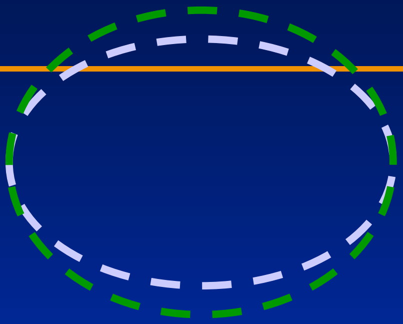
Biomechanical FEM Solution

Biomechanical Model



Assuming a linear elastic continuum with no initial stress or strains, the deformation energy of an elastic body submitted to eternally applied forces :

$$E = \frac{1}{2}\int_{\Omega} \sigma^{T} \varepsilon d\Omega + \int_{\Omega} Fud\Omega$$

F = F(x,y,z) is the vector representing the force applied to the elastic body
u = u(x,y,z) is the displacement vector field we want to compute

ε is the strain vector = Lu and σ the stress vector linked to the strain vector by the material constitutive equation.
Linear isotropic elastic brain tissue is modeled with two parameters:
Young's elasticity modulus and Poisson's ratio.

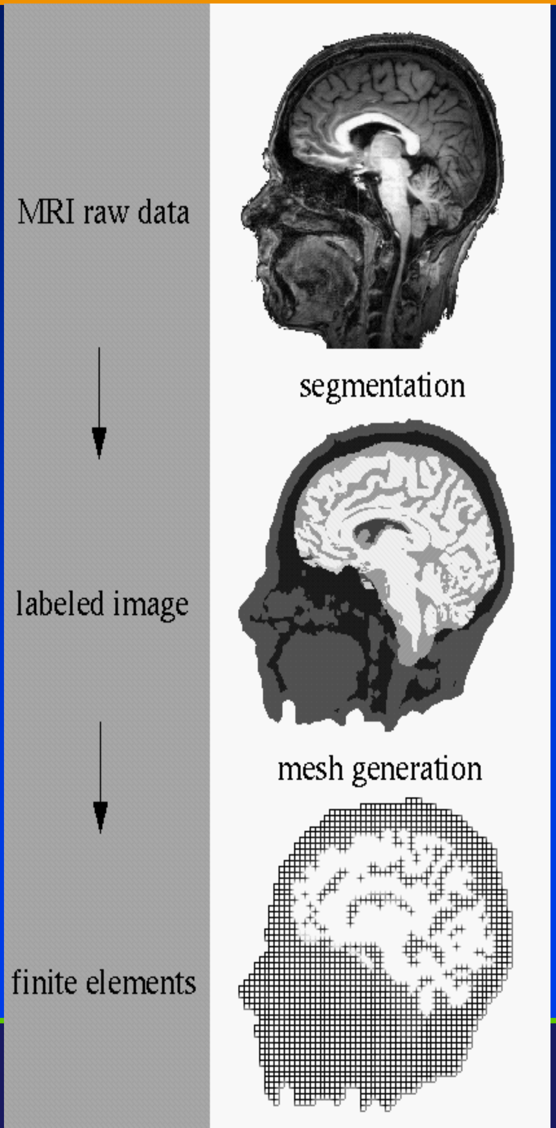
Introducing FE and some analysis,

Ku = -F (K is the rigidity matrix)

The displacements at the boundary surface nodes are fixed to match those generated by the deformable surface model.

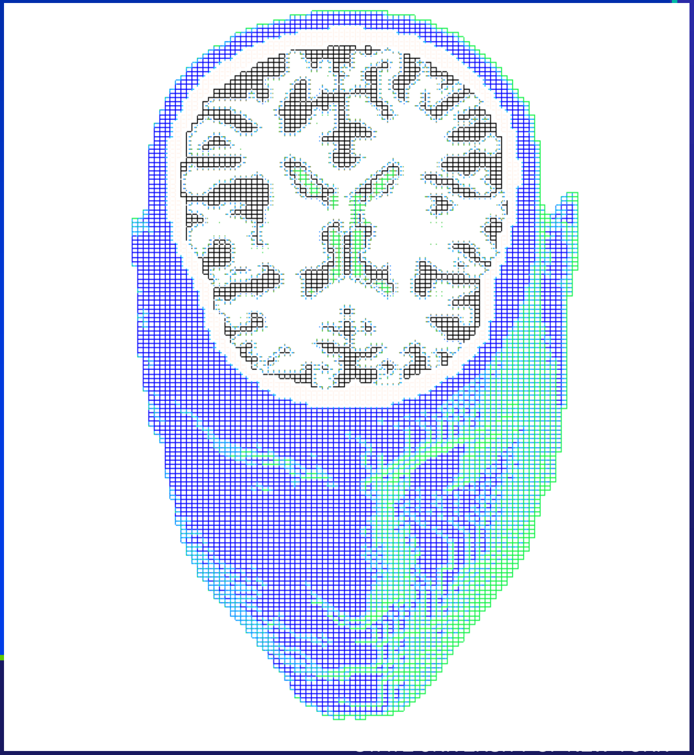
From Data to Model

- Modeling head geometry:



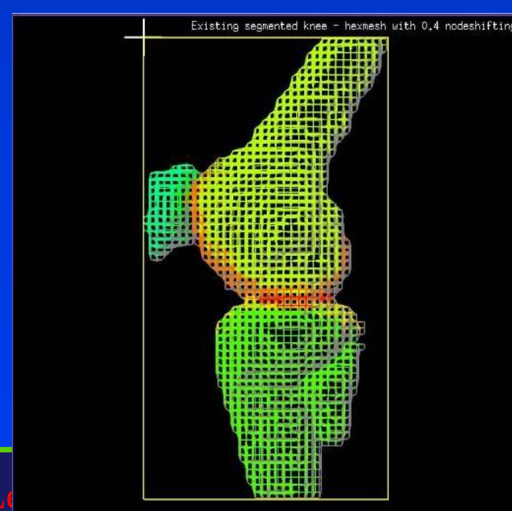
From magnetic resonance images (MRI)

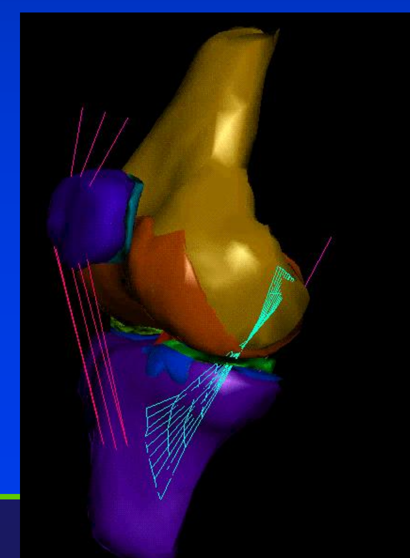
to finite element meshes of the human head



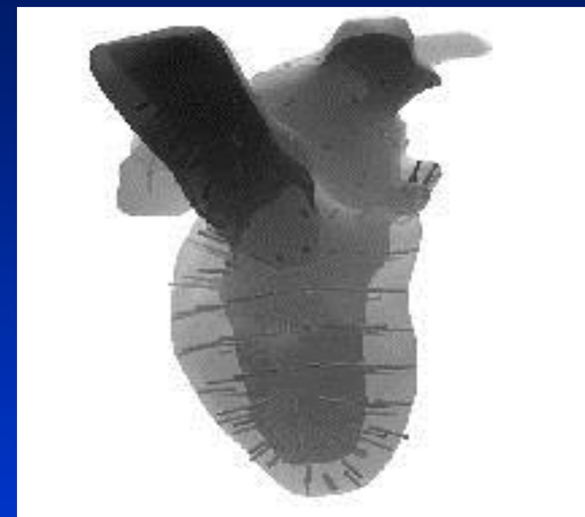
From Data to Model

- Actual scanned data from patients
- Useful for modeling and simulation





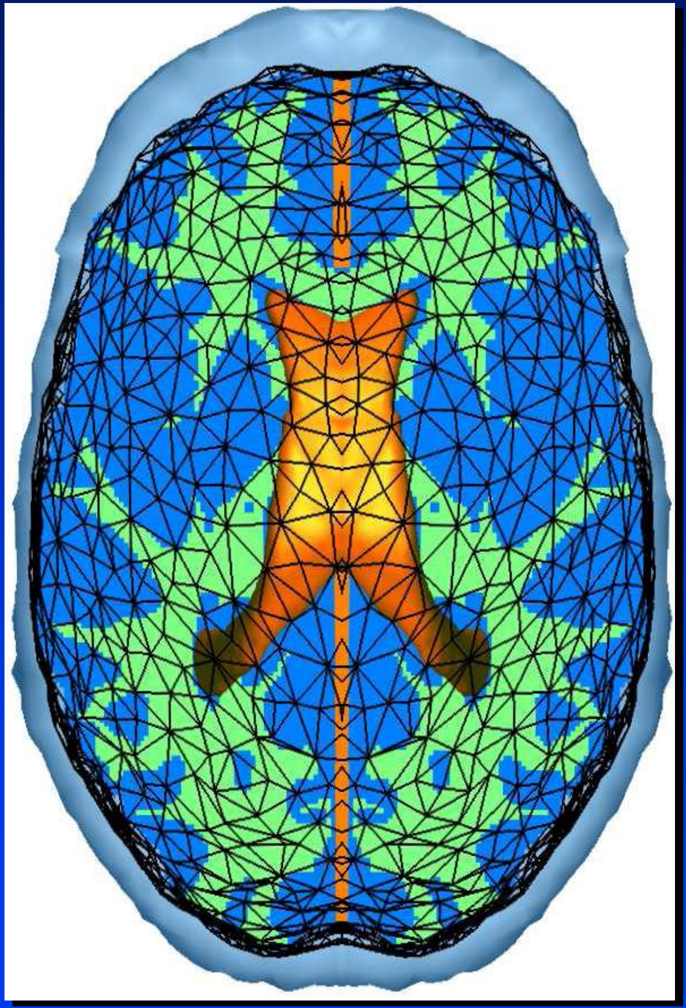
Interactive Segmentation



One model deformation step → Model visualisation update → User correction (interaction)

loop

Mesh Model with Brain Segmentation

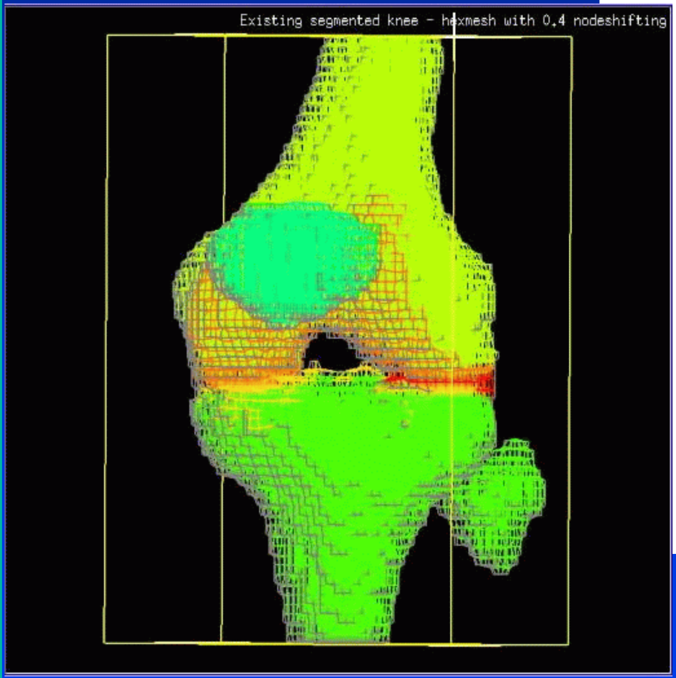


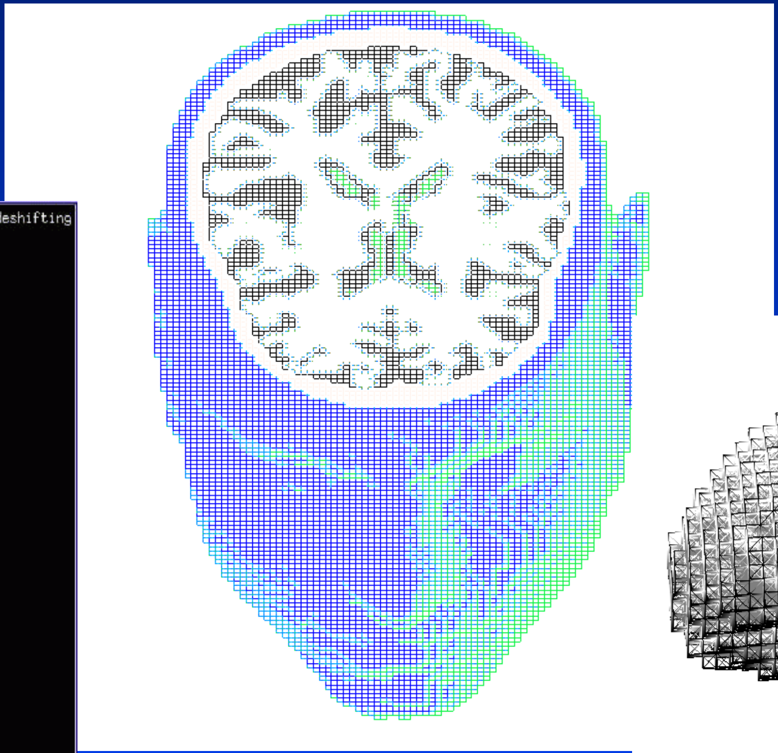
Patient-specific Finite Element Model Development

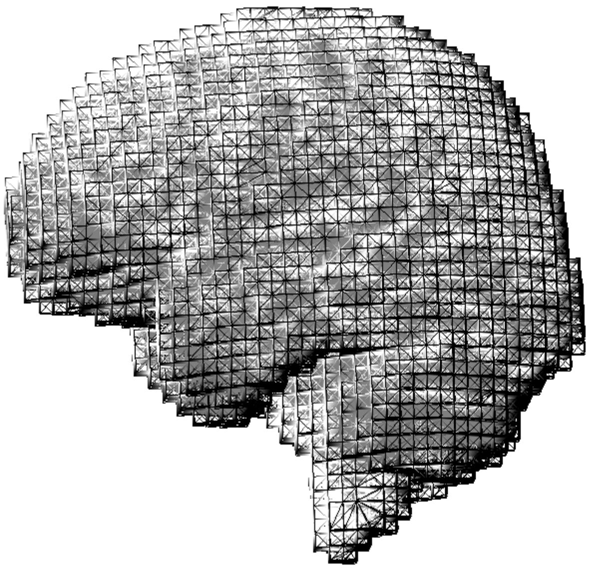
- Automatic generation of high-quality hexahedral meshes
- Inclusion of soft tissues such as cartilage
- Automated segmentation
- Validation

Finite Element Meshing

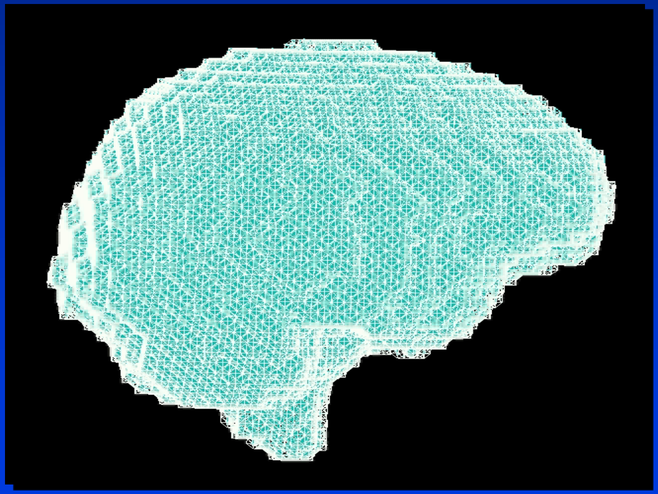
- FE meshes consist of hexahedral and tetrahedral elements



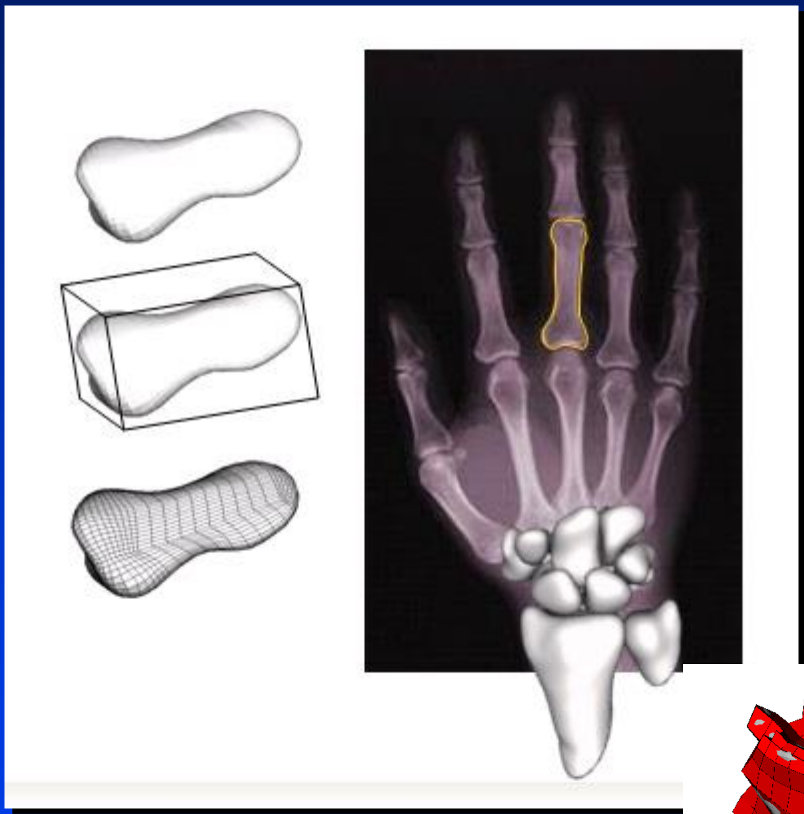


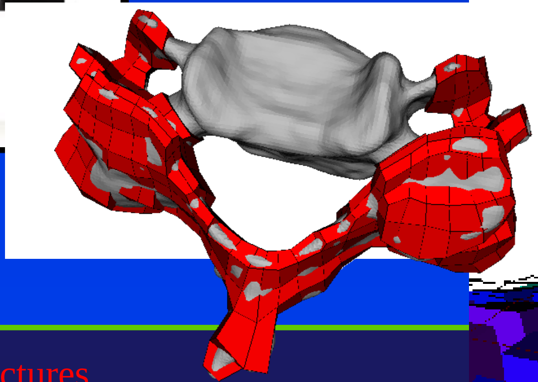


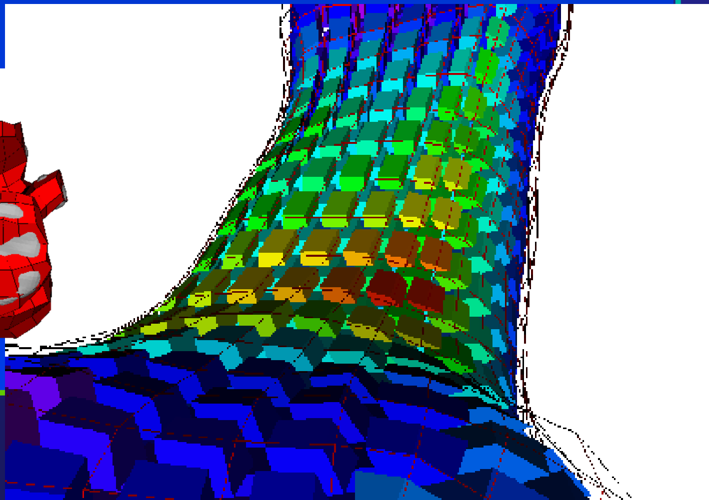
Finite Element Meshing



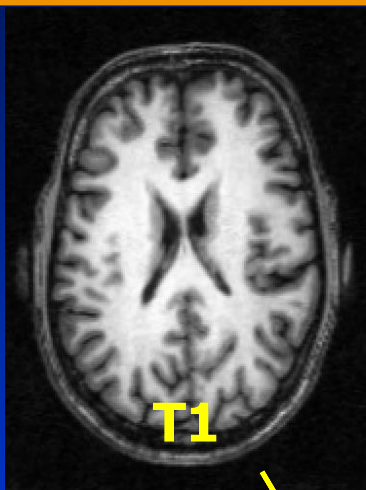
Finite Element Meshing

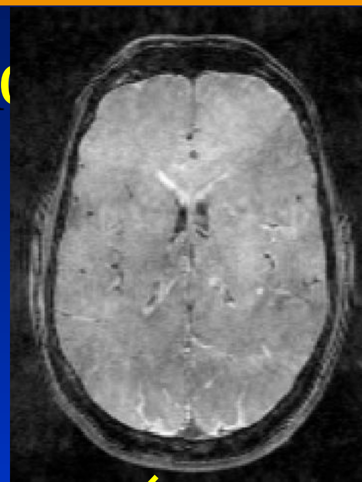




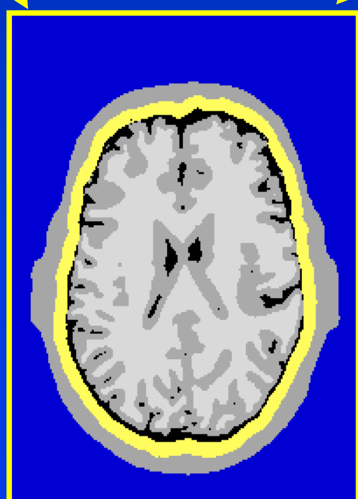


Segmentation and Registration





PD

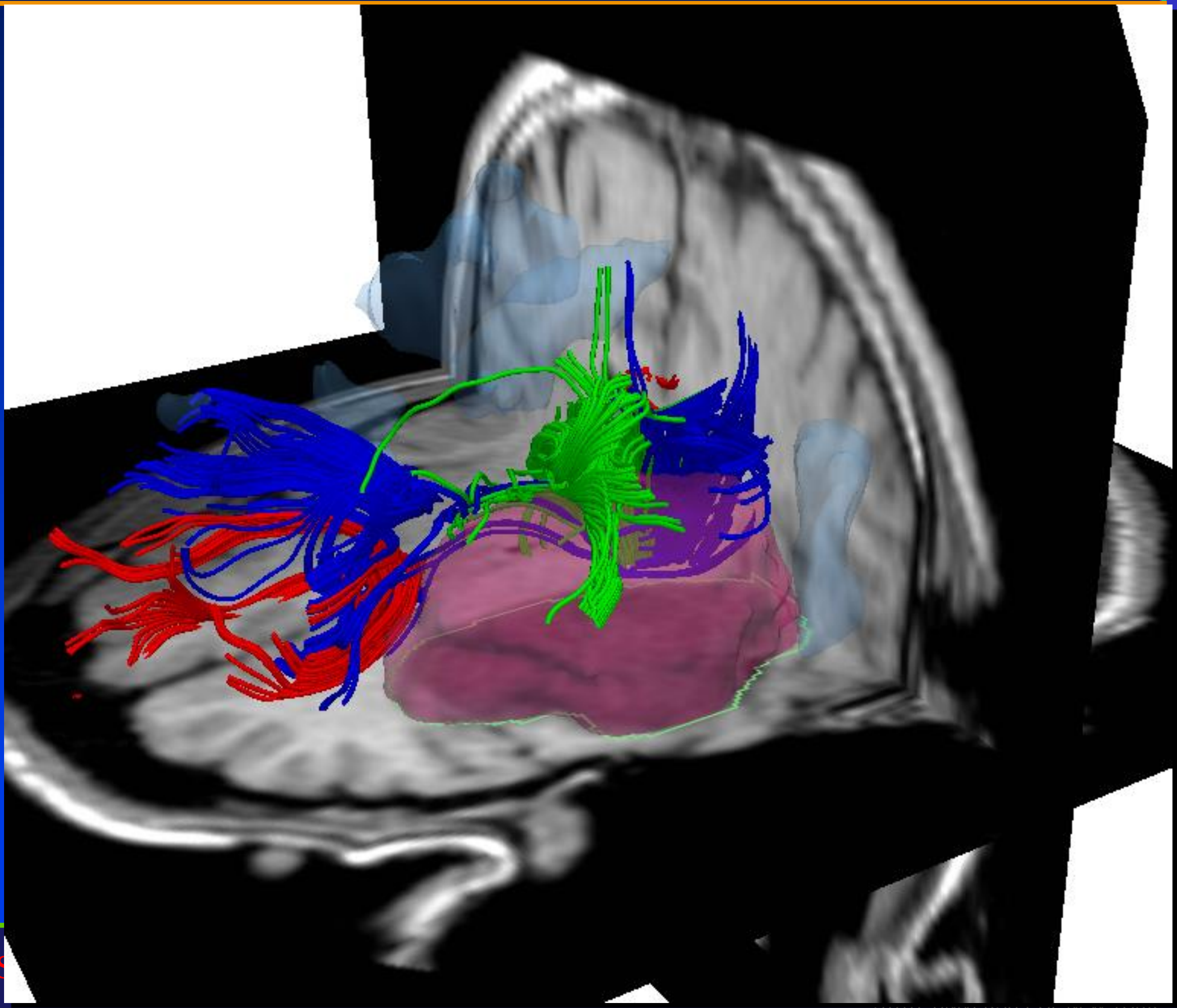


Segmentation result

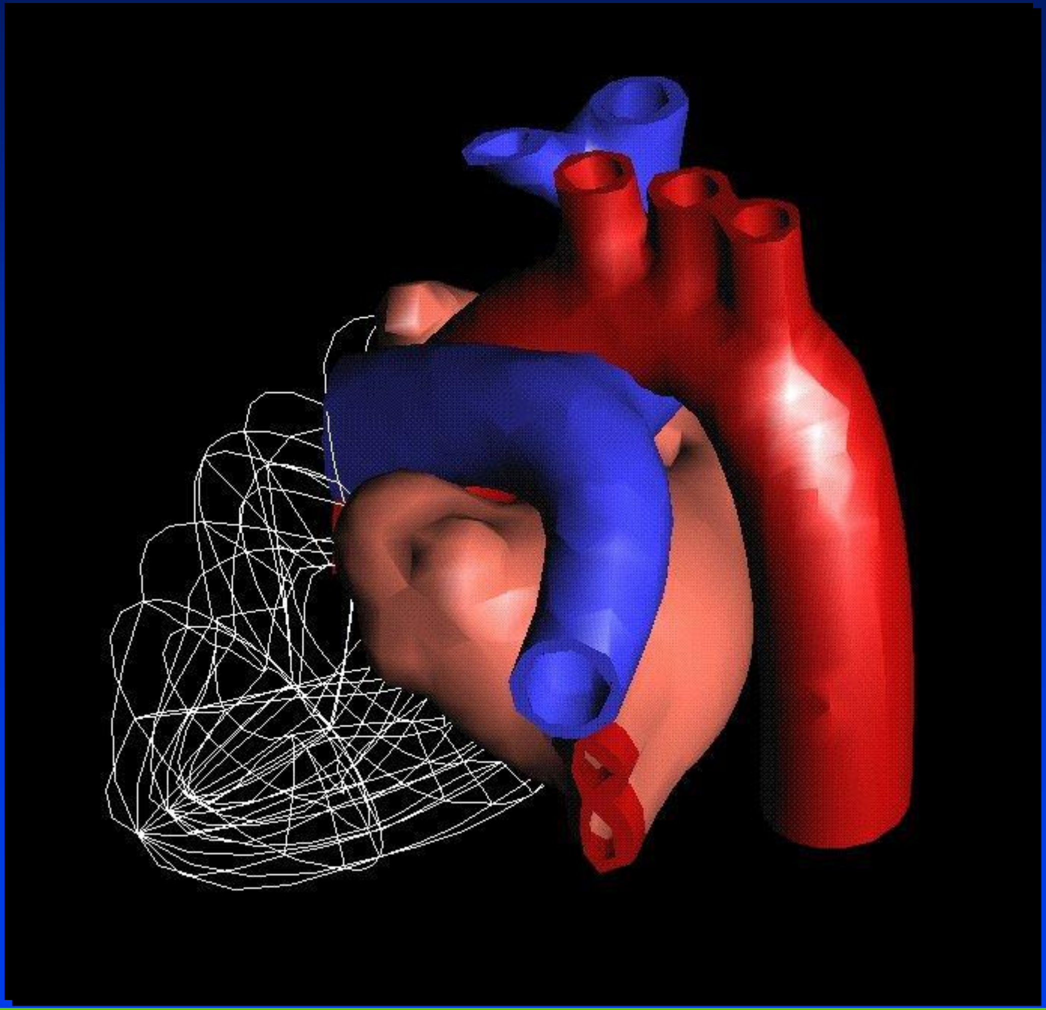
- **T1-weighted MRI: Appropriate for ventricle, white matter, cortex, and scalp segmentation**
- **PD (proton density)-weighted MRI: Appropriate for skull segmentation**
- **Registration of PD-image on T1-image by linear non-rigid edge registration of the segmented outer skull surfaces using genetic optimisation (Staib et al., 1994)**

Data Mapping

- Alignment of all pre-operative datasets to the intra-operative images achieved during the neurosurgery.



Physiology Modeling



Physiology Modeling

- Objectives: modeling organs anatomy, dynamics and physiology for image analysis

  bio-mecanical model (FEM)

  electrical model

  very complex structure

  biological scale out of range
- Heart model-based segmentation

  30 000 nodes model, ~ 1 Gbyte of memory

  30 minutes of computation time / volume
- Heart model-based motion estimation

  10^5 to 10^6 nodes model, more than 10 Gbytes of memory

  FEM parallelization

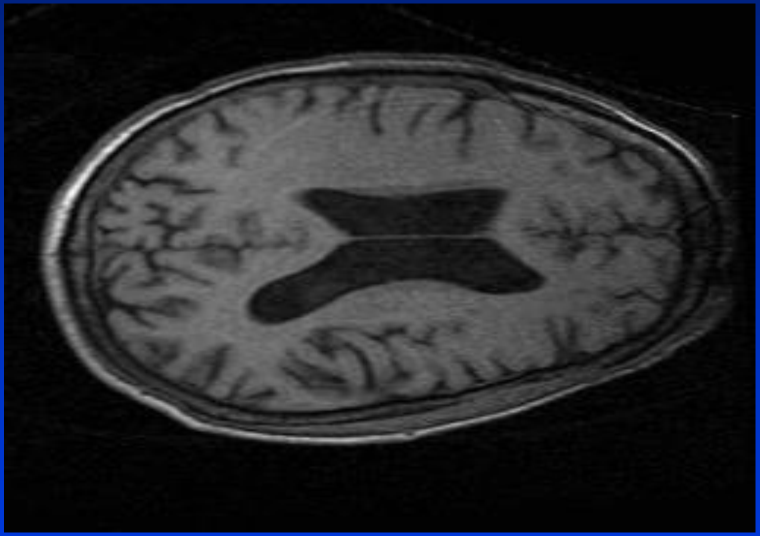
Neurosurgery Challenges

- **Challenges :**
  – Remove as much tumor tissue as possible
  – Minimize the removal of healthy tissue
  – Avoid the disruption of critical anatomical structures
  – Know when to stop the resection process

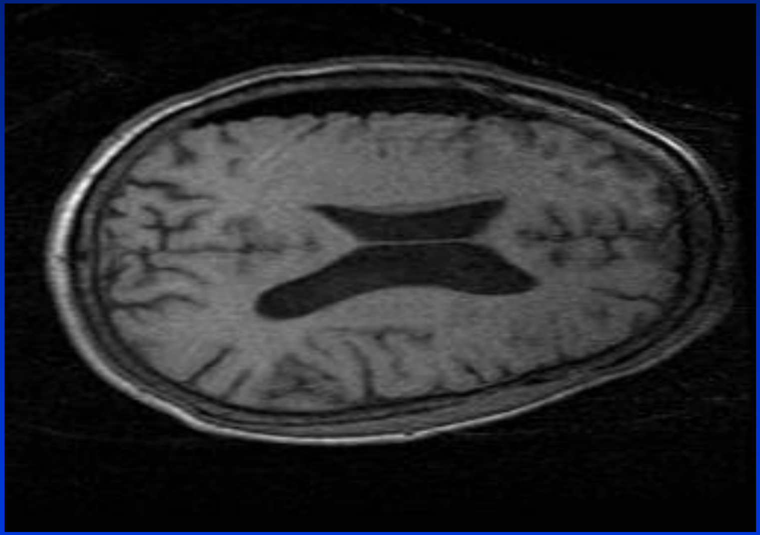
Neurosurgery

- **Pre-operative MRI compounded by the intra-operative brain shape deformation as a *result of the surgical process***
- **Important to quantify and correct for these deformations while surgery is in progress**
- **Real-time constraints – provide images ~once/hour within few mins during surgery lasting ~6 hours**

Brain Deformation



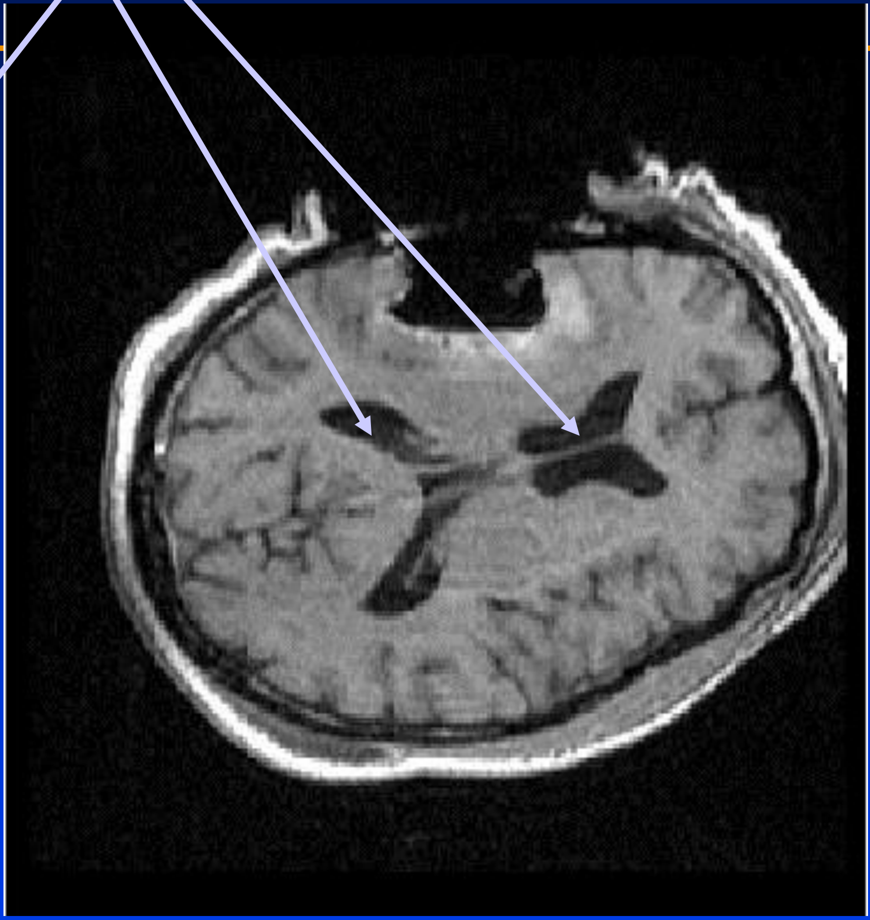
Before surgery



After surgery

Tumor Ventricles

Pre-operative Image



Intra-operative image, after dura opened and partial tumor resection

Automatic Construction of Patient-Specific Finite Element Models from Medical Images

Finite Element Techniques

- Invaluable tool in musculoskeletal research
- There have been strong demands towards the effective and accurate modeling of the geometrically complex structures for the human body
- Oftentimes, the existing approaches limit its utility to only restrict analyses to baseline models by using simple, generic models
- Conventional meshing techniques often prove inadequate

Patient-specific Models

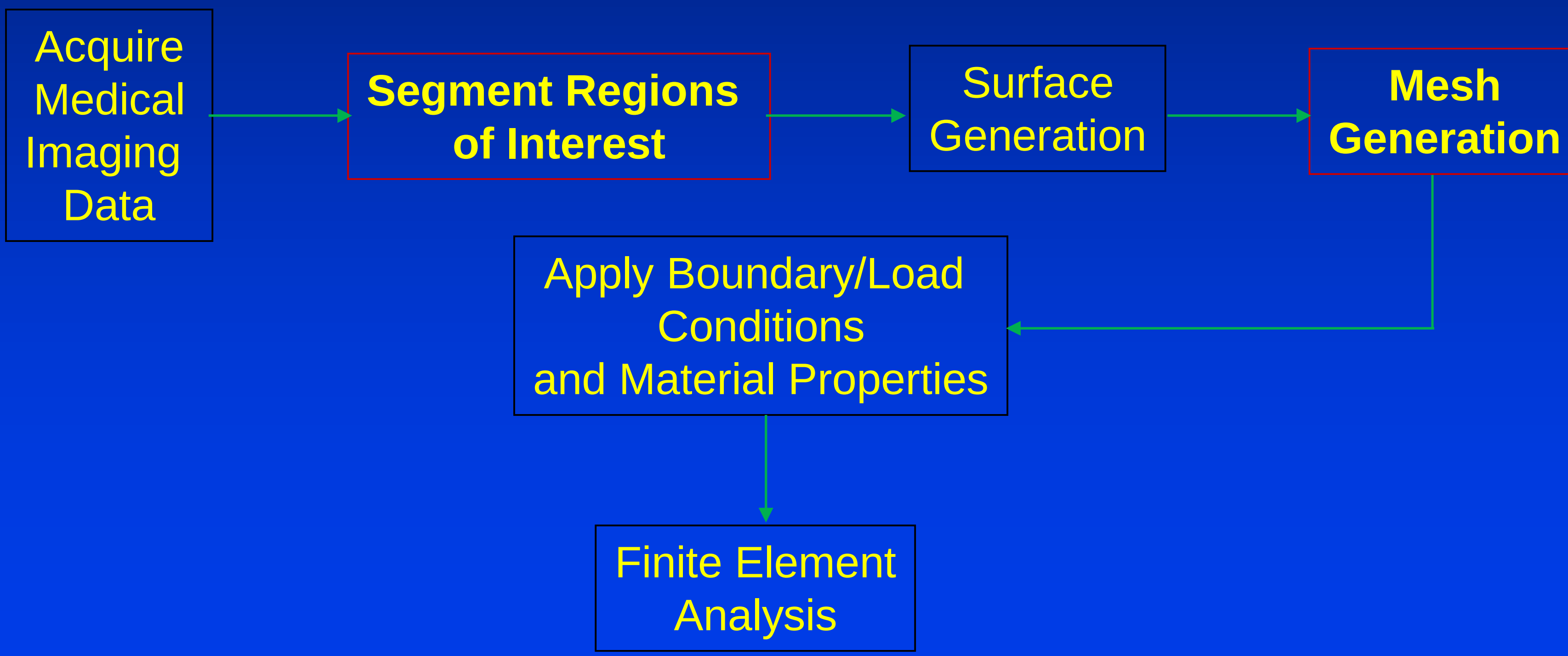
- In order to bring geometric models and physics-based models to the "bedside" with a goal to guide surgical procedures, the Finite Element technique must be employed to facilitate the transition from the image segmentation to mesh generation process
- Overcome the limitations of generic models, so we strongly prefer individualized, or patient-specific models

Intraoperative MRI Scanner at BWH (0.5 T)

Objectives

- Automate the generation process of high-quality hexahedral meshes
  - Projection method
  - Mapped Meshing
- Inclusion of soft tissues such as cartilage
- Automated segmentation in the preprocessing stage
  - Neural network
  - Level set
  - EM segmentation
- Validation
  - Segmentation using surface scanning for model comparison
  - FE analysis using physical testing

Finite Element Techniques: From Data to Models

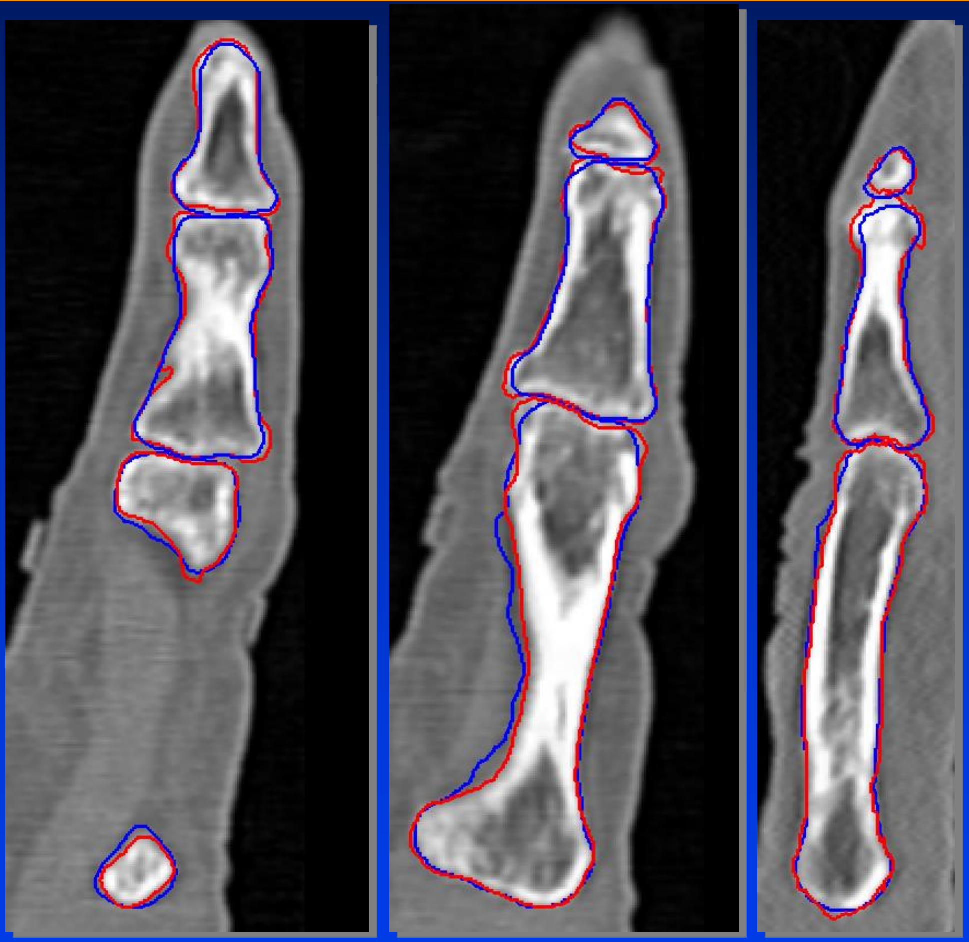


Bones of Interest

Why initiate with the bones of the hand?

- Long bones and cuboidal bones because of topological simplicity
- Number of bones per cadaveric specimen
- Can be readily extended to the other bones of the body

Regions of Interest (ROIs)



Segmentation of ROIs

- Manual segmentation
  - We should have experienced rater to manually evaluate the reliability and validity
- Automated segmentation
  - Neural network algorithm
  - EM segmentation
  - Level set segmentation

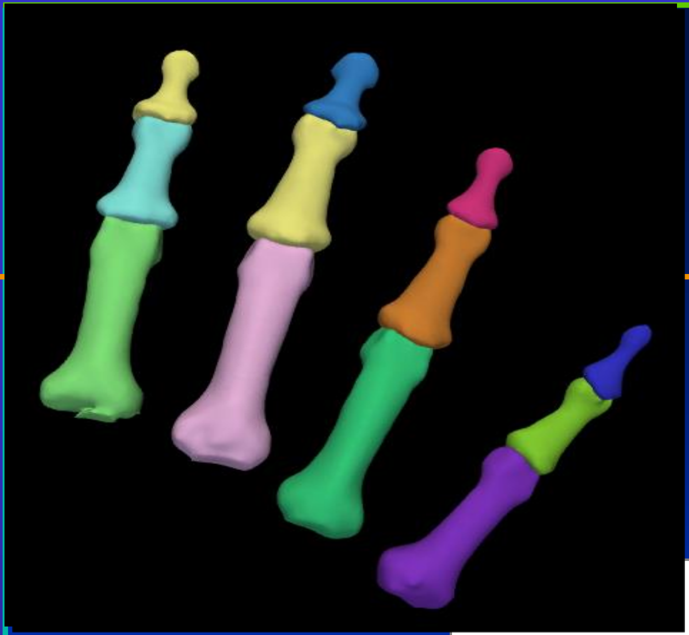
EM Preprocessing for Image Segmentation

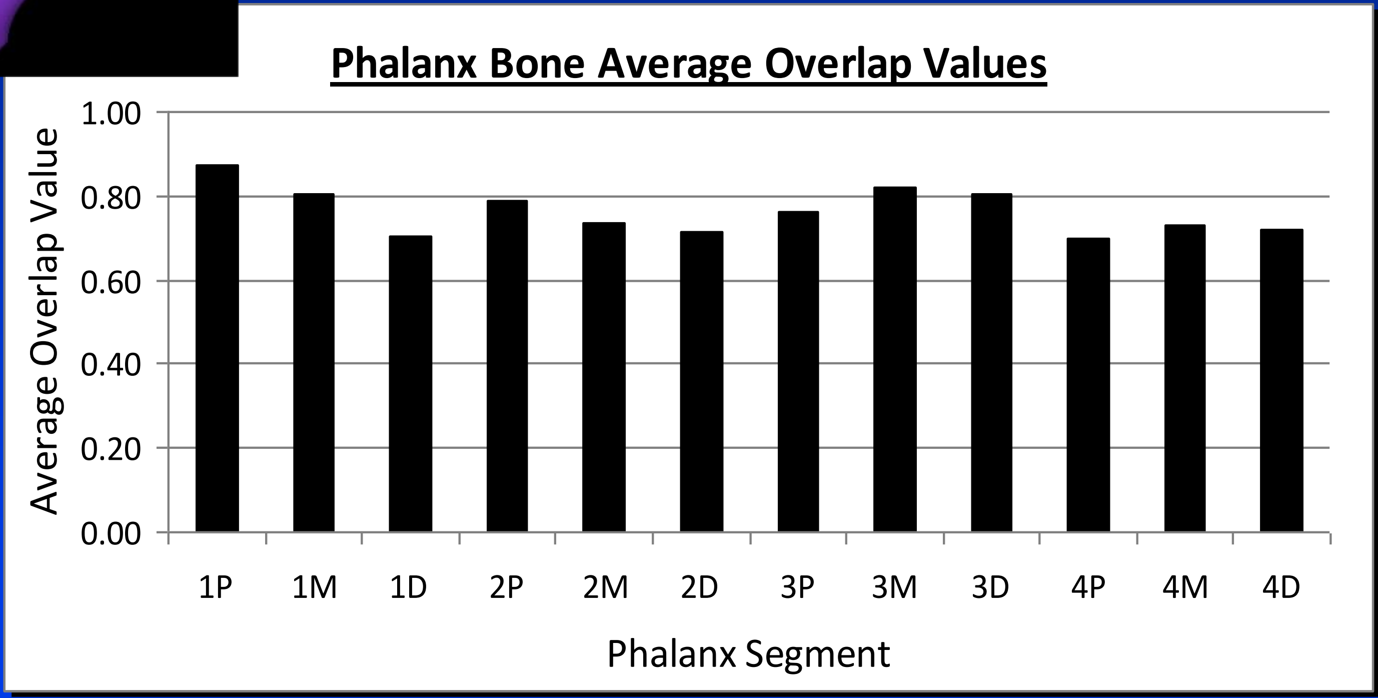
- Goal: Apply EM Algorithm to the segmentation of the phalanx bones using Slicer 2.7
- Preprocessing
  - Manually define phalanx bones of the atlas image
  - Gaussian filter the manual segmentations to create a probability map
  - Define landmarks to initialize a Thirion Demons registration of the atlas image to each of the specimens
  - Warp probability maps to each subject

EM Segmentation

- Applied to 14 cadaveric specimen datasets
- Hierarchical model used
  - Define image into bone, soft tissue and background
  - Further refine regions into individual bones (proximal, middle, distal) for the index, middle, ring and little fingers
- Resulting label maps were cleaned of islands and filled
- Compare reliability and validity of segmentation
  - Human rater defined regions
  - index finger on all datasets
  - Complete hand on two datasets
  - Laser scanning performed on 5 specimens for the Index finger
- Developed a Training Guide for this application

EM Segmentation Results





Evaluation Metric: Relative Overlap

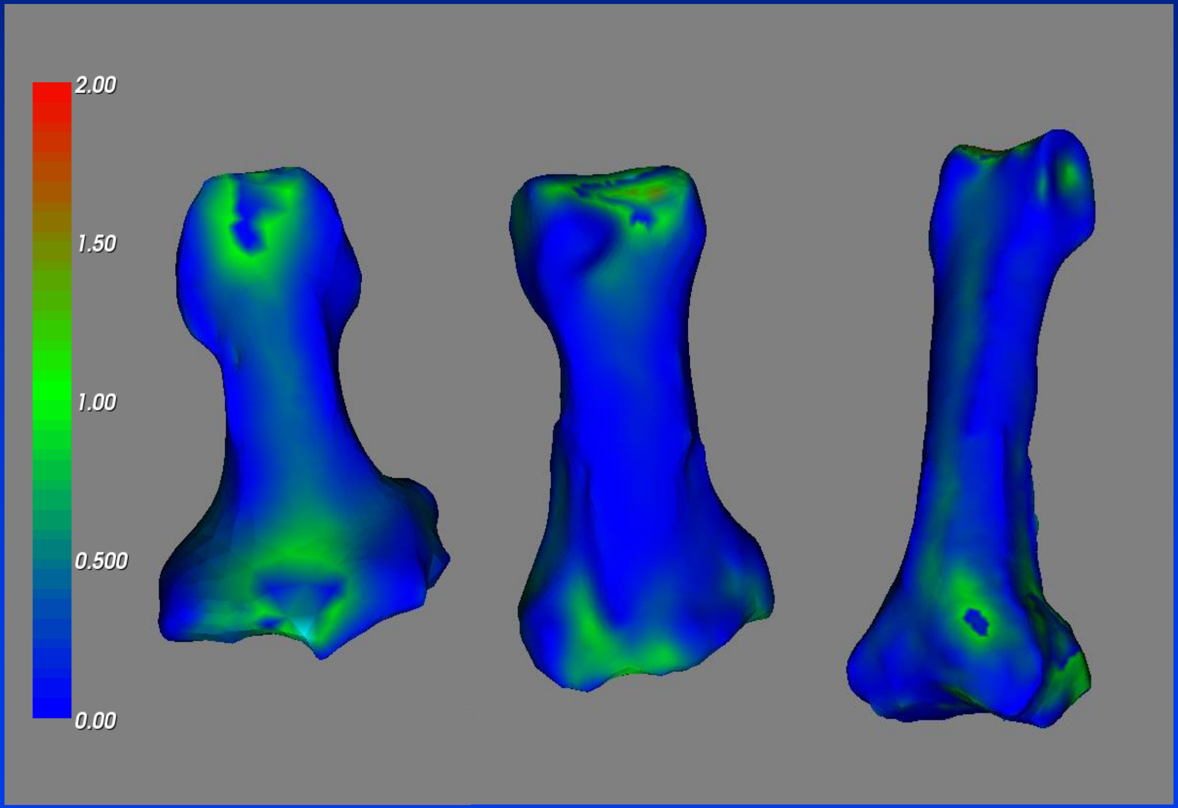
$$Relative\ Overlap = \frac{Volume(Automated\ \ Segmentation \cap Manual\ Segmentation)}{Volume(Automated\ \ Segmentation \cup Manual\ Segmentation)}$$

Automated Segmentation Method	Proximal Phalanx Overlap	Medial Phalanx Overlap	Distal Phalanx Overlap
EM	0.87	0.80	0.70
ANN	0.87	0.82	0.76

A Timing Comparison

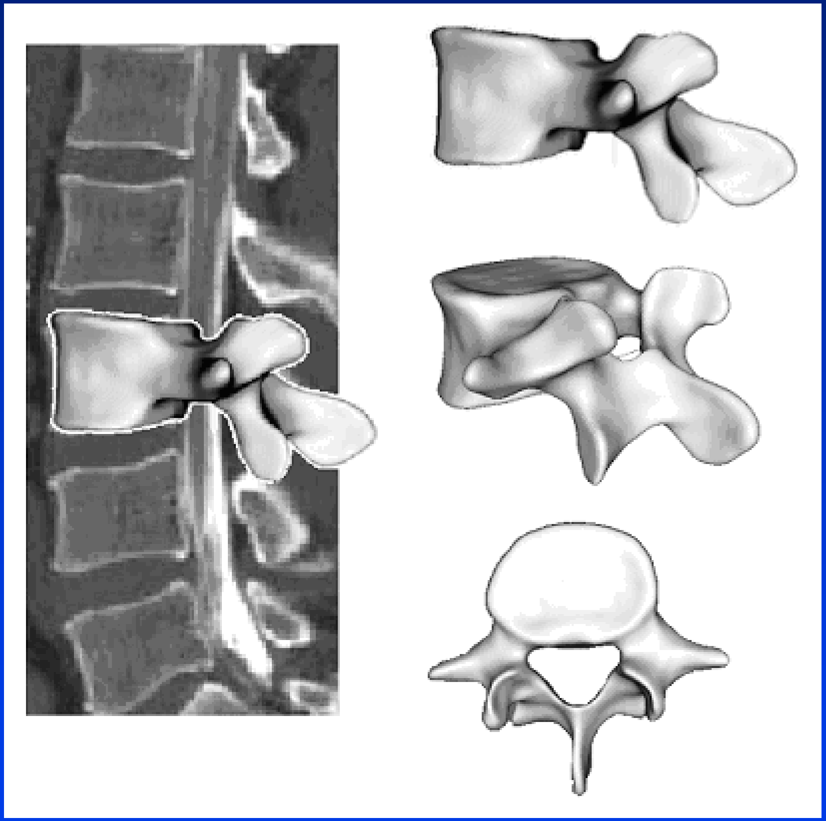
Segmentation Method	Average Segmentation Time
Manual Tracing	58.47 min
EM Method	4.75 min
Artificial Neural Network	1.83 min

Comparison with Laser Scan



Bones of Interest

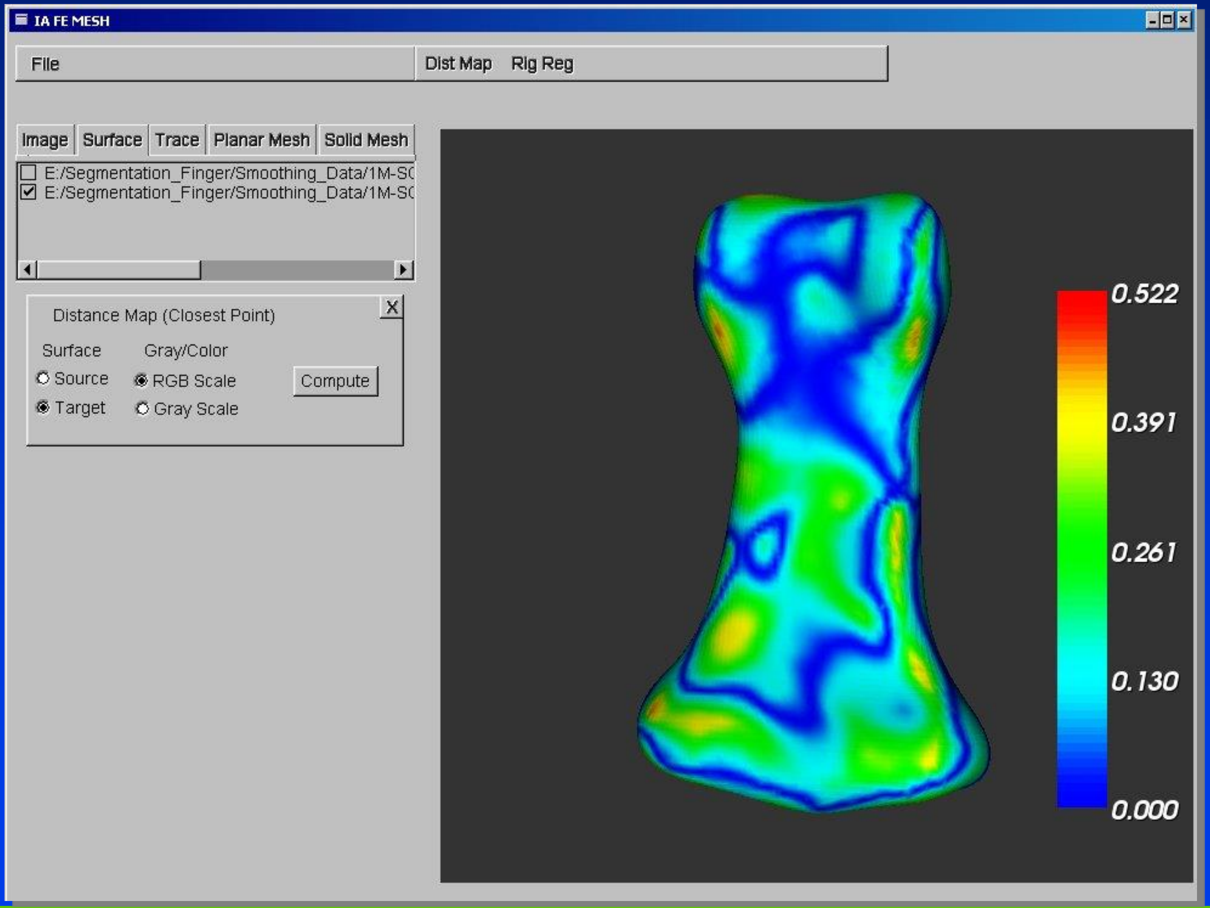
- Generalization to irregular bones such as the vertebrae



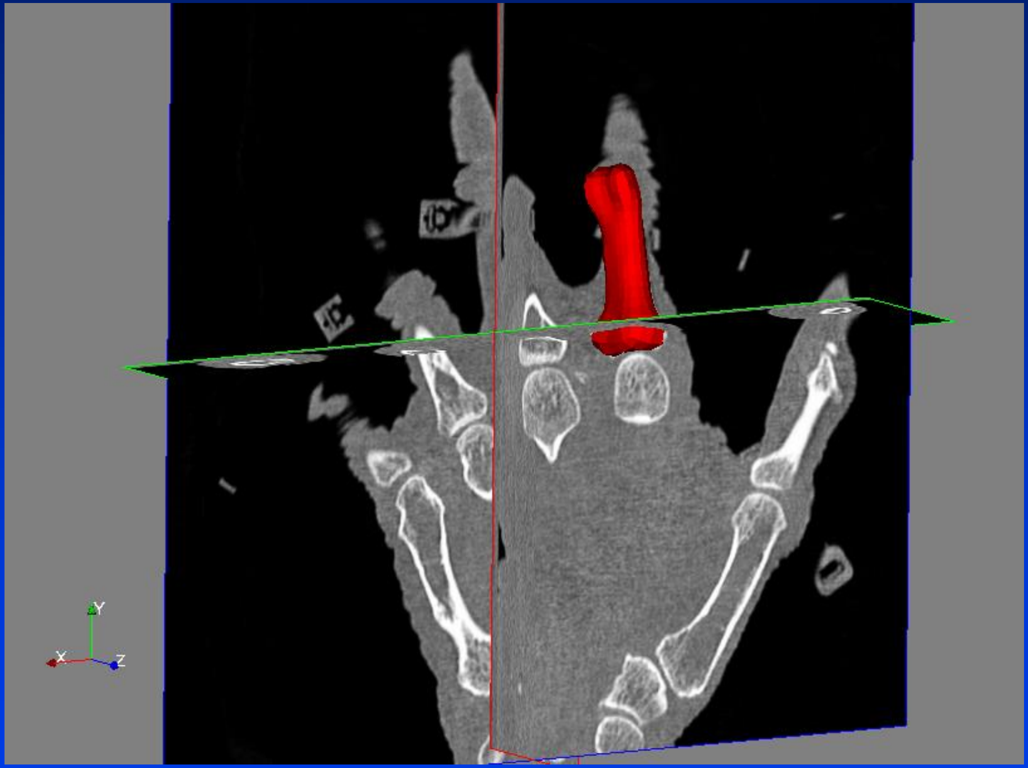
Segmentation Validation

- Cadeveric specimens dissected and scanned using a 3D laser scanner
- Physical scan surface co-registered with CT surface representation using ICP registration
- Distance between manual and automated definitions compared to physical scans

Surface Distance Measurement Tool



Material Properties from Imaging Data



Material Property Assignments

$$E = a + b\rho_{app}^{c}$$

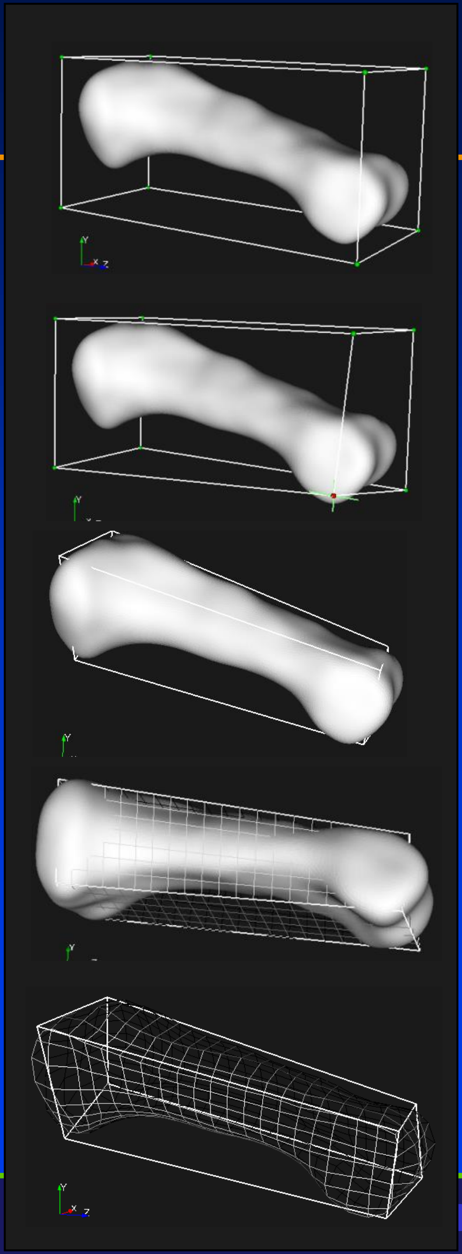
where,

E is the elastic modulus,
r_{app} the apparent density, and
a, *b*, and *c* the model parameters

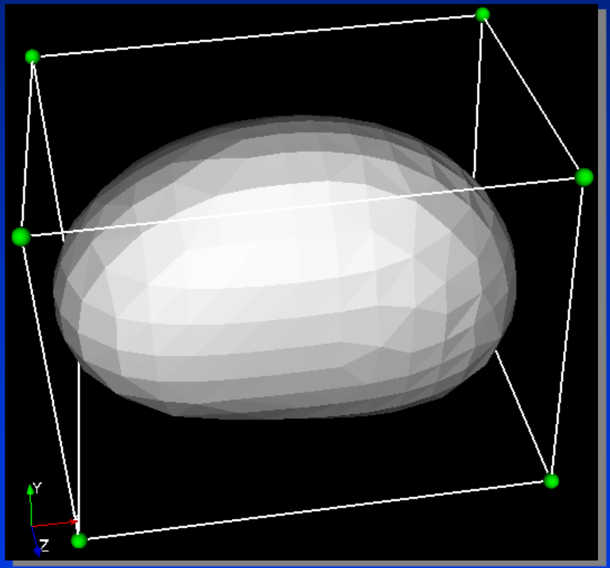
Finite Element Meshing

Objectives:

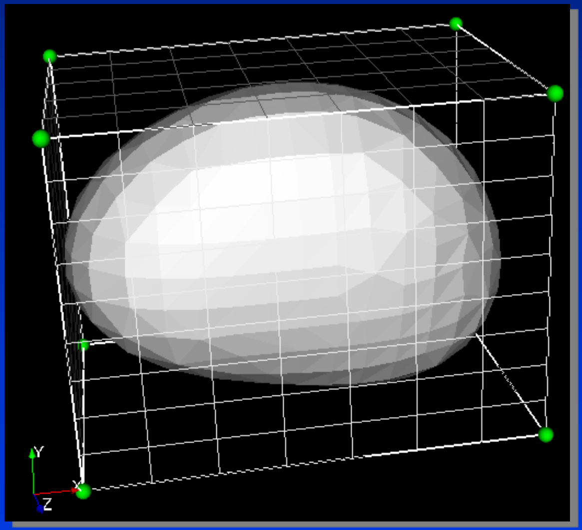
- Reduce the amount of time being spent to generate the models (i.e., toward automated mesh development)
- Improve mesh quality
- Couple imaging data directly



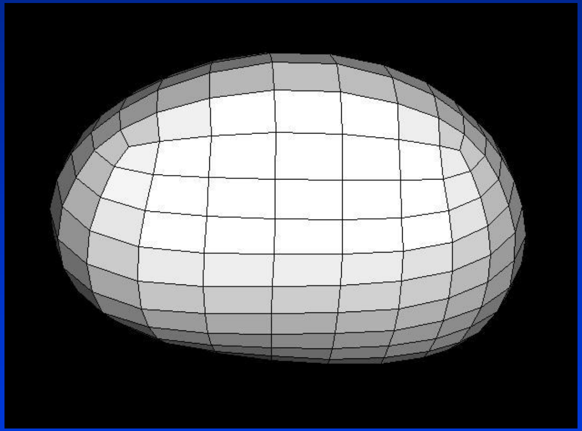
Projection Method
Carpal Bone



Initial Bounding Box

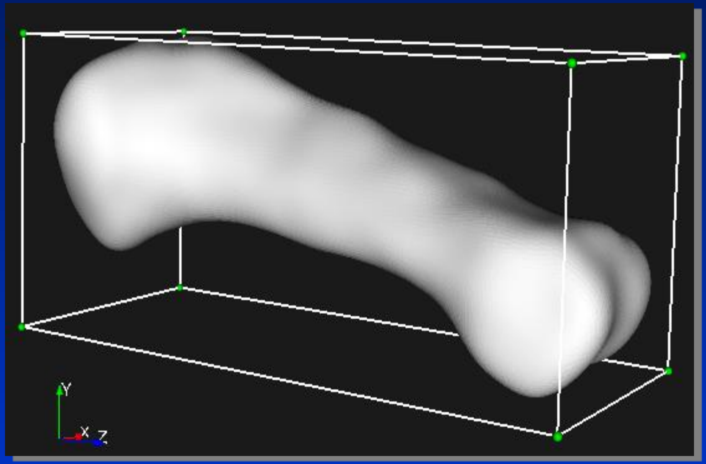


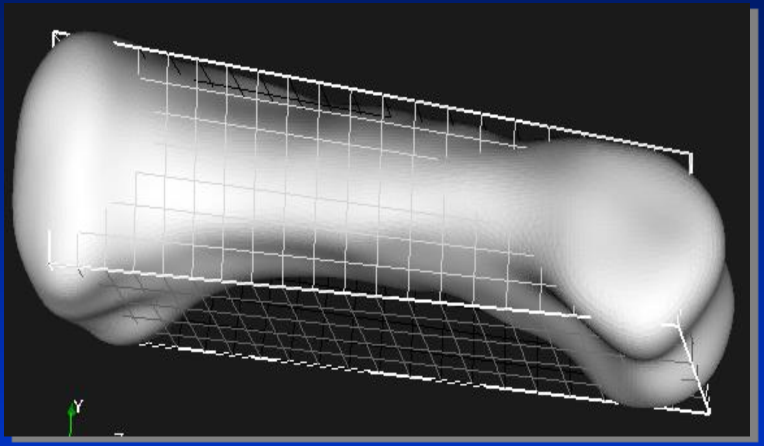
Bounding Box with assigned Mesh Seeding

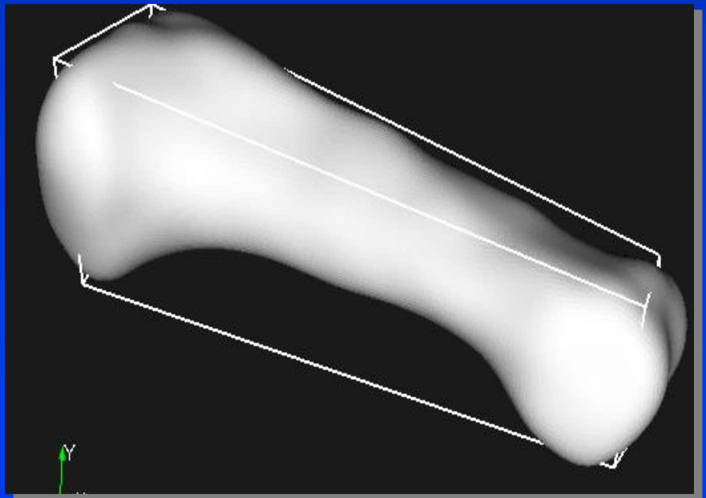


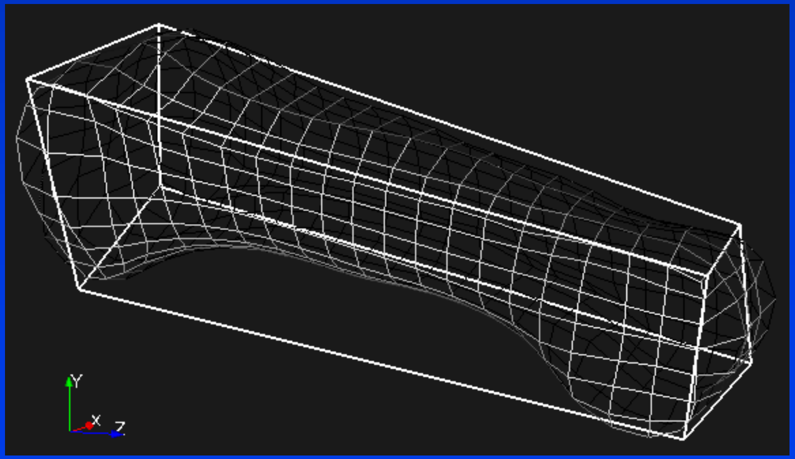
Projected Mesh

Projection Method Example – Proximal Phalanx Bone



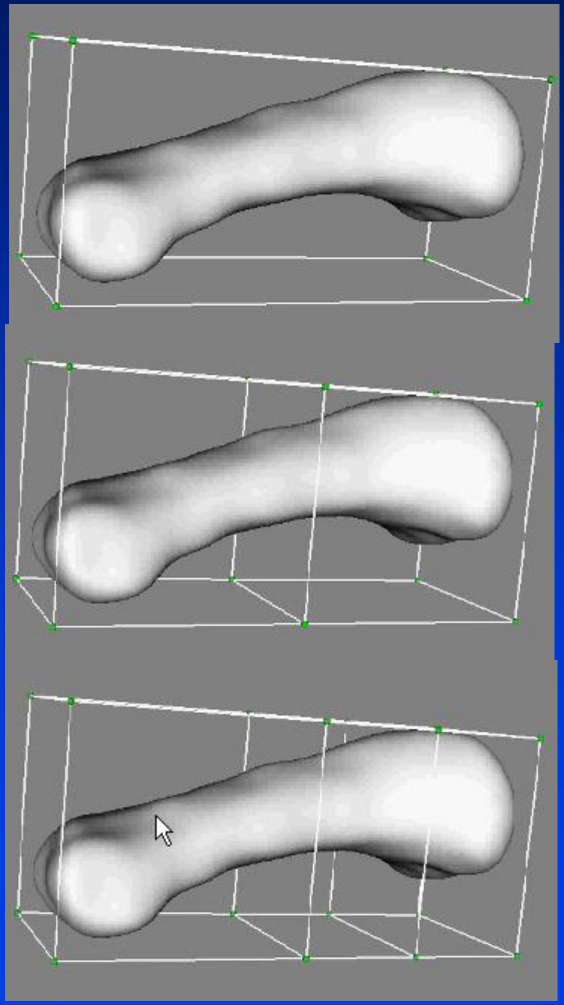




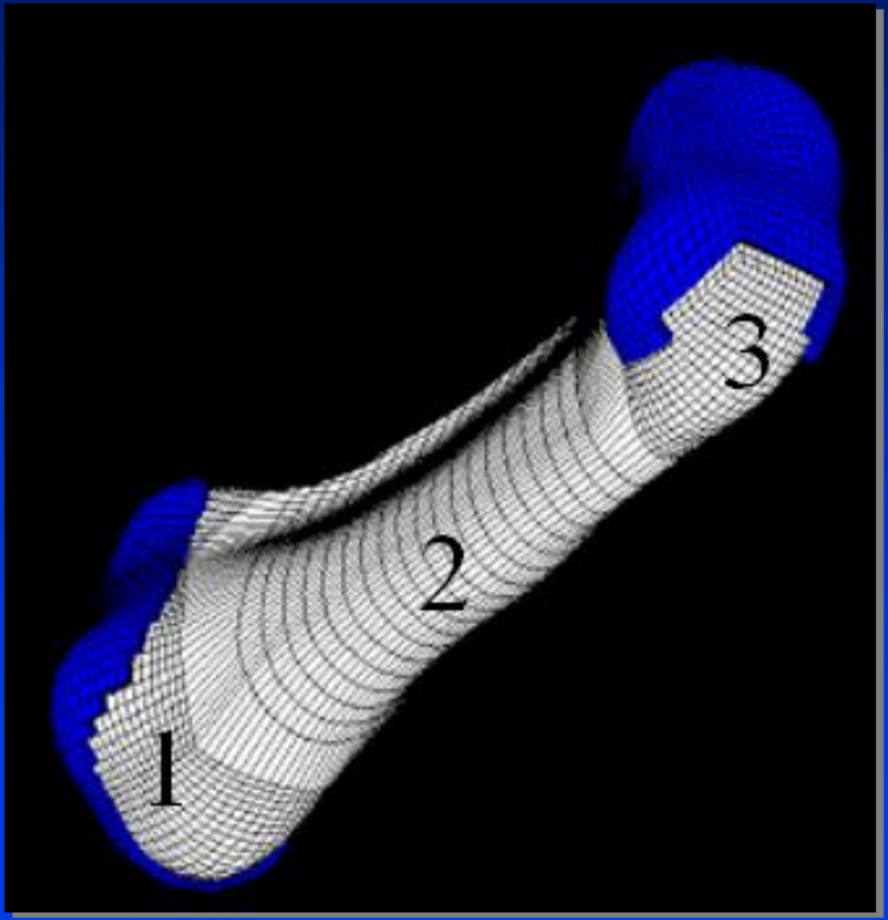


Extending Projection Method

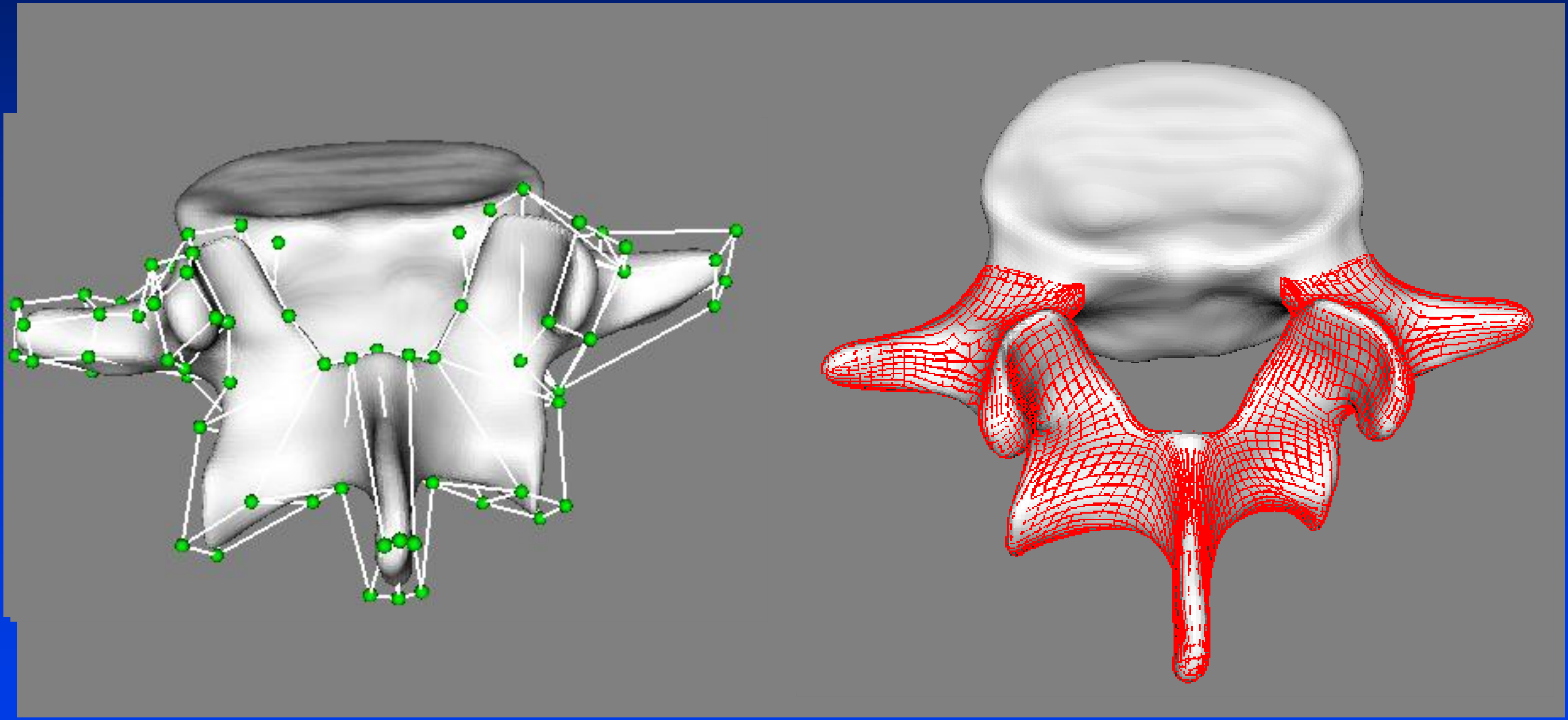
- A single bounding box coupled with the projection technique may not always prove sufficient
- Method has been extended to add multiple boxes and/or subdivide existing boxes



Projection Method Multiple Boxes

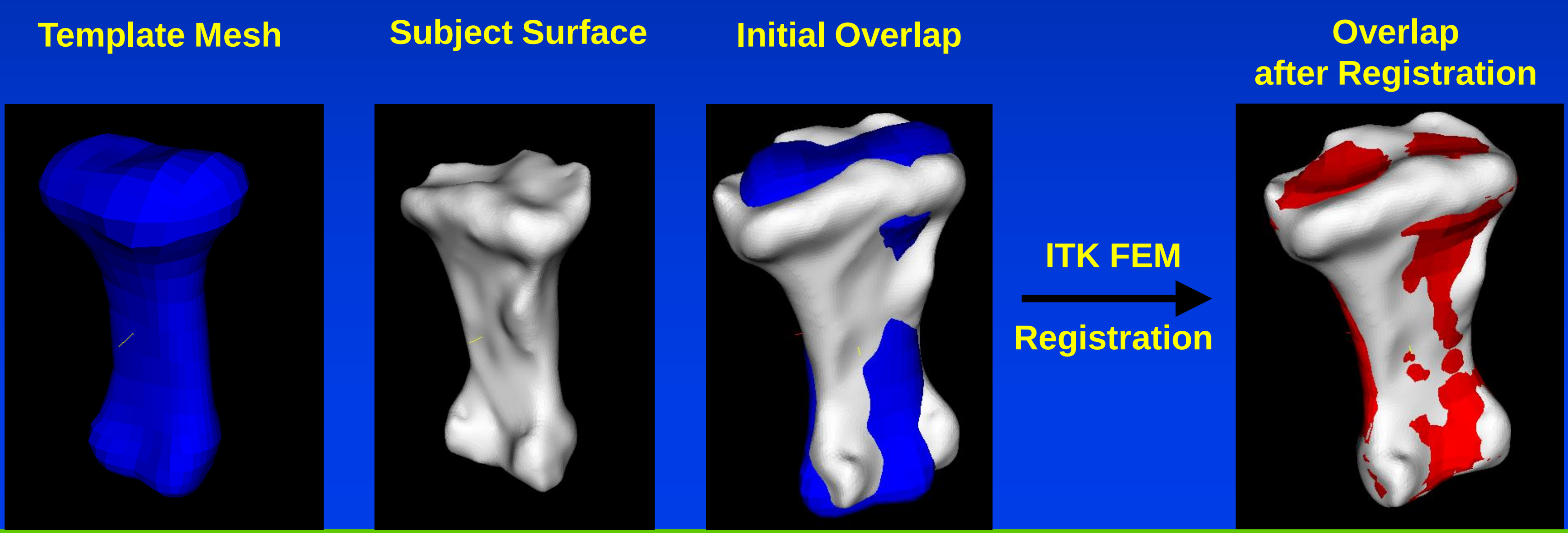


Multiple Bounding Boxes Spine



Mapped Meshing

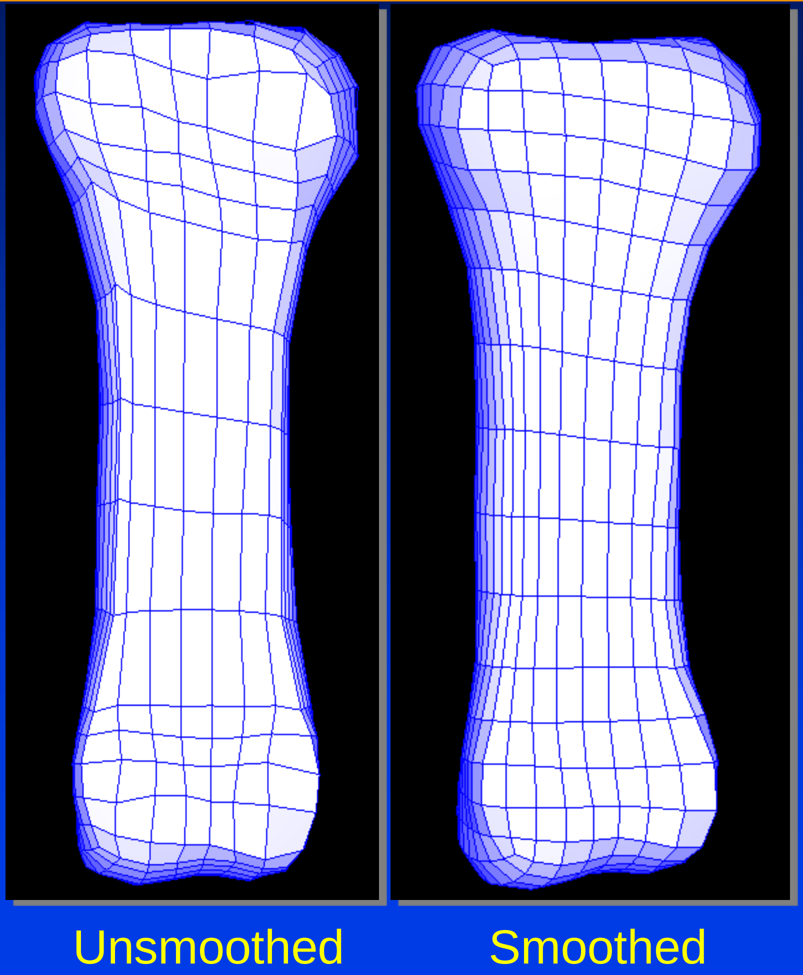
- Map a template mesh to a new subject
  - Use FE framework in ITK
  - Apply forces based on distance from mesh surface to surface representation

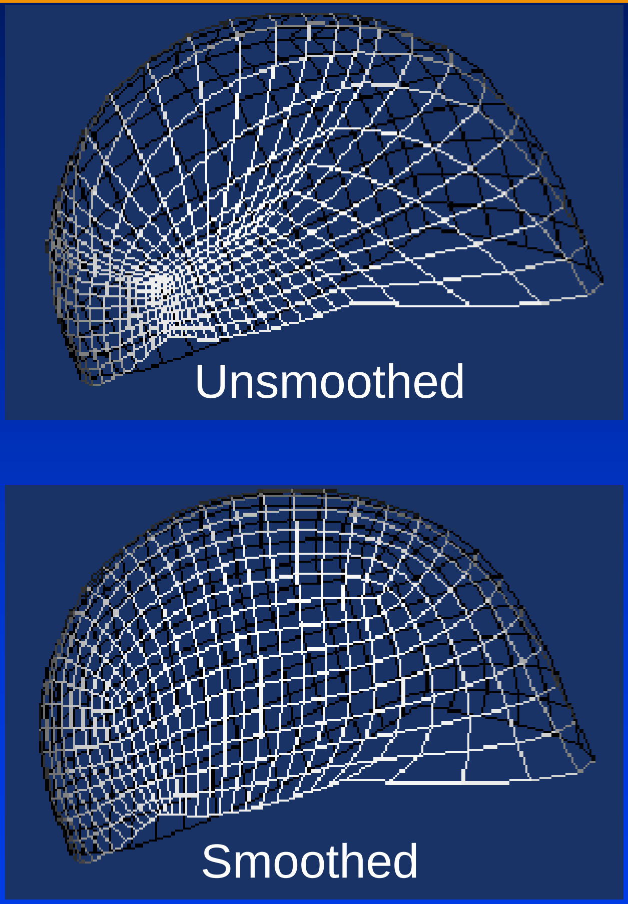


Solid Mesh Smoothing

- Projection of initial mesh onto the surface oftentimes yields distorted elements
- Need to smooth resulting mesh – Iterative Laplacian smoothing for solid mesh
- Method
  - Apply Laplacian smoothing to surface nodes holding interior nodes fixed
  - Project nodes back onto the original surface
  - Smooth interior nodes with surface nodes held fixed
  - Iterate for specified number of iterations or until convergence threshold is reached

Results of Mesh Smoothing

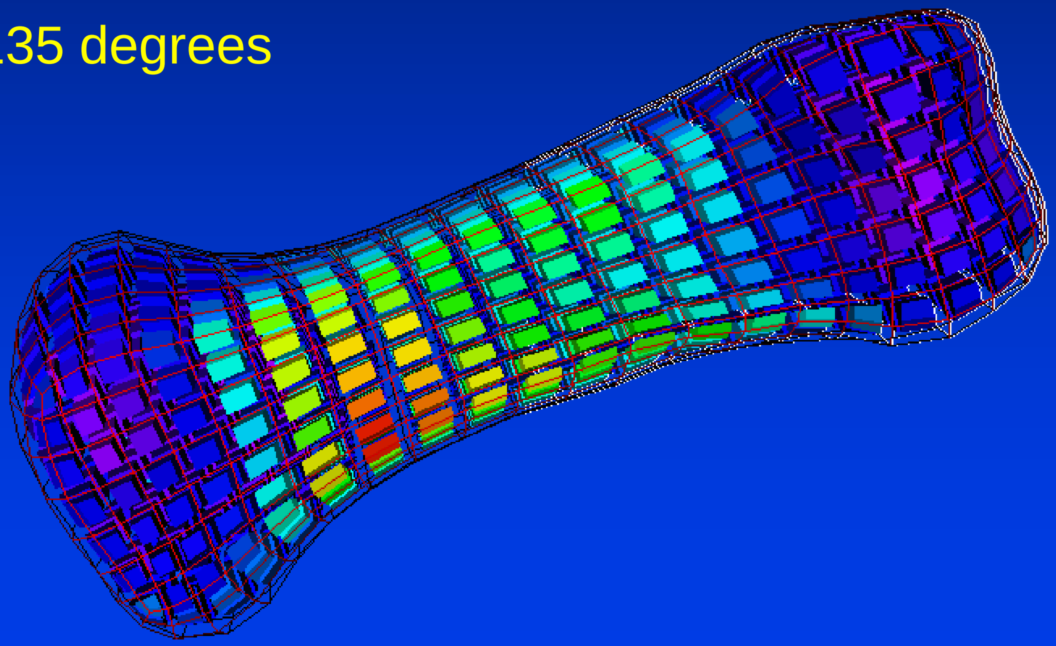


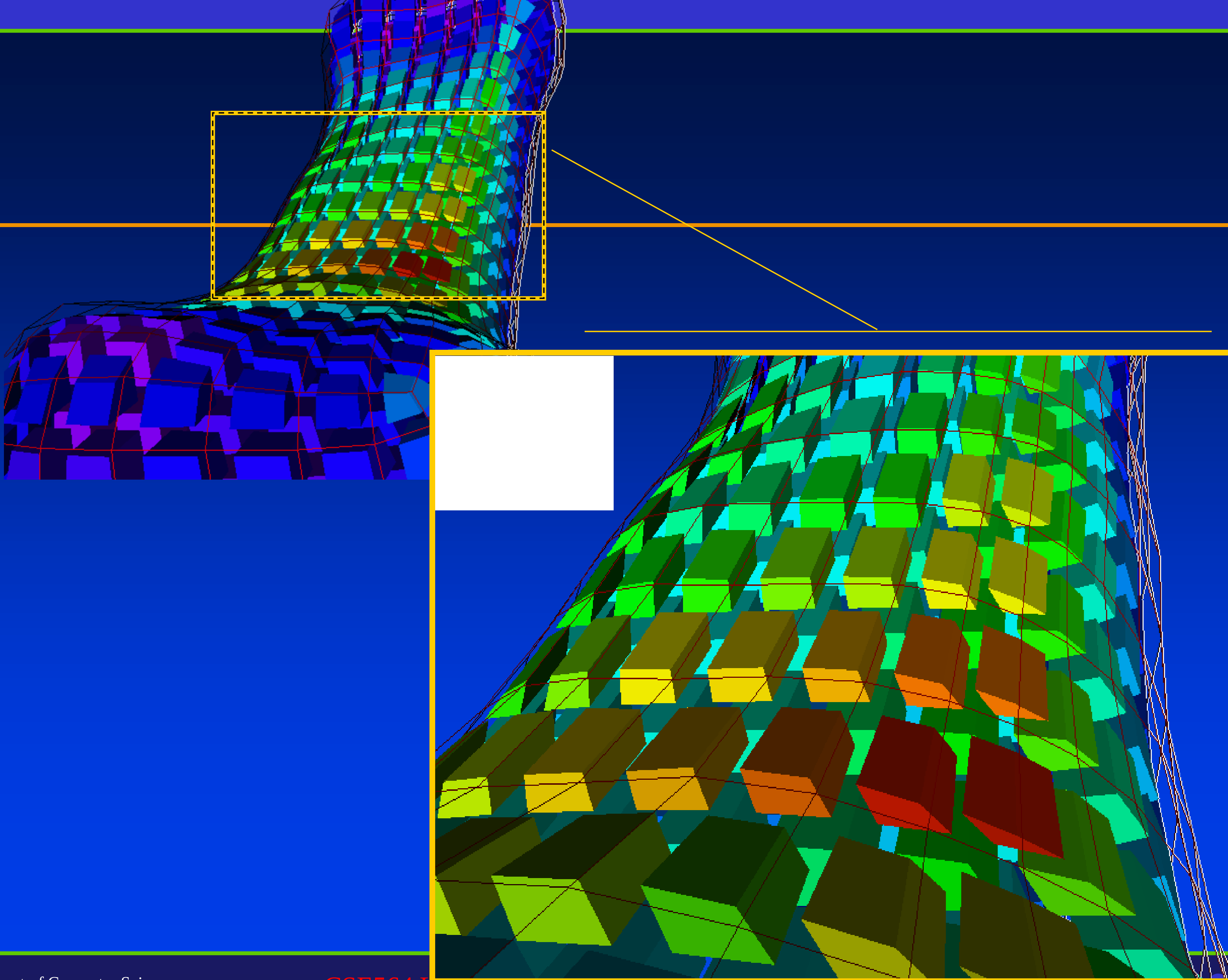


Mesh Quality Check

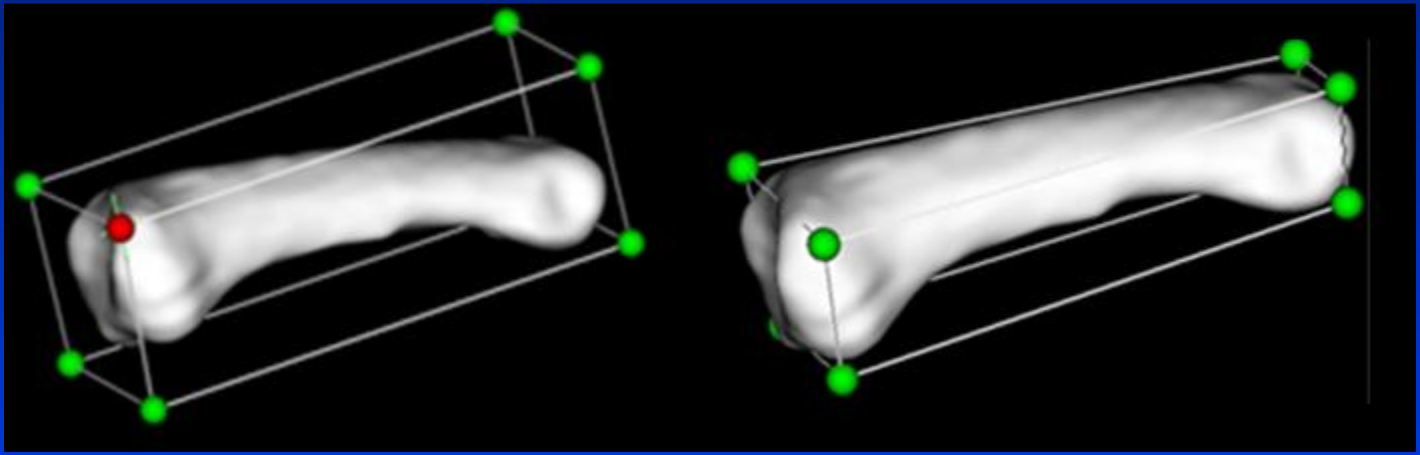
- Aspect Ratio: Excess of 100 to 1
- Distorted Isoparametric Elements:

  Angle between isoparametric lines
  < 45 degrees or > 135 degrees



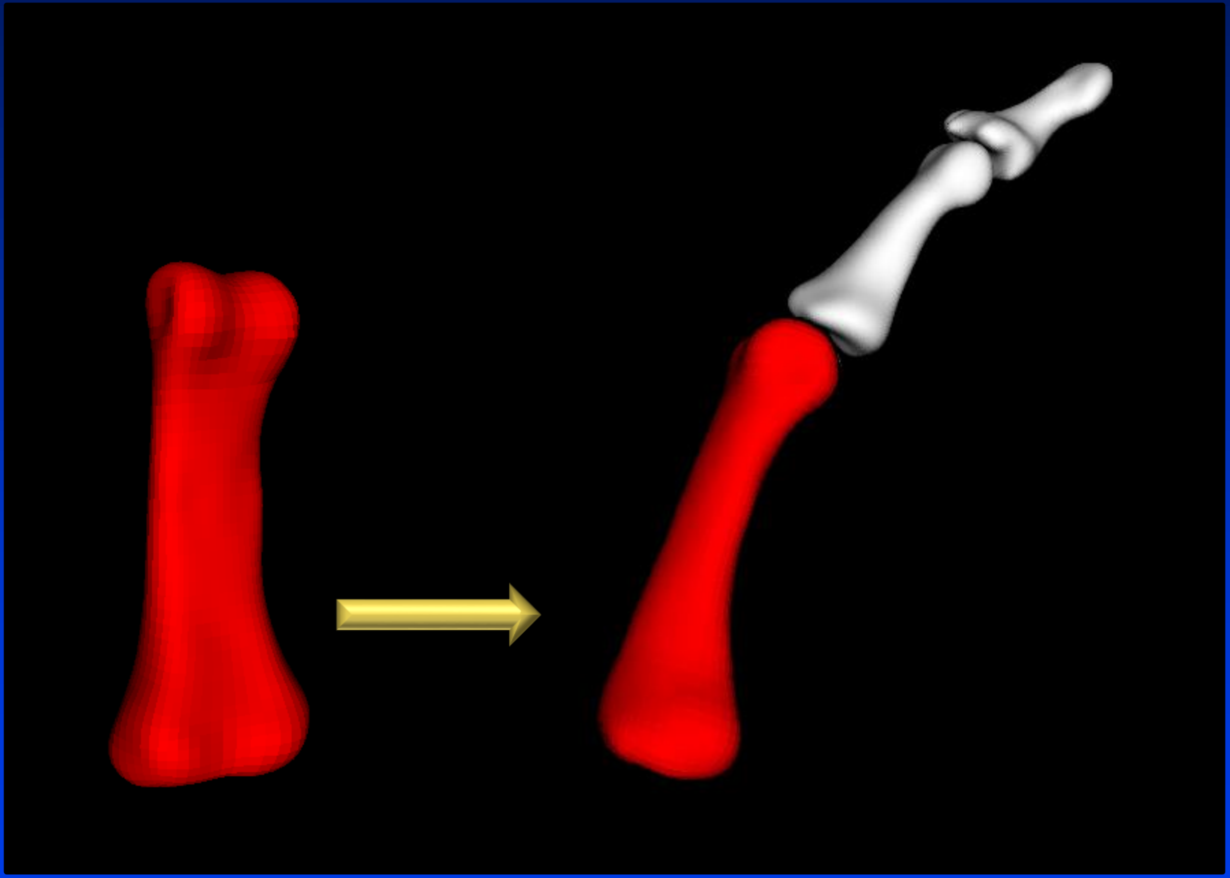


Interactive Building Block Operations



Vertex Manipulations

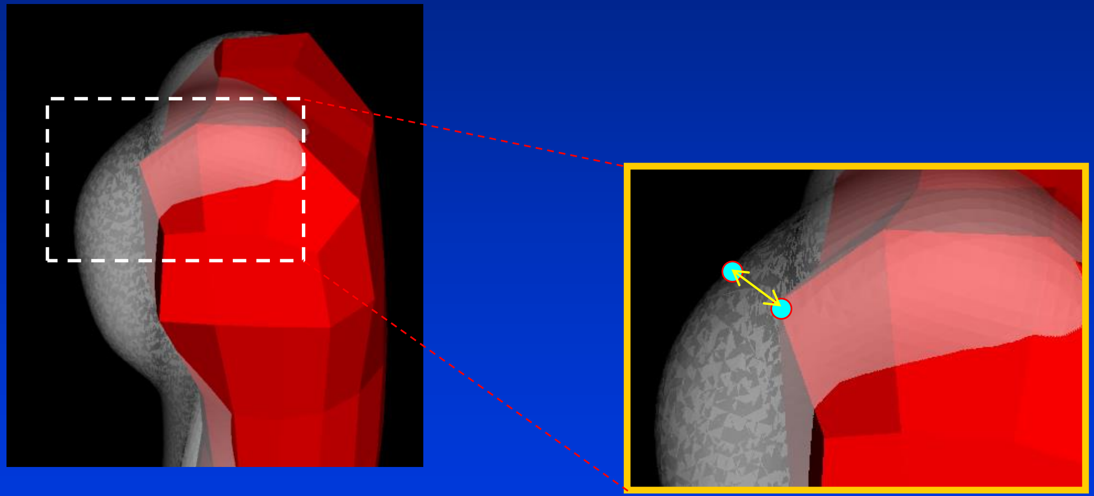
Model Registration via Deformation



Template mesh warped to a target surface

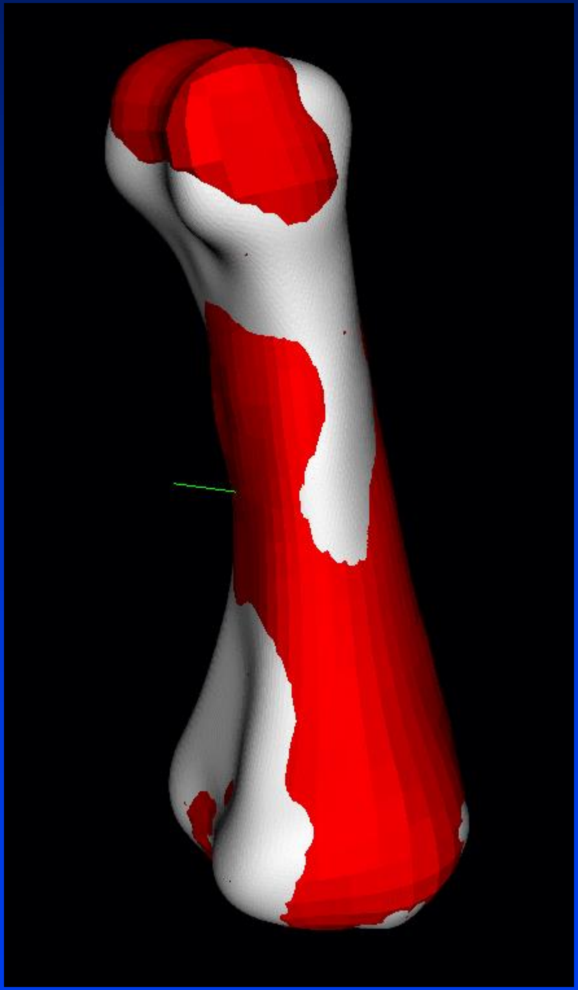
Deformable Registration

FE Method based registration



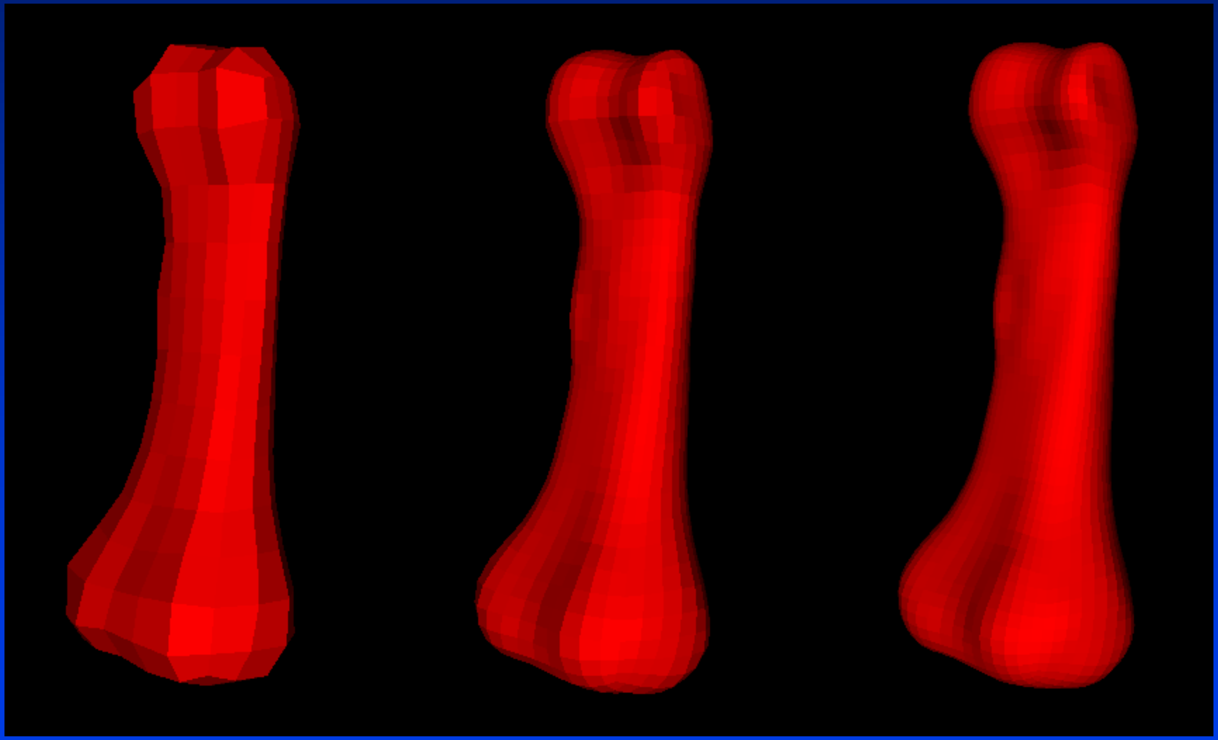
Forces used to drive the registration are based on the distances between the surface of the template solid mesh and the target surface.

Applied in the direction of the point normal.



Deformable Registration

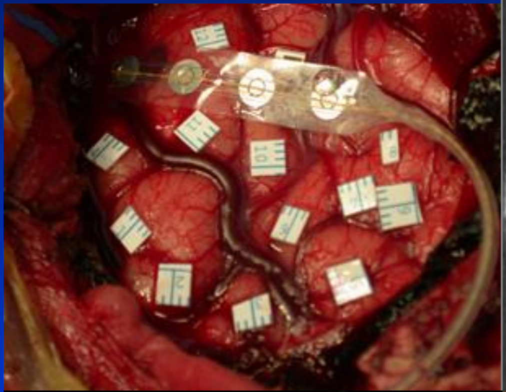
Multiple levels of Mesh Refinement

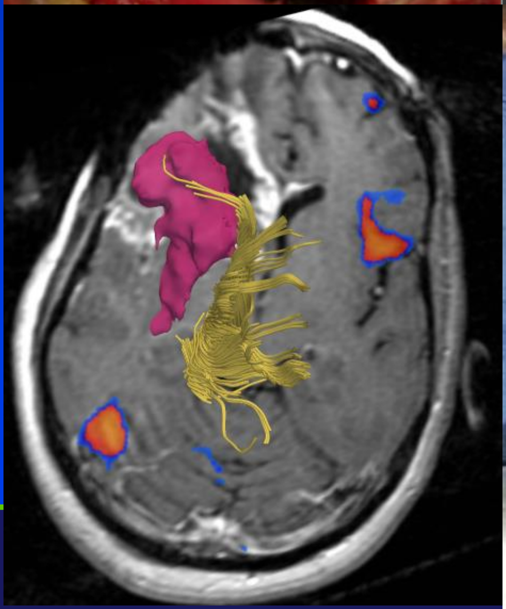
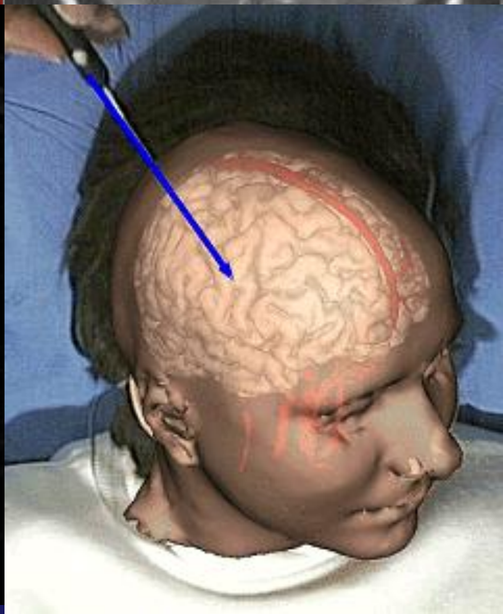


Increased mesh refinement

Image-guided Therapy (IGT)

- Is the active visualization of medical images to aid in decision making during a procedure.
- Allows physician to
  - See beyond the surface
  - Define targets
  - Control the interventions
- Enables new procedures, decreases invasiveness, optimizes resection

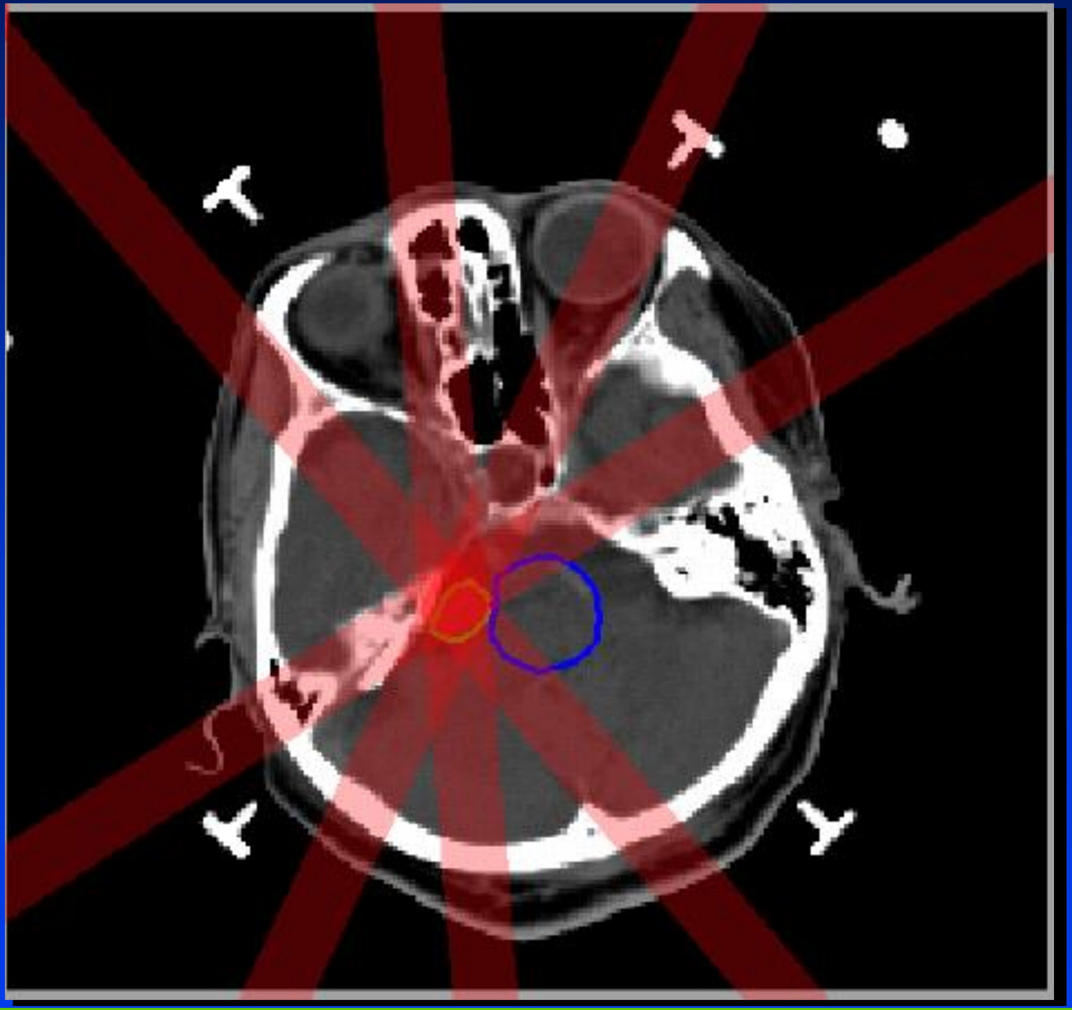


Radiosurgery

- Non-invasive procedure
- Moving beam of radiation to ablate (destroy) brain tumors
- **The problem** is delivering
  - **Enough** dose of radiation to the tumor to **destroy** the tumor
  - **Minimum** dose of radiation to the healthy and dose-sensitive tissue (e.g., brain stem and optic nerves) **not to destroy** them
- The solution is
  - Crossfiring at the tumor: several weaker beams from different directions

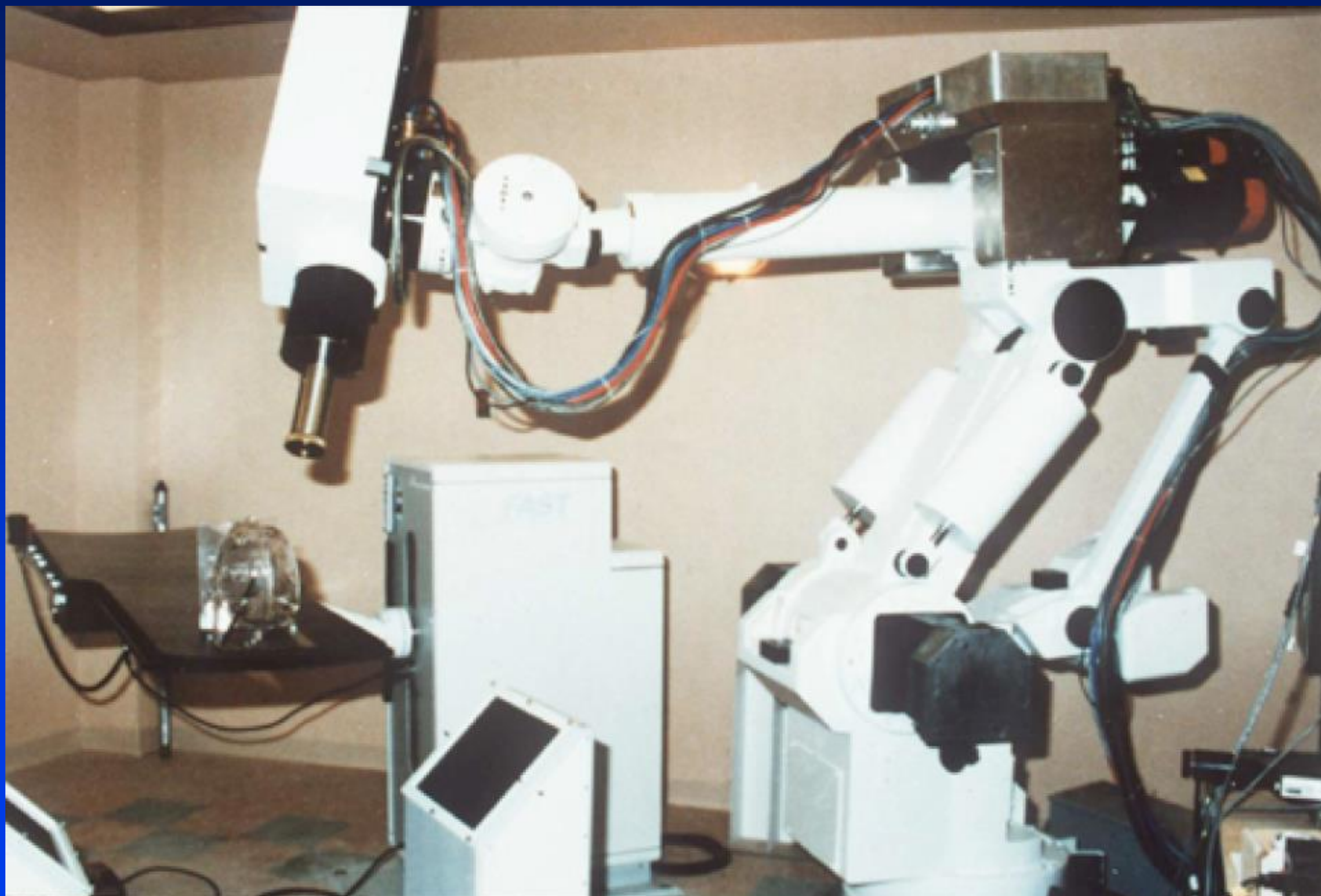
Radiosurgery



Treatment Planning in Radiosurgery

- Determination of a series of beam configuration (position and orientation)
- Constraints:
  - The beams should intersect to form a region of high-dose on the tumor
  - The dose distribution should match the shape of the tumor
  - Healthy or critical tissues should get minimum or no radiation

A Treatment Planning System

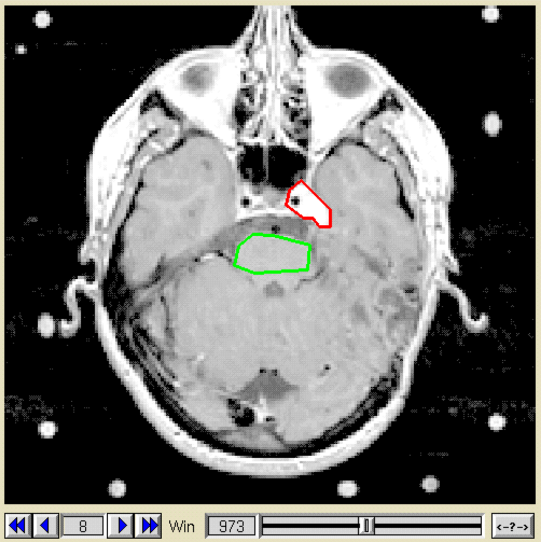


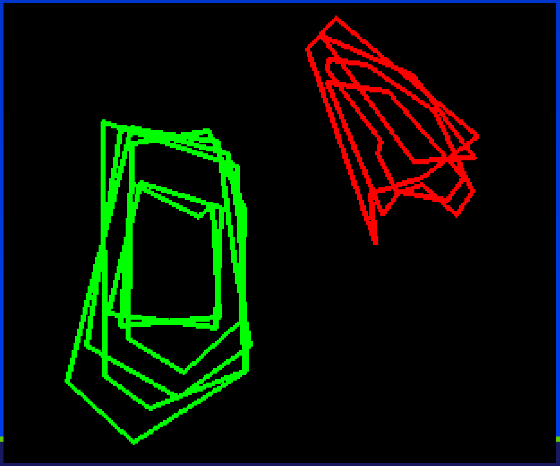
A Treatment Planning System

- 6-dof robotic manipulator arm
  – Positions the radiation source
- Real-time imaging system
  – Monitors patient's motion continuously
- A treatment planning algorithm
  – Allows the surgeon to specify particular region of interest (e.g., tumors, dose-sensitive tissue) and range of dose
  – Uses **linear programming** to optimize the plans and satisfy constraints

Treatment Planning: Step-1

- The surgeon specifies regions of interest on the CTs (e.g., the tumor and critical structures)
  - the system makes a 3D reconstruction of the geometry
- Imposes constraints on the amount of radiation that these regions should receive.
  - Eg., Tumor should get 2000 rads min and brain stem should get 500 rads max





Treatment Planning: Step-2

- Beam selection
  - **Target point selection:** Evenly space targets on the surface of the 3D tumor model coming from the CT
  - **Source point selection:** Select source points making use of pre-recorded robot configurations. Record the target point and robot configuration.
  - **Path generation:** Connect all beam configurations into a path such that the robot traverses in a collision-free path in the environment.

Treatment Planning: Step 3

- Plan refinement
  - **Problem!** Beam selection **does not** consider the location of critical tissues and **does not** guarantee a highly homogeneous dose distribution on the tumor
  - Given these constraints, **Linear Programming** adjusts and finds the **optimal values** of the dose and diameter of individual beams.

Treatment Planning: Step 4

- Plan evaluation
  - The surgeon is provided with the results of planning
    - 3D iso-dose surfaces, dose-volume histograms, etc.
  - If the surgeon is not satisfied, planning is restarted from the desired step

Minimally Invasive Surgery

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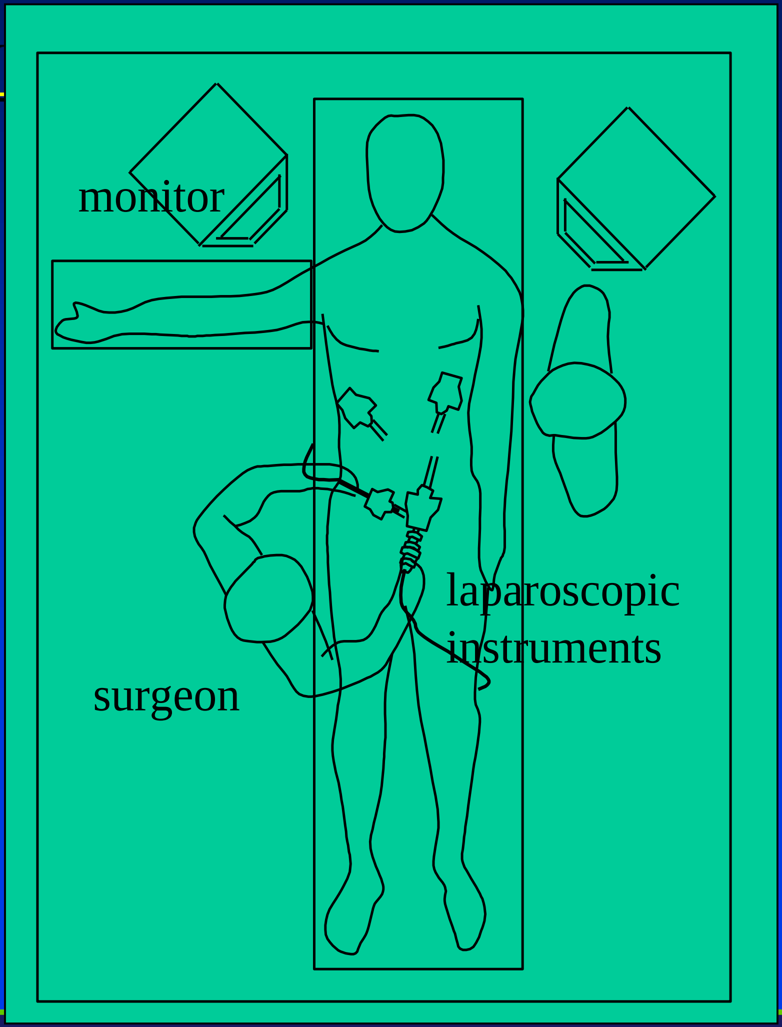
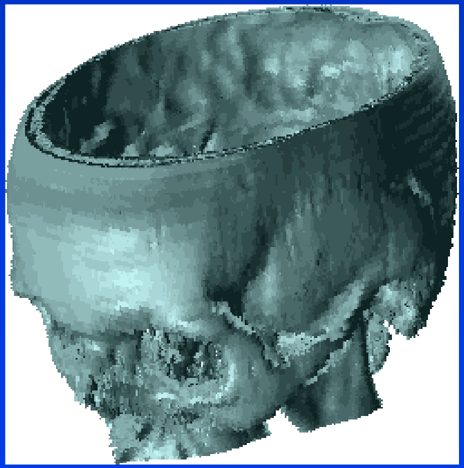


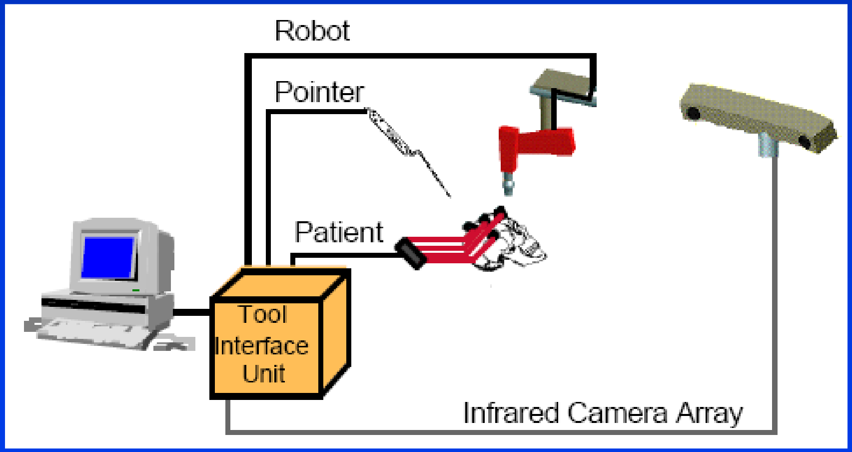
Motion Planning for MIS Training

- An enclosure (box) with openings for surgical instruments
  - Surgical tasks are performed within the box
- Surgical instruments are mounted with motion sensors
  - The maneuvers of the trainee are recorded during the performance
- Given the task, the optimal traverse of the surgical tools calculated
  - The optimal traverse is compared with the maneuvers of the trainee for performance assessment

Maxillofacial Robotic Surgery

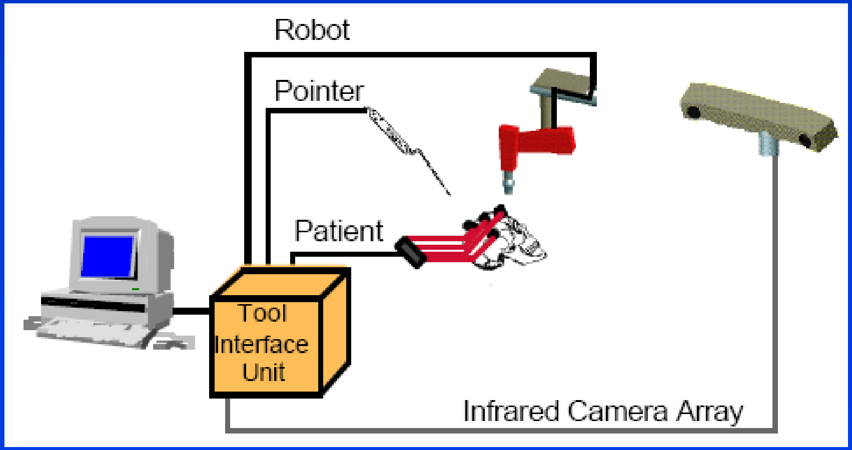
- Maxillofacial surgery: Surgery in the maxilla and face area
- Motion of the surgical robot should be planned for
  - Bone cutting
- Planned motion should
  - be **safe and adequate**
  - Have **online capabilities** to **react dynamical changes** (i.e. movements of the patient and surgical instruments)

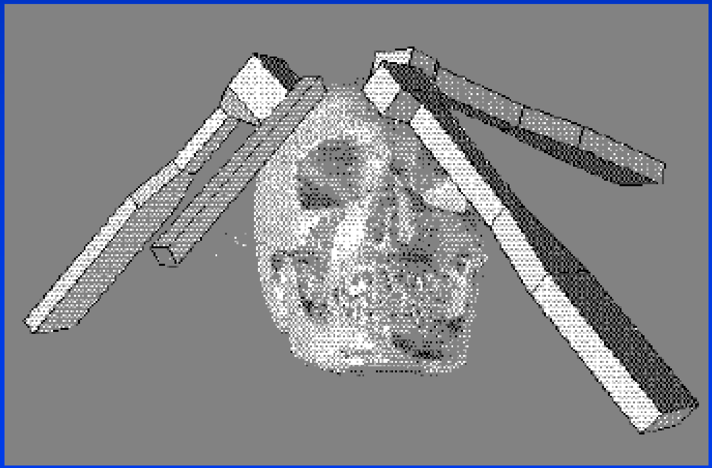




Motion Planner

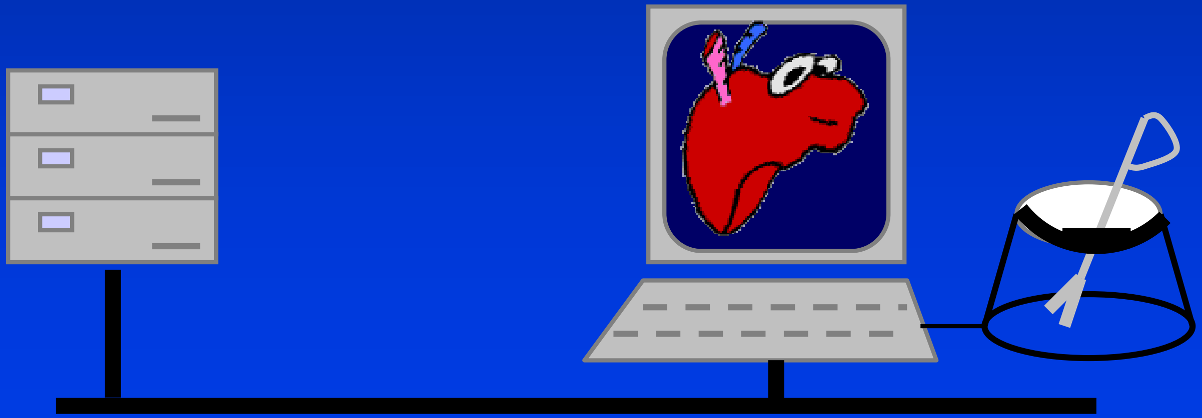
- A volume and surface model of the patient data is constructed beforehand
- Surgery setup:
  - 6-dof surgical robot for
    - Bone cutting, hole creating in patient's skull
  - Infrared navigation system for
    - Detecting and monitoring the positions of
      - Patient's skull, robot's tools, surgeons instruments
- Environment modeling
  - 3D modeling of the whole environment including patient data and surgical tools and screws attached to the skull
- Online collision-free motion planning for the 6-dof robot
  - The planner reacts according to the current state of the environment



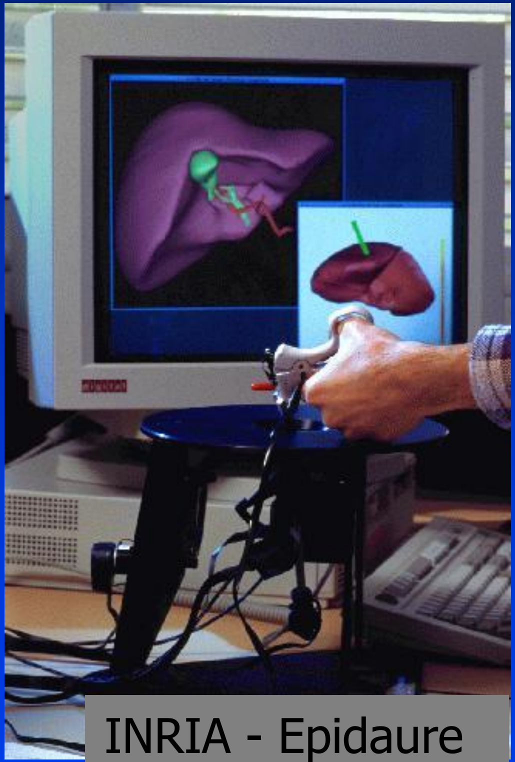


Surgery Simulation

- Objective: real-time model interaction
  - Position tracking
  - Biomedical model-deformation
  - Real time visual (25 Hz) and force (300 Hz) feedback



Surgery Simulation

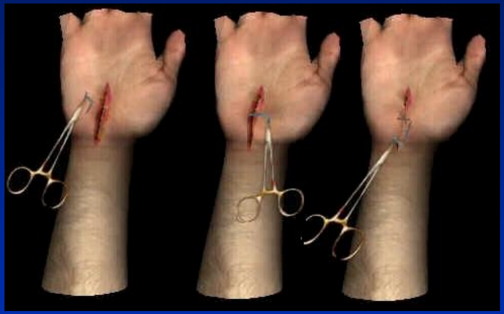


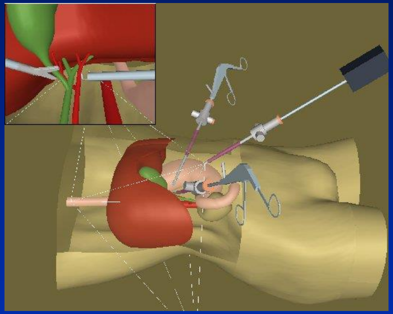
INRIA - Epidaure

Medicine

- Researchers are using virtual reality technology to create 3D ultrasound images to help doctors diagnose and treat congenital heart defects in children
- The medical application of VR was stimulated initially by the need of medical staff to visualize complex medical data, particularly during surgery and for surgery planning, and for medical education and training.

Training in Virtual Reality





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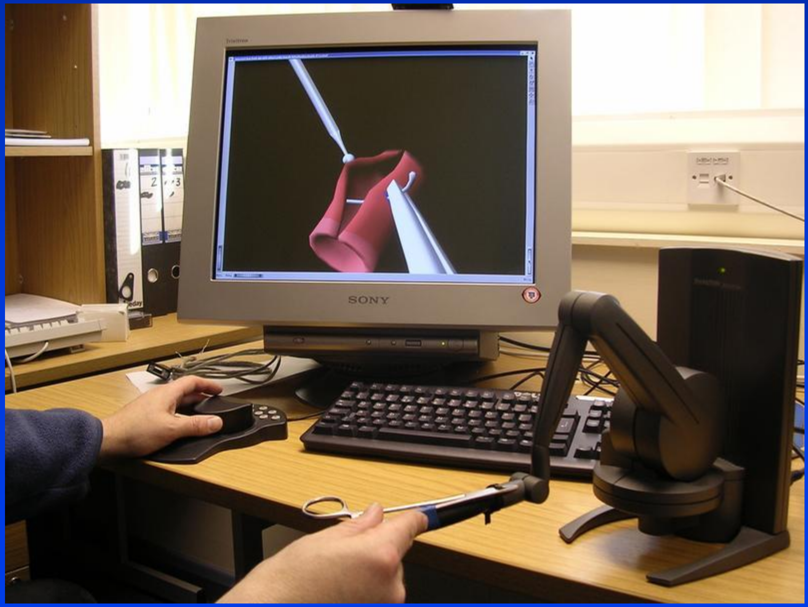

Training

- United States: The military used it as flight simulators to train pilots.
- National Aeronautics and Space Administration (NASA) use VR technology to construct a model of the Hubble Space Telescope (HST). In September, 1993, approximately 100 members of the NASA HST flight team received over 200 hours of training using the VR...

Training to Become a Surgeon

- Cost
- Realism
- Reusability
- Ethics