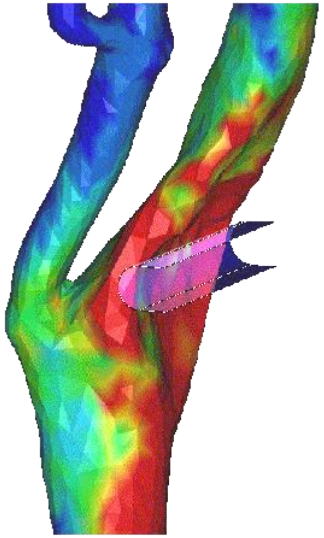
Advanced Human Body Modeling
Solid Mechanics Basics Bootcamp



Course Instructors

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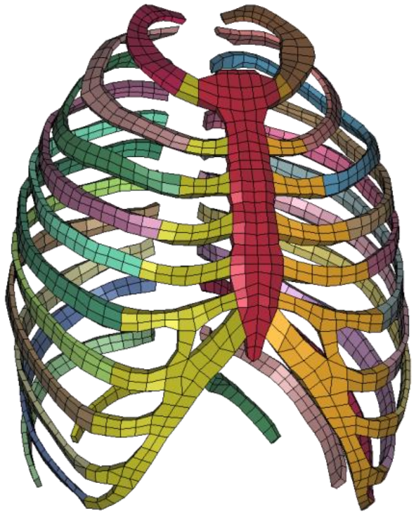


Center for Injury Biomechanics

Wake Forest School of Medicine

CIB

Virginia Tech Wake Forest University

School of Biomedical Engineering and Sciences

Class Basics

Image Analysis

Segmentation and quantitative analysis of medical images

Mimics, Simpleware, Osirix, Slicer, etc.

CAD Generation

Polygon to NURBS (CAD)

Geomagic Studio, Solidworks

Mesh Generation

CAD to FEA mesh

Hyperworks, Ansa, Truegrid, IA-FEMesh, gmsh

Pre & Post Processing

Get models ready to run and then read info back

Hyperworks, LS-PrePost

Solving

Solving FEA HBM models

LS-Dyna

You can spend years on this topic but we'll cover the basics in 25 min ☺

What is Human Body Modeling?

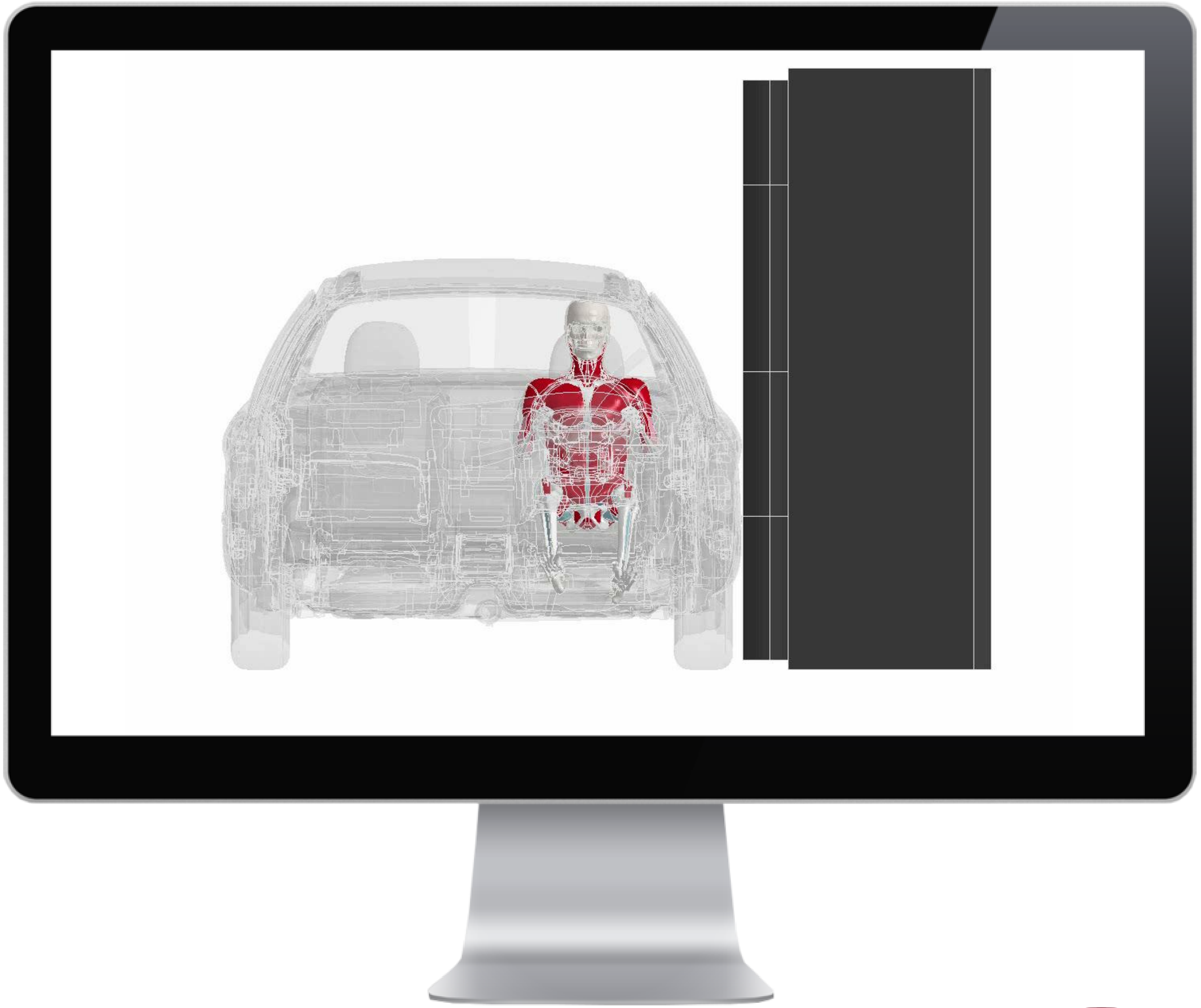
Computational Model

Loads on the Body

Injury Risk

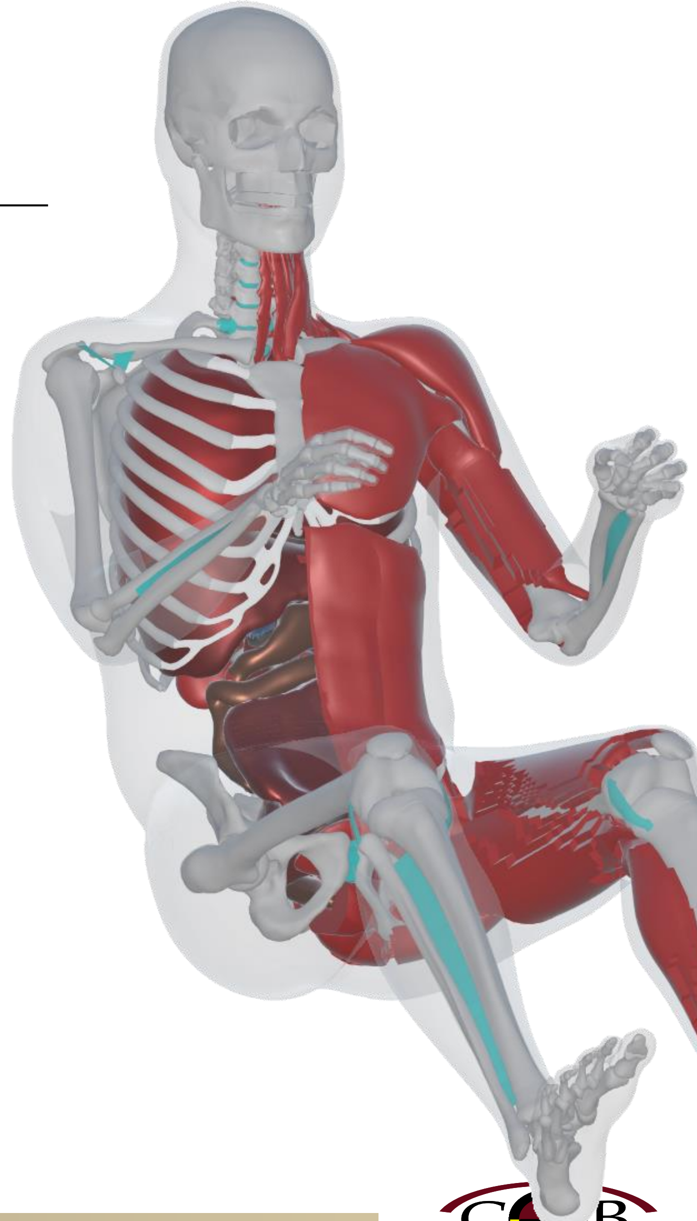
Injury Mechanisms

Foundational Biomechanics, Regulation, Product Design, Consumer Awareness



Why Take a Simulation Approach?

	Traditional Dummy	Computational Model
Life span	Approx. 10 years	Indefinite
Height / Weight	Fixed sizes	Infinitely variable
Cost	↑ Similar Order of Magnitude ↓	
Per Test Cost	$30,000 ↑	$Minimal ↓
Sensors / data points	55-200	100,000 – 3 million + ↑
Applications	Directional/ Traditional Seated	Omnidirectional/ Posable/ Regional/ Versatile



Why Modeling?

- Emerging Problems:
  - Can investigate new or future concerns
    - Spaceflight, autonomous vehicle safety, sports concussion
- Targeted demographics:
  - Models can represent ages, sex, comorbidities
- Environment Control:
  - Control input look at difference response for different models, etc.
- Volume of Trials:
  - What is the effect of changes X, Y and Z?
- Pretest Prediction:
  - What will happen if we test this way? What is the most important factor to test in my real experiments
- Injury Criteria Development:
  - Can see forces/displacements or stress/strains at individual parts of the problem

Applications for Biomechanical Solid Mechanics Models

Ground Transportation

- Safety system design evaluation
- Regulatory

Aerospace

- Assess injury risk in space-flight landing conditions
- Safety system design evaluation
- Regulatory

Military

- Solider protection in accelerative loading environments
- Integrate w/ PPE
- Safety system design evaluation

Healthcare

- Assess design performance *in-silico*
- Assess designs for different patients (size, shape, age)

Sports

- Integrate models with safety equipment
- Virtual prototyping
- Equipment Design & Performance enhancement

Very Basic Key Steps in Modeling

Pre-processing

Run the Simulation

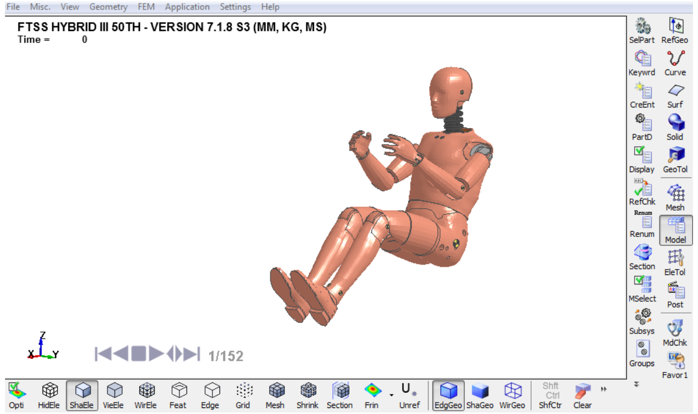
Post-processing

Debugging the input file

What's the most important step in modeling?

Preprocessing

- Select preprocessor
  - Hypermesh (Altair)
  - Primer (Oasys)
  - LS-PrePost
- Geometry
- **Mesh !!! (Extremely Important)**
- Select element types
- Select material models
- Implement contact algorithms
  – Very important in dynamic modeling
- Boundary conditions
- Initial conditions



Differences vs implicit

CAD Development Overview

- Various types of image data is used in the development of geometry data for biomechanical models

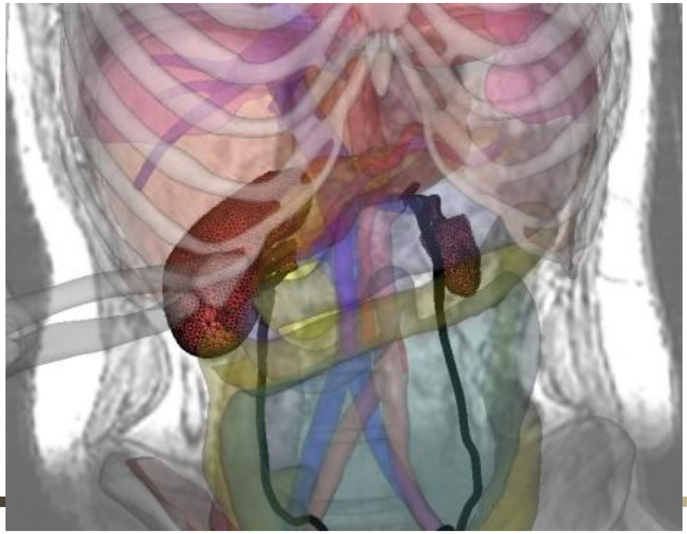
Segment → Condition → Assemble → NURBS (CAD)

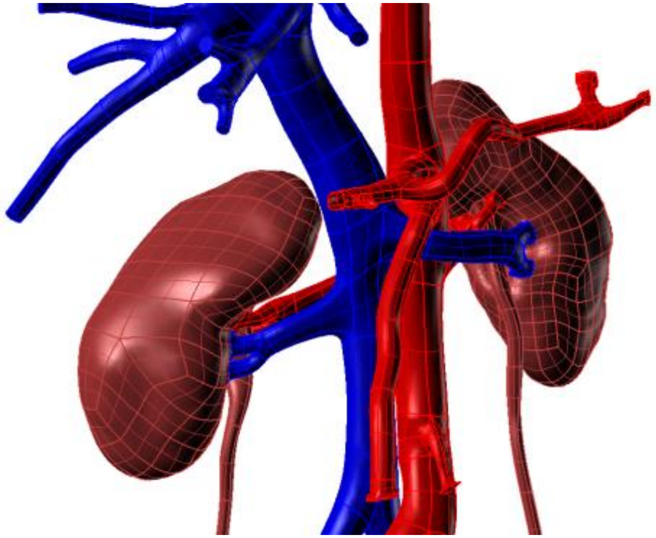
Segment
- Best image data by structure
- Various techniques
  - Manual
  - Semi-automated
  - Atlas based

Condition
- Polygon data
- Symmetry where appropriate
- Remove artifacts
- Literature survey

Assemble
- Upright MRI
- Quasi-seated CT
- Reposition to scan CS

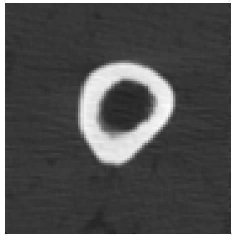
NURBS (CAD)
- Apply NURBS surfaces



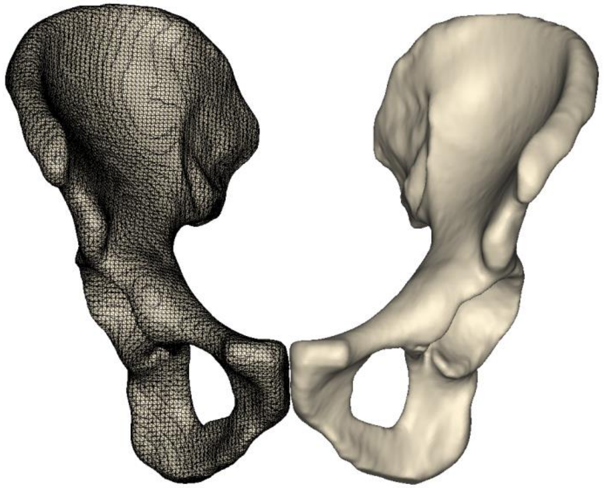


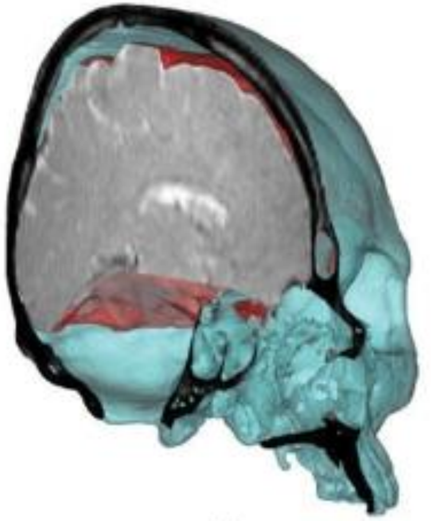
Geometry

- Why develop specific geometry for biomechanical modeling?
  - Anatomic structures are typically complex
  - ‘Organic’ shapes (no simple geometry)
  - Strength / injury is based on unique geometry
  - Not easily re-created in mesh phase
  - Most commercial products will be geared towards common structural applications (flat plate, cylinder, sphere, etc.)



Femur midshaft

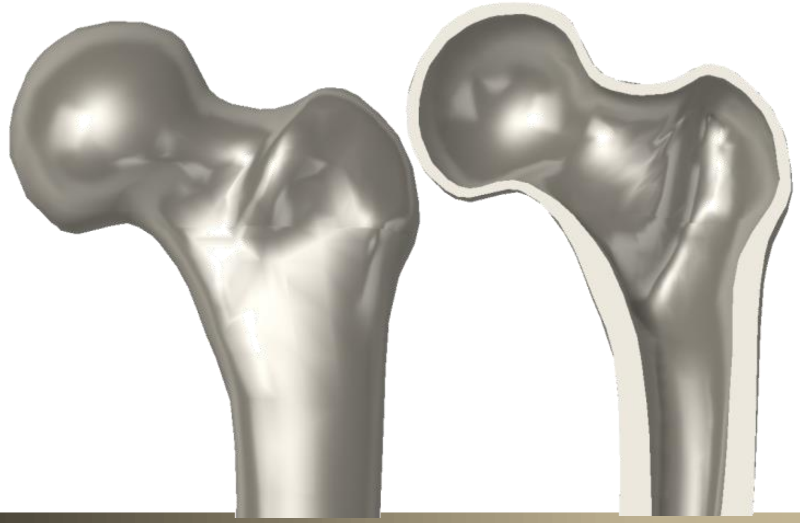


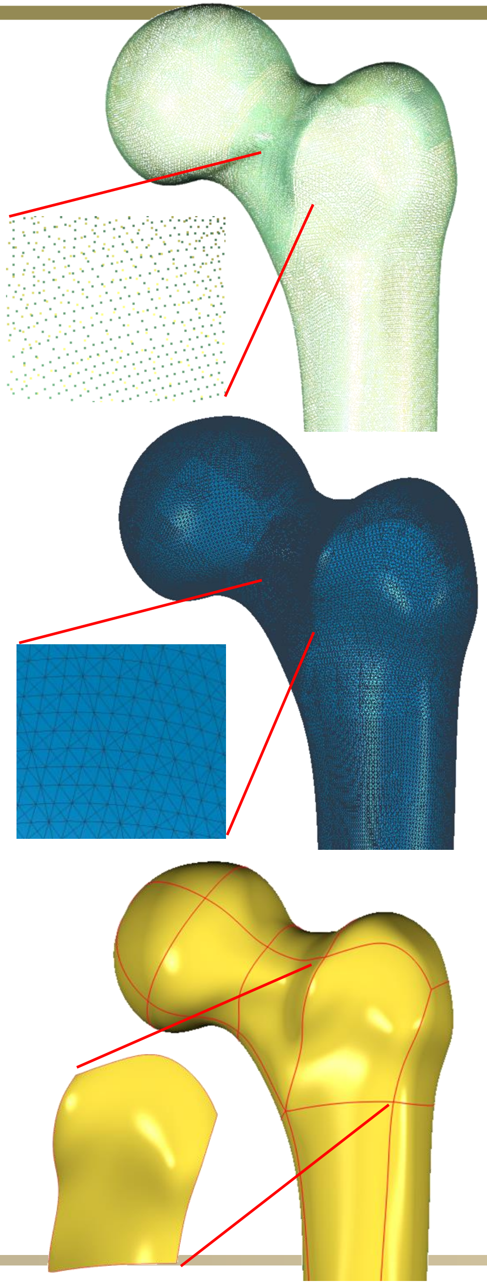


http://www.materialise.com/materialise/view/en/4440092-The+ultimate+virtual+crash+test+dummy.html?cat=2414686
http://www.materialise.com/download/en/4219802/image///view/pelvis_triangulated.png

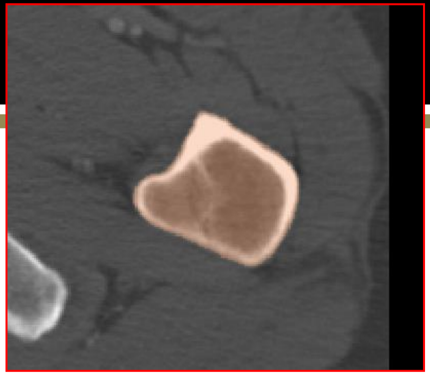
Geometry

- ‘Geometry’ file types
  - Points (.txt): “Scan data”
    - X Y Z coordinates
  - Surfaces: “Medical Image / RP”
    - Polygonal (.stl, .obj, etc.)
    - NURBS – ‘CAD’ (.iges, .step)
  - Solids: “Mechanical Design”
    - ‘CAD’ (.iges, .step, mostly individual software packages)





Geometry Workflow



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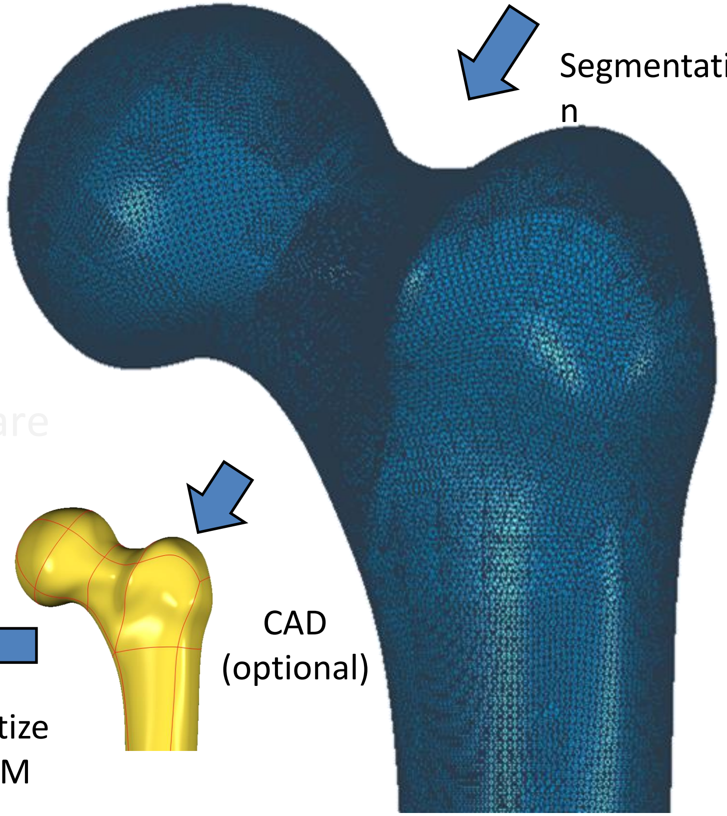
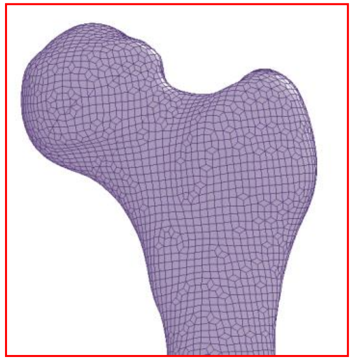
Segmentation



Polygonal Data

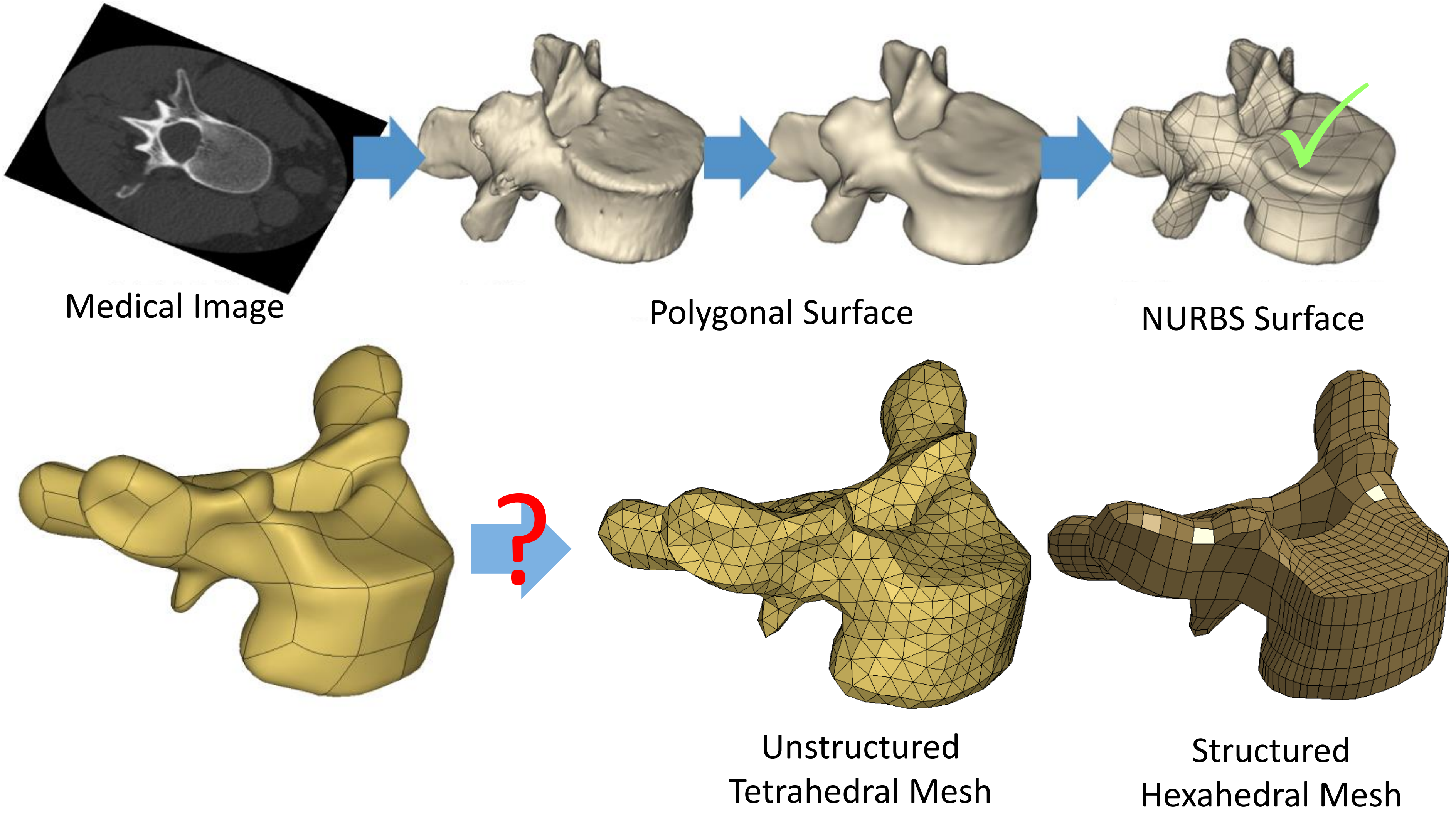
CAD (optional)



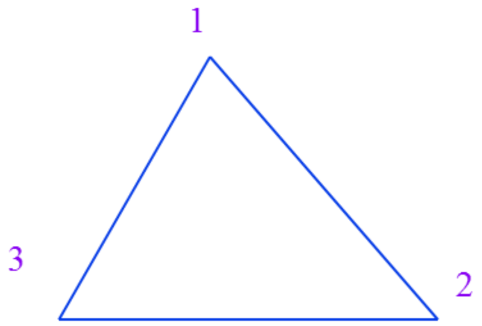
Discritize for FEM

Medical image to 3D Polygonal Model = Segmentation

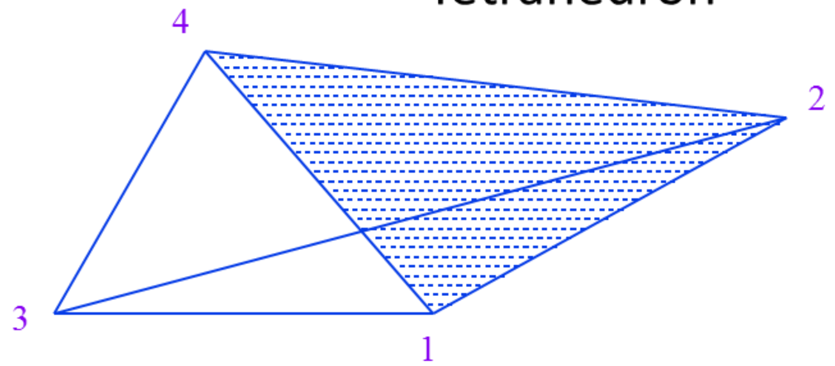
Mesh Workflow



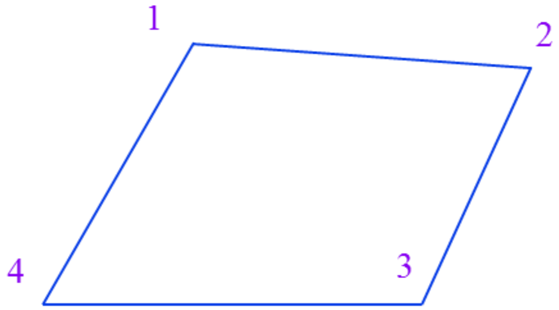
Review of Element Types



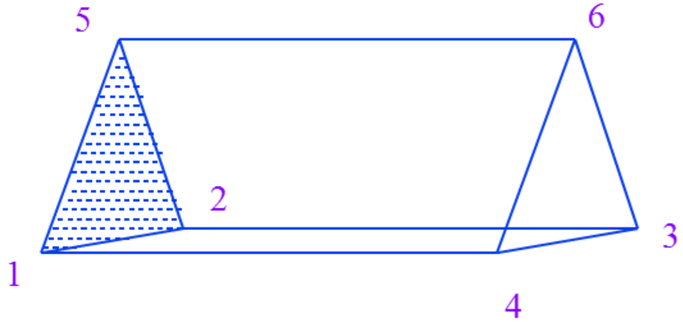
Tria



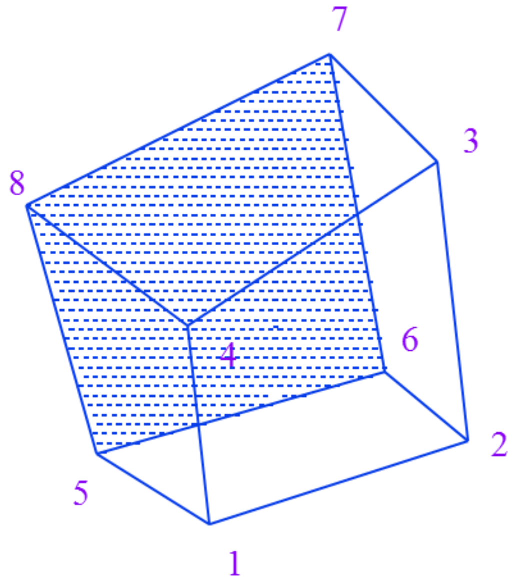
Tetrahedron



Quad

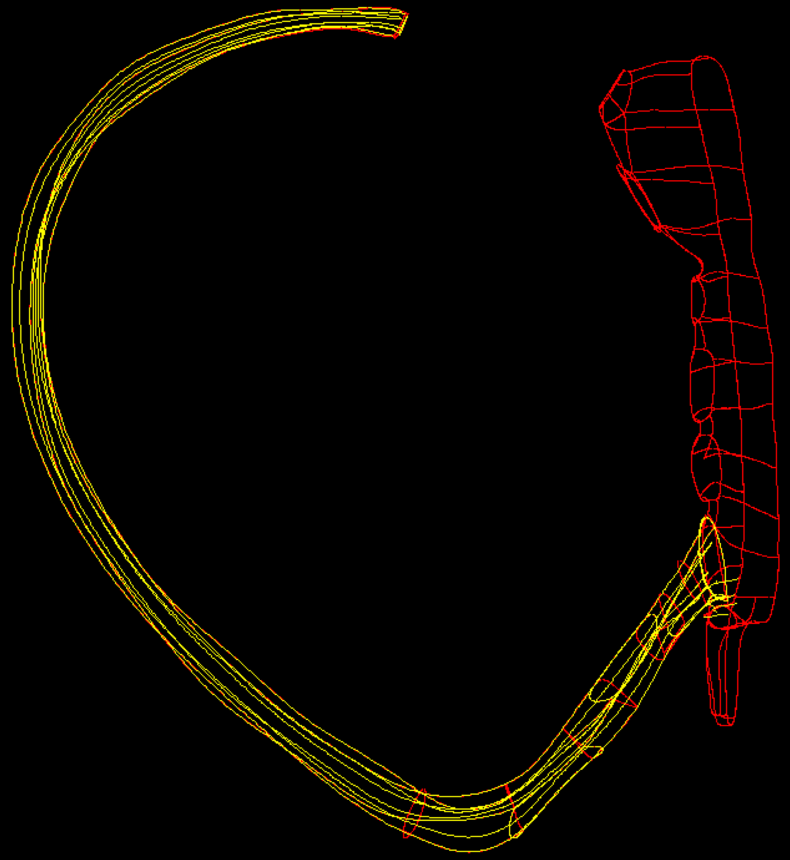


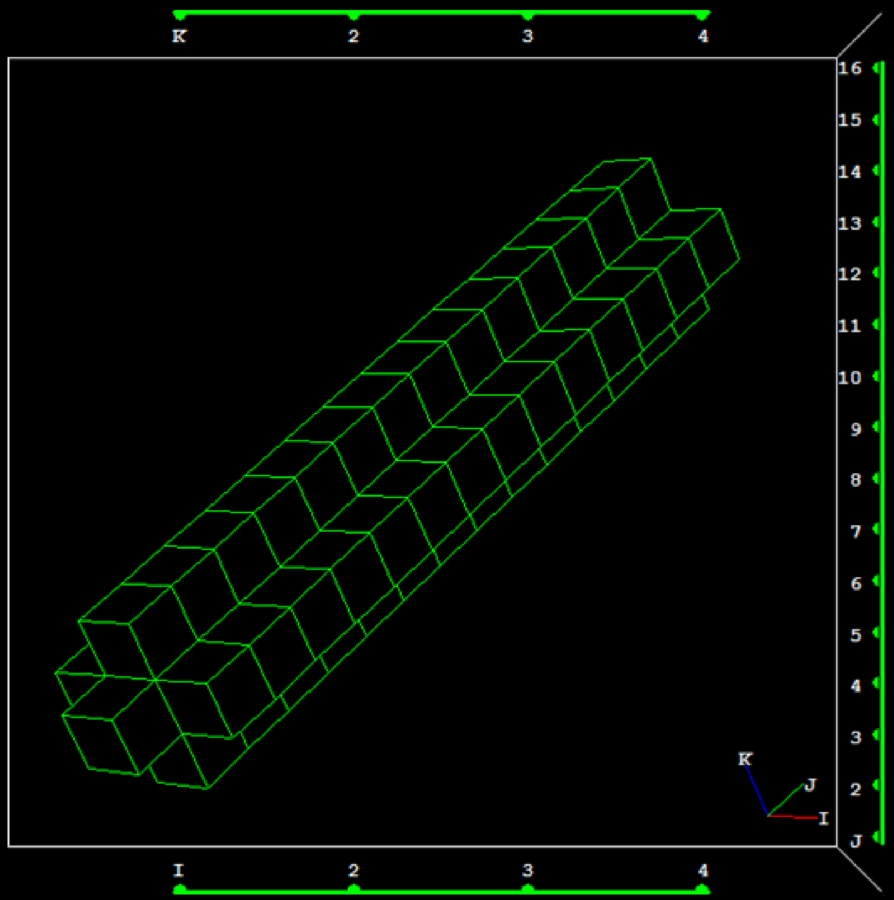
Pentahedron



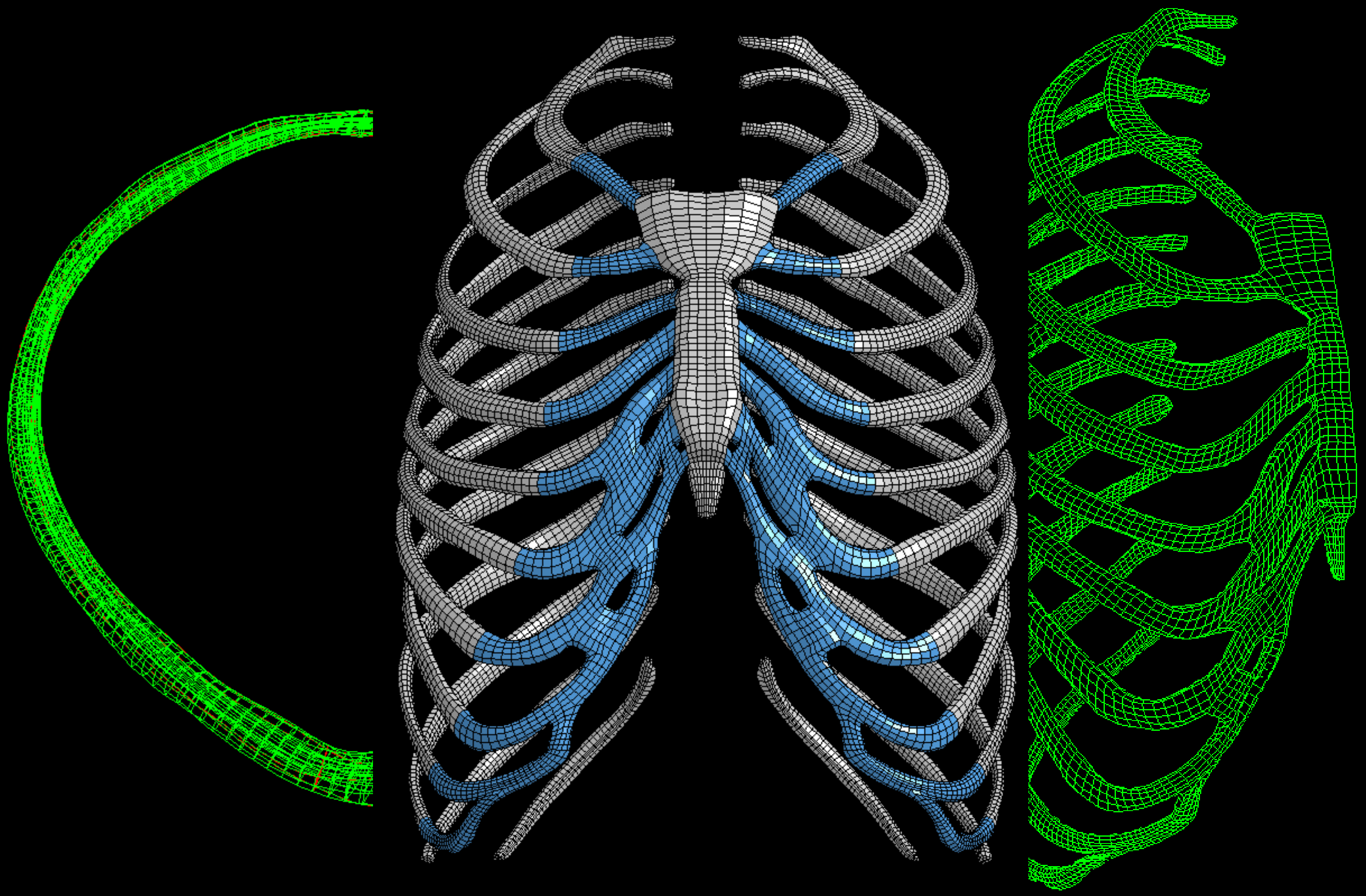
Hexahedron

Structured Hex Mesh





Structured Hex Mesh



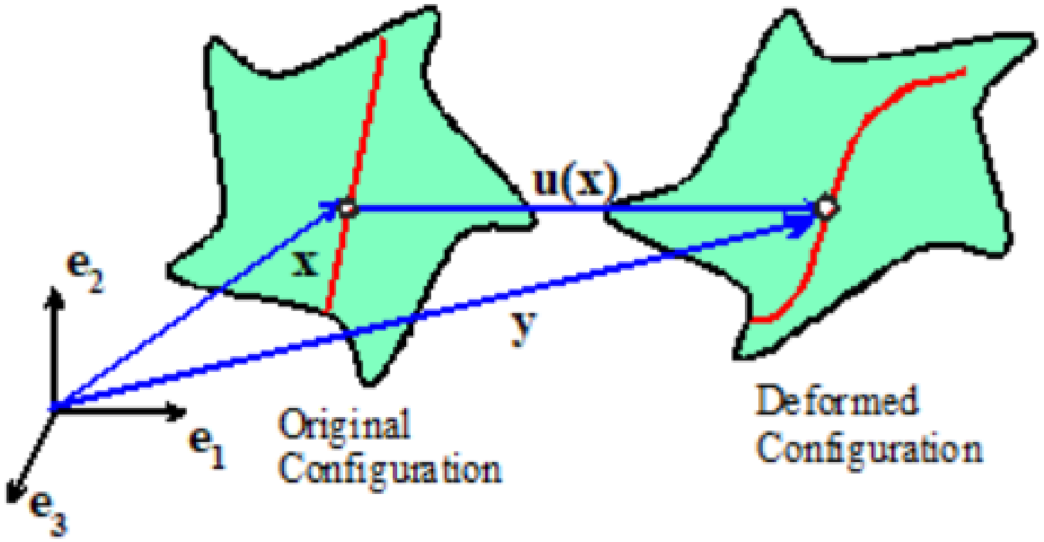
Mesh Convergence

- One of the most overlooked issues in computational mechanics that affect accuracy is mesh convergence. This is related to how small the elements need to be to ensure that the results of an analysis are not affected by changing the size of the mesh
- How do we measure convergence?
  - Error of the displacements
  - Error of the strains
  - Error of the stresses
  - Compare to experimental results

Basics of the FEA Method

- The finite element method (FEM) is a technique for solving partial differential equations.
- One application is to predict the deformation and stress fields within solid bodies subjected to external forces.

To make this precise, visualize a solid deforming under external loads. Every point in the solid moves as the load is applied. The displacement vector ***u(x)*** *specifies the motion of the point at position* ***x*** *in the undeformed solid. Our objective is to determine* ***u(x)***. *Once* ***u(x)*** *is known, the strain and stress fields in the solid can be deduced.*



https://www.brown.edu/Departments/Engineering/Courses/En1750/Notes/FEA_Intro/FEA_Intro.htm

Basics of Time Integration (LS-Dyna)

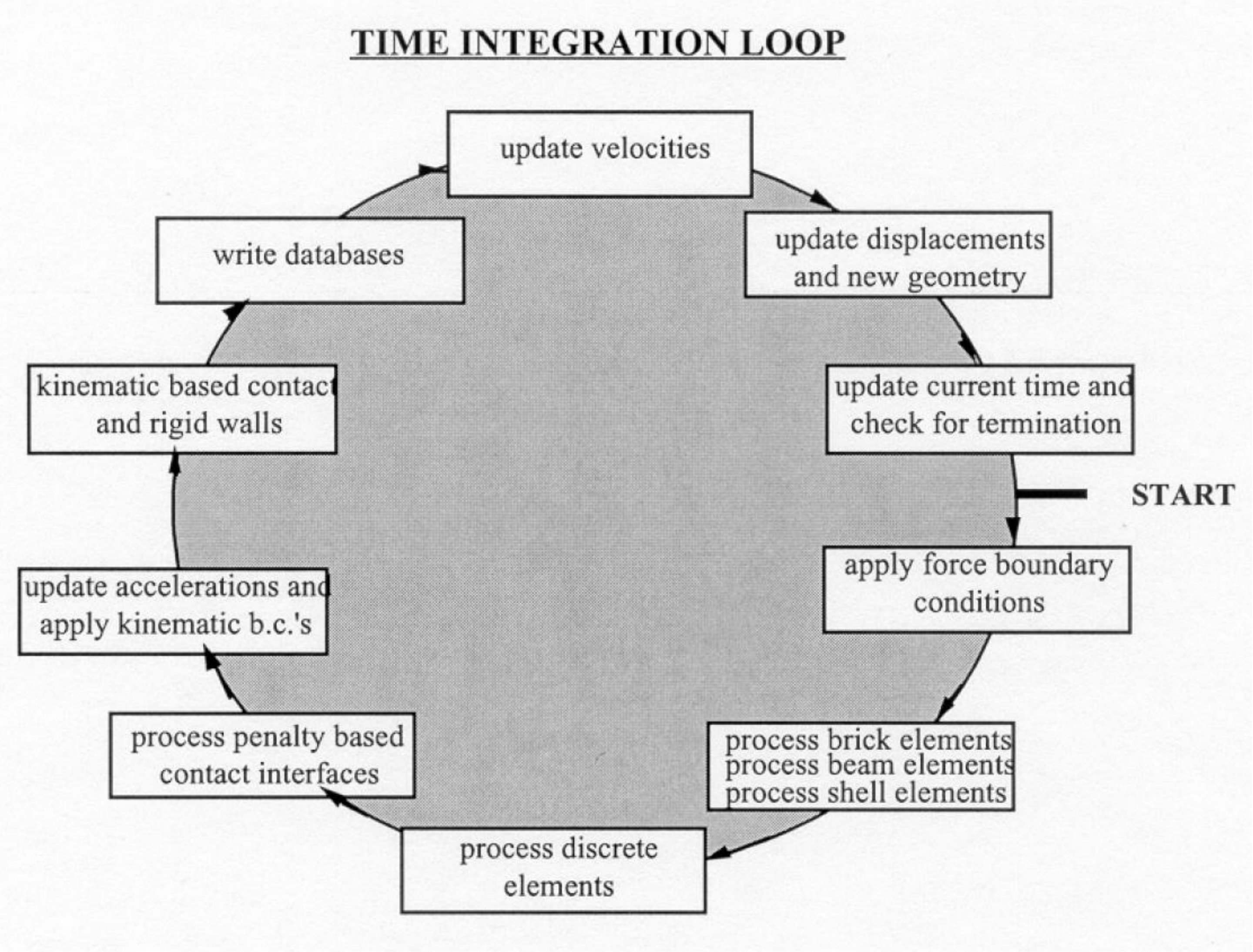


Figure 24.7. The time integration loop in LS-DYNA.

Key underlying principles:

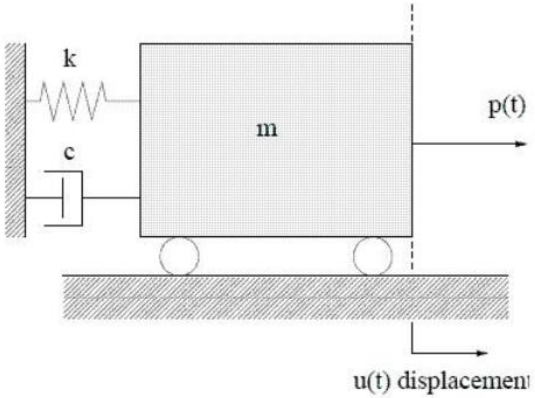
Newton's laws!

1. Conservation of momentum
2. F = ma
3. Equal and opposite forces when objects interact

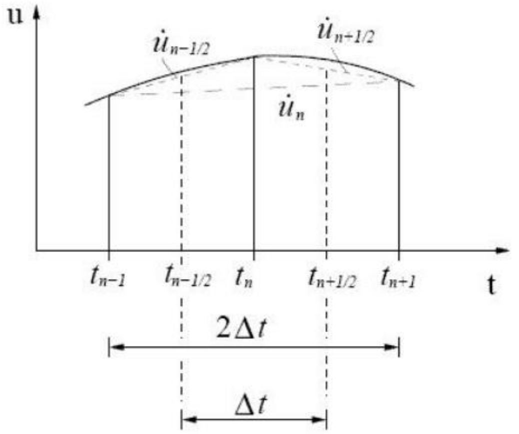
In dynamic problems we must solve equations over a time domain, often milliseconds.

Explicit Time Integration

- Central Difference Algorithm
  - Just a way of solving a partial differential equation
- Solve General Equations of Motion (Partial Differential Equations)
- Assume ***linear*** displacement over integration time step – used to estimate velocities and accelerations
- Not stable above a certain time step or below a certain speed



$$\boxed{m\ddot{u} + c\dot{u} + f_S(u) = p(t)}$$ nonlinear ordinary d.e.



https://www.dynasupport.com/tutorial/ls-dyna-users-guide/time-integration

Explicit Time Integration

- Conditional stability of central difference scheme (Courant criterion)
- Limited time step
  Dt ≤ 2/w
  w is the maximum eigenfrequency in the mesh
- Example for a linear 2-node truss

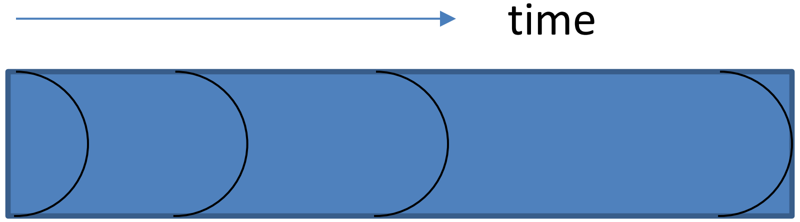
$$\Delta t \le \frac{2}{\omega} = \sqrt{\frac{\rho A L}{EA/L}} = \frac{L}{c}$$

L = element length
E = Young's modulus, rho density
C = Dilatational wave speed

$$c = \sqrt{\frac{E}{\rho}}$$

Explicit Codes

- Time step must stay below a critical level based on:
  - Velocity of stress wave in media (speed of sound – transverse wave)
  - Length of **shortest dimension** of **smallest element** in model
- Mesh density studies can help you minimize time while having good accuracy

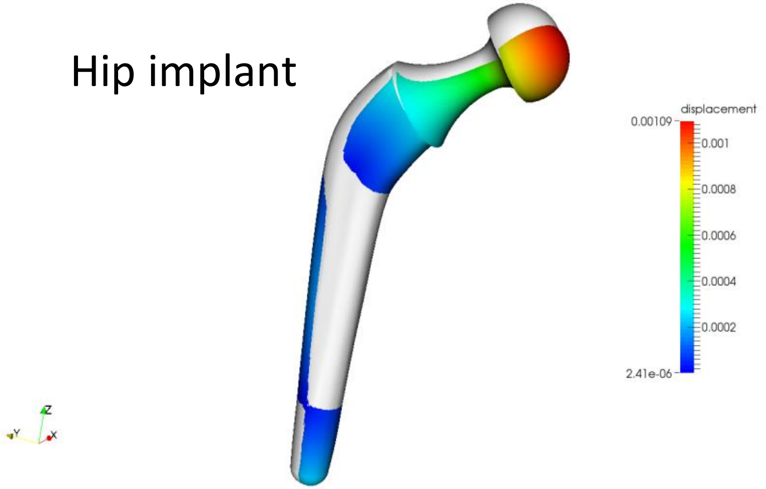


The time step must be shorter than the time for the wave to traverse the element

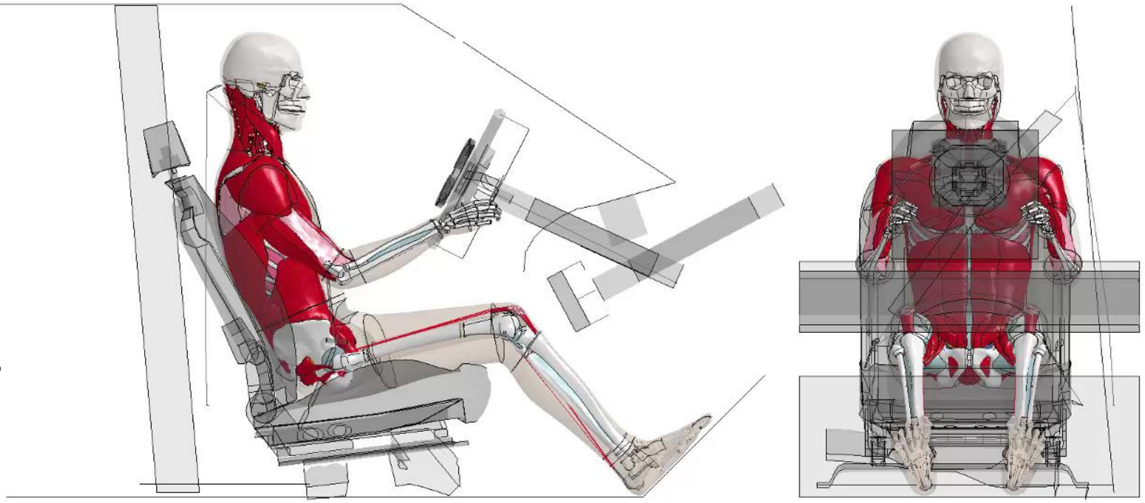
Implicit vs Explicit

- Implicit better for largest variety and number of problems
- Explicit better for
  - Highly nonlinear like biomechanics
  - Extreme deformation
  - High velocity impact with stress wave propagation

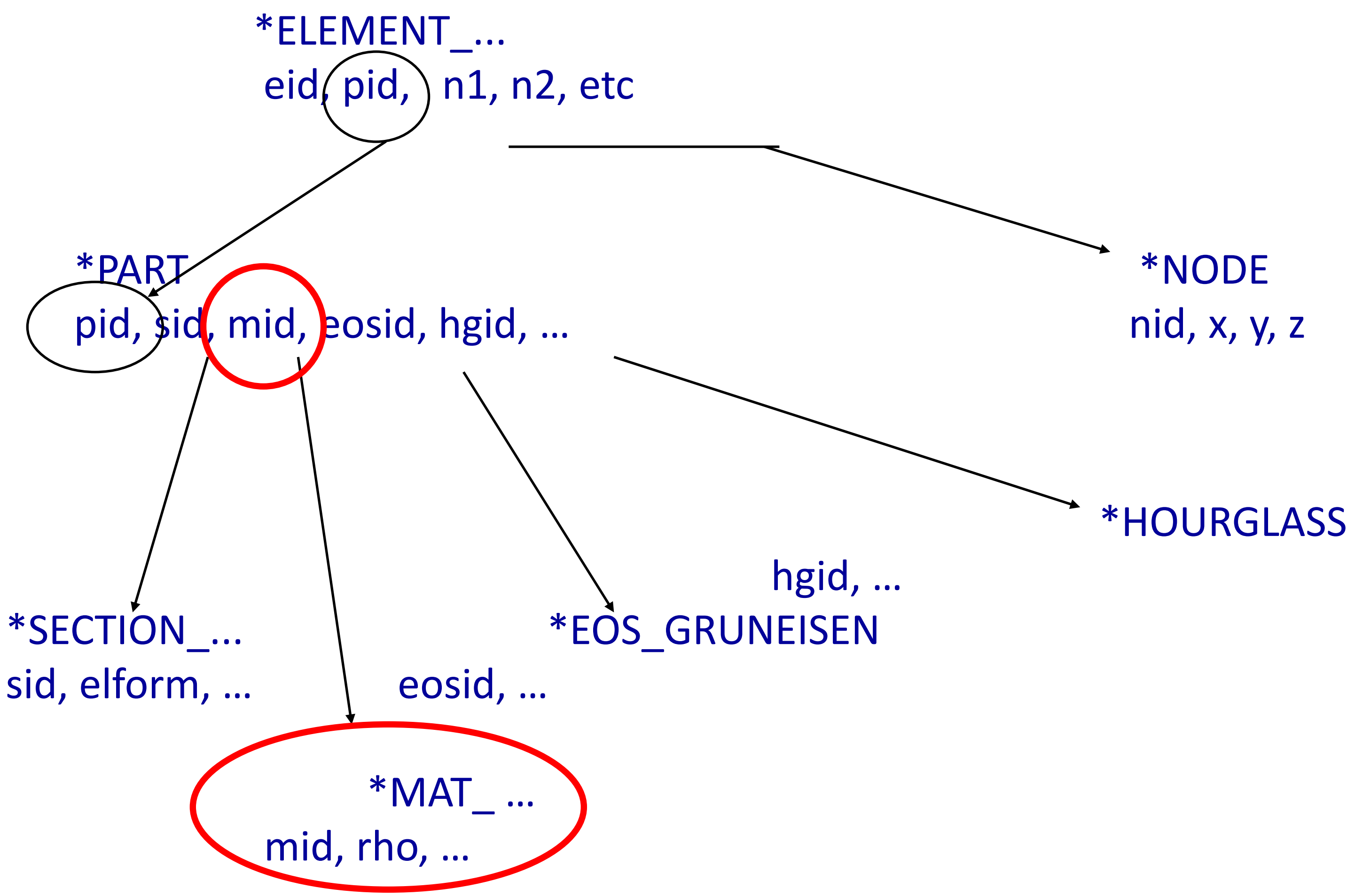
Hip implant



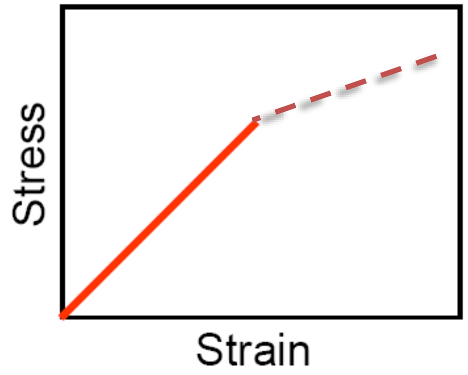
- In general: The explicit method should be used when the strain rates/velocity is over 10 units/second or 10 m/s respectively. These events can be best exampled by extreme scenarios such as an automotive crash, or ballistic event. In these cases, the material models do not only need to account for the variation of stress with strain but also the strain rate. On this scale, the *strain rates* play a particularly important contribution.



Defining a Material



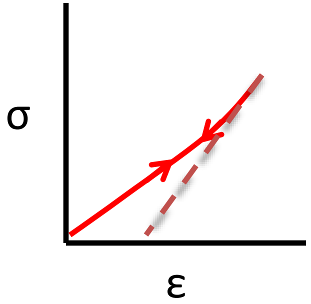
Material Types

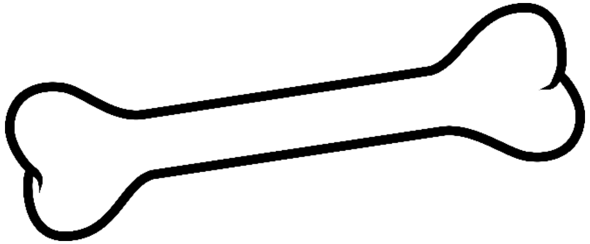


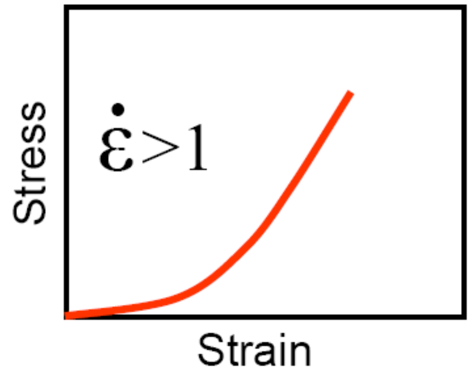
- Linear Elastic

  Piecewise linear

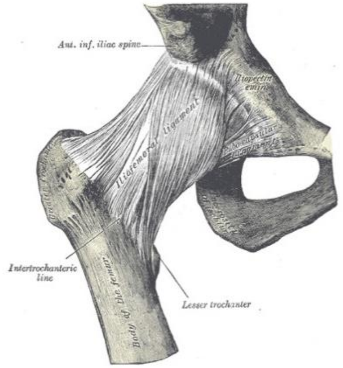
  Plastic deformation

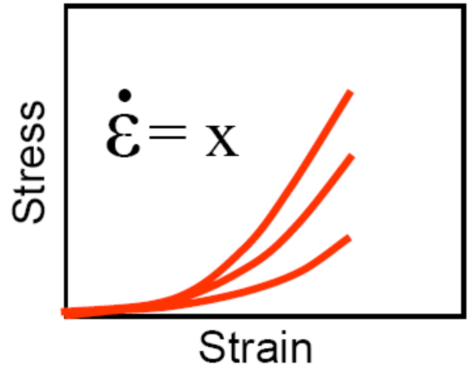




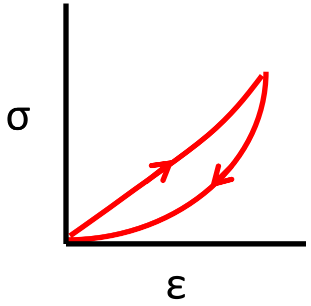


- Nonlinear Elastic
  – Quasi-static
  – Dynamic





- Viscoelastic



Bone as Composite Material

- Bone is a composite of collagen and hydroxyapatite
- Apatite crystals
  - E = 165 Gpa
- Steel, aluminum
  - E = 200, 70 Gpa
- Collagen
  - Tangent modulus 1.24 Gpa
- Bone ~ 18 Gpa young's modulus (tensile femur)

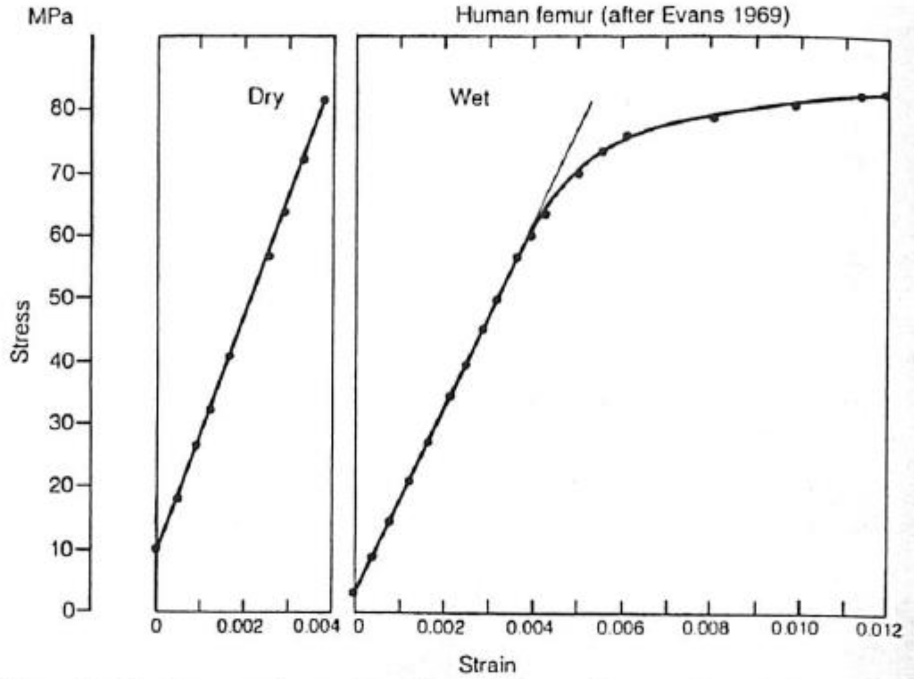
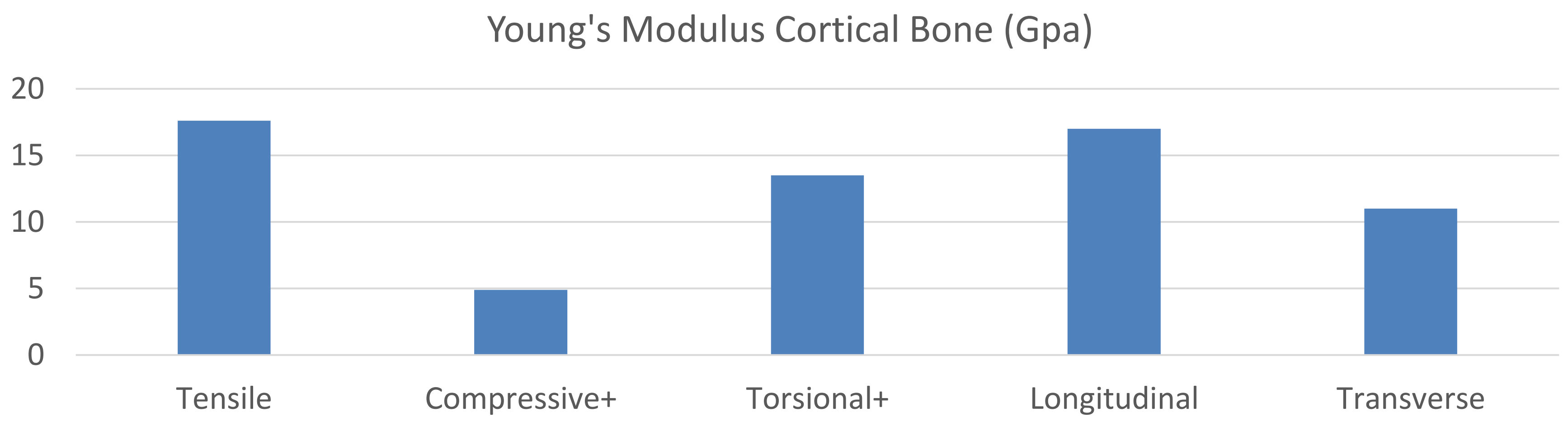


Figure 12.4:1 Stress–strain curves of human femoral bone. Adapted from Evans (1969).

Mechanical Properties of Bone are Complex

- Cortical bone is hard and has stress-strain similar to many engineering materials
- Cancellous bone is soft and is more like a soft tissue
- Bone is a non-homogenous, anisotropic, composite structure
  - + Age, sex, shape dependence…

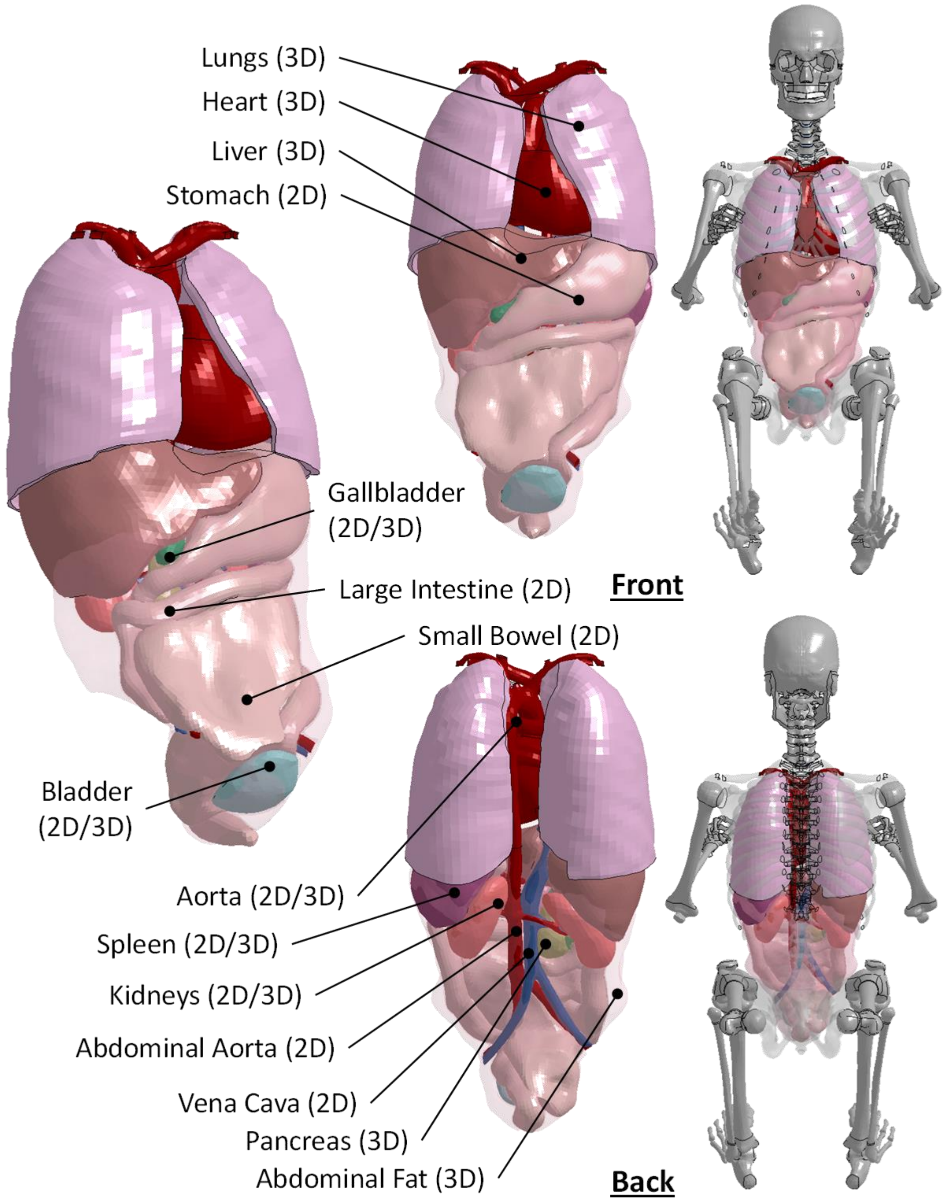


Soft Tissue Biomechanics in Human Body Models

- Soft Tissue Biomechanics are applied in various anatomical structures throughout the body
  - Solid Organs
  - Hollow Organs
  - Cartilage (fibrocartilage, discs)
  - Muscle (active and passive)
  - Ligaments/tendons

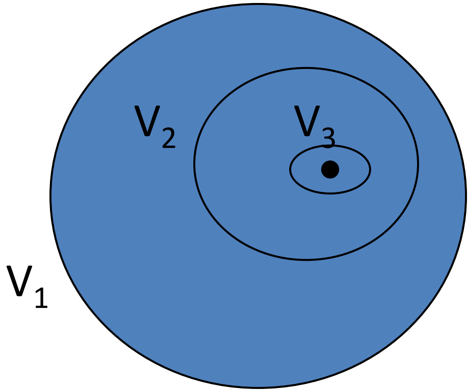
- Similar to skeletal structures, impact on **kinetics, injury risk prediction, and model stability** all drive the modeling techniques implement

- The new frontier: Brain, vessel, organ injury prediction is something that hasn't historically been answered
- More questions than answers!



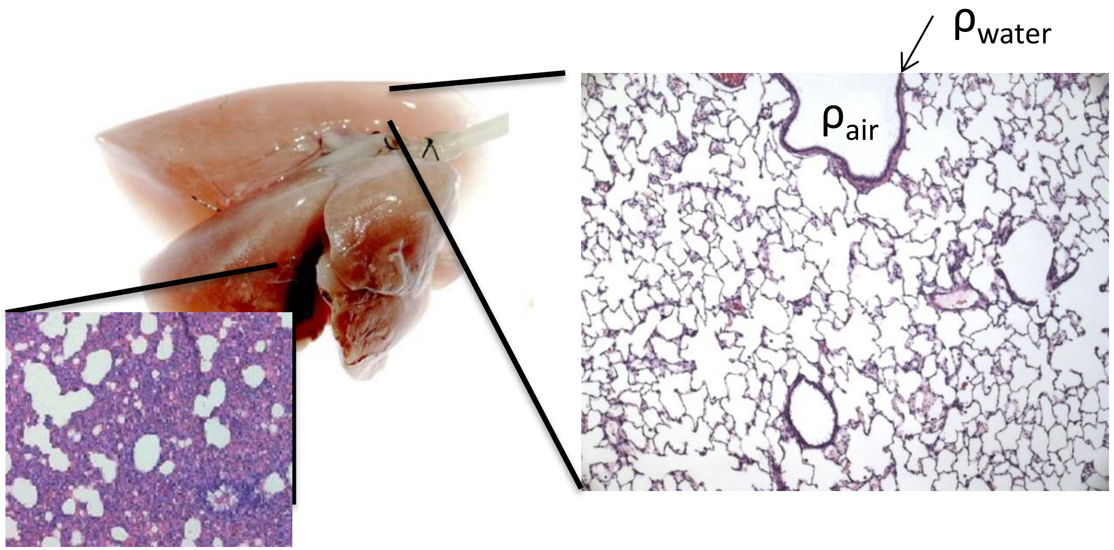
Review: Definition of a Continuum

- What do we mean by a continuum?
  - Mathematical example – a number line
  - Physical examples – time, space
  - Material continuum, an assumption we make in human body modeling
  - Stress can be defined anywhere in the continuum, and it is related to strain and strain rate



General example, density definition

$$\rho(P) = \lim_{\substack{n\to\infty \\ Vn\to 0}} \frac{Mn}{Vn}$$



Biological example, in reality, we often do not have a continuum even at micro scale

YC Fung, A first course in continuum mechanics, 3rd ed.

Constitutive Lung Material Model

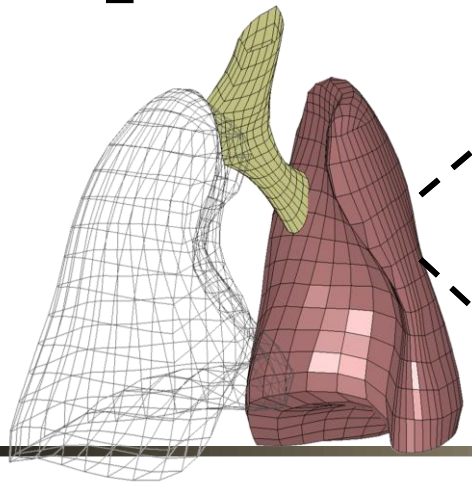
- Material Model:
  - *MAT_LUNG_TISSUE
  - C, α, β, C1 and C2, hyperelastic material coefficients
  - **Δ -** unstressed alveolar diameter, **K**- bulk modulus
  - Lung model has uniform composition (continuum)

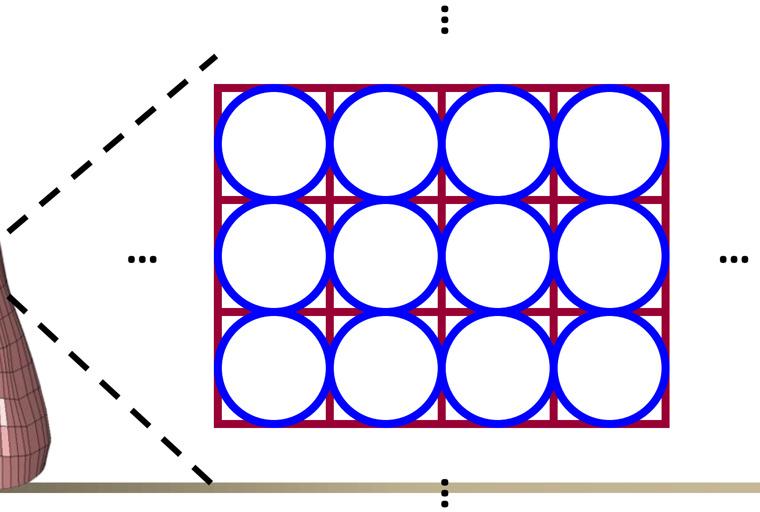
$$W(I_1, I_2) = \boxed{\frac{C}{2\Delta} e^{(\alpha I_1^2 + \beta I_2)}} + \boxed{\frac{12C_1}{\Delta(1+C_2)}\left[A^{(1+C_2)} - 1\right]} \rightarrow \text{Deviatoric}$$

Deviatoric
- **Septa**
- **Surface tension**

$$W_H(J) = \frac{K}{2}(J-1)^2 \rightarrow \text{Hydrostatic}$$

Hydrostatic





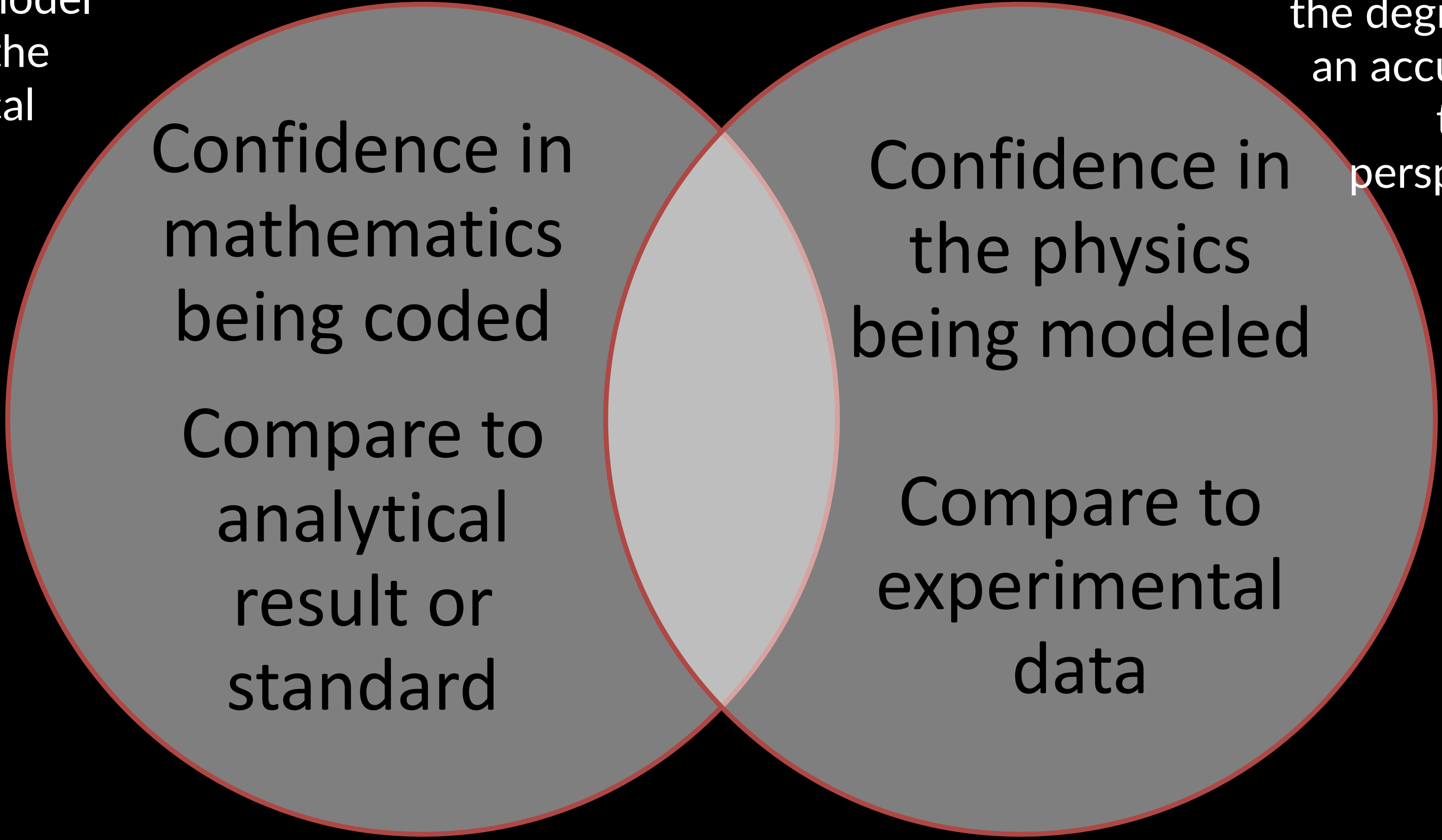
V&V in the Context of FEA Models

***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 SETTING THE STANDARD

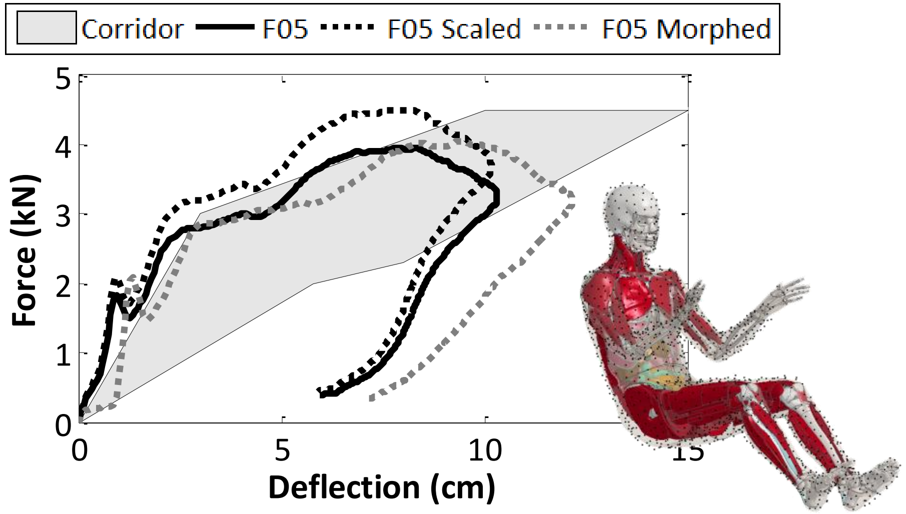
2 Los Alamos NATIONAL LABORATORY EST. 1943

Validation: Best Practices in Human Modeling

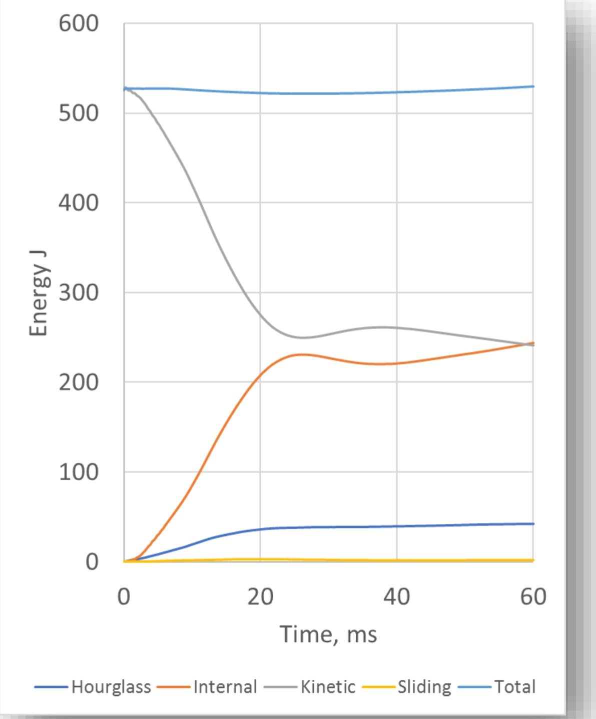
Do at Every Level (tissue, organ, region, full body) & Attempt to Quantify Sources of Uncertainty

Before → After

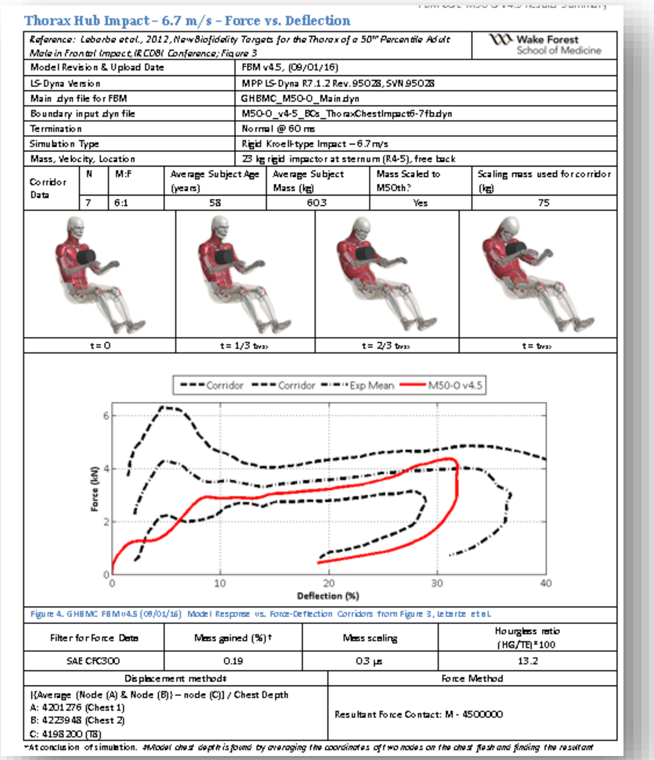
Morph to Match[1] *and/or* *Prepare Experimental Data*



Simulation Quality Checks



Robust Reporting



Thorax Hub Impact – 6.7 m/s – Force vs. Deflection

Reference: Lebarbe et al., 2012, New Biofidelity Targets for the Thorax of a 50th Percentile Adult Male in Frontal Impact, IRCOBI Conference; Figure 3	Wake Forest School of Medicine
Model Revision & Upload Date	FBM v4.5, (09/01/16)
LS-Dyna Version	MPP LS-Dyna R7.1.2 Rev. 95028, SVN 95028
Main .dyn file for FBM	GHBMC_M50-O_Main.dyn
Boundary input .dyn file	M50-O_v4-5_BCs_ThoraxChestImpact6-7fb.dyn
Termination	Normal @ 60 ms
Simulation Type	Rigid Kroell-type Impact – 6.7 m/s
Mass, Velocity, Location	23 kg rigid impactor at sternum (R4-5), free back

Corridor Data	N	M:F	Average Subject Age (years)	Average Subject Mass (kg)	Mass Scaled to M50th?	Scaling mass used for corridor (kg)
	7	6:1	58	60.3	Yes	75

Figure 4. GHBMC FBM v4.5 (09/01/16) Model Response vs. Force-Deflection Corridors from Figure 3, Lebarbe et al.

Filter for Force Data	Mass gained (%)†	Mass scaling	Hourglass ratio (HG/TE)*100
SAE CFC300	0.19	0.3 µs	13.2

Displacement method‡	Force Method
[{Average (Node (A) & Node (B)} – node (C)] / Chest Depth A: 4201276 (Chest 1) B: 4223948 (Chest 2) C: 4198200 (T8)	Resultant Force Contact: M - 4500000

†At conclusion of simulation. ‡Model chest depth is found by averaging the coordinates of two nodes on the chest flesh and finding the resultant

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.

Summary

- FEA is a method of solving partial differential equations describing the motion and internal mechanics
- This talk focused on solid mechanics where mesh generally deforms with the body
- We covered generation of models, time integration and very basic material modeling
- We also ended on the validation process
- Other topics: Boundary conditions, input/output are covered in demo coming up!