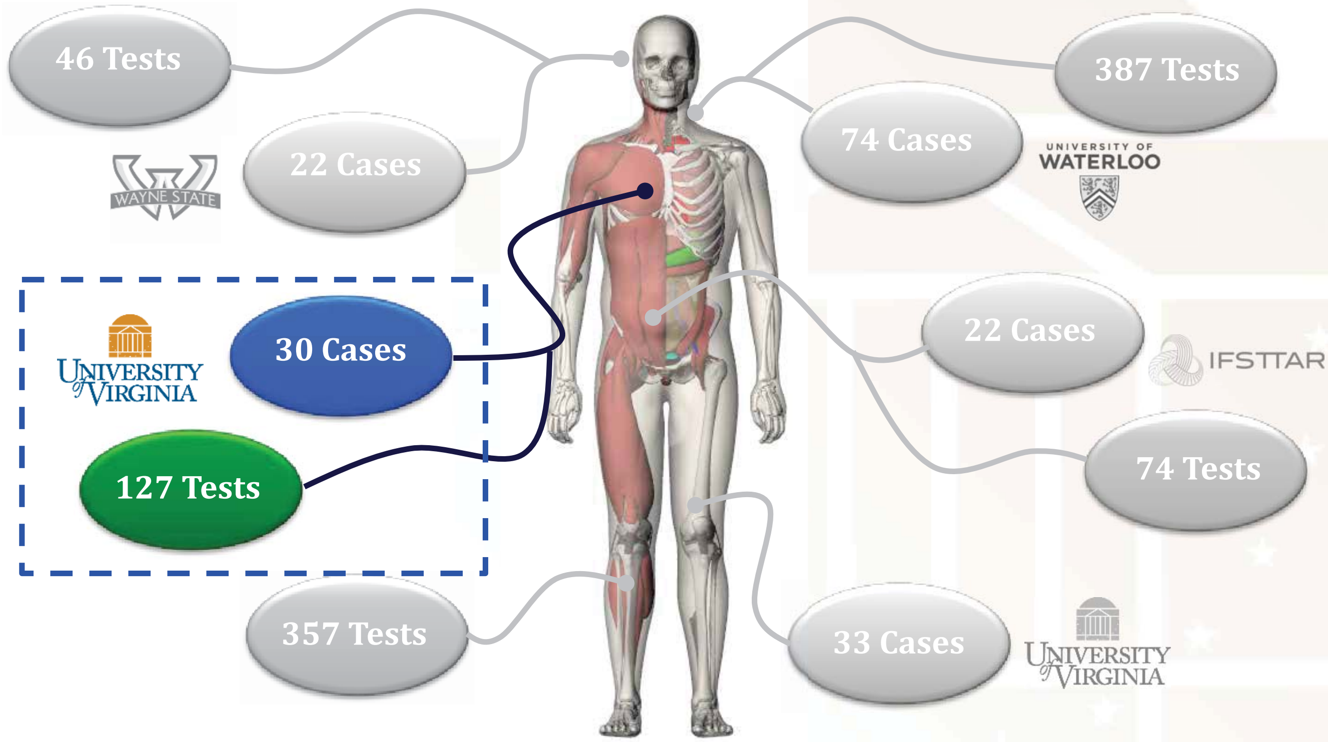


Number courtesy of Mark Neal, GHBMC

HBM-42

Body Region Validation

- GHBMC M50 body region validation cases and test data



Number courtesy of Mark Neal, GHBMC

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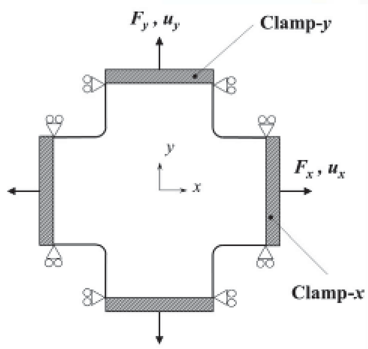
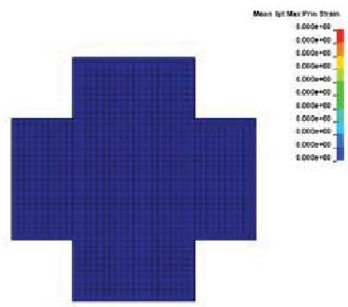
Validating at the Tissue (Material) Level

Tissue Level Validation

- Tissue level validation/verification is essential but often overlooked step in the body region model validation process
- *Verification* → Did I put the right parameters into the right constitutive model? Check using a single-element simulation.
- *Validation* → Does the simulation output of my material model match the output from the experiment? Reproduce the test.





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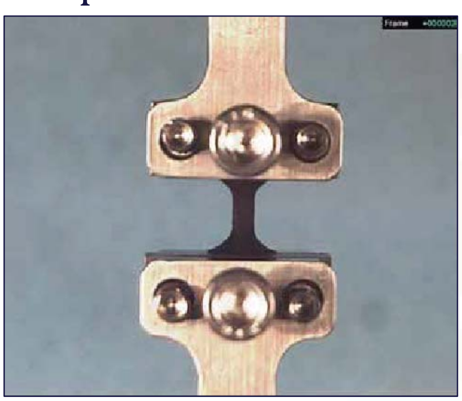
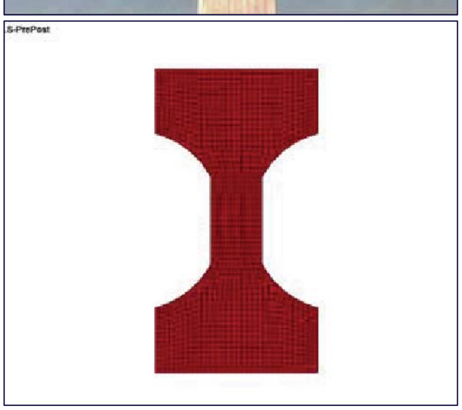
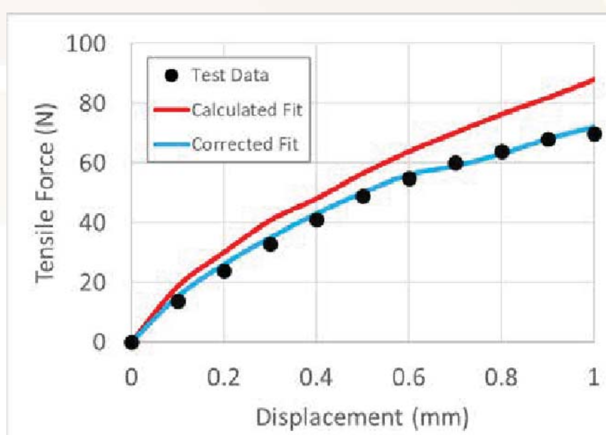
Tissue Level Validation

- Example in material validation





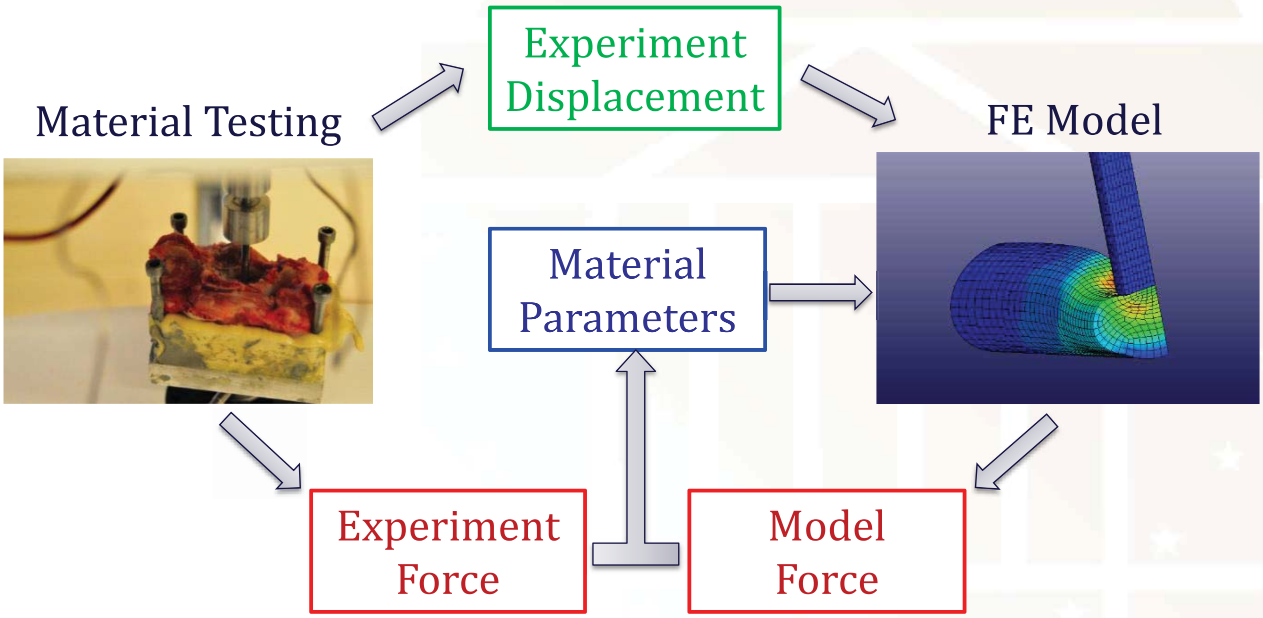


Calibrated material models may be more critical for injury prediction when simulation material failure
→ Element failure criteria are highly mesh dependent!

HBM-44

Tissue Level Validation

- Inverse FE methods are becoming feasible for characterizing material models for using in FE simulation



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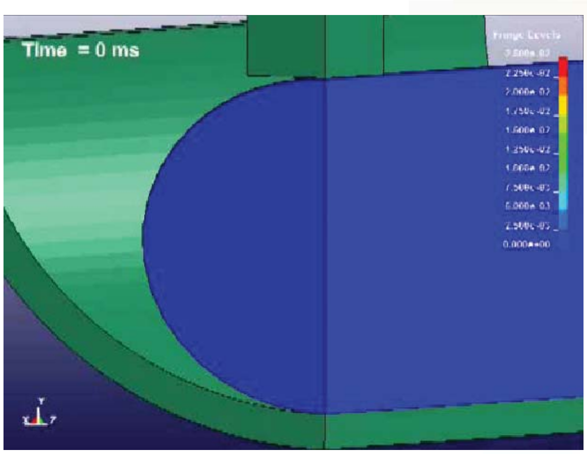
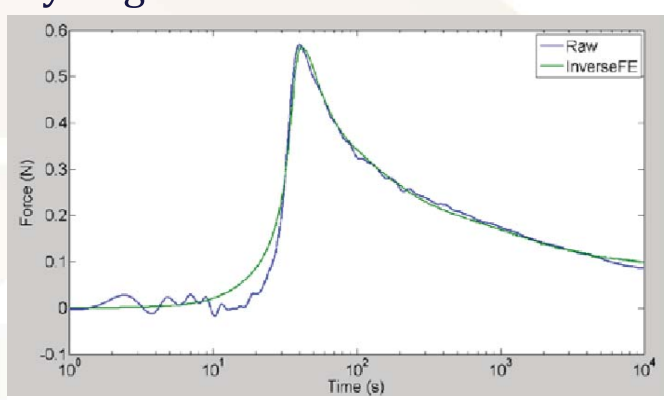
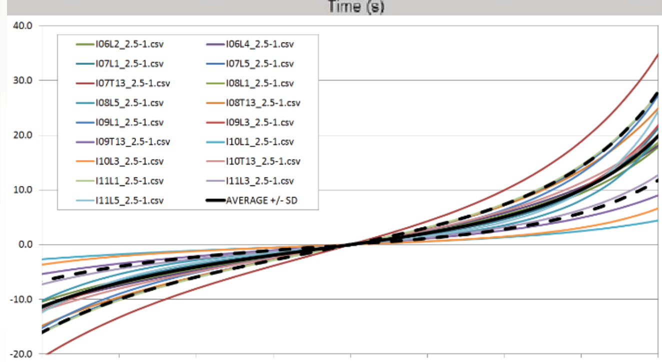
Tissue Level Validation

- Inverse FE material models ready to go for use in FE models and have good accuracy



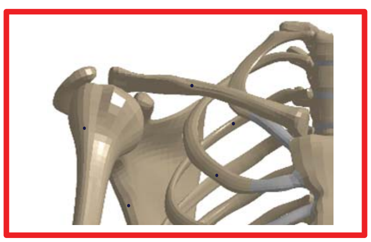


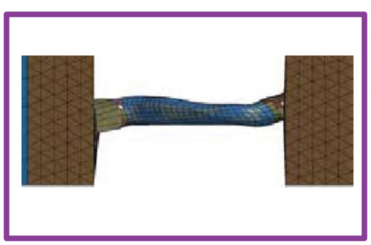


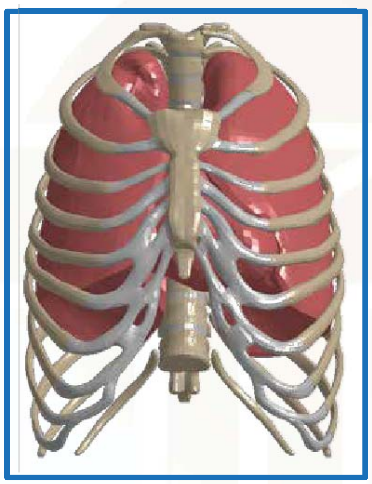
Validating at the Organ Level

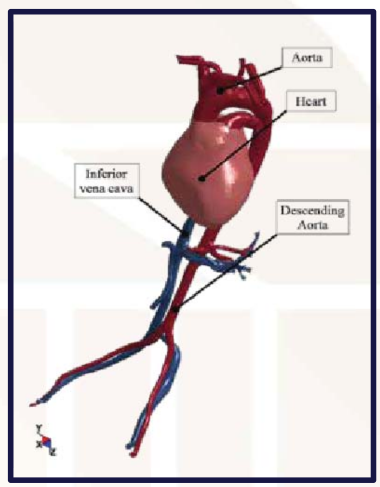
Thoracic Organ Validation

- Thoracic Organ Validation





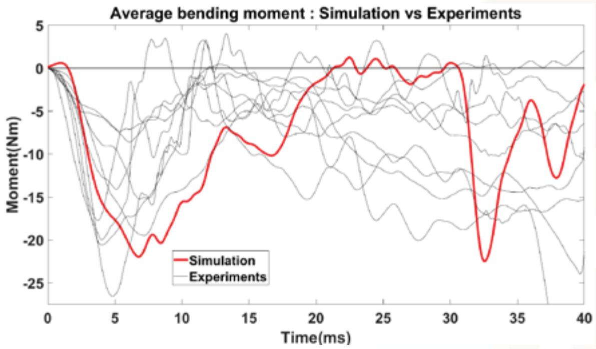


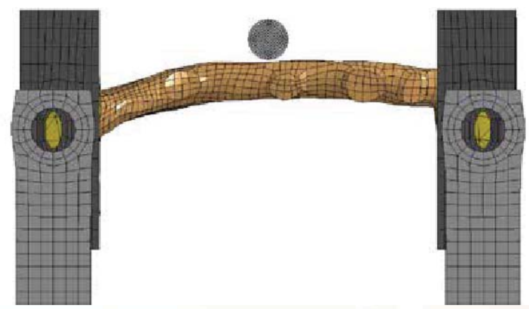


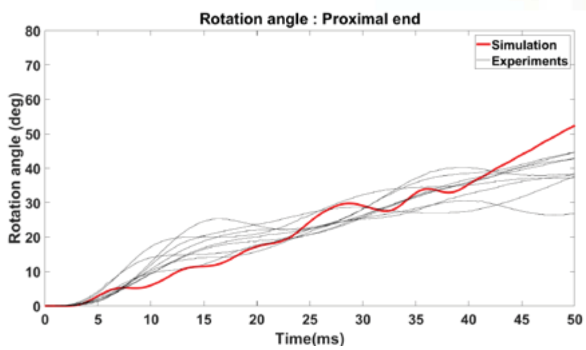
Validation Case	CORA	
	F05	M50
Clavicle (Zhang et al. 2014)	On going	
Sternum (Kerrigan et al. 2010)	On going	
Costal Cartilage (Forman et al., 2010)	On going	
Aorta (Lee and Kent, 2006)	On going	

Thoracic Organ Validation

- Sternum

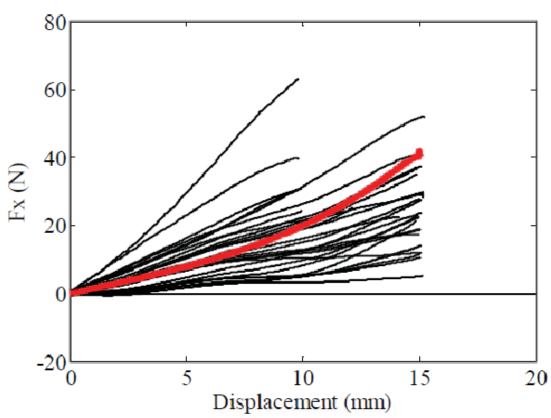


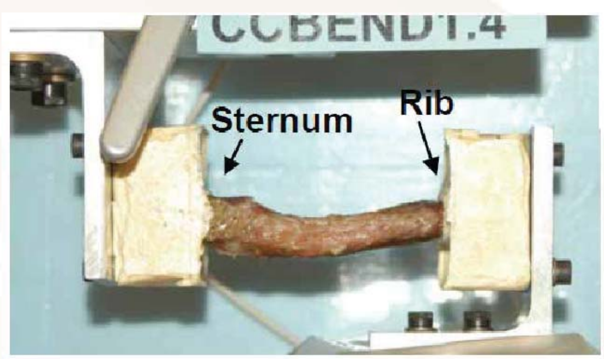


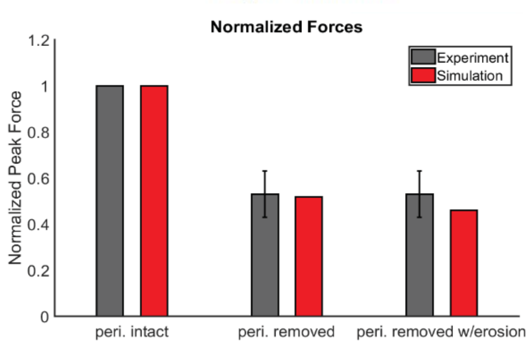


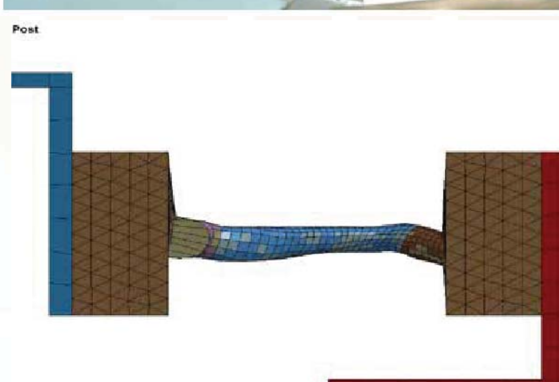
Thoracic Organ Validation

- Costal cartilage and perichondrium







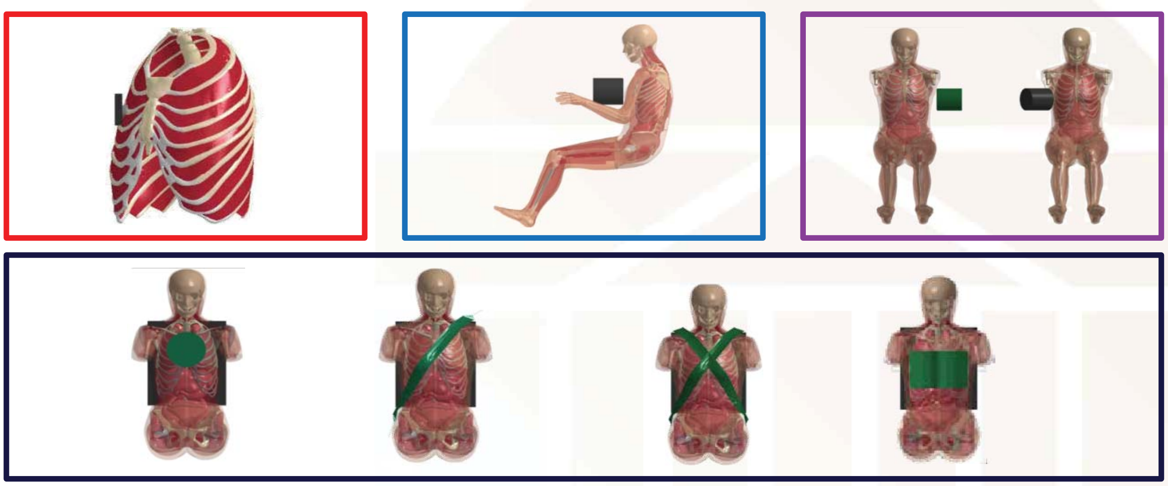


HBM-47

Validating at the Biosystems Level

Thoracic Validation

- Thoracic Validation Cases

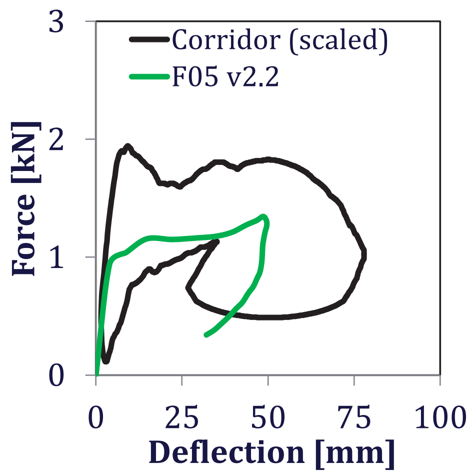


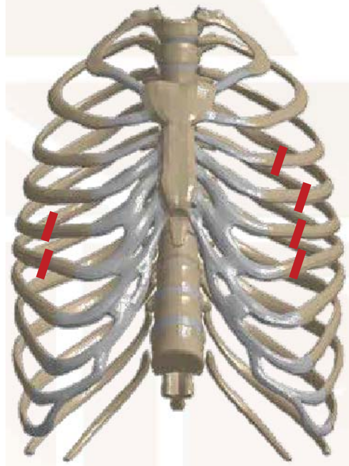
Validation Case	CORA	
	F05	M50
Ribcage Point Loading (Kindig et al. 2006)	0.79	0.80
Frontal Pendulum Impact (Kroell et al. 1974)	0.80	0.84
Pendulum Impact (Baudrit and Trosseille 2015)	0.87	0.83
Table Top Belt Loading (Kent et al. 2004)	0.82	0.86

HBM-48

Thoracic Validation

- Frontal Pendulum Impact

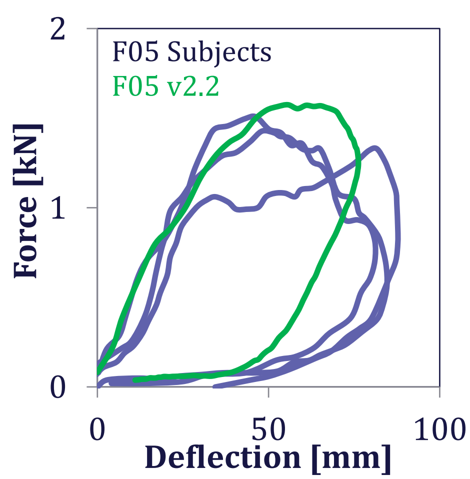


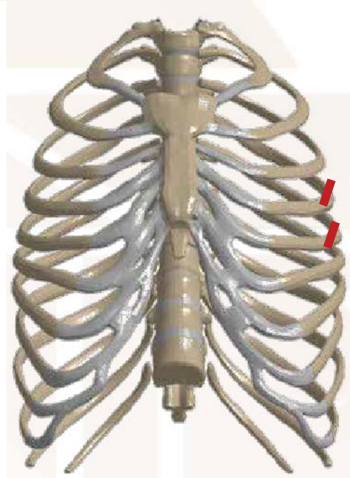


Experiment Injury (n=12)	Simulated Injury
Rib fractures (9+: 36%) Sternal fracture (13%)	Rib fractures (n = 2)

Thoracic Validation

- Lateral Pendulum Impact

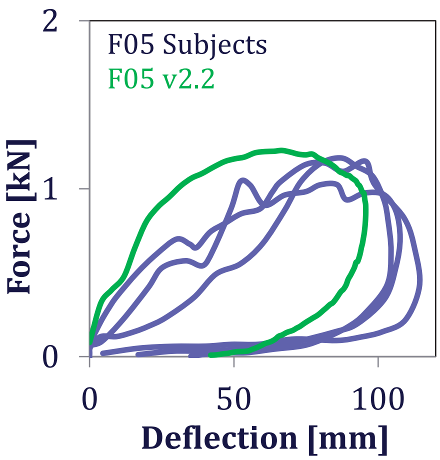


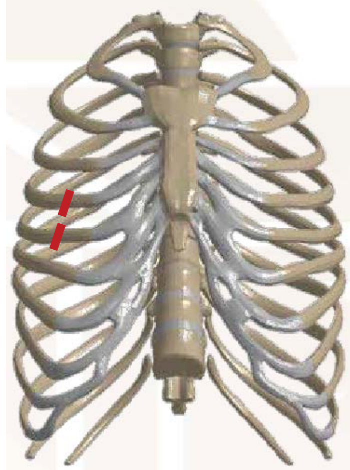


Experiment Injury (n=6)	Simulated Injury
Rib fractures (4+: 66%) Uninjured (17%)	Rib fractures (n = 2)

Thoracic Validation

- Oblique Pendulum Impact

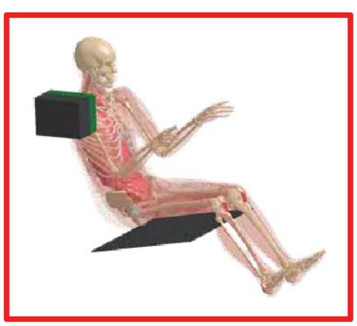


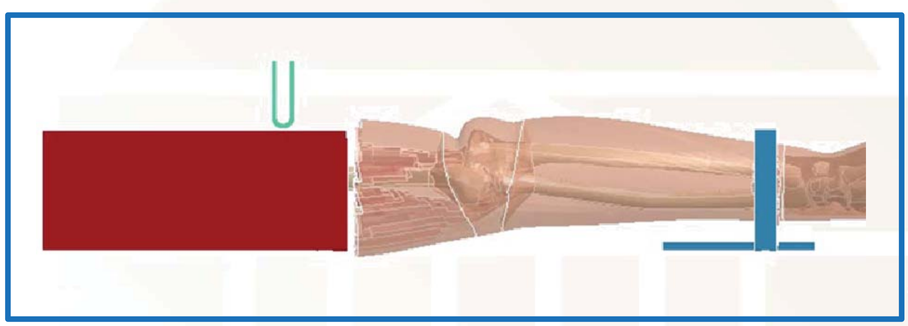


Experiment Injury (n=6)	Simulated Injury
Rib fractures (5+: 66%) Uninjured (33 %)	Rib fractures (n=2)

Upper Extremity Validation

- Upper Extremity Validation Cases

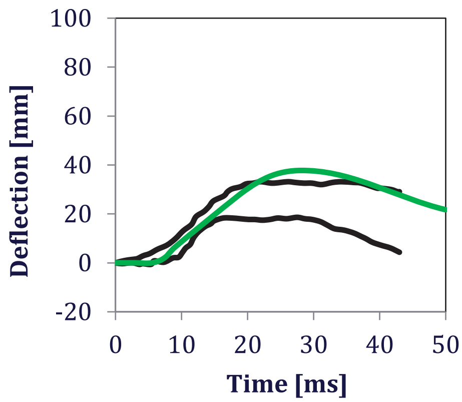


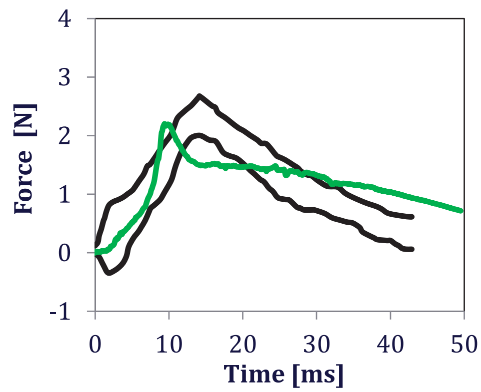


Validation Case	CORA	
	F05	M50
Shoulder Pendulum Impact (Koh et al. 2005)	0.71	N/A
Elbow Hyperextension (Duma et al. 2004)	0.77	N/A

Upper Extremity Validation

- Shoulder Impact (4.5 m/s Unpadded)

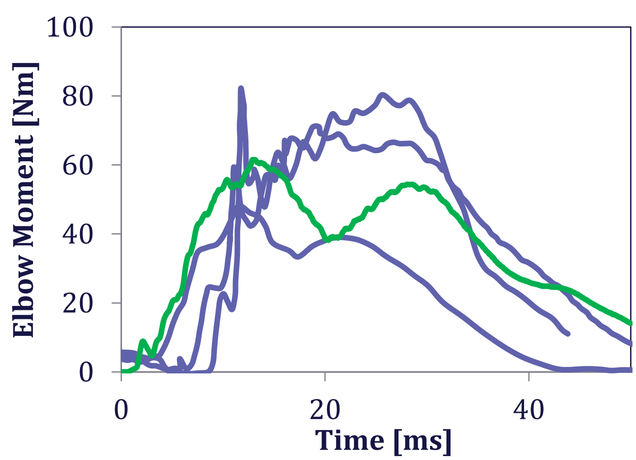


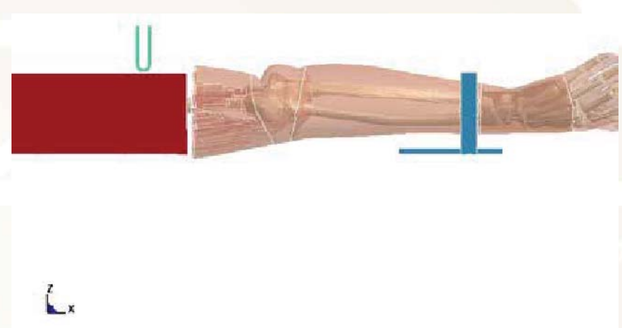


Experiment Injury (n=12)	Simulated Injury
Clavicle fracture (18%) Scapular Fracture (18%) Gleno-humeral joint injury (18%) Sterno-clavicular joint injury (0%) Acromio-clavicular joint injury (0%)	None

Upper Extremity Validation

- Elbow Hyperextension (Low Energy)

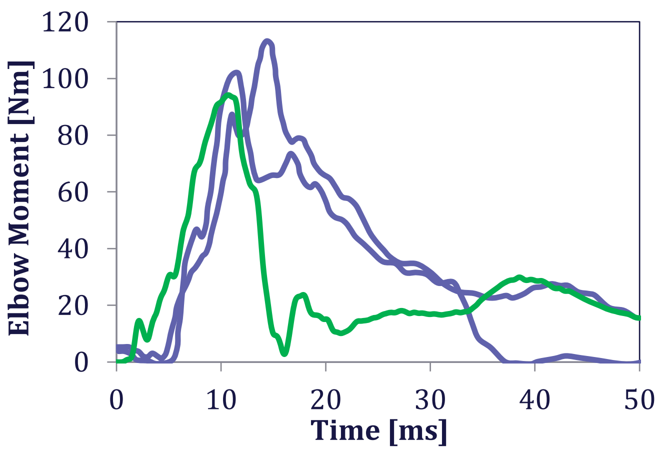


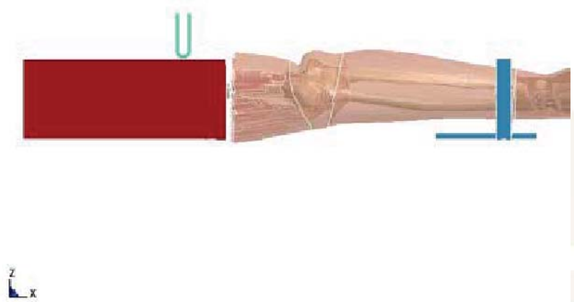


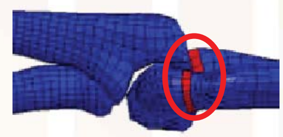
Experiment Injury (n=12)	Simulated Injury
Humerus Fracture (8%) Ulna Fracture (17 %) Elbow Joint Injury (8%)	None

Upper Extremity Validation

- Elbow Hyperextension (High Energy)





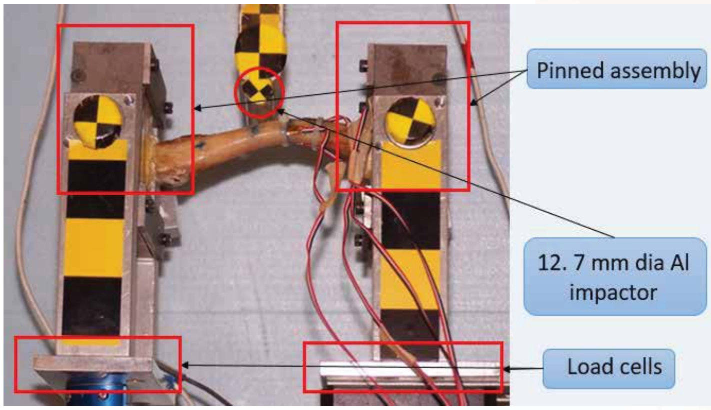


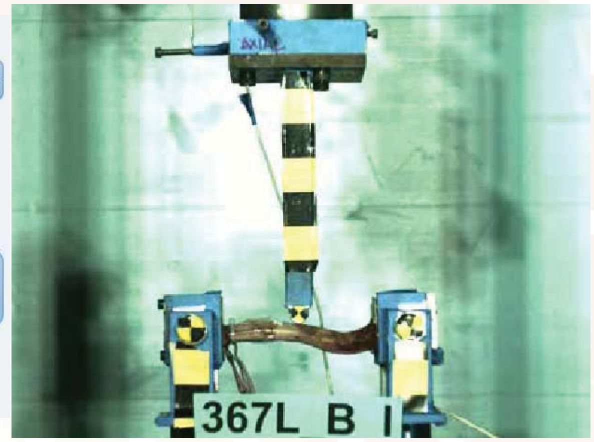
Experiment Injury (n=12)	Simulated Injury
Humerus Fracture (42%) Ulna Fracture (25 %) Elbow Joint Injury (33%)	Humerus Fracture

A Case Study of Clavicle Fracture

Case Study: Clavicle Modeling

- Experimental 3-pt bending setup (Zhang et al., 2014)

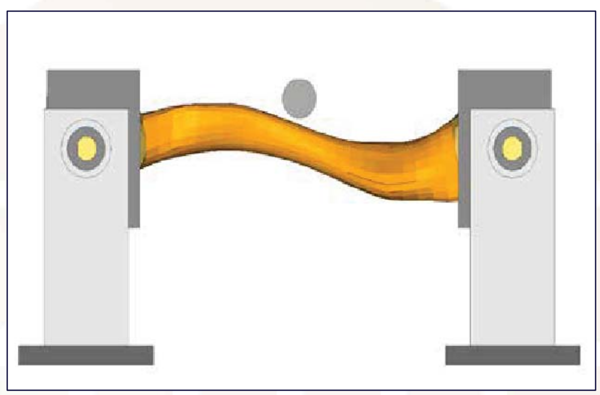


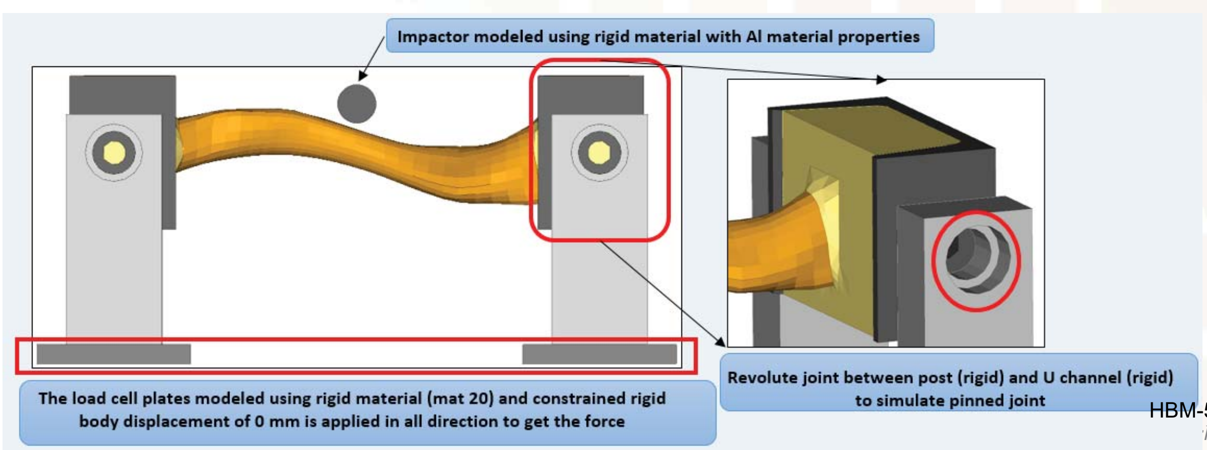


Experimental data was targeting the 50th male subject.

Case Study: Clavicle Modeling

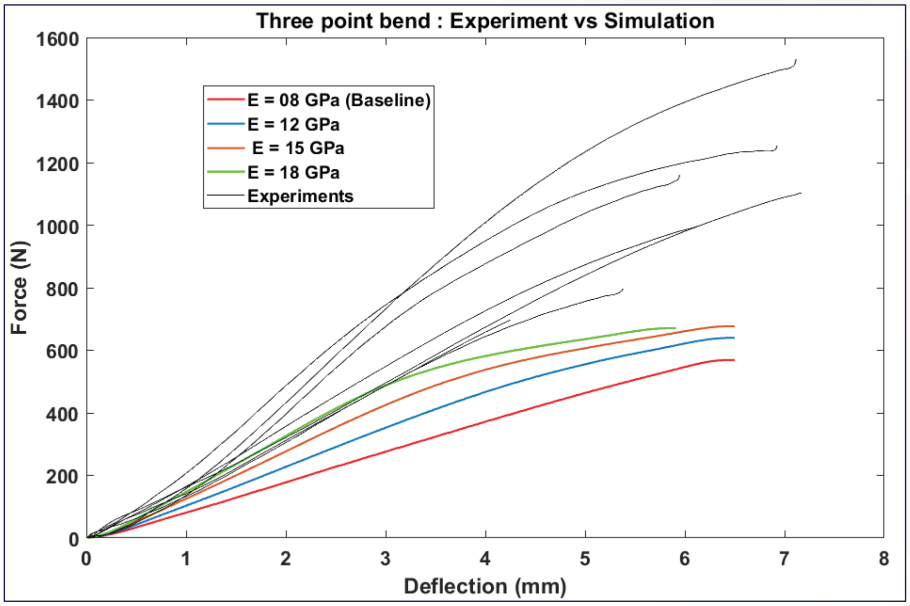
- Model of 3-pt bending





Case Study: Clavicle Modeling

- Material properties of clavicle cortical bone
- Perform material sensitivity study on the Young's Modulus



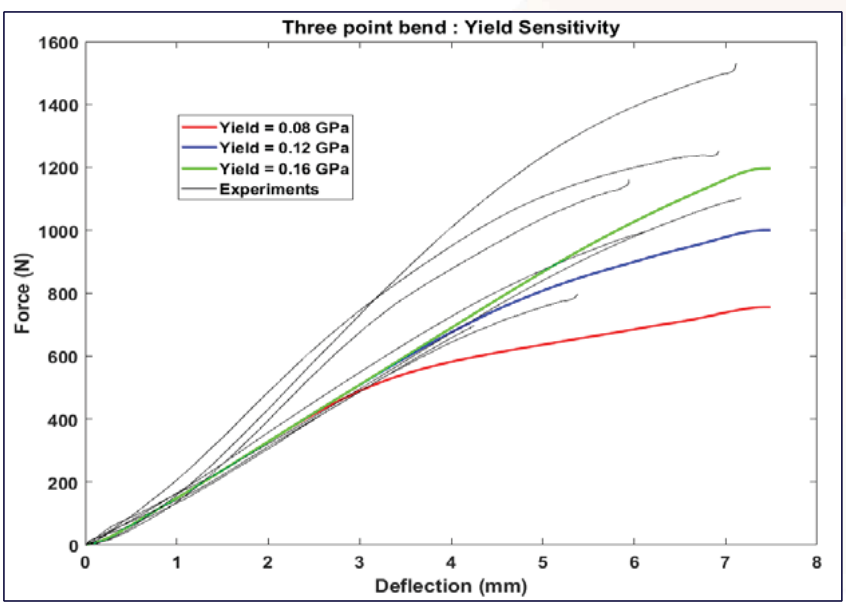
Baseline (current) model with E = 8 GPa is lower than experiment results.

Varied the Young's modulus until the initial slope of force response matches the test data

At E = 18 GPa, the slope was found to match the test. This is a realistic parameter for cortical bone.

Case Study: Clavicle Modeling

- Material properties of clavicle cortical bone
- Perform material sensitivity study on the yield strength



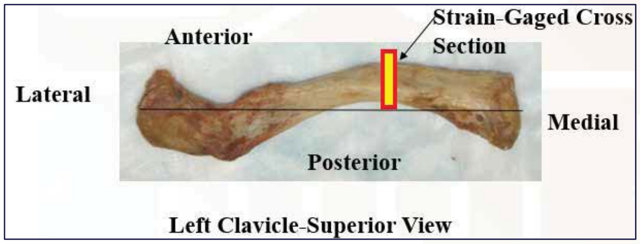
E was fixed at 18 GPa, and yield strength was varied to match the test peak force.

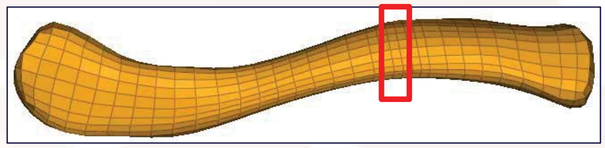
At yield strength of 160 MPa, the simulation force deflection curve matches the test curves.

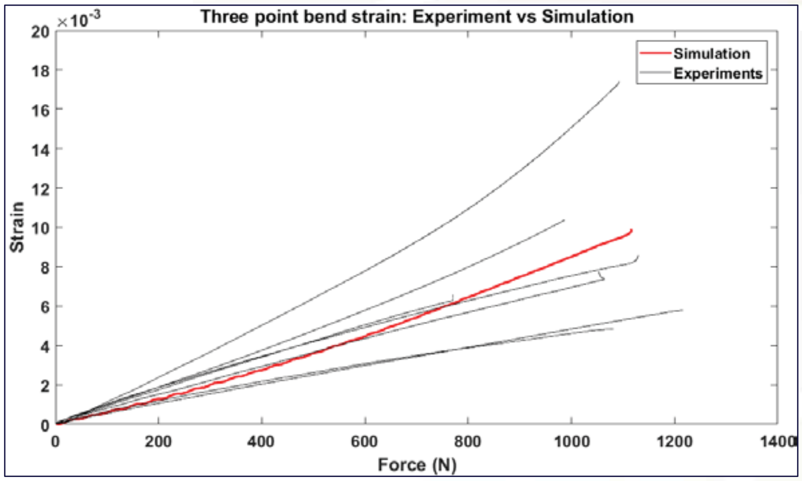
Model parameters	Current Model	Modified Model
Youngs modulus (GPa) (Cortical)	9	18
Yield strength (GPa) (Cortical)	0.8	0.16
ε max (Cortical)	NA	0.03
ε max (Trabecular)	NA	0.08
NLOC (Cortical Shell)	0	-1

Case Study: Clavicle Modeling

- Verify response using strain data







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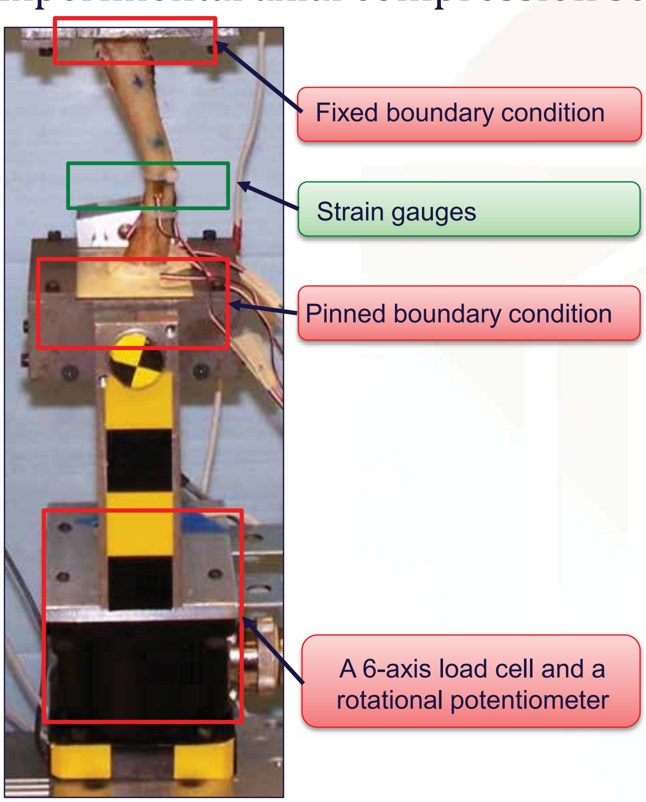
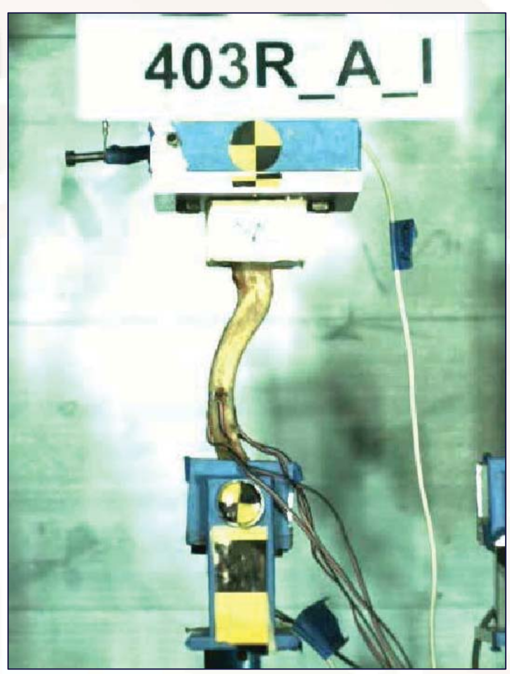
Case Study: Clavicle Modeling

- Experimental axial compression setup (Zhang et al., 2014)

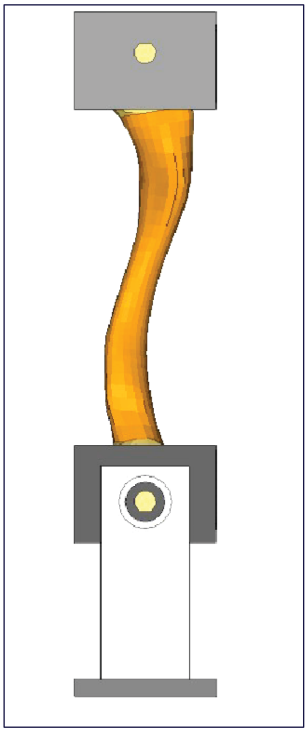




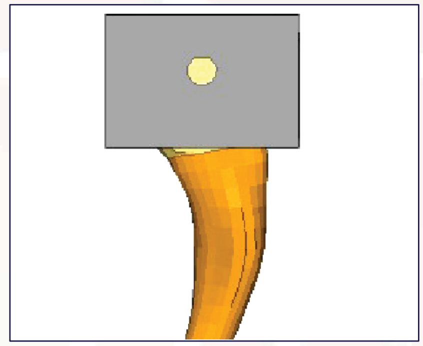
HBM-55

Case Study: Clavicle Modeling

- Model of axial compression



- Simulation results were stiffer compared to experiments
- Compliance on the fixation was found in experiments

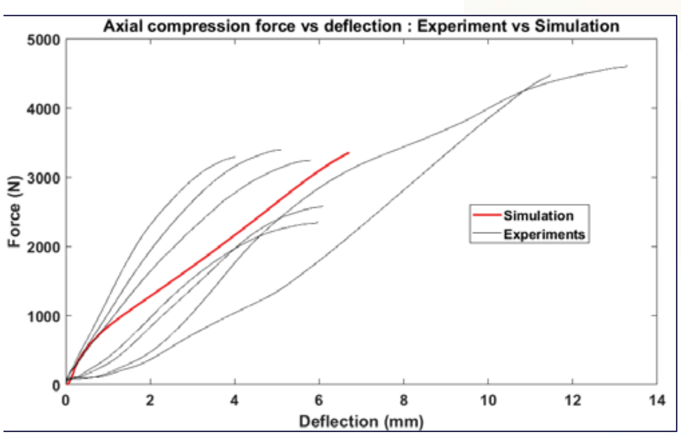


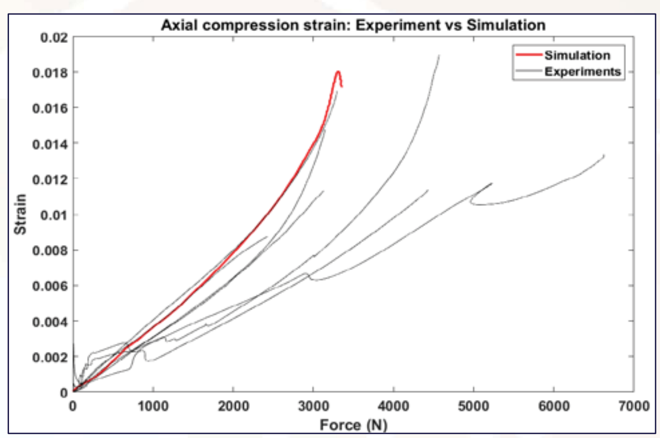
- Modify the boundary conditions to include deformable potting material to give more compliance

Case Study: Clavicle Modeling

- Verify response using force-deflection and strain data

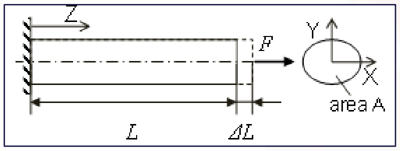
Using the defined parameters from the 3-point bending sensitivity study, the simulation results (both force-deflection and strain –force) matched the experimental results





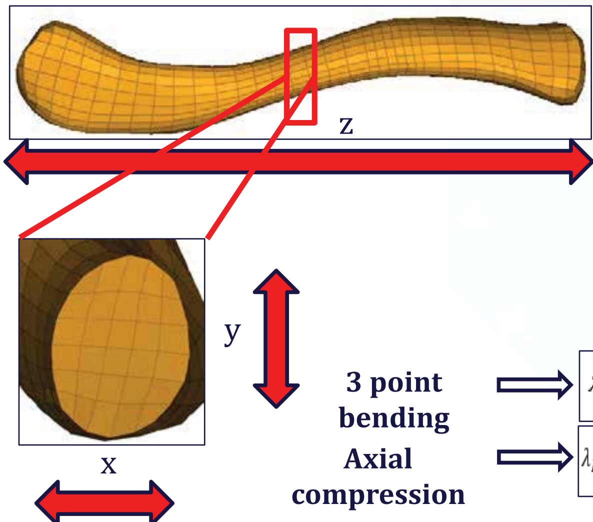
Case Study: Clavicle Modeling

- Scaling to 5th percentile female model
  - Experimental data was close to 50th percentile male anthropometry



Mass Based Scaling			
	Cortical bone	Trabecular bone	Total
M50 Clavcle mass	0.017	0.024	0.041
F05 Clavicle mass	0.028	0.057	0.085

λ_m	2.07
λ_l	1.28
λ_mt (Bending)	2.07
λ_F (Axial)	1.63



Structure based scaling			
	x	y	z
F05 Clavicle mass	10.115	12.265	147.111
M50 Clavcle mass	8.173	7.98	129.515

λ_x	1.23
λ_y	1.53

λ_mt (Bending)	2.879
λ_F (Axial)	1.8819

3 point bending ⇒

$$\lambda_M = \frac{\lambda_X \cdot \lambda_Y{}^3 \cdot \lambda_E}{\lambda_Y} = \lambda_X \cdot \lambda_Y{}^2 \cdot \lambda_E$$

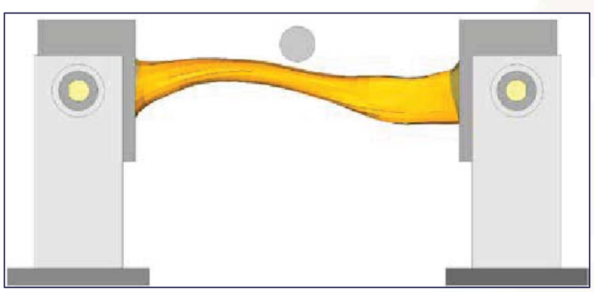
Axial compression ⇒

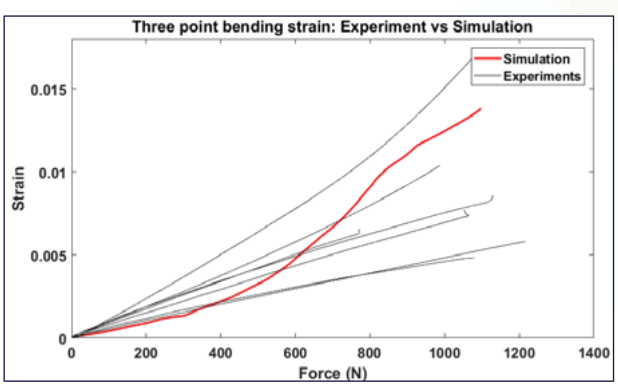
$$\lambda_F = \frac{\lambda_Z \cdot \lambda_X \cdot \lambda_Y \cdot \lambda_E}{\lambda_Z} = \lambda_X \cdot \lambda_Y \cdot \lambda_E, \quad \lambda_D = \lambda_Z$$

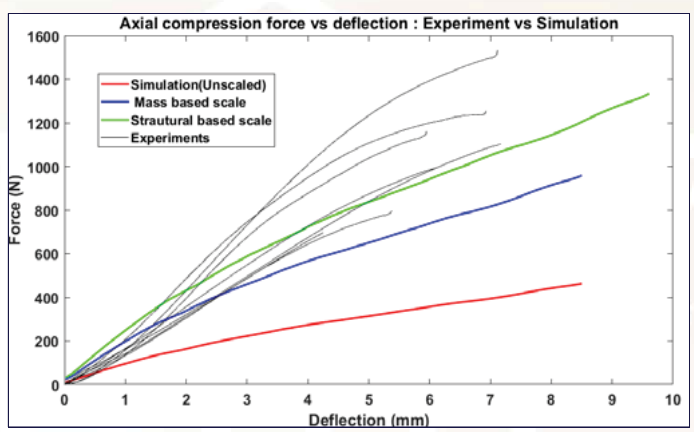
Bones approximated as a beam model of a constant cross-sectional area

Case Study: Clavicle Modeling

- F05 model compared to scaled data



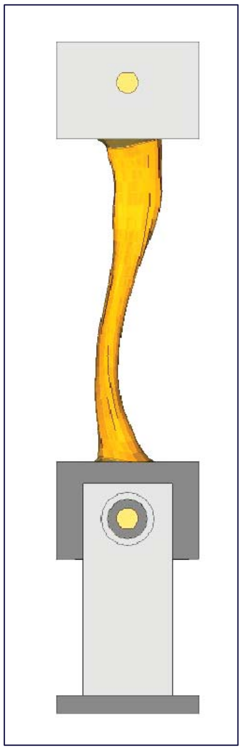


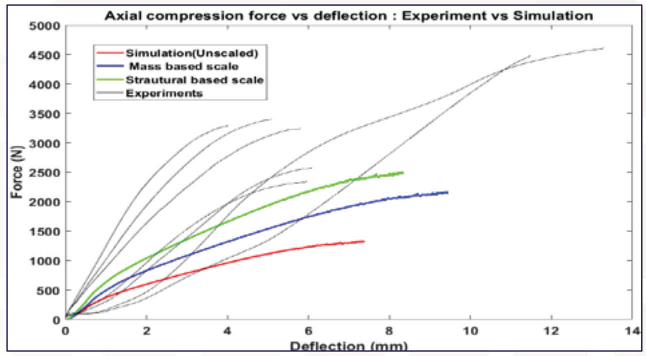


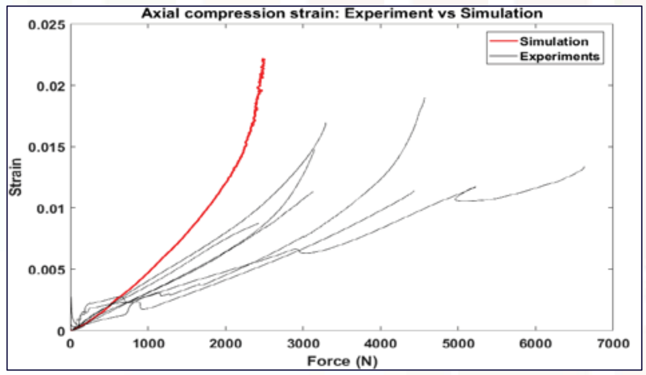
The force deflection graph showing comparison of scaled and unscaled response

Case Study: Clavicle Modeling

- F05 model compared to scaled data







Challenges in Body Region Validation

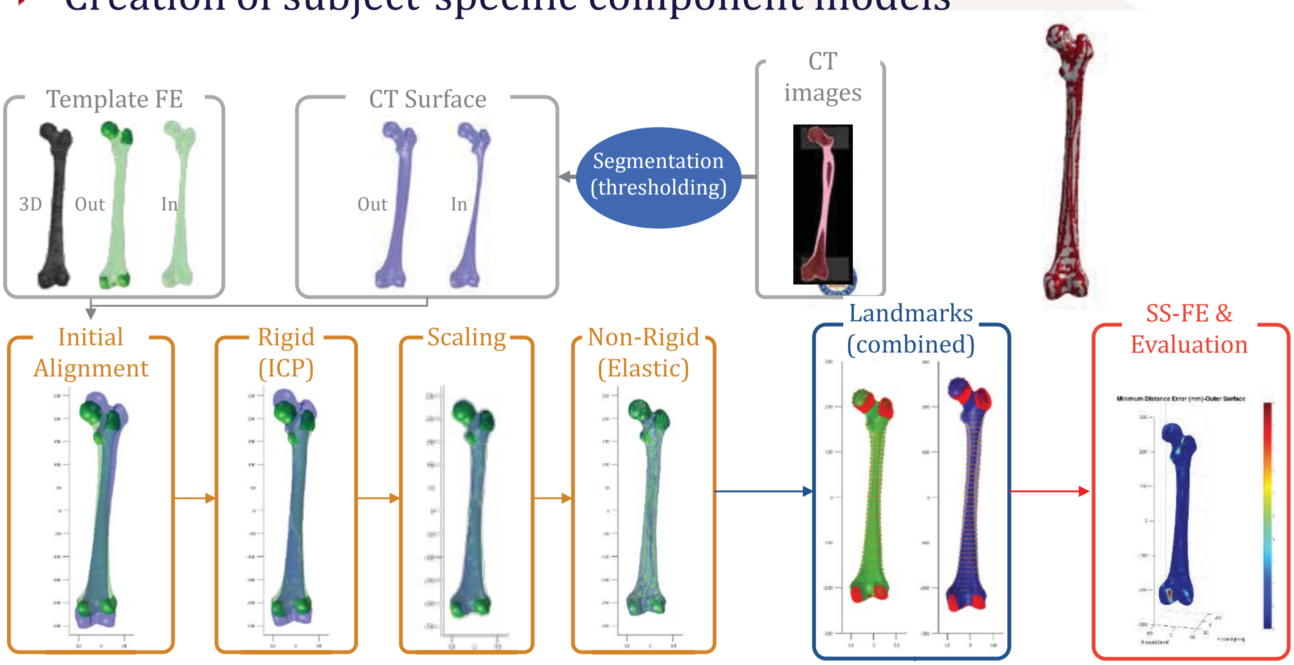
Challenges

- It is difficult to use experimental data for body region model validation without the following:
  - Simple boundary conditions that are clearly documented
  - Rigid fixtures for large force application
  - High-speed video and photographs of test setup (pre- and post-test)
  - Detailed description of specimen anatomy
  - Individual specimen data rather than corridors

A move towards subject-specific validation

Towards Subject-Specific Validation

- Creation of subject-specific component models



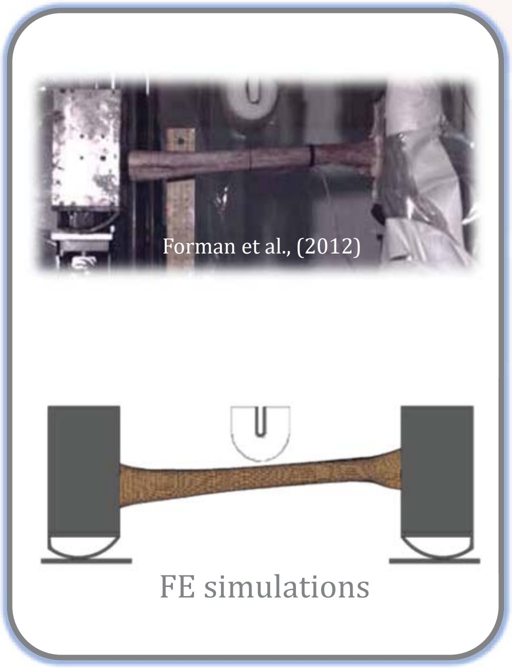
Step1: Model preparation
Step2: Registration
Step3: Selecting control points
Stap4: Morphing & Eval

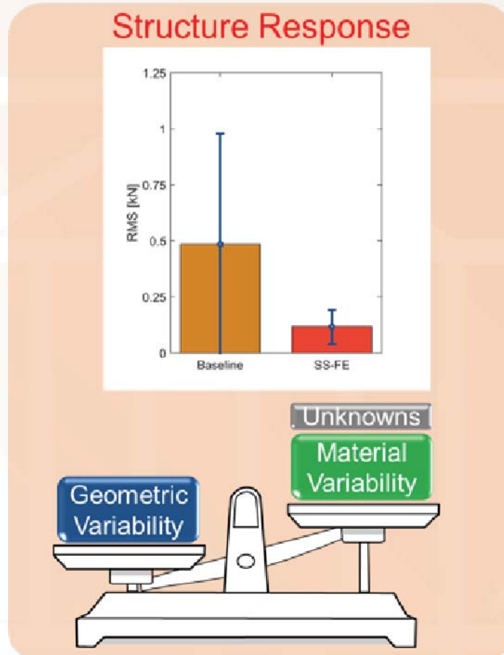
Morphing
(Radial Basis Function with Thin Plate Spline)

Park et al., 2017

Towards Subject-Specific Validation

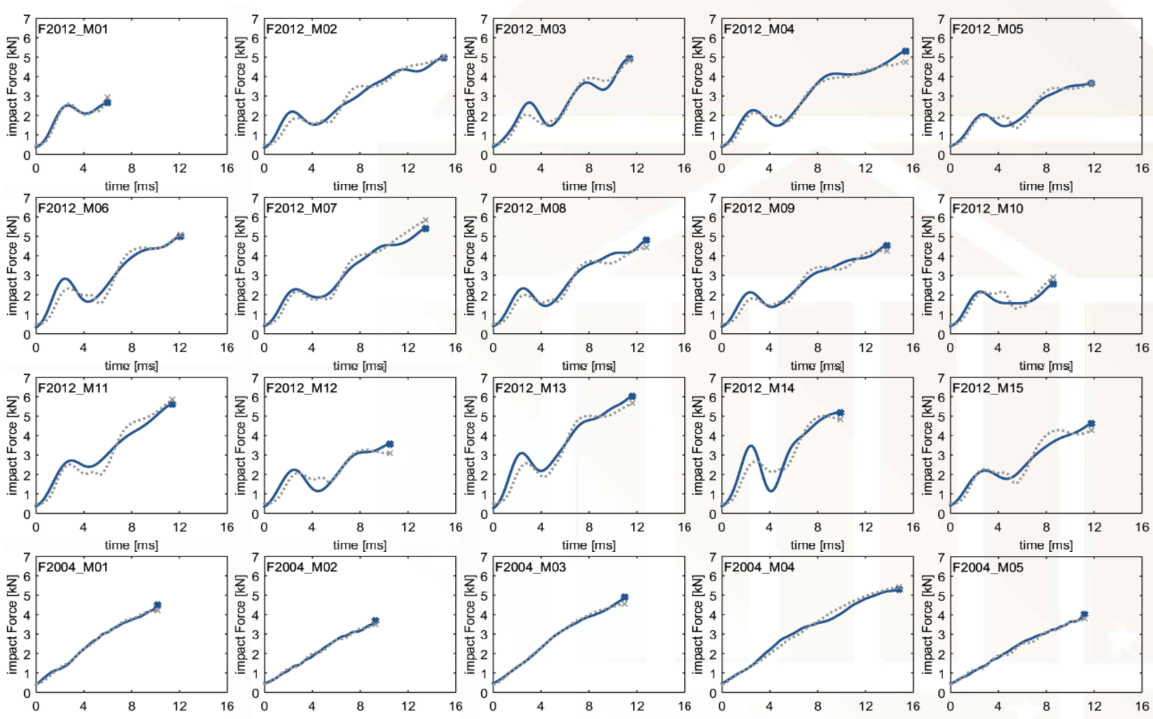
- Anatomy has large effect on biomechanical response





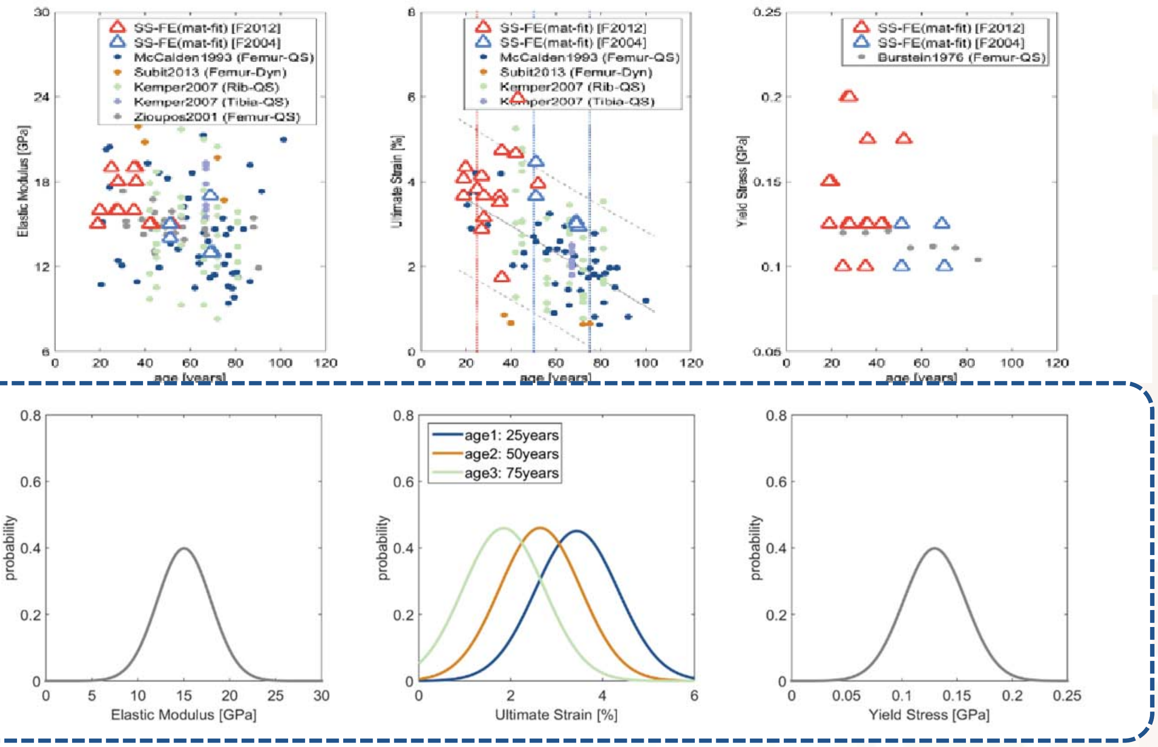
Towards Subject-Specific Validation

- Subject-specific models can closely match experimental tests



Towards Subject-Specific Validation

- Population-based material properties, with confounding factors



 Park et al., 2017

Body region modeling and validation

Matthew B. Panzer, PhD

Center for Applied Biomechanics
University of Virginia

Pre-IRCOBI Workshop on Human Body Modeling
September 11, 2018
Athens, Greece

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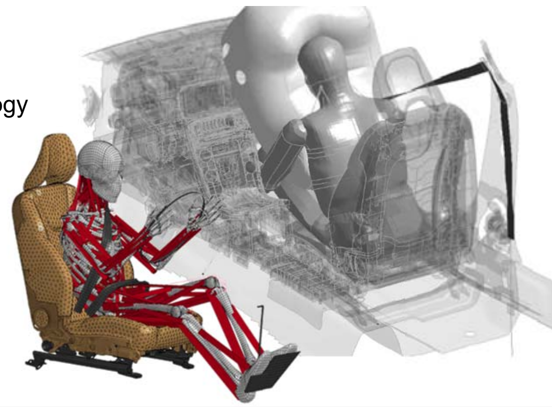
Active musculature in HBM

IRCOBI 2018 Workshop: Human Body Modeling and Validation with Biomechanics Experiments

Prof. Karin Brolin

Chalmers University of Technology
Gothenburg, Sweden

karin.brolin@chalmers.se



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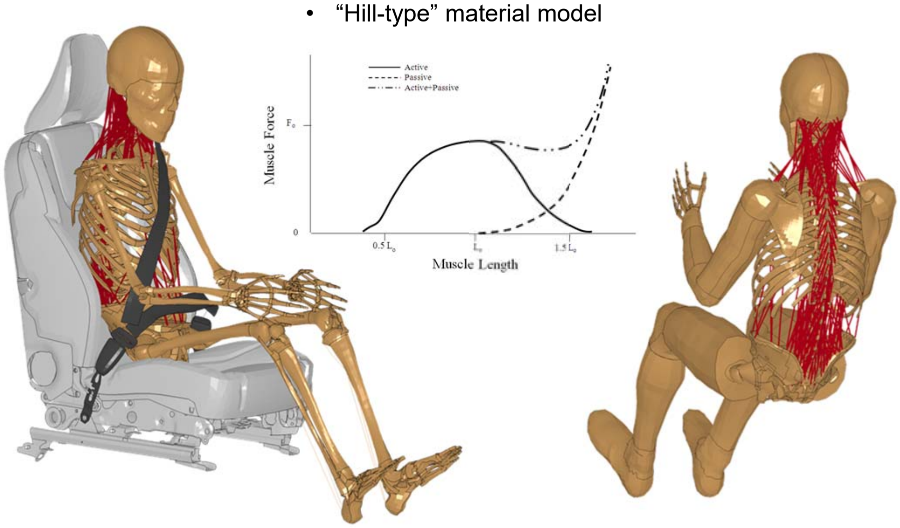
Integrated safety

Muscle elements

- Line elements
- “Hill-type” material model



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Active muscle control in HBM

- Open-loop control
  - Active THUMS (Iwamoto et al. 2012)
    - Reinforcement learning with simplfied model provides pre-determined activation levels

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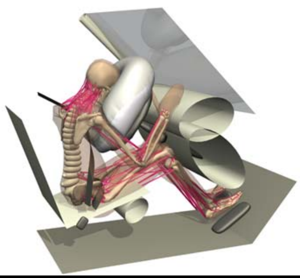
Active muscle control in HBM

- Open-loop control
  - Active THUMS (Iwamoto et al. 2012)
- Closed-loop control
  - TNO Active Human Model (Meijer 2012)
  - SAFER A-HBM (Östh et al 2014a)



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SAFER A-HBM

AIM

A biofidelic Human Body Model (HBM) for simulation of sequences of events:

- combined emergency and crash events,
- run off road events, and
- other long duration crash events

PROJECT START 2009

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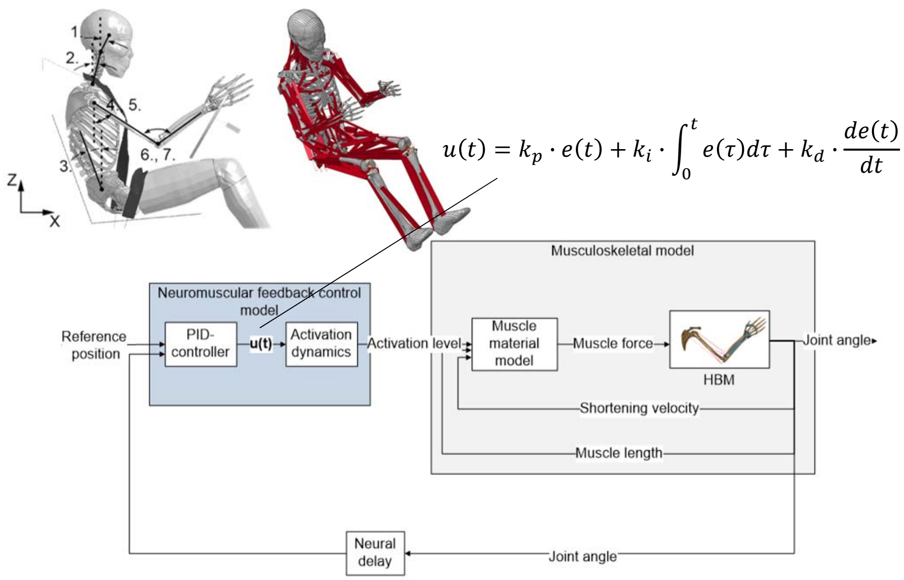
Control strategy



$$u(t) = k_p \cdot e(t) + k_i \cdot \int_0^t e(\tau)d\tau + k_d \cdot \frac{de(t)}{dt}$$

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Tuning of controller gains

$$u(t) = k_p \cdot e(t) + k_i \cdot \int_0^t e(\tau)d\tau + k_d \cdot \frac{de(t)}{dt}$$

The gains vary for each muscle and depending on the scenario.

- Tuning to experimental data in similar/relevant scenario.
  - Lap belt only.
  - Lap and shoulder belt.
  - Holding on to steering wheel.

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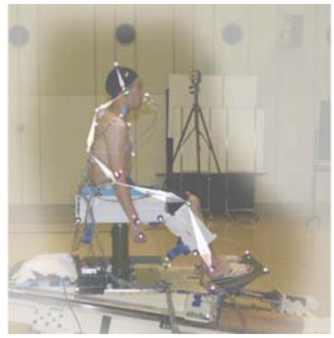
Tuning to sled test 1



- Sled test with lap belt only (Ejima et al. 2007)
  - 10 m/s^{-2} acceleration over 0.2 s
  - Instruction to be relaxed

Passive

Active 1

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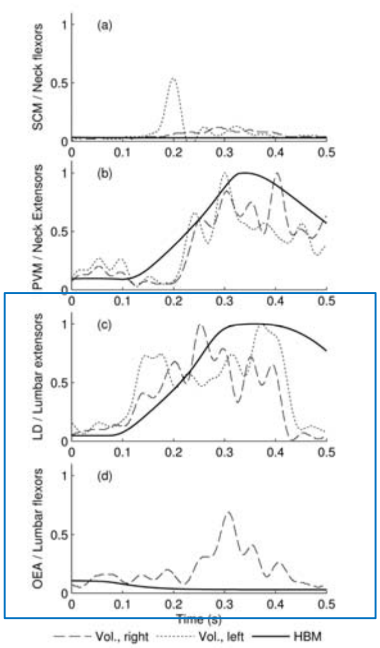
Resulting muscle activity



Östh J, Brolin K, Carlsson S, Wismans J, Davidsson J (2012) The Occupant Response to Autonomous Braking: A Modeling Approach that Accounts for Active Musculature. Traffic Injury Prevention 13(3):265–277.

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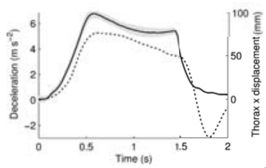
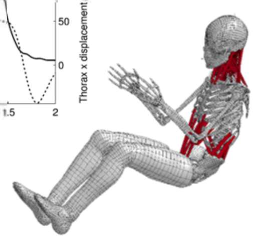
Tuning to Passenger Autonomous Braking





Active 1 was too soft => Active 2

Östh J, Brolin K, Carlsson S, Wismans J, Davidsson J (2012) The Occupant Response to Autonomous Braking: A Modeling Approach that Accounts for Active Musculature. Traffic Injury Prevention 13(3):265–277.

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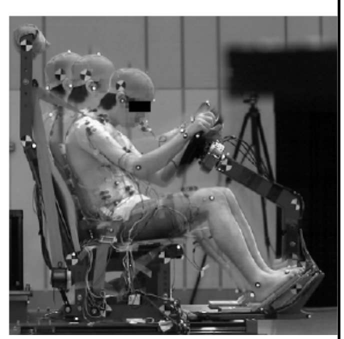
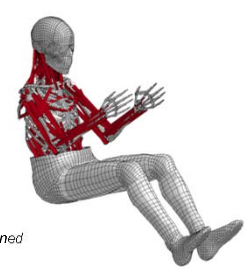
Tuning to sled test 2

- Sled test with 3-point belt (Ejima et al. 2008):
  - 8 m/s^2 acceleration over 0.6 s
- Active 2 => Active 3
- Tune controller gains:
  - 144 simulations
  - single stage iteration
  - meta model

$$u(t) = k_p \cdot e(t) + k_i \cdot \int_0^t e(\tau)d\tau + k_d \cdot \frac{de(t)}{dt}$$



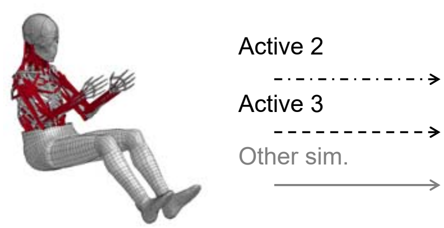
Ejima et al. (2008)

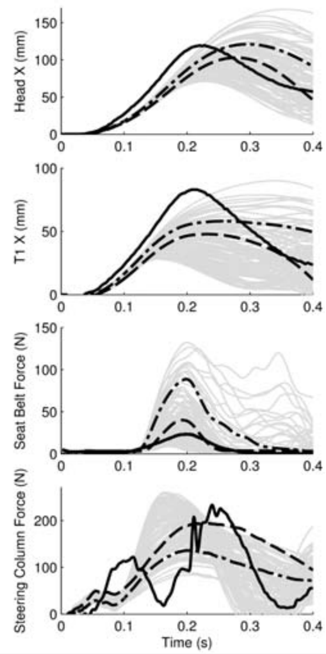


Östh J, Brolin K, Bråse D (2015) A Human Body Model with Active Muscles for Simulation of Pre-Tensioned Restraints in Autonomous Braking Interventions. Traffic Injury Prevention,16:304-313.

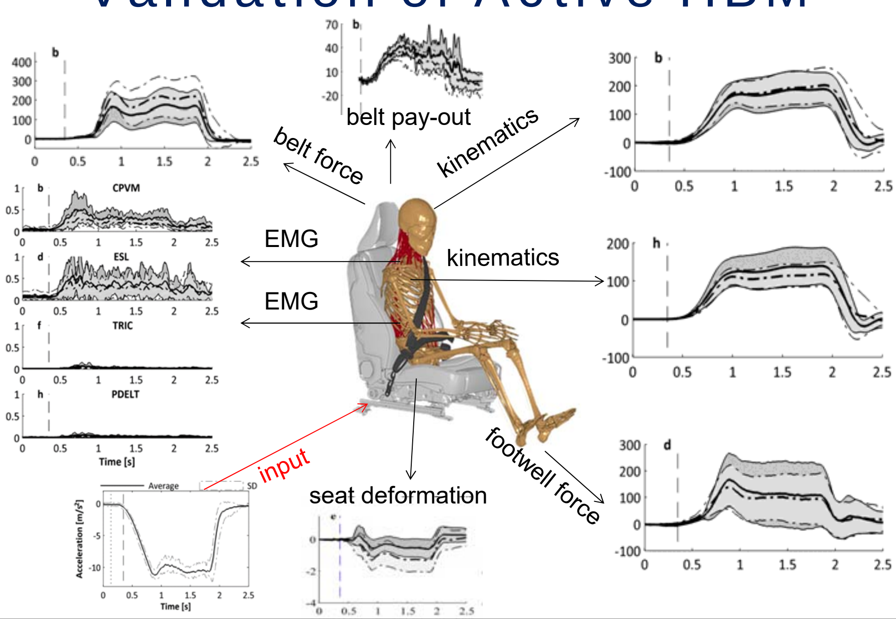
Tuning to sled test 2

Ejima et al. (2008)





Validation of Active HBM



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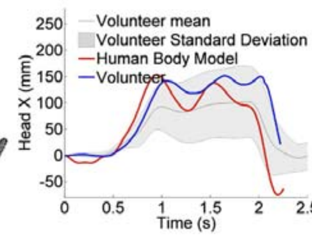
Validation to Autonomous Braking

- $11 m/s^2$ autonomous braking interventions (Östh et al. 2013)



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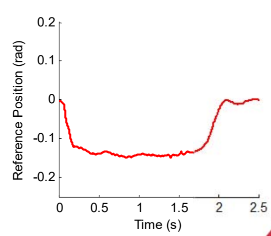
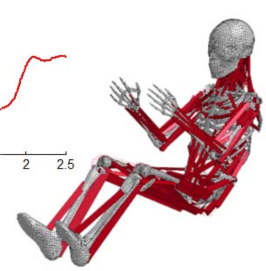
Driver Braking

- Anticipatory postural response present in voluntary driver braking.
- Modelled by changing the reference positions in proportion to the acceleration load.





Östh J, Eliasson E, Happee R, Brolin K (2014) A Method to Model Anticipatory Postural Control in Driver Braking Events, Gait & Posture. 40(4):664-669.

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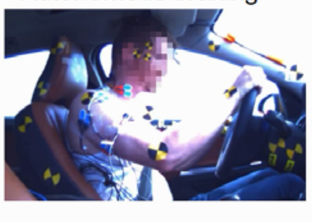
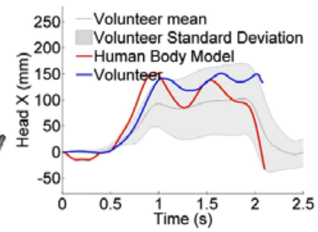
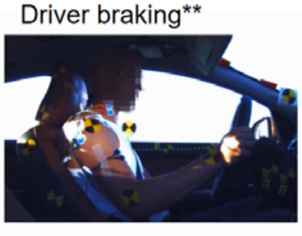
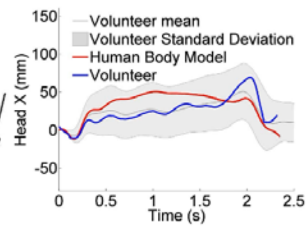
Autonomous braking*





Driver braking**





** Östh J, Brolin K, Bråse D. A Human Body Model with Active Muscles for Simulation of Pre-Tensioned Restraints in Autonomous Braking Interventions. Traffic Injury Prevention, 16:304-313, 2015.*
*** Östh J, Eliasson E, Happee R, Brolin K. A Method to Model Anticipatory Postural Control in Driver Braking Events, Gait & Posture. 40(4):664-669, 2014.*

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Omnidirectional active HBM

- Muscle activity varies for individual muscles
  - Individual muscle control
  - Muscle recruitment strategies for dynamic events
  - Postural control in pre-crash
    - Muscle spindles - Repositioning
    - Vestibular system - Acceleration
- Validation data
  - Kinematic data
  - Muscle activity (normalized EMG)
  - Boundary conditions

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SAFER A-BHM: Ongoing / unpublished work

- Implemented muscle control for omnidirectional events using feedback control of
  - Body angles, and
  - Muscle length of individual muscles.

- New experimental volunteer tests series:
  - Drivers and passengers in test vehicle
  - Muscle activity, vehicle data and 3-D kinematics
  - Autonomous events and driving:
    - Lane change w/o and with braking
    - Braking
    - U-turns
  - A subset of data presented in IRC-18-80.

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Omni-directional SAFER A-HBM

Lane Change with Braking

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Acknowledgements

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Modeling Population Heterogeneity for Crash Safety Assessments

Matthew P. Reed, PhD
Jingwen Hu, PhD

2018-09

TRANSPORTATION RESEARCH INSTITUTE
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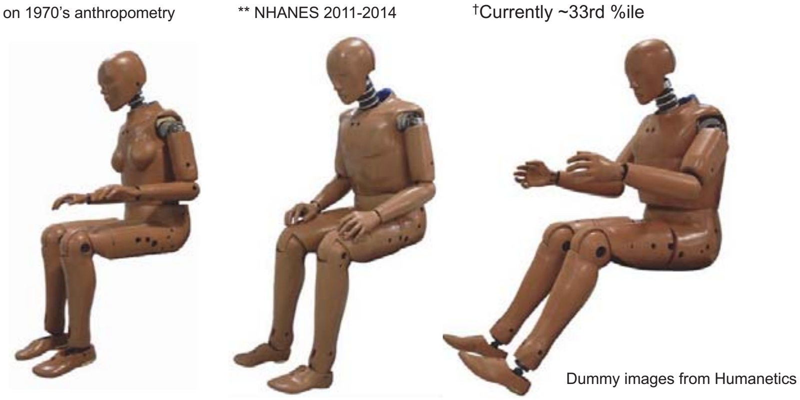
Adult ATD Sizes

Hybrid III	5^{th} %ile female	50^{th} %ile male	95^{th} %ile male
Dummy Specification*	152 cm 47 kg	176 cm **78 kg†**	188 cm **102 kg**
Current US Population**	150 cm 50 kg	176 cm **86 kg**	188 cm **125 kg**

*Based on 1970's anthropometry ** NHANES 2011-2014 †Currently ~33rd %ile



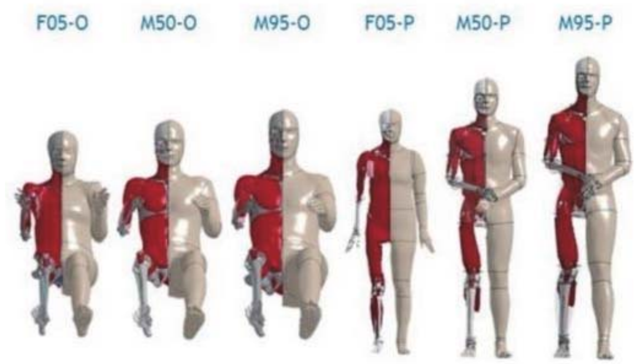
Dummy images from Humanetics

Adult FE HBM Sizes

(SAME)

Hybrid III	5^{th} %ile female	50^{th} %ile male	95^{th} %ile male
FEM Specification*	152 cm 47 kg	175 cm **77 kg†**	188 cm **102 kg**
Current US Population**	150 cm 50 kg	176 cm **86 kg**	188 cm **125 kg**

*Based on 1970's anthropometry ** NHANES 2011-2014 †Currently ~33rd %ile



Model images from Elemance

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Critical Questions

1. What do simulations with a small number of FE model sizes tell us about the population experience in similar events?
2. Does optimizing occupant protection for a small number of body sizes result in good protection across the population?

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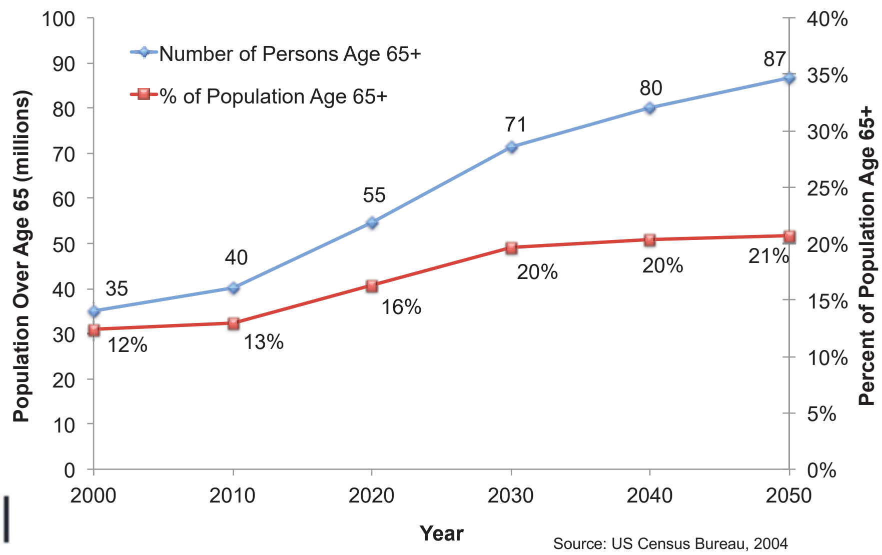
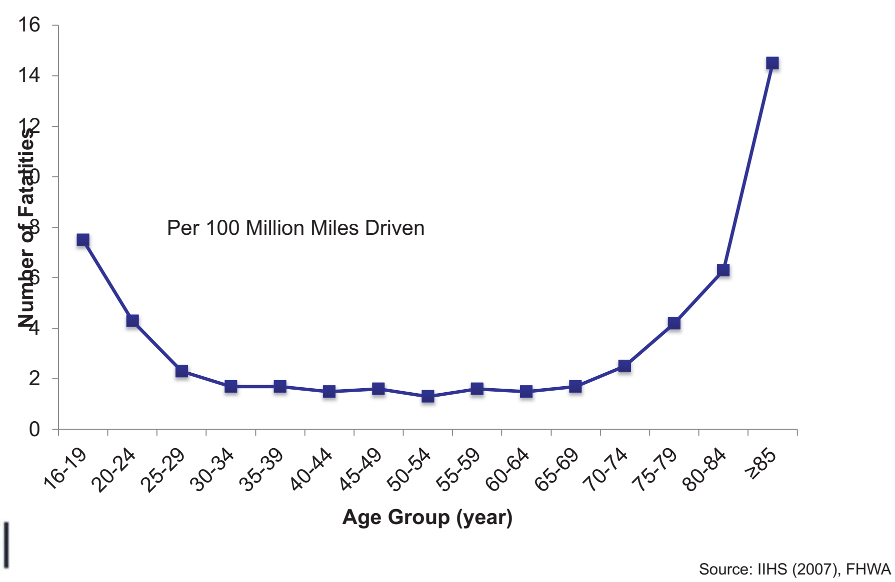
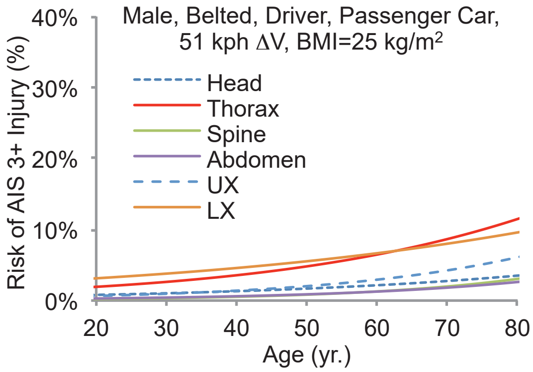
Demographic Changes: Aging of the U.S. Population

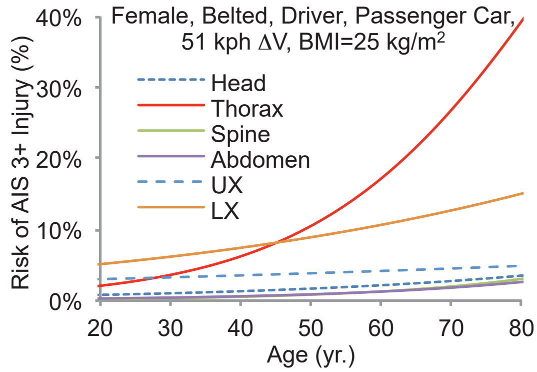


Effects of Age on Fatality Rate



Effects of Occupant Age, BMI, and Sex on the Risk of AIS 3+ Injury





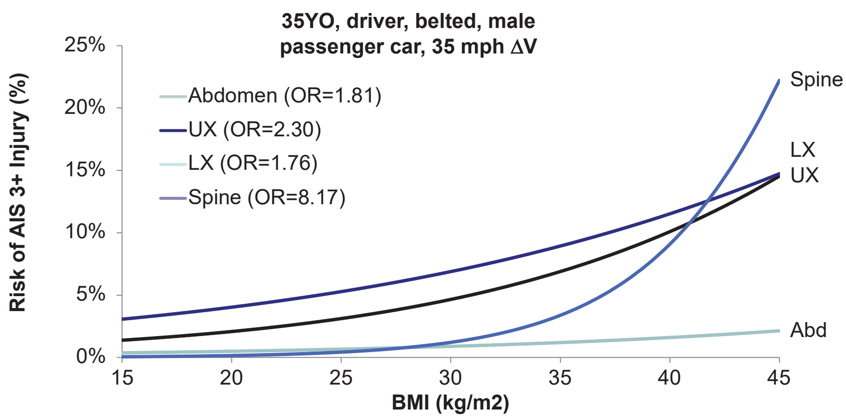
From Ridella, Poland and Rupp (2012), Carter et al. (2013)

Effects of Obesity on AIS 3+ Injury in Frontal Crashes

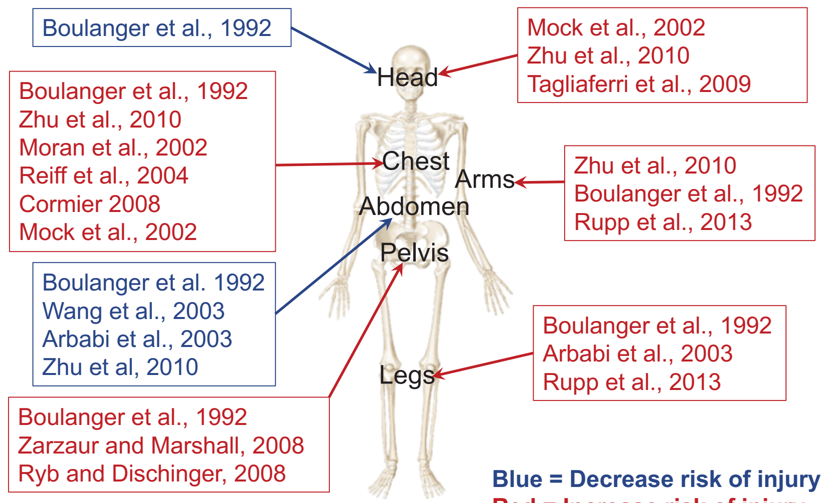
Obesity mainly affects injury risk in frontal crashes.

- More mass to stop → higher force to stop occupant.
- Worse belt fit → tougher to apply forces to bony anatomy, especially the pelvis.

Currently about 40% of US adults are obese (BMI ≥ 30 kg/m²



Obesity Effects on Injury Risks for Adult Males in Motor Vehicle Crashes



Blue = Decrease risk of injury
Red = Increase risk of injury

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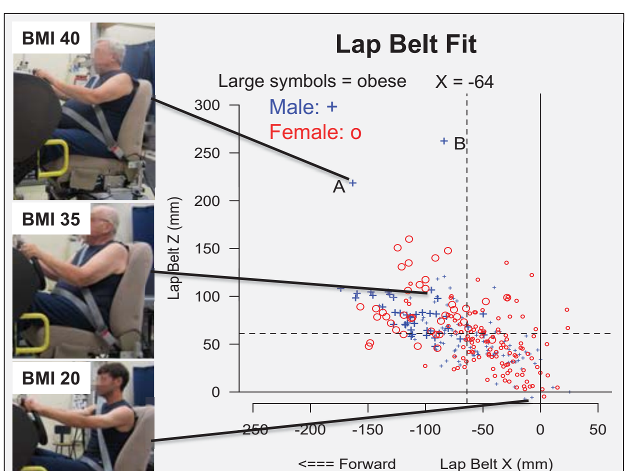
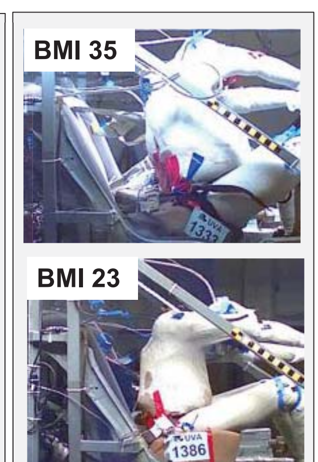
Why Obesity Matters in Crashes

Body shape induces poor belt fit

Increased mass



Reed et al. (2013)



Kent et al. (2009)

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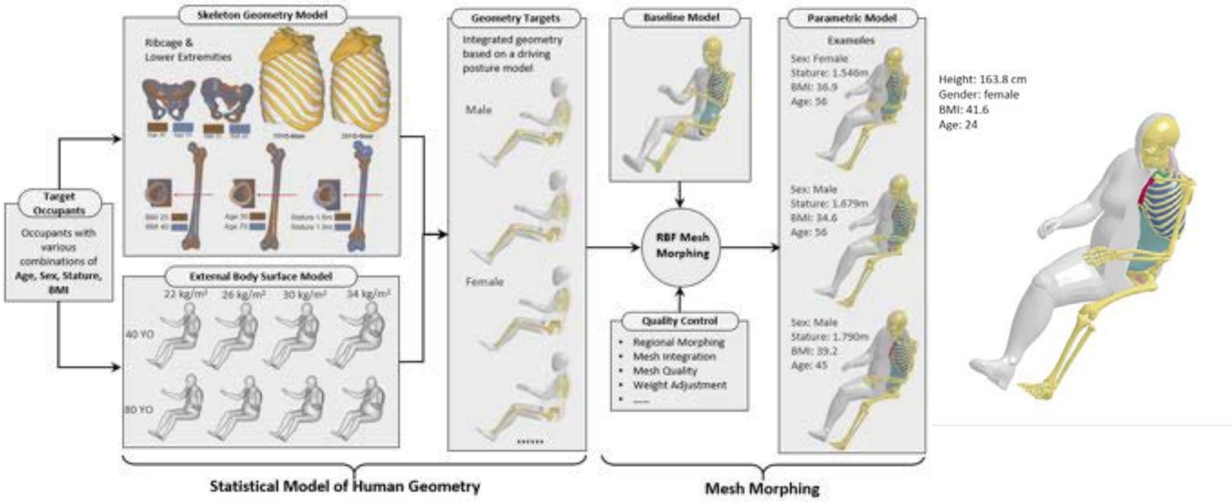
Parametric Human Body Modeling



Funded by NHTSA, Toyota, NSF and GM

Led by Jingwen Hu, PhD

Shi et al. (2015) CMBBE
Hu et al. (2016) DHM
Hwang et al. (2016) SAE&Stapp
Hu et al. (2017) IRCOBI

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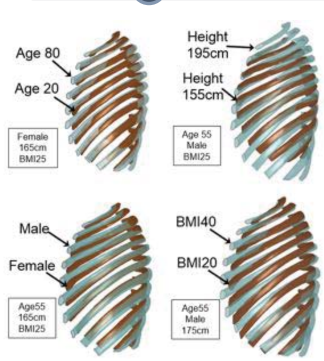
Statistical Skeleton Geometry Models

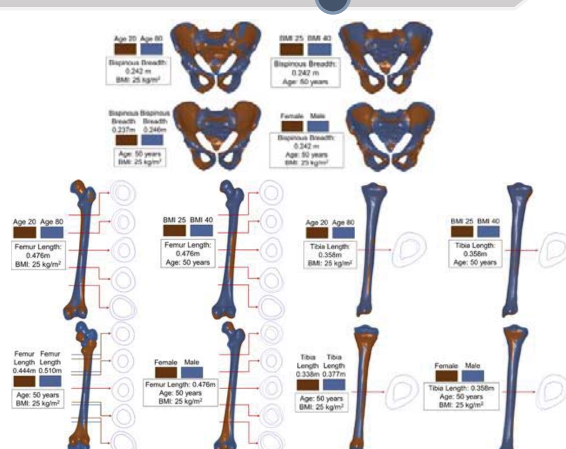
Based on CT data from ~300 subjects

Ribcage

Lower Extremities



Shi et al., 2014, J. Biomech
Wang et al. 2016, J. Biomech



Klein et al., 2015, ABME

Klein, 2015, PhD dissertation

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HumanShape.org

Online 3D body shape resources

Dr. Byoung-Keon Daniel Park

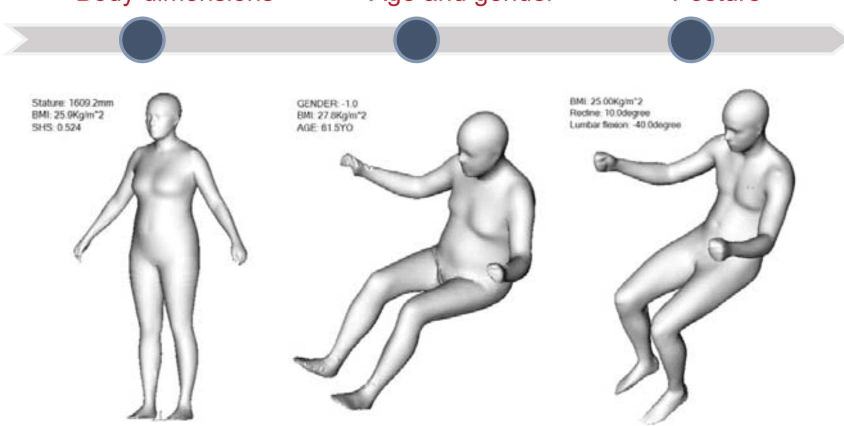
Parametric Body Shape Models

Based on body scan data from ~200 subjects

Predictors:
Body dimensions

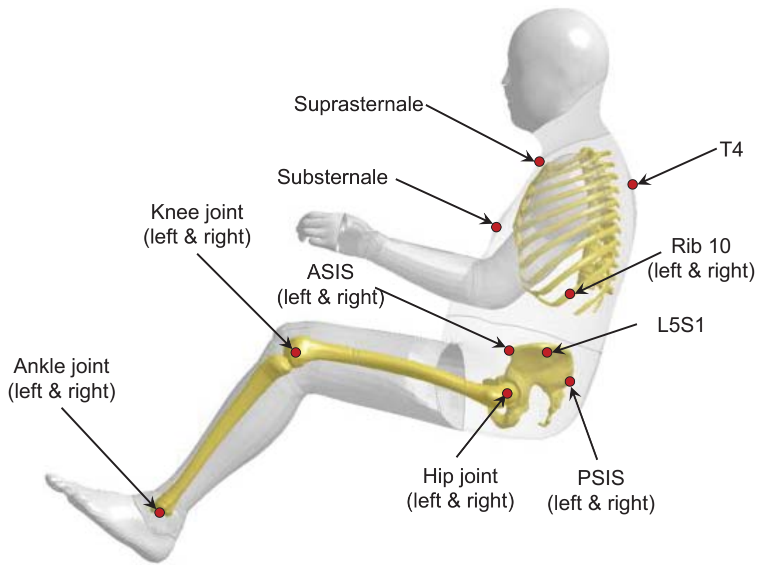
Predictors:
+ Age and gender

Predictors:
+ Posture



Reed and Park 2016 New UMTRI data

Integration of Skeleton and Body Shape



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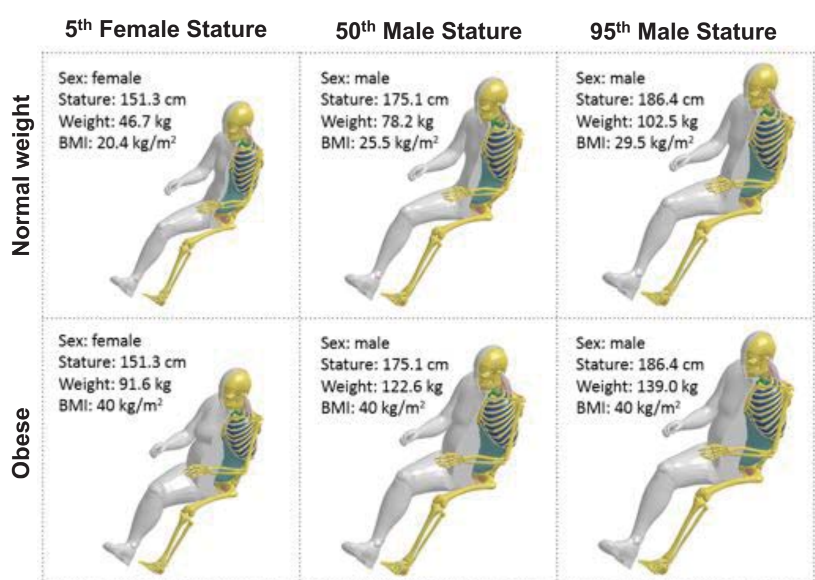
Morphed Human Models



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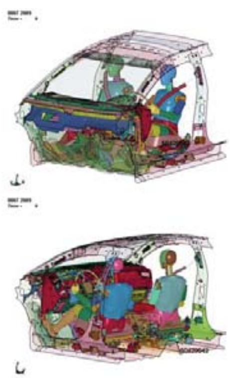
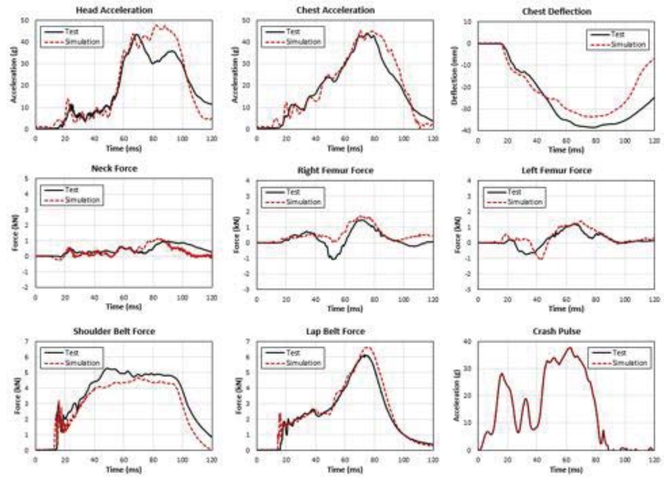
Vehicle Model

Midsize Sedan Model:

• 3 kN steering column • 2.85 kN load limit • retractor and anchor PTs





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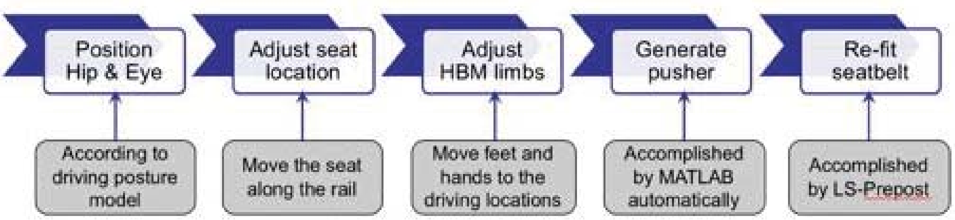
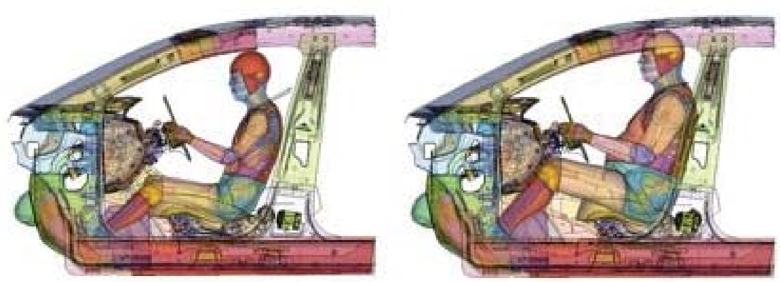
Frontal Crash Simulation Setup (56 kph)





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Injury Risk Prediction

P_{joint}=1- (1-P_{head}) x (1-P_{neck}) x (1-P_{chest}) x (1-P_{KTH})

	Midsize Male	Small Female	Large Male
Head (HIC15)	$P_{head}(AIS3+) = \phi\left(\frac{ln(HIC15) - 7.45231}{0.73998}\right)$ Where Φ=cumulative normal distribution		
Neck (tension / compression in kN)	$P_T(AIS3+) = \frac{1}{1+e^{10.9745-2.375T}}$; $P_C(AIS3+) = \frac{1}{1+e^{10.9745-2.375C}}$; $P_{neck} = Max(P_T, P_C)$	$P_T(AIS3+) = \frac{1}{1+e^{10.9745-3.770T}}$; $P_C(AIS3+) = \frac{1}{1+e^{10.9745-3.770C}}$; $P_{neck} = Max(P_T, P_C)$	$P_T(AIS3+) = \frac{1}{1+e^{10.9745-2.003T}}$; $P_C(AIS3+) = \frac{1}{1+e^{10.9745-2.003C}}$; $P_{neck} = Max(P_T, P_C)$
Chest (deflection in mm)	$P_{chest}(AIS3+) = \frac{1}{1+e^{10.5456-1.568*D^{0.4612}}}$	$P_{chest}(AIS3+) = \frac{1}{1+e^{10.5456-1.7212*D^{0.4612}}}$	$P_{chest}(AIS3+) = \frac{1}{1+e^{10.5456-1.488*D^{0.4612}}}$
Knee Thigh Hip (femur force in kN)	$P_{femur}(AIS2+) = \frac{1}{1+e^{5.795-0.5196F}}$	$P_{femur}(AIS2+) = \frac{1}{1+e^{5.7949-0.7619F}}$	$P_{femur}(AIS2+) = \frac{1}{1+e^{5.7949-0.4090F}}$

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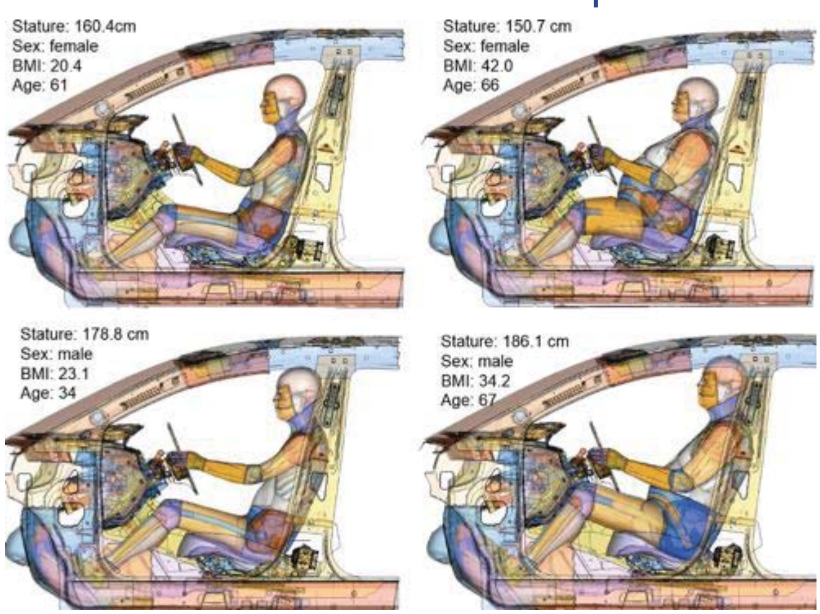
Same injury risk curves for obese and non-obese occupants with the same stature

NCAP Simulation Examples



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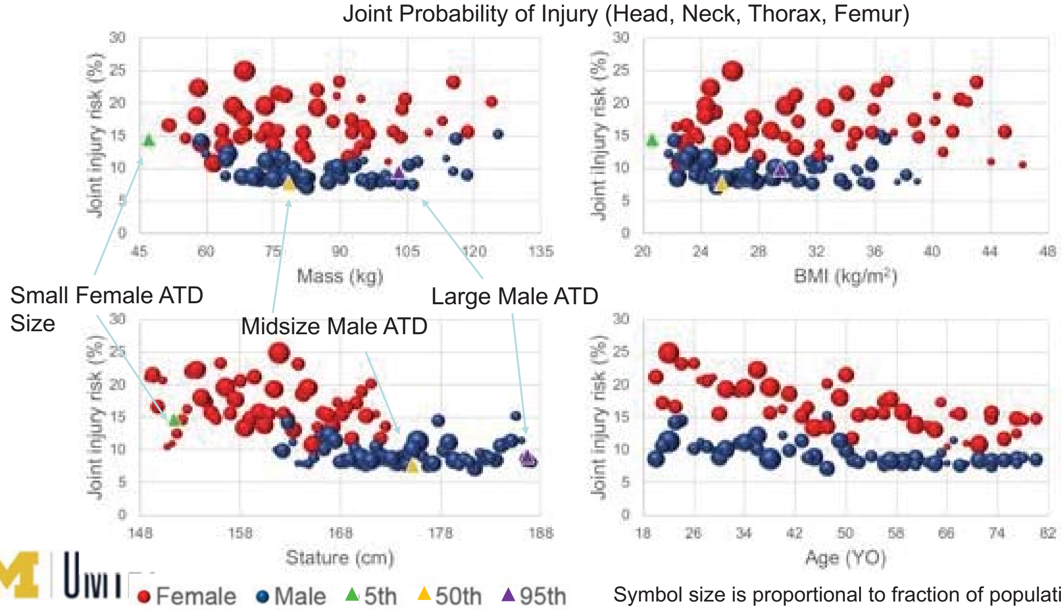
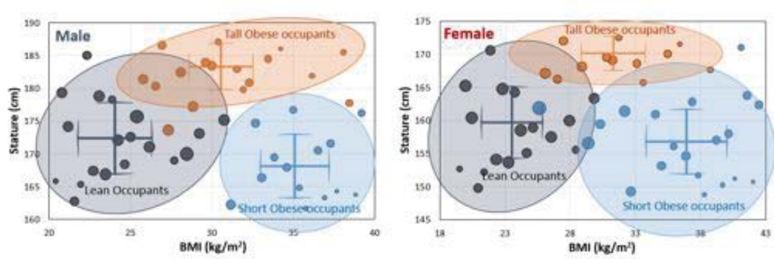
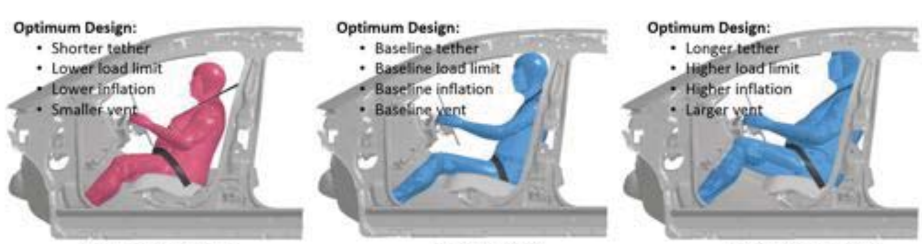
It’s Good to be (the size of) a Dummy



Symbol size is proportional to fraction of population

Parametric Simulations and Optimization



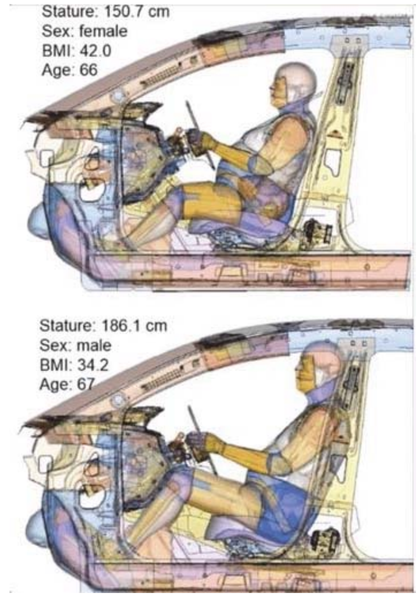


Short Obese Female | Midsize Male | Large Obese Male

Simulated Crash Outcomes: Population Simulations

For these frontal crash simulations:

- Occupants who are the size of the ATDs show lower predicted injury risks than most other occupants
- Both body size and body shape have strong effects on predicted injury risk
- Considering only "5th%ile female to 95th%ile male" misses most of the variance in the outcome measures



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What's Next

Subject-specific validation: current methods for normalizing, scaling, and generating corridors from biomechanics data leave out most of the interesting parts of the data

Improved population sampling algorithms: we know that "5th and 95th" is inadequate, but which models should we use to be most efficient?

Adaptive Restraints: Can we make protection for humans as good as it is for dummies?

Humility? The more we know about how much posture and body shape affect crash outcomes the less confident we are in what the ATDs (and similar-size human models in normal postures) are telling us about population risks.

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Acknowledgements

This work was supported by a wide range of sponsors, including General Motors, Ford Motor Company, Toyota Collaborative Safety Research Center, the U.S. Army, the U.S. National Science Foundation, and the U.S. National Highway Traffic Safety Administration.

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IRCOBI 2018 Workshop Series

Human Body Modeling and Validation with Biomechanics Experiments

HBM repositioning

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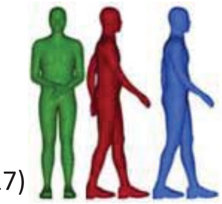
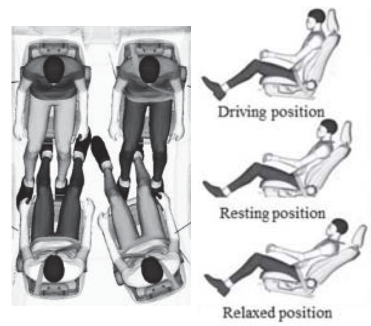
Introduction: some needs

- Procedures / regulation, R&D, research: different applications and requirements…
- Pedestrian EuroNCAP: standard posture determined (Coherent). Does not change with vehicle. Done.
- Occupant: needs to seat in vehicles…
  - Like a dummy (E.g. SAE J826) or a human (preferred postures? naturalistic driving?)
  - New seating (vehicle automation) = new challenges
  - Future procedures: several HBM in the same posture?
- Match a specific posture: HBM validation using PMHS, Accident reconstructions, at onset of impact after precrash phase predicted by another model…
- Study sensitivity of risk to posture, etc.

Klug et al. (2017)

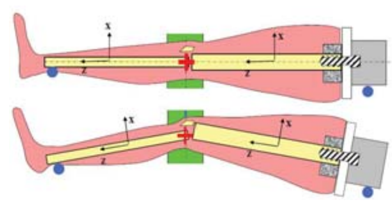




Thums positioning
Kitagawa et al. (2017)

Introduction: effect of postural variations

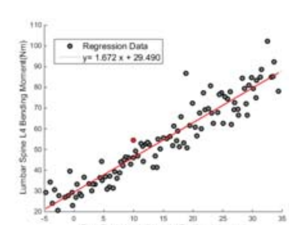
- May affect (widely) response and injury depending on configuration
  - Some PMHS studies: challenging (especially for injuries)… Not enough to validate wide postural changes?
  - Many modelling studies for FE-HBM
- Sensitivity would set the effect on what it expected in accuracy of posture change…



E.g. Petit et al. (2014) 18 paired tests: flexion affects injury risk…

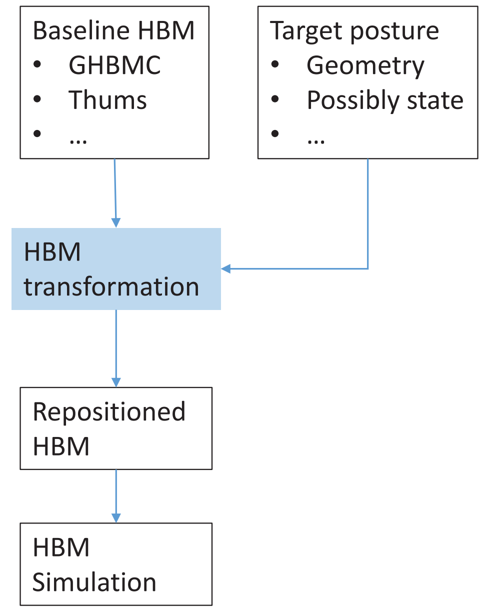
Contact loading in side impact (Poulard et al., 2014)

Lumbar moment vs. recline angle "gravitationally settled and positioned in baseline posture" (Ye. et al., 2018)



Introduction: process

- FE HBM ≠ dummies or rigid body models
  - Soft tissues + contact ➔ need specific process
- Practice is diverse and as old as FE HBMs
  - Since Humos2 at least, early 2000's
- Repositioned HBM
  - Represents same "individual" (only posture changed)
  - HBM must be runnable at the end
- Target: often not defined explicitly
  - Depends environment (e.g. vehicle), HBM (size, d.o.f.)
  - Definitions: activity (e.g. driving), known variables (e.g. landmark)…
- Validation? Is Repositioned HBM valid?
  - Posture definition?
  - Model response and injury prediction?



Scope

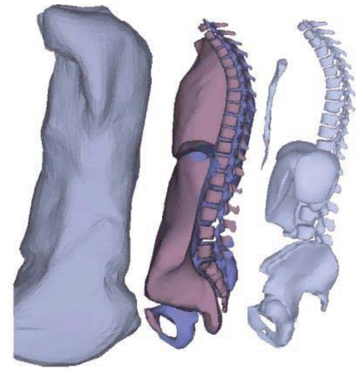
Objectives:

- Review some of the options and highlight some challenges for:
  - Target determination
  - Transformation methodologies
- Provide some illustrations / pointers

- Note:
  - Focus on FE HBM
  - Not necessarily exhaustive… (practice is diverse, more focus on recent efforts)
  - Remeshing not included (topic in itself)
  - Some illustrations based on PIPER software framework and project

Target definition

- Full target for FE HBMs: all bony positions, soft tissues geometry, etc. corresponding to HBM in usage scenario
  - In practice: joint angles
- User knowledge typically limited. E.g.
  - Activity: e.g. driving = hands on wheel, walking
  - Data: dummy angles, naturalistic driving videos, PMHS landmarks



Seated to standing geom. change (based on pos MRI), Beillas et al. (2009)

Target definition (2)

- Other knowledge needed to "augment" the target up to the point where is it not ambiguous anymore
  - Biomechanics / physiological constraints/ RoM, external surface deformation, imaging and stat models
  - Postural references, discomfort, etc. ➔ Target may not be unique (family of targets)
  - Could be already integrated in other models (ergonomics/kinematic models for joint angles, animation for "realistic" skin aspect

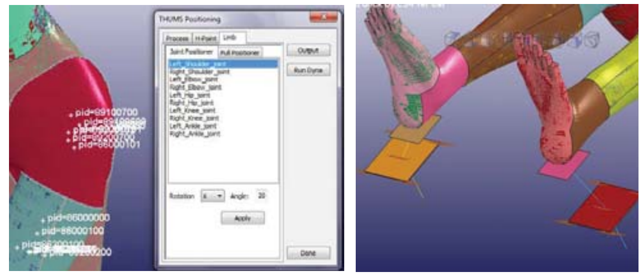
… but need to make it compatible with HBM

- Different size, joint geometry, etc.

Chinese vs **French** subjects (same stature, Peng et al., 2018)

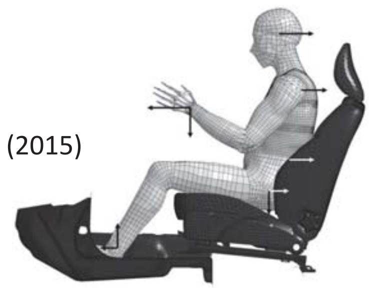
Target determination:
From FE Simulation

- Rotate, pull, apply gravity… let model move
- Most common practice. With script or tools
- Advantages: uses biomechanical knowledge built in model (joint, contact)=compatible



Joint rotation and pull in LsPP Thums positioning tool (Ho, 2012)

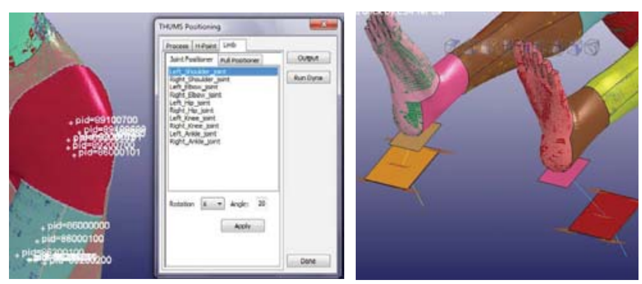
SaferHBM
Eliasson and Wass (2015)



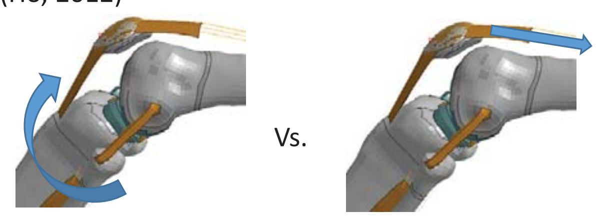
Target determination:
From FE Simulation

- Rotate, pull, apply gravity… let model move
- Most common practice. With script or tools
- Advantages: uses biomechanical knowledge built in model (joint, contact)=compatible

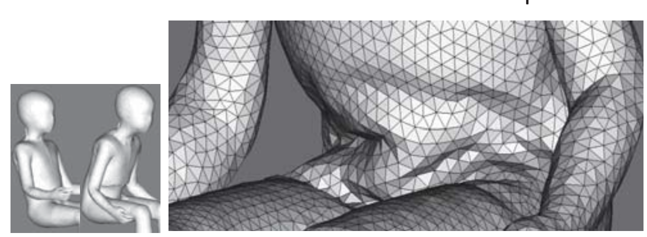
- Issues: only impact biomechanics
  - Muscles do not create motion but are subjected to it, Contacts can open, attachments…
  - Not validated for physiological range but 20g = properties? Soft tissues?
  - No postural preferences…
  - Not interactive (long simulation time)
- Possible improvements:
  - Alternate properties, muscles, same geometry…



Joint rotation and pull in LsPP Thums positioning tool (Ho, 2012)



GHBMC M50 knee: rotate vs. muscle pull

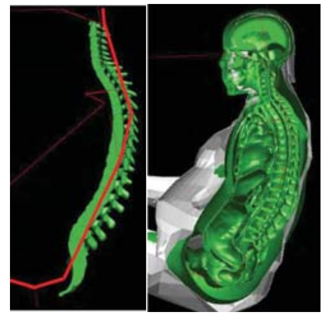


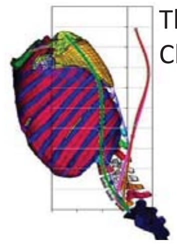
Soft tissue artefacts – PIPER child model (Janak et al., 2018)

Target determination: Other models

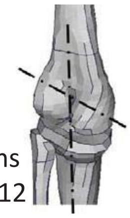
- For ergonomics: mostly skeletal
- Pre-crash or long kinematics
  - E.g. from Madymo to FE Thums active…
- Kinematics with some “clinical” knowledge
  - e.g. Chawla et al. (2010), Desai et al. (2012)…
- Others??
  - MSK modelling: Anybody? OpenSim?
  - Computer animation with skinning: value for skin?
- Challenges:
  - Ergonomics: limited internal validation ?
  - Soft tissues?
  - Less detailed internally: compatibility? Linkage between models?

Ramsis overlay with Thums (Mayer et al., 2017)

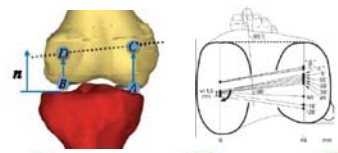




Thums Chawla et al. 2010



Thums Desai et al., 2012

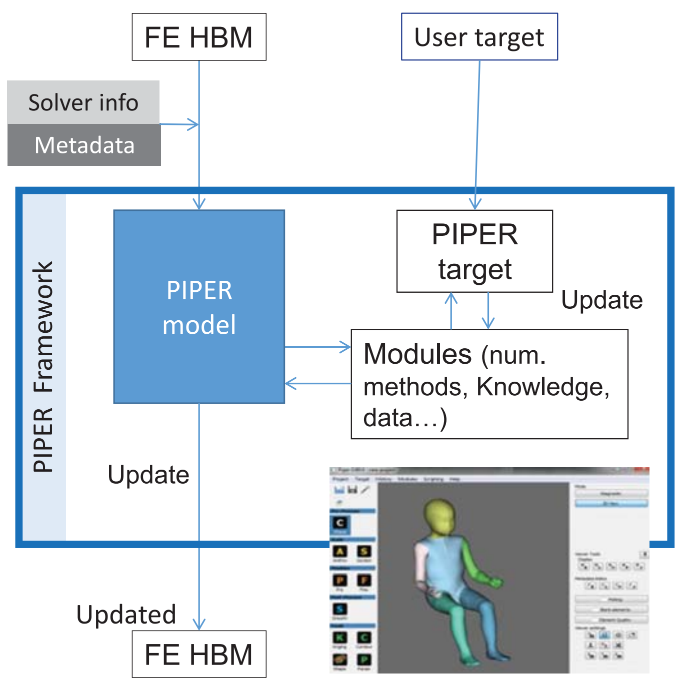


GHBMC Tang et al. (2017)

Target determination: PIPER pre-position

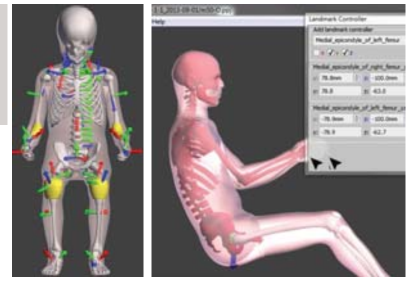
PIPER Software Framework?

- Aims to help users scale and position HBM, share methods between HBMs
  - HBM and solver agnostic,
  - Modular, interactive
  - Open Source software (GPLv2)…
  - PIPER EU project. Now: PIPER Open Source
- Has been used with
  - Thums V3, V4 (Dyna)
  - GHBMC M50 (and others) (Dyna)
  - PIPER Child Occupant and Pedestrian (Dyna), Occupant Radioss (ongoing)
  - VIVA



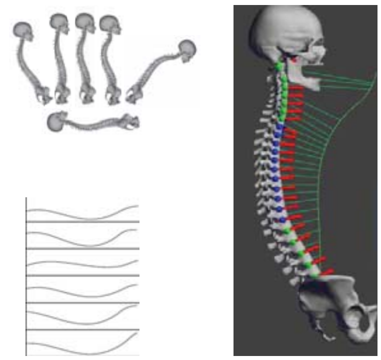
Target determination: PIPER: pre-position

- HBM compatible model built at import (metadata)
  - Rigid bones, joints, collision, contacts,
  - Soft tissues (interp. based on voxelization).
  - Lightweight physics simulation (meshless, SOFA)…
- <u>Interactive</u> simulation under constraints ➔ **DEMO**
  - Fixed bones, User controllers (angles, positions, landmarks)
  - *A priori*: for now, only spine curvature
- Interest: build target based on weighted constraints and HBM geometry (even if scaled)
  - Target fully defined (bone frames/landmarks)
- Limitations:
  - Soft tissue model (far from plausible skinning),
  - Limited amount of a priori knowledge, no direct link to other models (e.g. Anybody)…
  - Contact with environment



e.g. ~5 min GHBMC (default parameters)

Database of *in vivo* postural data

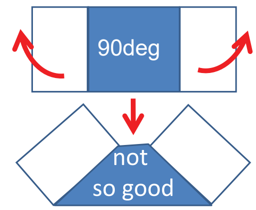


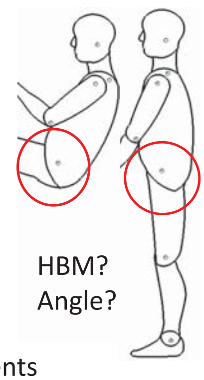
Target summary

- Variety of approaches used, with strengths and weakness
  - No comparisons, no common practice, some duplication
- Reproducibility and validation ?
  - Publicly available datasets in realistic conditions to set benchmarks?
  - When reference exist: distance to it not always provided
- Other models may help (already have some validation) but need compatibility resolution against FE HBM
  - automatic linkage would be useful
- Comparisons are difficult: lacking common definitions?
  - First step: common definition and exchange format (e.g. agreed set of landmark + method to compute angle) could help (e.g. PIPER?)

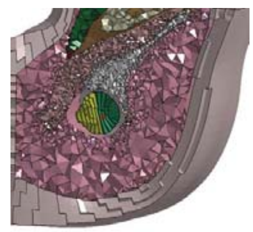
Transformation approaches

- From initial position to known target… Challenges:
  - Maintain Element quality
  - Keep model runnable (inverted elements, penetrations)
  - Cost (time), etc.
  - Respect model (sliding, etc.) that was validated
  - Realism of transformation…
- Approaches
  - FE simulation
  - Geometrical methods
  - PIPER models

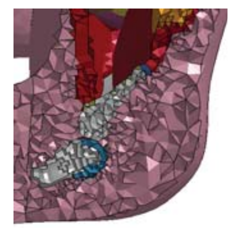




Typical metrics:
Jacobian of 3D elements
(see Jolivet et al. (2015) for discussion)



GHBMC M50

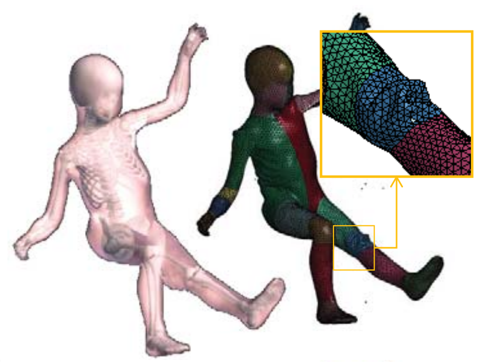


PIPER Child Occupant

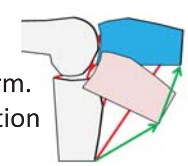
Transformation approaches: FE simulation

- Most common approach. Push, pull, rotate, gravity... And save the model at the end.
  - Often: combined with target determination
  - PIPER: tool to help prepare FE simulation
- FE Advantage: no negative elements, respect of biomechanics (e.g. volume)
- Limitations: same as previous…
  - Contact loss, soft tissue realism, etc.
- Model improvement would help…
  - Different sets of properties, etc…
  - But challenges likely to remain…

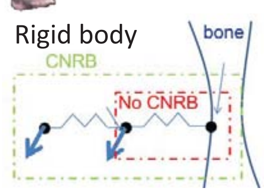
PIPER
Export
FE deck
(python)



Interm.
position



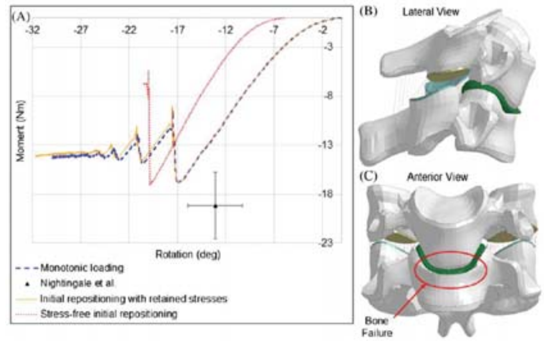
Rigid body



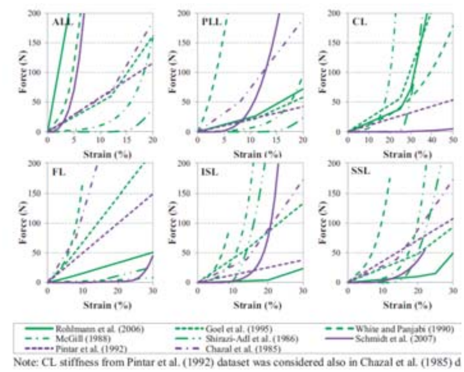
GHBMC PTW
Reco. (Secu2RM)

Note on FE transformation: initial strain/stresses

- Many biomechanical structures are non linear
  - With neutral zone / unloaded (e.g. slack) *in situ*
  - Partially loaded *in situ* (knee cruciate ligaments)
- Deforming the model and cancelling strain history will affect the response. How much?
  - E.g. Neck: Boakye-Yiadom and Cronin (2018)
- But:
  - Should the baseline be considered as a neutral posture? Or should stresses be added there too?
  - Aren't properties already adjusted for posture in the baseline model? And should be adjusted after the posture change?
- May depend on HBM, region and posture. More investigation needed



Neck: effect of retained stress on injury (Boakye-Yiadom and Cronin, 2018)

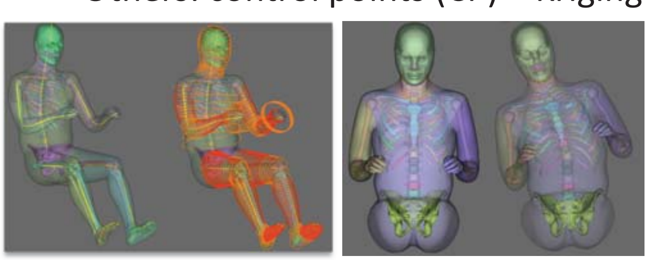


e.g. Review by Naserkhaki et al. (2018) on lumbar ligaments

Transformation approaches: Geometrical methods

- Use features known in source and target
  - E.g. landmarks, bones (rigid), skin (obtained by skinning)

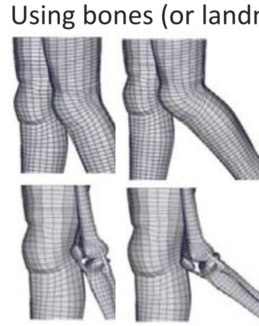
+interpolation methods in between
  - IITD: Bones ➔ "Contours" (Skinning)
  - Others: control points (CP) + Kriging / RBF



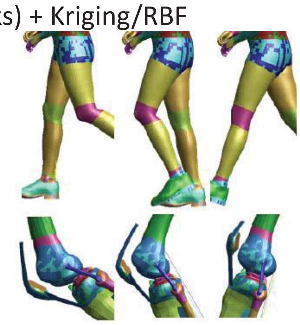
Contours (Chhabra et al., 2017a,b) – In PIPER

Precrash on GHBMC Simplified ➔ Detailed (51 landmarks, Kriging). Guleyupoglu, et al. (2017)

Using bones (or landmarks) + Kriging/RBF



Kriging (Desai et al., 2012)



Tang et al. (2017)

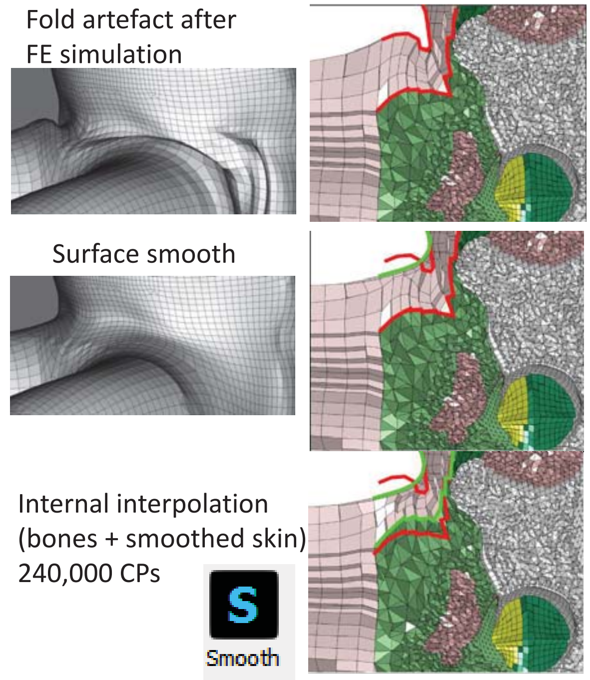
TABLE I
MESH QUALITY OF ADJUSTED MODELS COMPARING TO BASELINE

Model	Number of shell elements (Jacobian value <0.7, minimum value in bracket)	Number of solid elements (Jacobian value <0.3)
Baseline	3862 (2%, 0.40)	0 (0%, 0.3)
Toe-off	3865 (2%, 0.40)	5 (0%, 0.16)
Mid-swing	3870 (2%, 0.40)	2 (0%, 0.30)
Heel contact	3871 (2%, 0.40)	5 (0%, 0.18)

Transformation approaches: Geometrical methods

- PIPER Kriging / Transformation smoothing:
  - Allow using all bones and skin nodes as CP and re-interpolate soft tissues between (after any transformation) ➔ Janak et al (2018) Wednesday.
- Geometrical methods: faster than FE but:
  - Many CP points may be required to ensure bones remain rigid…
  - No constraint for interpolated nodes inside = ligament sections may change, no volume conservation, no sliding

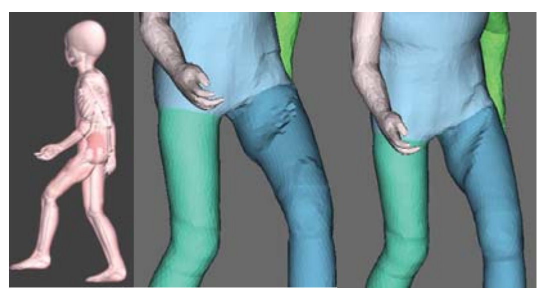
  ➔ no evaluation seen. Countermeasure: internal constraints?



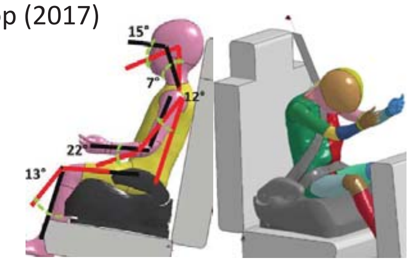
Janak et al (2018)

Transformation approaches: PIPER models

- PIPER models to transform all FE nodes
  - Pre-position: many skin artefacts
  - Position: more d.o.f. in soft tissues
  - Typically: requires transformation smoothing
- Limitations:
  - artefacts (skin+internal) + not locally physical (e.g. volume conservation, etc). ➔ better functions needed



Thums precrash (OM4IS ➔ PIPER PrePos+smoot)
Peres – PIPER workshop (2017)



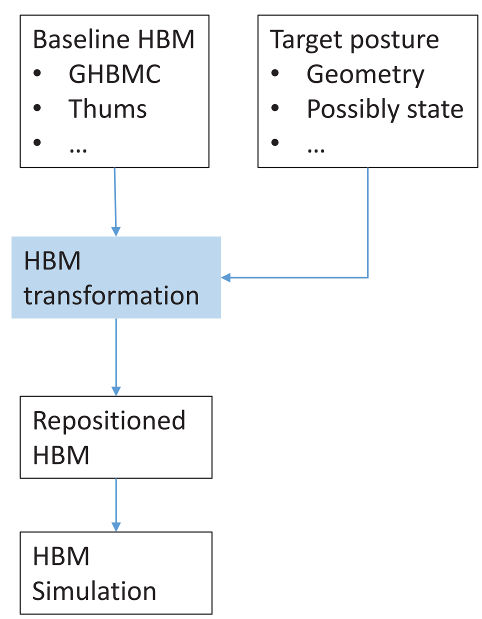
Child reconstruction
Giordano et al. (2017)

Transformation summary

- Transformation is complex, realism often questionable (soft tissues)
- Physics of motion change not captured (Muscles, initial strains, etc), and all methods show artefacts:
  - FE: soft tissues artefacts…
  - Other methods: no guarantee on local field (volume conservation)
  - Transformation smoothing can help
  - Coupling with other models / data could help: e.g. skin deformation.
- Effect of approximations on the response not clear
  - Evaluations are needed (e.g. with and without artefacts / initial strains…)

Conclusions

- Many methodologies developed that can lead to runnable simulations
  - Effort duplication sometimes.
  - Research needed on various ascpects
- Which on to choose? It depends…
  - Objective evaluations / comparisons seems to be lacking
  - Some strength and weaknesses reviewed…
- What could be a good practice?
  - Checking sensitivity of response at the end
  - Providing information on target (angles, metrics)



Thank you for your attention!

- Question? Comments?
- philippe.beillas@ifsttar.fr

- piper-project.org
  - manual, executables, datasets, models, videos, code, models, forum, wiki, tutorials, vision, FAQ…
- Contact: forum preferred (*Called "Issues"*)

PIPER Child
Pedestrian
J. Peres
Thursday

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Model Integration, Verification and Validation

F. Scott Gayzik

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Virginia Tech – Wake Forest University Center for Injury Biomechanics

Center for Injury Biomechanics

Wake Forest School of Medicine

CIB

Virginia Tech Wake Forest University

School of Biomedical Engineering and Sciences

MODEL INTEGRATION

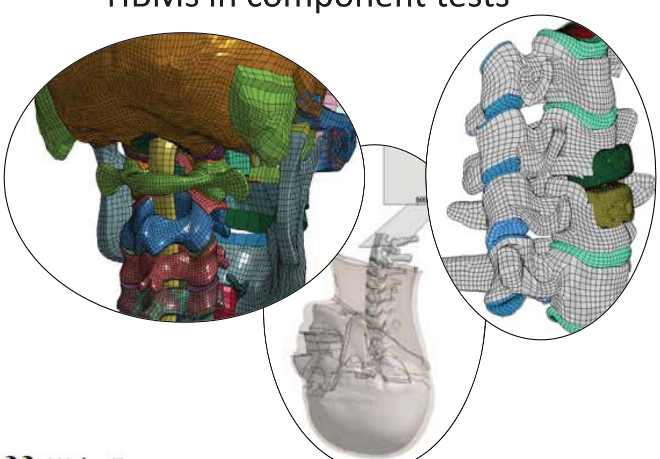
Types of Model Integration

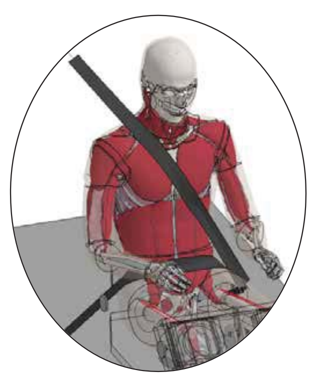
Intra-model

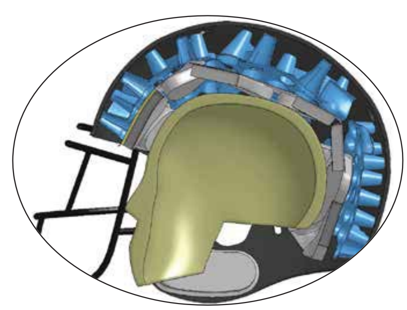
- Human body region integration
- Device model integration in HBMs
- HBMs in component tests

Inter-model

- Human model into environment
- Donning equipment or countermeasures on HBMs





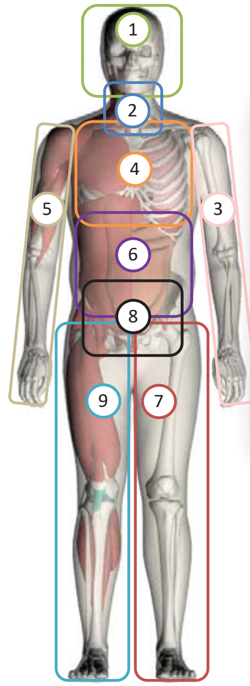


Human Body Model Region Integration

Intra-

Laying the ground work -
Define, communicate, adhere to:

- Intended use of the model
- Performance specs across platforms
- Model size considerations
  - Calculate time step, number of elements based on geometry, mass scaling limits
- Element quality standards
- Numbering and naming schemes
  - Nodes, elements, parts, sets, contacts, curves, etc.
  - Leave room for the environment models
- File structure



RegionCode_TissueType_Aspect_ComponentName_ElementType_PartNature

RegionCode	TissueType	Aspect	ComponentName	ElementType	PartNature
HE	SK	L	Disc-T11-T12	1D	Rigid
NK	FL	R	Rib5	2D	Airbag
TX	MU	Blank	Int-TarsoMetatarsal	3D	Null
AB	OR		...		Blank
PV	FT				
UX	CA				
HN	VE				
LX	FC				
FT	LG				
	TN				
	BC				
	BT				
	...				

Some examples

TX_BC_T1_3D_Rigid
TX_BT_L_Rib5_3D
LX_LG_L_Ant-Talo-Tibia_1D
FT_LG_Int-Tarso-Metatarsal_1D
AB_BC_L1_3D_Rigid
AB_OR_Small-Bowel-Cavity_2D_Airbag
TX_MU_L_Biceps_2D_Null

$$\Delta t = \frac{l_s}{C}$$

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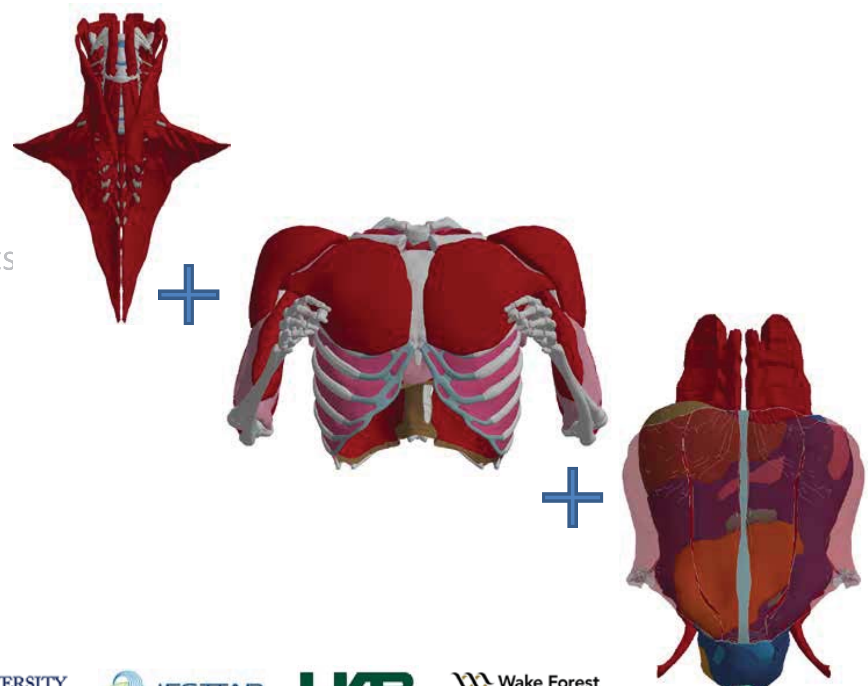
Subassembly Model Integration

Intra-

Lessons learned

- There are no clean planes between regions
- Node to node connections vs. contacts
- Mesh topology/density
- Consistent modeling approach
- Model updates and information flow



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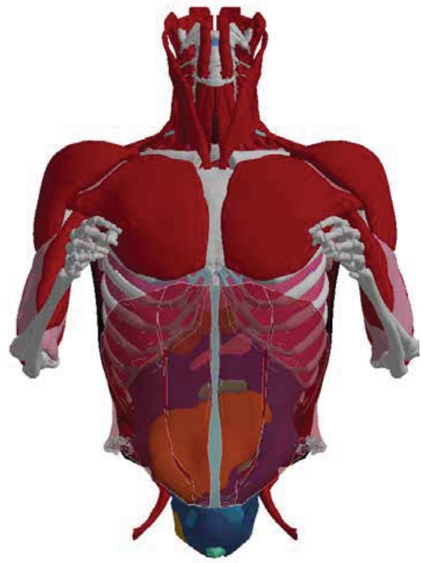

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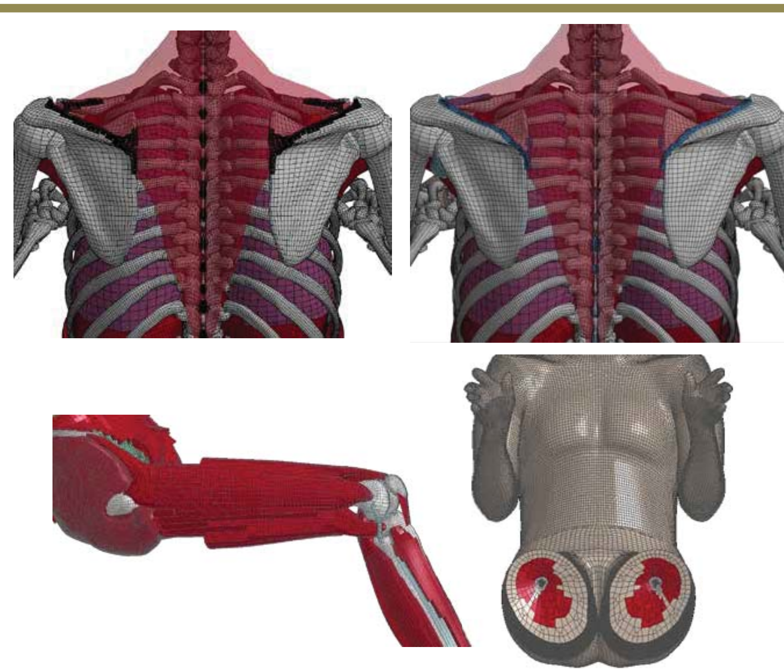

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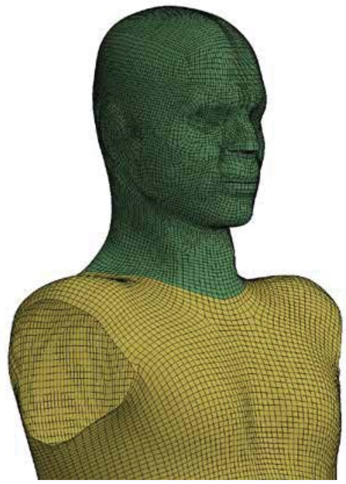
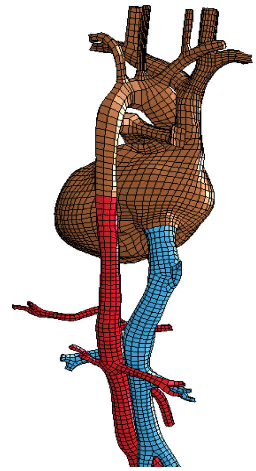


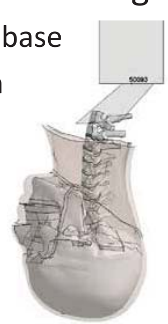


Component level Integration: Mini Case Studies

Inter-

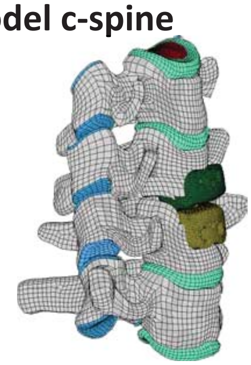
Human Model into dummy cert test

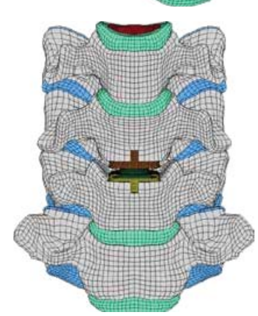
- **Purpose**: Understand matched pair performance of human model in ATD cert procedure
- Disarticulation of model from body
- Attachment of model to test rig
  - Constrain rigid part to base
  - PMMA like connection



Simulated Arthroplasty w/ model c-spine

- **Purpose**: C5 and C6 modified to study the effects of cervical total disk replacement
- Reverse engineer from samples
- Mesh size considerations
  - Direct mesh vs. tied contacts
  - Modification of baseline human model





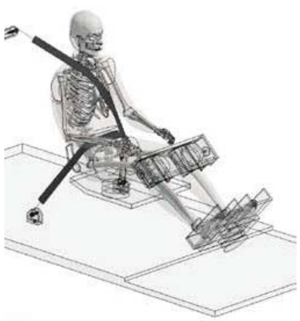
White et al. I J Crashworthiness. 2016 May 19; 21(4), 1-15

Environment or Equipment Integration

Inter-

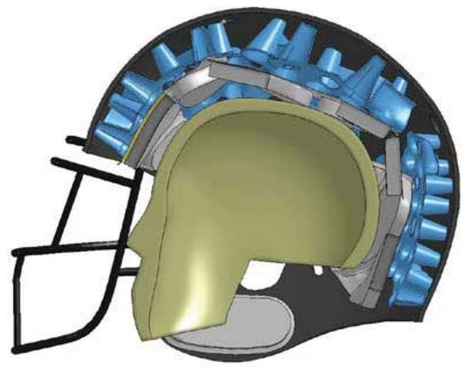
Integration into test rig environment

- Gross positioning (FEA motion or software)
- Gravity settle
- Belt fit and pre-tensioning
- Contact birth/death times



Donning protective equipment

- Pre-shrink and grow to fit or pre-expand and shrink to fit
- Careful to not over-constrain
- Use post-fit checks



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MODEL VERIFICATION AND VALIDATION

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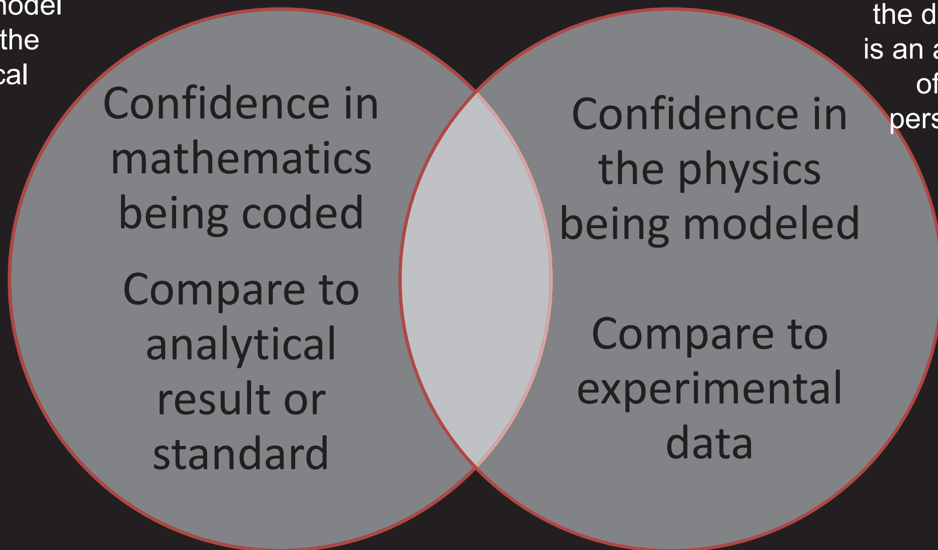
V&V in the Context of FEA Models

Verification[1]

The process of determining that a computational model accurately represents the underlying mathematical model and its solution.

Validation[1,2]

The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.



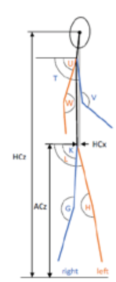
1 ASME

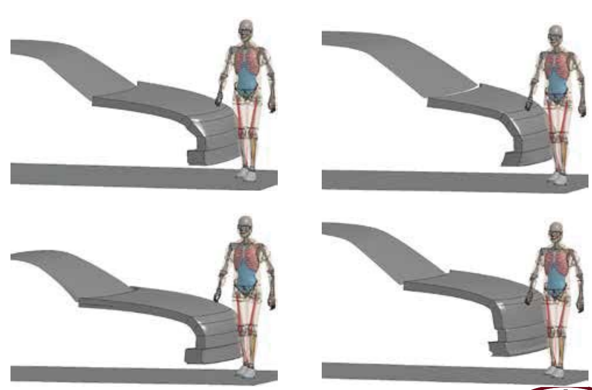
2 Los Alamos National Laboratory

Performance Verification in Human Modeling

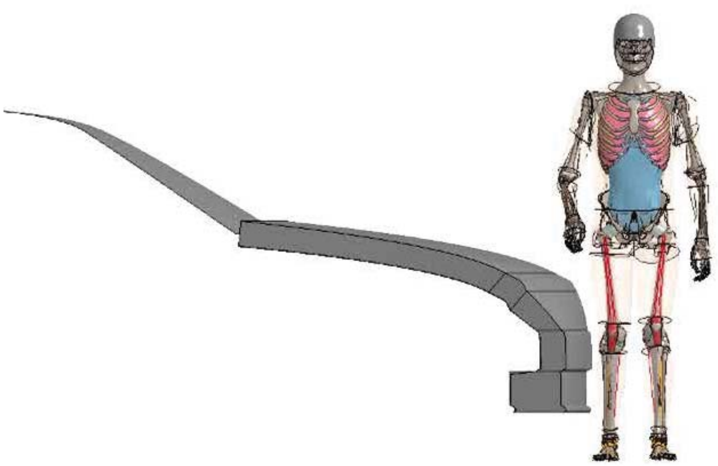
- Euro NCAP Pedestrian Protocol TB 24
  - "A combination of physical testing and numerical Human Body Model (HBM) simulations is required to demonstrate the suitability of the sensing system for the range of pedestrian sizes"
  - HBM compliance to a standard must be demonstrated (verified performance)
  - User reports solver (version, platform, precision, CPUs)
  - Simulation details regulated (mass scaling, various settings, shoes, output parameters, positioning)
  - Controlled impact environment
  - Substantial pre- and post-simulations checks

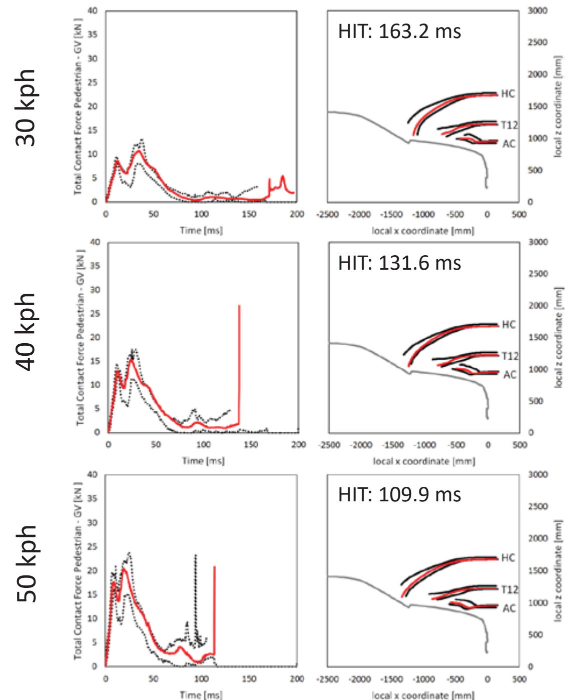
04. Checks			
(Thresholds and Quality creiteria from Imviter Project)	FCR		
	30kph	40kph	50kph
Contact force (between HBM and vehicle) is zero at simulation start	OK	OK	OK
Surfaces getting in contact do not cross each other (visual control)	OK	OK	OK
Surfaces getting in contact do not get trapped one in the other (visual control)	OK	OK	OK
Total energy remains constant (taking into account external works) within a 15% tolerance	OK	OK	OK
Hourglass energy <= 10% of the total energy	OK	OK	OK
Contact energy at the simulation start <= 1% of the total energy	OK	OK	OK
Elastic contact energy <=10% of the total energy	OK	OK	OK
Artificial energy (like elastic contact energy and hourglass energy) <= 15% of the total energy	OK	OK	OK
Artificial mass increase for moving parts <= 3%	OK	OK	OK
Time step does not fall and stays excessively low (check message file)	OK	OK	OK
Contact Force is within corridor (not necessary for test phase)	OK	OK	OK
Trajectories are within corridor (not necessary for test phase)	OK	OK	OK
HCT is within tolerance (not necessary for test phase)	OK	OK	OK





Performance Verification in Human Modeling





Validation: Best Practices in Human Modeling

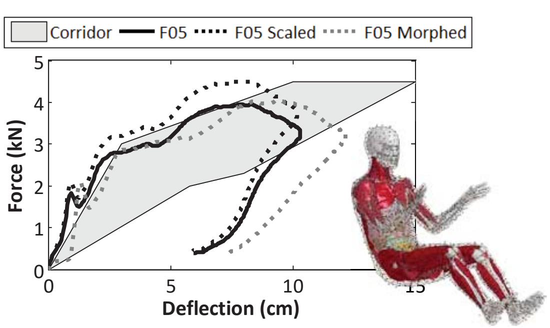
Do at Every Level (tissue, organ, region, full body) & Attempt to Quantify Sources of Uncertainty

Before → After

Morph to Match[1]

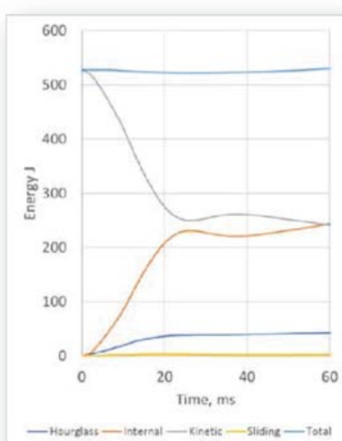
and/or

Prepare Experimental Data

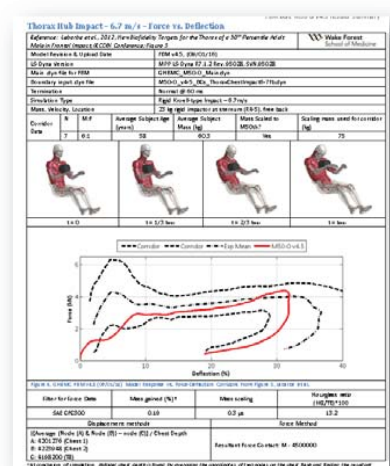


1. Davis M. L et al., 2016, Development and Full Body Validation of a 5th Percentile Female Finite Element Model, Stapp Car Crash J, vol. 60: pp. 509-544.

Simulation Quality Checks



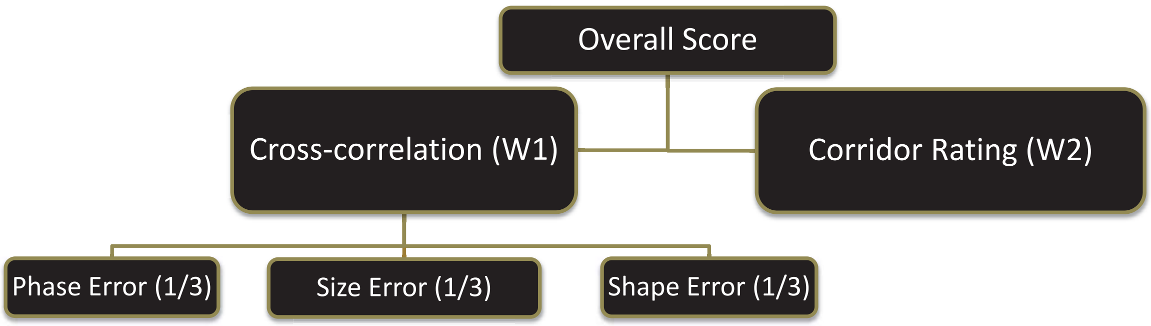
Robust Reporting



Objective Evaluation Techniques

Two commonly applied techniques for objective rating time history signals for dynamic systems

1. CORA
2. ISO/TS 18571



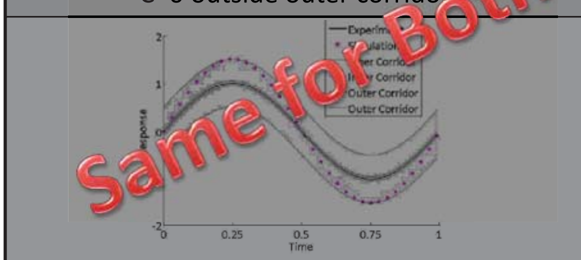
Recreated from ISO/TR 16250, Fig. 10-1

1. Gehre et al., *ESV Proceedings*, 2009
2. Zhan et al., *SAE 2011-01-0245*, 2011
3. Barbat et al., *ESV Proceedings*, 2013

Comparison Scoring

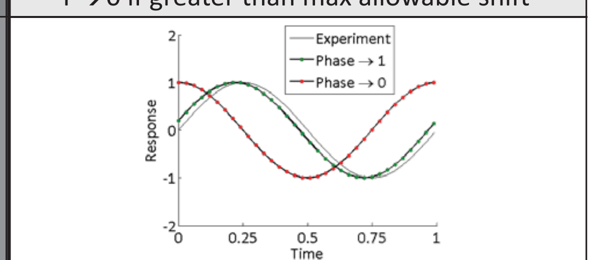
Corridor

C=1 inside inner corridor
C=0 outside outer corridor



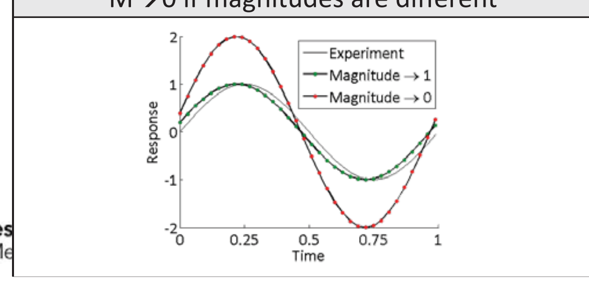
Phase

P→1 if perfectly in phase
P→0 if greater than max allowable shift



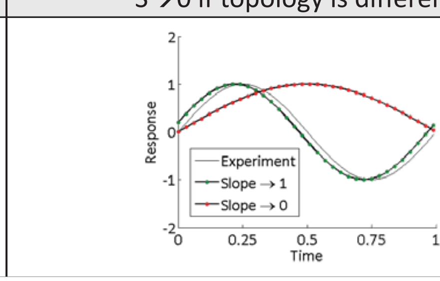
Size

M→1 if magnitudes are equal,
M→0 if magnitudes are different



Shape

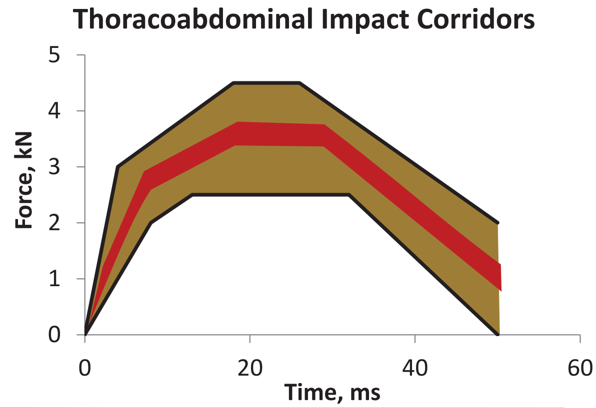
S→1 if topology is similar,
S→0 if topology is different



1. Gehre et al., *ESV Proceedings*, 2009
2. Zhan et al., *SAE 2011-01-0245*, 2011
3. Barbat et al., *ESV Proceedings*, 2013

Objective Evaluation: Corridor Rating

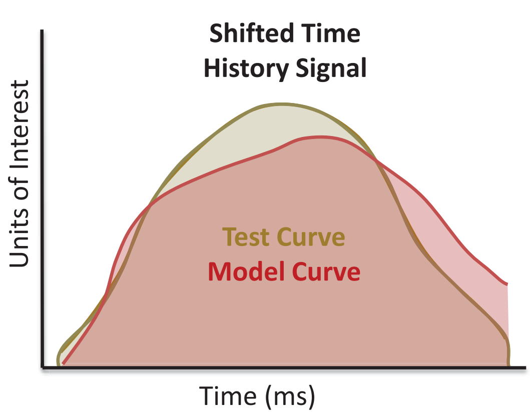
- **Corridor rating is a simple way to factor in experimental uncertainty**
- Model is compared to two sets of corridors (an inner and outer) that can be automatically defined or input from experimental data (ex. ± 2 σ curves)
- If evaluated curve is within inner corridor the score is “1”
- If the evaluated curve is outside of the outer corridor the score is “0”
- Scores in between established using a regression



Differences in score? Size (aka Magnitude)

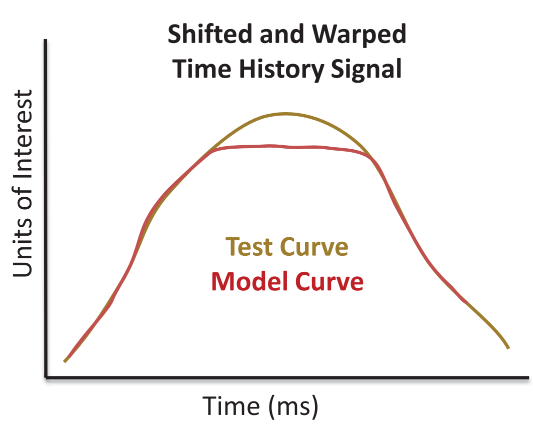
CORA

- Size score calculated from area underneath the curves after the applied phase shift
- Developed as a ratio of squared areas



ISO

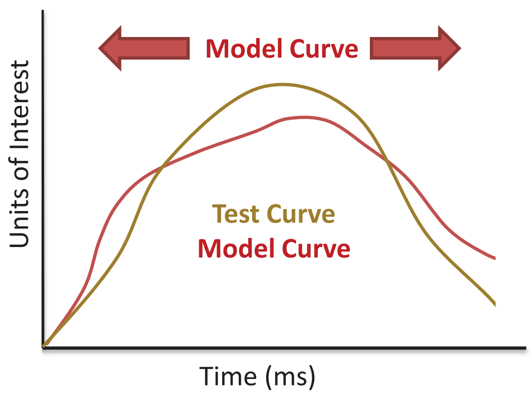
- Calculation performed after phase adjustment between the two signals
- EEARTH technique employs a function known as dynamic time warping (DTW)
- Calculation based on vector norms between the two curves



Differences in score? Phase

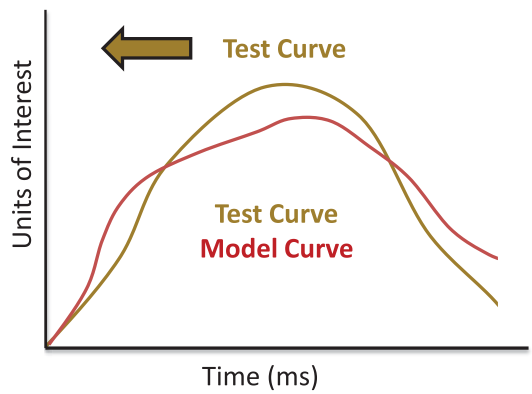
CORA

- Shift model signal by multiples of Δt in relation to the test curve to determine max cross-correlation
- Amount of shift used to calculate the phase score



ISO

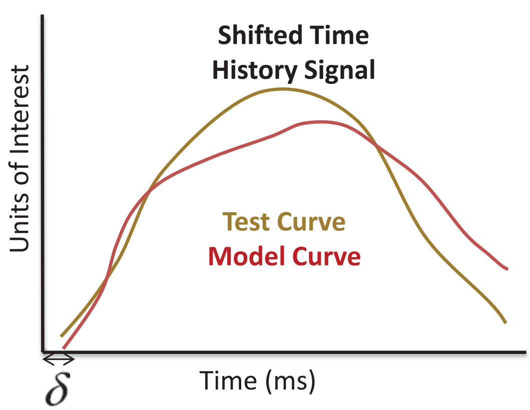
- Similar to CORA
- Mean signal value taken into account in cross-correlation calculation



Differences in score? Shape (aka Progression or Slope)

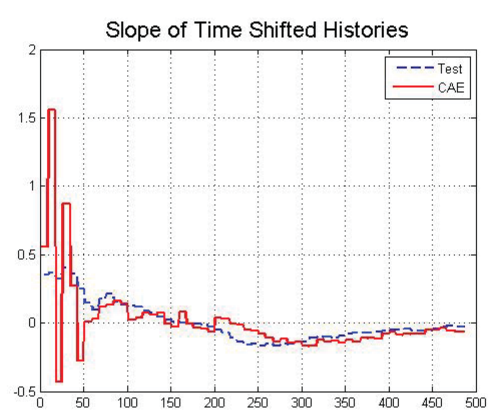
CORA

- Derived directly from maximum cross-correlation, *p* $\longrightarrow Z_{2c} = \frac{1}{2}(\rho+1)^{k_{Z2c}}$
- As a result, indicates how closely the two curves are related in terms of overall shape

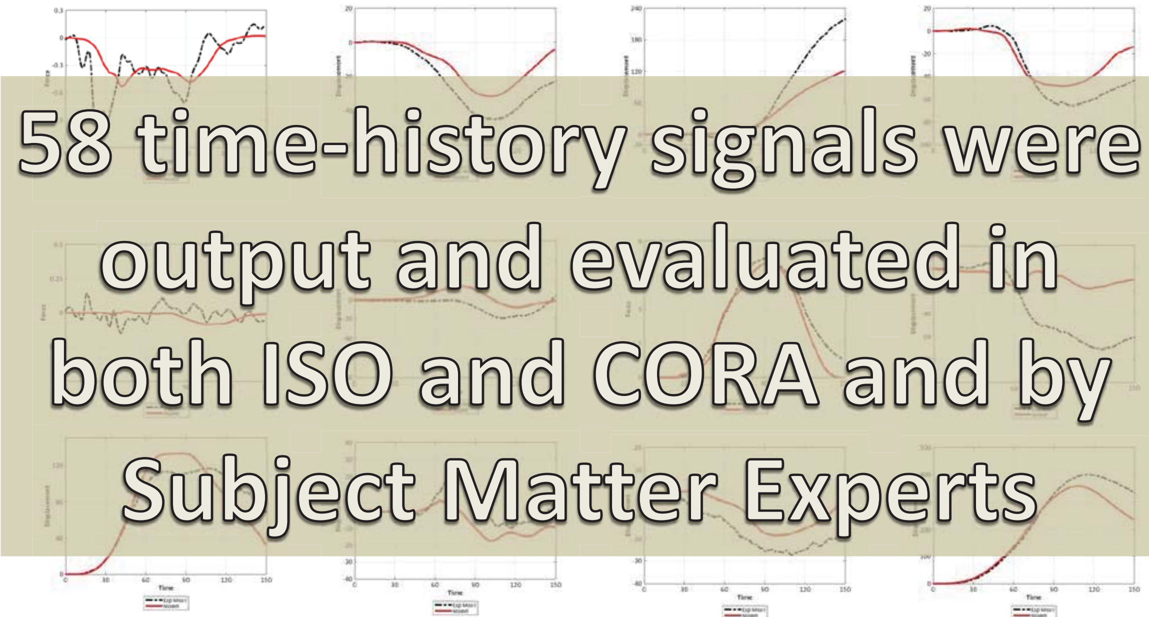


ISO

- Evaluates topological error
- Topology is defined as slope over each interval
- Slope is calculated from the shifted time histories



CORA and ISO Compared with Engineering Intuition?



58 time-history signals were output and evaluated in both ISO and CORA and by Subject Matter Experts

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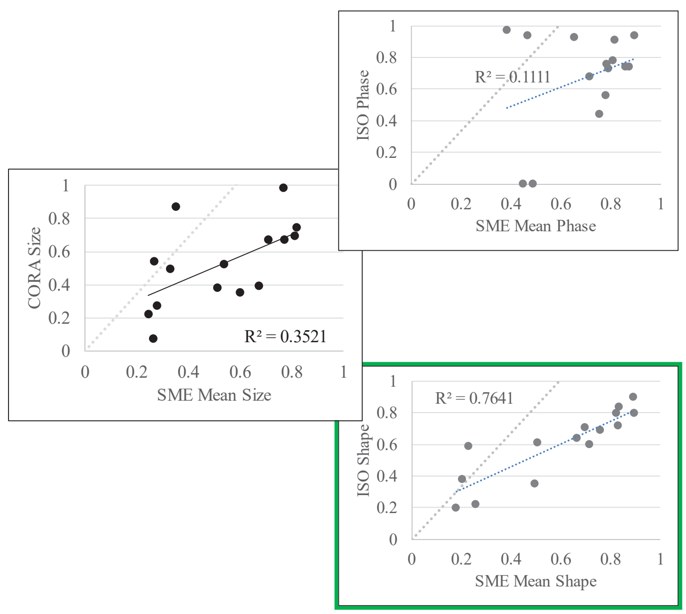
CORA and ISO Compared with Engineering Intuition?

- Survey of subject matter experts
- Asked to rate signals on the same basis (phase, mag, shape)
- Experts agreed with:
  - CORA Size ✓
  - ISO Shape and Phase ✓✓



Gayzik FS, Davis, ML, Koya, B., Schap, J, Hsu, FC, Comparison of Objective Rating Techniques vs. Expert Opinion in the Validation of Human Body Surrogates, ASME J. Verification, Validation and Uncertainty Quantification, *in review*

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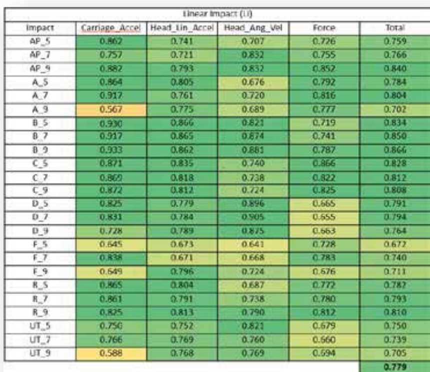
Objective Evaluation: Pros and Cons

Pro

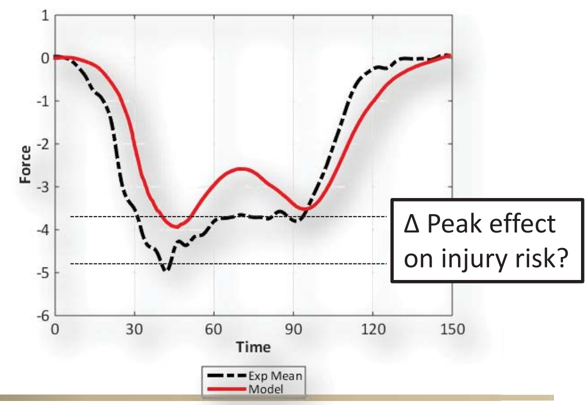
- Understand variation in performance
- Track model improvements
- **Quickly analyze many trials**



Linear Impact (LI)					
Impact	Carriage_Accel	Head_Lin_Accel	Head_Ang_Vel	Force	Total
AP_5	0.862	0.741	0.707	0.726	0.759
AP_7	0.757	0.721	0.832	0.755	0.766
AP_9	0.882	0.793	0.832	0.852	0.840
A_5	0.864	0.805	0.676	0.792	0.784
A_7	0.917	0.761	0.720	0.816	0.804
A_9	0.567	0.775	0.689	0.777	0.702
B_5	0.930	0.866	0.821	0.719	0.834
B_7	0.917	0.865	0.874	0.741	0.850
B_9	0.933	0.862	0.881	0.787	0.866
C_5	0.871	0.835	0.740	0.866	0.828
C_7	0.869	0.818	0.738	0.822	0.812
C_9	0.872	0.812	0.724	0.825	0.808
D_5	0.825	0.779	0.896	0.665	0.791
D_7	0.831	0.784	0.905	0.655	0.794
D_9	0.728	0.789	0.875	0.663	0.764
F_5	0.645	0.673	0.641	0.728	0.672
F_7	0.838	0.671	0.668	0.783	0.740
F_9	0.649	0.796	0.724	0.676	0.711
R_5	0.865	0.804	0.687	0.772	0.782
R_7	0.861	0.791	0.738	0.780	0.793
R_9	0.825	0.813	0.790	0.812	0.810
UT_5	0.750	0.752	0.821	0.679	0.750
UT_7	0.766	0.769	0.760	0.660	0.739
UT_9	0.588	0.768	0.769	0.694	0.705
					0.779

Con (Caution)

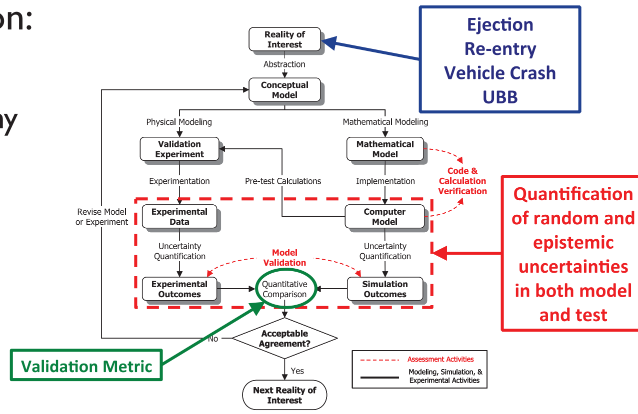
- Standardize configuration files used
- Window and weight appropriately
- **Consider key aspects of your analysis**
- Leaves out uncertainty quantification



CONSIDERING UNCERTAINTY IN THE MODEL

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

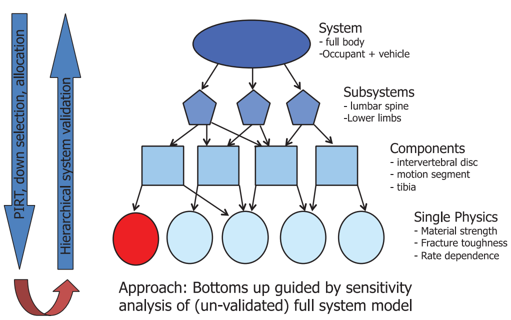


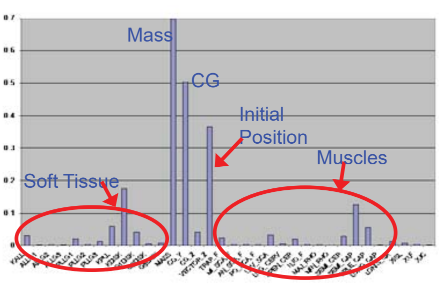
Dan Nicolella
Southwest Research Institute
San Antonio, TX

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



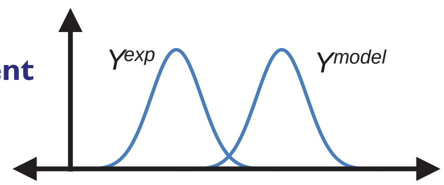


- Validation hierarchy
  - Breaks the problem into smaller parts
  - Validation process employed for every element in the hierarchy (ideally)
  - Allows the model to be challenged (and proven) step by step
  - Dramatically increases likelihood of right answer for the right reason
- Customer/stakeholder establishes intended use and top-level validation requirement
- 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
- Full system (un-validated) sensitivity analysis can provide guidance

Validation Metrics

How do you define valid?

- A metric is the quantitative <u>*measure*</u> of the mismatch between model predictions and experimental data
- Typically some type of a difference measure in system response quantities (statistics, probability distributions, etc.)
- Generally, multiple response quantities and associated metrics are better than one (right answer for the right reason)
- Desired features of a validation metric
  - **Consider uncertainties in both the model and the experiment *– implies a statistical comparison***



Francis et al. (2012): Implementation and validation of probabilistic models of the anterior longitudinal ligament and posterior longitudinal ligament of the cervical spine, CMBBE

ACTIVE V & V FOCUSED WORKING GROUPS

ASME V&V40: *Verification and Validation of Computational Modeling for Medical Devices*

ASME V&V CHARTER	**Coordinate, promote, and foster the development of standards that provide procedures for assessing and quantifying the accuracy and credibility of computational models and simulations.**

V&V 10	Computational Solid Mechanics
V&V 20	Computational Fluid Dynamics and Heat Transfer
V&V 30	Computational Simulation of Nuclear System Thermal Fluids Behavior
V&V 40	**Computational Modeling of Medical Devices**
V&V 50	Computational Modeling for Advanced Manufacturing

Tina M. Morrison
Chair, FDA Modeling and Simulation Working Group

- Not how to do V&V but how to determine the level of evidence needed to support using a computational model for a specific ***context of use***

  KEY ASPECTS
  - new concepts regarding context of use, model risk and credibility goals
  - risk-informed credibility assessment framework
    - rigor of V&V is commensurate with **model risk**
  - emphasize documentation and reporting

Slide source:
https://www.imagwiki.nibib.nih.gov/sites/default/files/Flash--FDA_6.pptx

Verification and Validation of Computational Modeling and Simulation - A community effort.
- https://dx.doi.org/10.6084/m9.figshare.3468962.v1

POSTER: Risk-informed Credibility Assessment Method.
- https://dx.doi.org/10.6084/m9.figshare.3409291.v1

Summary

Model Integration

- Intra-model integration
  - GHBMC like development
- Inter-model integration
  - More commonly faced challenge
  - Discussed some best practices

Verification and Validation

- Verification examples in human modeling
- Validation best practices
- Objective evaluation techniques
- Account for uncertainty in both model and experiment
- Working groups focused on standardizing validation

Acknowledgments: Modeling Team at WFU

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Acknowledgements

Sponsors:

GHBMC
Global Human Body Models Consortium

FCA
General Motors Corp.
Honda R&D Co.
Ford Motor Co.
Hyundai Motor Co.
NHTSA
Nissan Motor Corp. Ltd
PDB
Renault s.a.s.
Takata Corp.
PSA Peugeot-Citroën

NHTSA

NSF

WAKE FOREST HPC DEAC CLUSTER

BIOCORE

Contributing information used in presentation from:

EURO NCAP FOR SAFER CARS

SwRI

ASME SETTING THE STANDARD

FDA

Los Alamos NATIONAL LABORATORY EST. 1943

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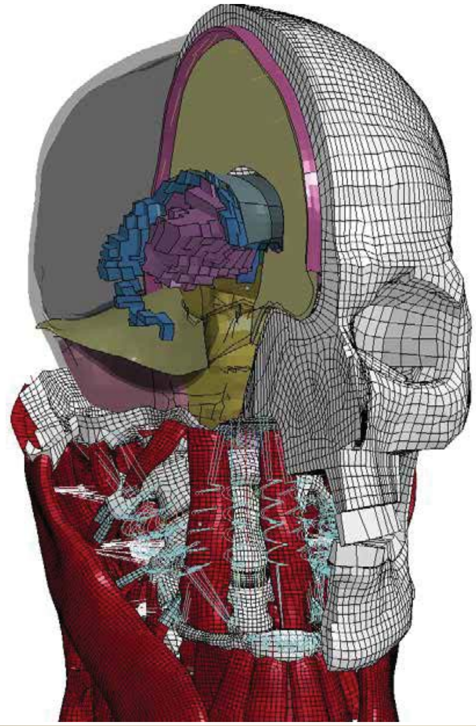
Acknowledgements

Thank you!



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IMMC

IRCOBI 2018 Workshop Series

IRCOBI
International Research Council on Biomechanics of Injury

Human Body Modeling and Validation with Biomechanics Experiments

Duane S. Cronin PhD, PEng, Professor
University Research Chair in Impact Mechanics and Material Characterization
Professor, Department of Mechanical and Mechatronics Engineering
Cross-Appointed to Applied Health Sciences
Board Member and Council Member, International Research Council on Biomechanics of Injury
Director, Impact Mechanics and Material Characterization Group

1

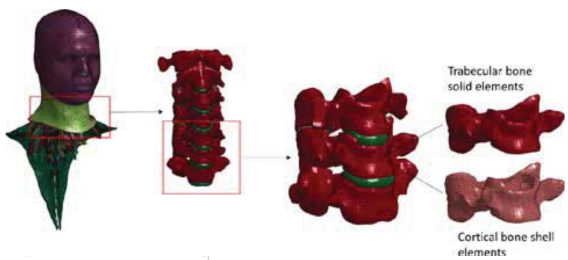
Can computational models actually tell us

anything

we don’t already know?

Yes… if we ask the right (simple) questions.

[Models can help us understand complex problems]



[INTENT and model SCALE are important]

Some thoughts on models

Models can allow us to:

- Interpret experimental results
- Investigate response to impact (sensitivity studies)
- Consider new designs for protection and safety

- Essentially, all models are wrong,
  but some are useful. [George Box 1976]

[A computational model must be designed with **balance**]

Original 41920 elements 1.4mm | Medium (Single Split) 222660 elements 0.7mm | Fine (Double Split) 1544880 elements 0.35mm

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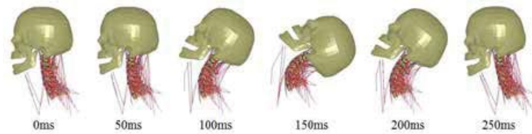
Some thoughts on models



- It is not possible to validate a model, only to invalidate a model. [Karl Popper]
  - Falsifiability
    - A theory or model is falsifiable, if we can conceive of an observation or experiment which can show the model to be false.

- Verification and Validation - V&V
  - Verification: solving the equations correctly
  - Validation: solving the correct equations

[Models are pretty good for some problems,

but a single model may not answer all questions]

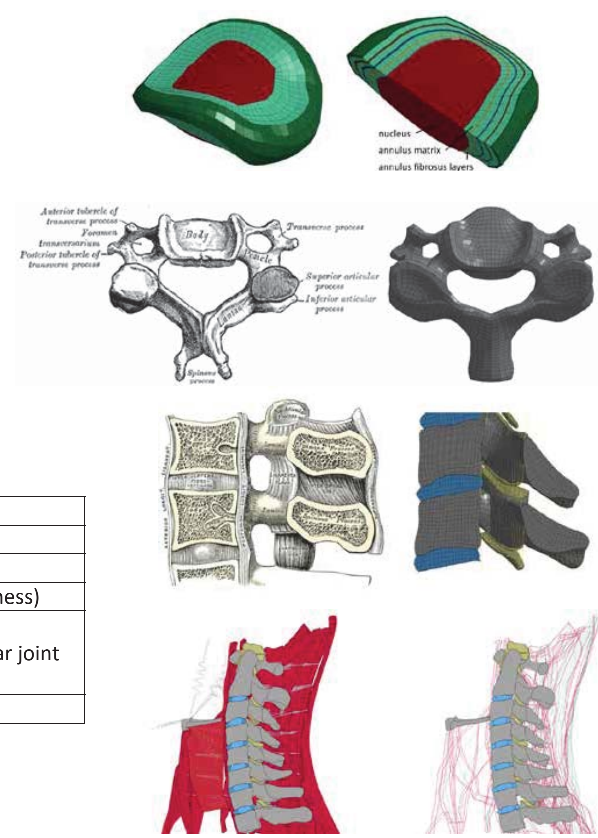
Assessment of Injury Risk

AIS	Injury Examples
1 (Minor)	Spinous ligament injury, Strain (acute) with no fracture or dislocation
2 (Moderate)	Disc injury, Dislocation (no cord involvement, no fracture), Fracture of the spinous process, transverse process, facet, lamina, pedicle (no cord involvement), Nerve root contusion or laceration
3 (Serious)	Cord contusion, Odontoid fracture, Bilateral facet dislocation, Vertebral body burst fracture (>20% loss of anterior height)
4 (Severe)	Incomplete cord syndrome
5 (Critical)	Complete cord syndrome (C4 or below), Cord laceration (C4 or below)
6 (Fatal)	Complete cord syndrome (C3 or above), Cord laceration (C3 or above)

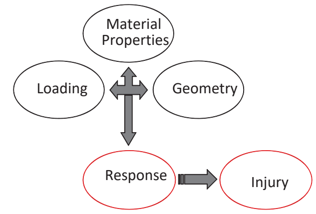
AIS injury scale and examples of cervical spine injury (AAAM 2005)

Grade	Clinical Presentation
0	No neck pain or physical signs.
I	Complaint of neck stiffness, pain, or tenderness. No identifiable physical signs.
II	Neck complaint and musculoskeletal signs (decreased range of motion and tenderness)
III	Neck complaint and neurological signs (includes decreased or absent deep tendon reflexes, dizziness, tinnitus, headache, memory loss, dysphagia, temporomandibular joint pain).
IV	Neck complaint and hard tissue fracture or dislocation.

Whiplash Associated Disorders, Clinical classification (Spitzer et al. 1995)

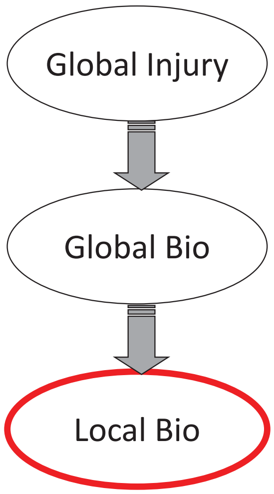


Prediction of Injury Risk

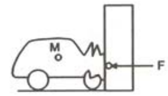


- A question of scale…

Model Scale

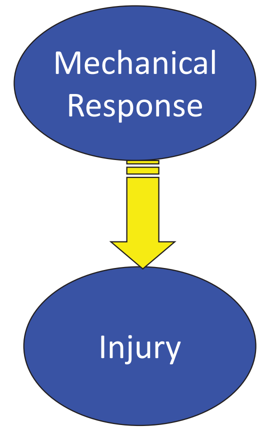


Load-based [vehicle g's]



Neck bending moment, axial load, kinematics

Local tissue injury



Experimentalists
Epidemiologists
Scientists
Medical
Engineers
…

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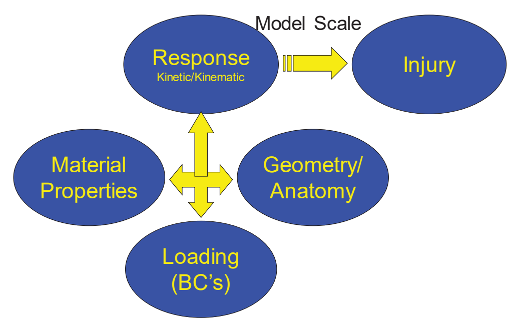
Assessment of injury

- Contributing Factors:
  - Anatomical dimensions, musculature, posture (Stemper et al., 2011)
  - Age
  - Population variability
  - Occupant position (Kaale et al., 2005, Watson and Cronin 2011, Gierczycka and Cronin 2015)

- Challenges:
  - Limited diagnostics
  - Mechanisms of injury still not completely understood (proposed locations/tissues)
  - Contribution of muscle and muscle activation
  - Increased risk of injury for out-of-position occupants (Ivancic et al., 2006; Winkelstein et al., 2000, Shateri and Cronin 2015)



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HBM

- A model must be developed with intent
- Models can provide new insights, if we ask the right questions

- What do we want the model to tell us?
  - Validation data?

    (and what is not possible with the model?)

- If you can model the problem, you better understand the process

[Sometimes it's the journey, not the destination]

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Side Impact Safety

UNIVERSITY OF Waterloo

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Improvement
of occupant safety
in vehicle side crashes

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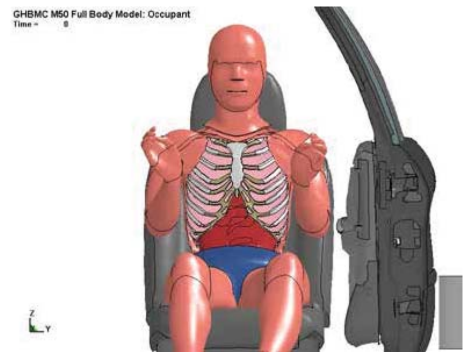
Moving Forward

- There will be some challenges,
  It will be a long road, but models can inform us



- Active musculature, low severity impact
- ‘Virtual Twin’
- Tissue-level injury prediction
  - Physiology
- Aging

Thanks!