# Surgical Planning and Biomechanical Analysis

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Department of Trauma Surgery[2]
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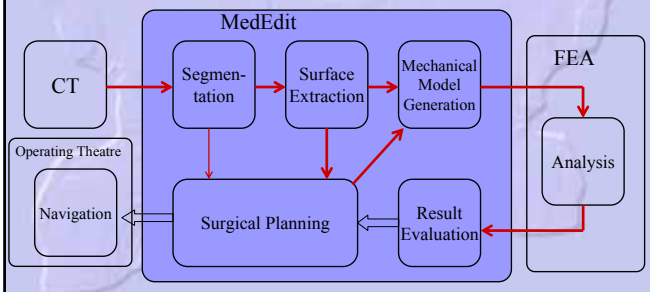
## System Overview

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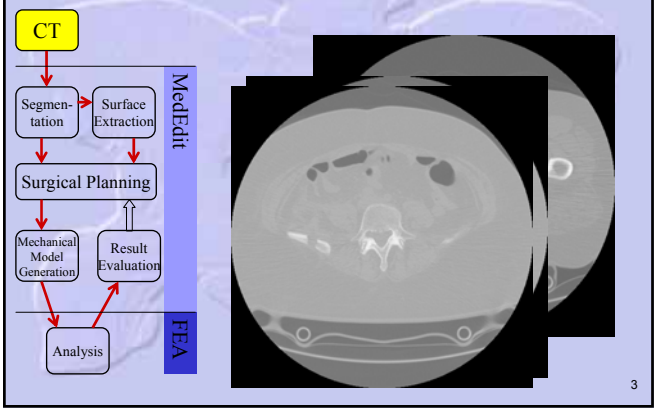
## System Overview - CT

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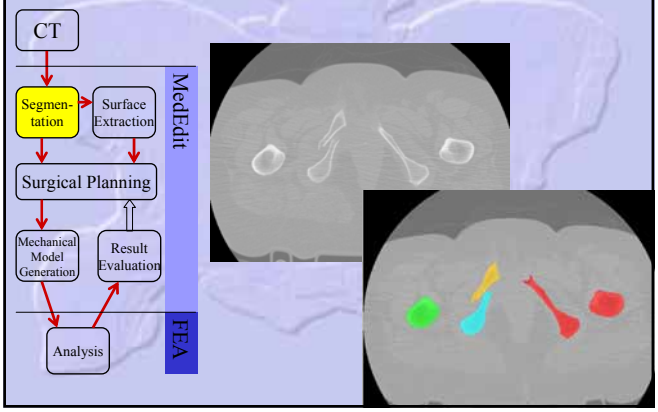
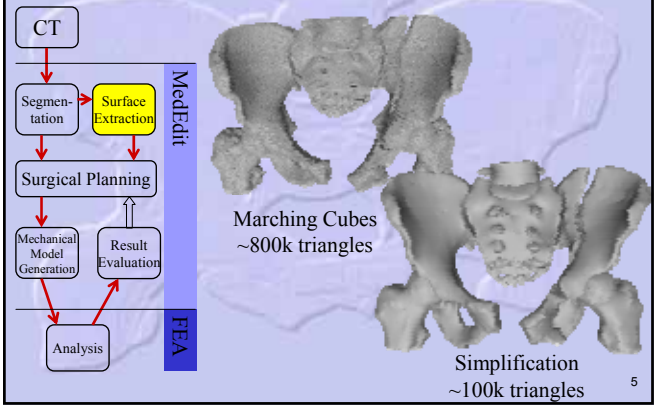
## System Overview - Segmentation




## System Overview – Surface Extraction

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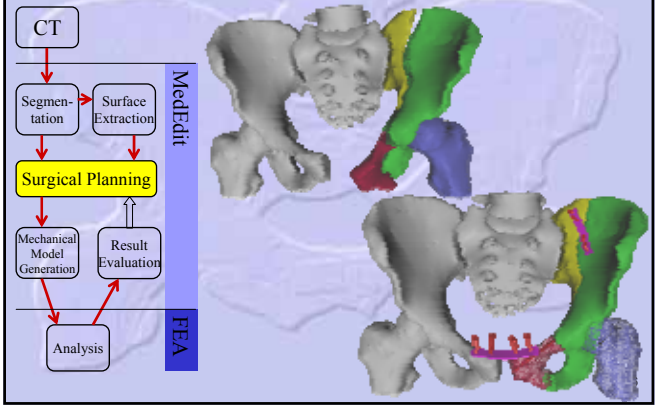
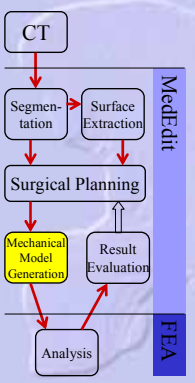
## System Overview – Surgical Planning



## System Overview – Mechanical Model

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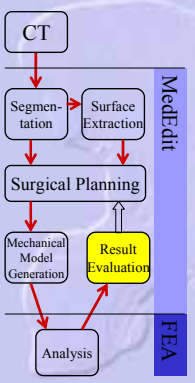
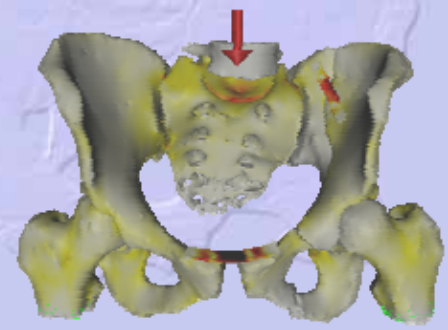
## System Overview – Result



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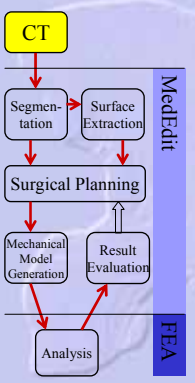
## CT




- DICOM (Digital Imaging and Communications in Medicine) format
- Image size: 512 x 512 px
- Slice thickness: 0.8–15 mm
- Number of slices: 80 - 350

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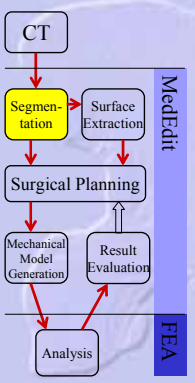
## Segmentation




- Convert 3D grayscale to 3D binary volume
- Algorithms
  - Threshold
  - Region Growing
  - Fuzzy Segmentation

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## Thresholding

Original image

Threshold value too low

Threshold value too high

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## Region Growing

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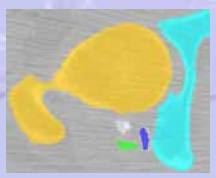
## Region Growing

- Joined regions
- Undetected regions



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## Fuzzy Connectivity

- The weakest link in the strongest path

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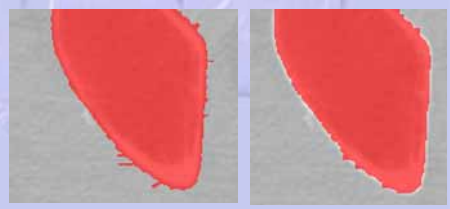
## Segmentation - Post Processing

- Remove possible noise
- Fill holes
- Morphological operations
  - Dilate
  - Errode
  - Opening
  - Closing



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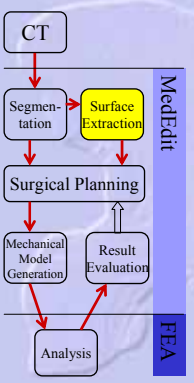
## Surface Generation




1. Use the Segmented volume and create a triangle mesh of the surface
   - **2D**

   - 3D

2. Simplify geometry

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## 2D contour reconstruction

- Bernhard Geiger (INRIA) : NUAGES
- Input: a set of simple closed polygons on parallel planes
- Output: 3D surface

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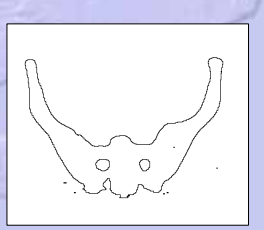
## Contour following

Segmented image



Contour points

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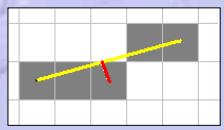
## Contour Simplification

- Collinear points are deleted
- Only the first and the last is kept
- Maximum distance as parameter of the simplification



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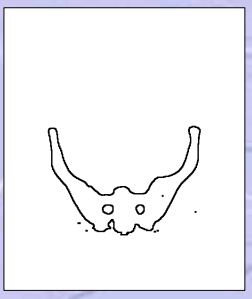
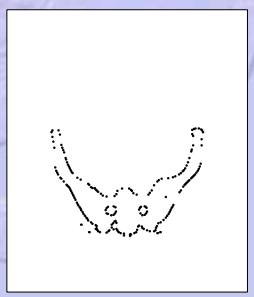
## Contour Simplification



All contour points before simplification



After simplification

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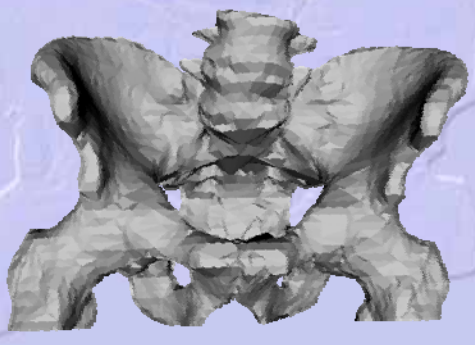
## 3D surface



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## 2D contour reconstruction

- Problems:
  - 2D contours
  - pelvic bone is not „tubular”
  - Horizontal resolution is low

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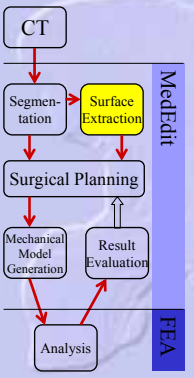
## Surface Generation




1. Use the Segmented volume and create a triangle mesh of the surface
   - 2D

   - **3D**

2. Simplify geometry

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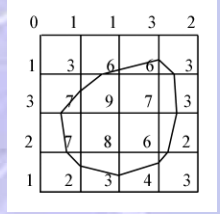
## Marching Squares I.

- Marching Squares (2D)
  - 16 configurations

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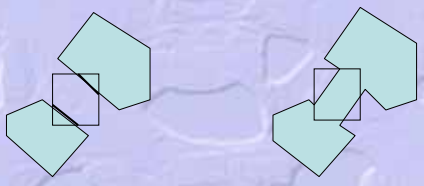
## Marching Squares II.

- The marching squares ambiguous cases



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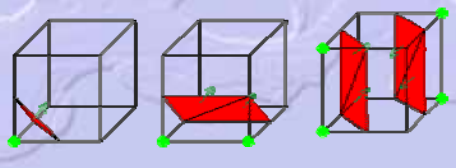
## Marching Cubes

- Fully 3D
  - 256 situations
  - generalized in 15 families by rotations and symetries



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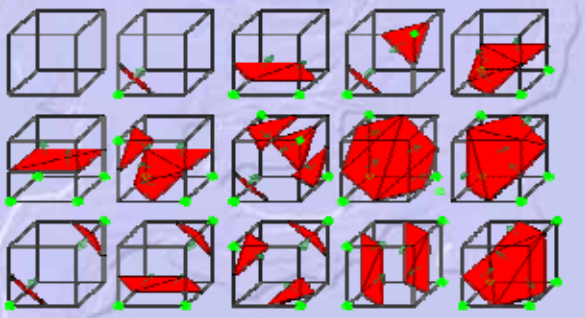
## Marching Cubes II.



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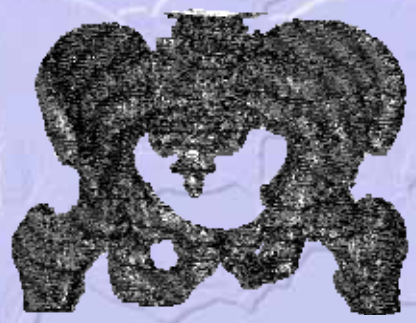
## Marching Cubes



Surface generated with the marching cubes algorithm.
Number of triangles ~800.000

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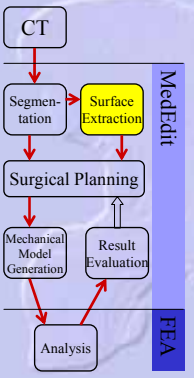
## Surface Generation




1. Use the Segmented volume and create a triangle mesh of the surface
   - 2D
   - 3D
2. Simplify geometry
   - Reduce rendering time
   - Reduce analysis resources

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## Surface Simplification Methods

- *Type of coarsening modifications:*

Vertex removal Edge collapse

- *Heuristics used to select a modification:*
  - usually, the one which causes the least increase in the approximation error
  - random selection

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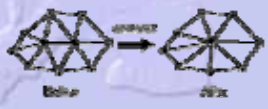
## Scheme of a edge collapse algorithm

- Examine all vertex pairs
- Build queue where $\left\|\vec{V}_1 - \vec{V}_2\right\| < t$
- **Loop**
  - choose a removable edge e
  - delete e and its triangles
  - Update queue
- **Until**
  - Queue is empty or target reduction reached



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## Mesh Decimation – Vertex removal

- Schroeder et al, 92
- Based on controlled removal of vertices
- **Loop**
  - choose a removable vertex *v*
  - delete *v* and its incident faces
  - re-triangulate the hole
- **Until**
  - no more removable vertex exists or reduction rate fulfilled

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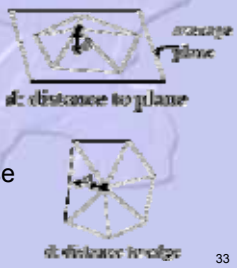
## Mesh Decimation

- Vertex is removable iff
  - Distance to average plane is lower than $e_{max}$
  - Distance to boundary is lower than $e_{max}$
- Properties
  - Efficient
  - Simple implementation & use
  - Works on large meshes
  - Implemented in VTK



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## Co-planar face merging

- Kalvin, Taylor '96
  - Partitions the surface into connected disjoint co-planar regions
  - Regions are replaced by a polygon
  - Polygon boundary is simplified
  - Boundary retriangulated

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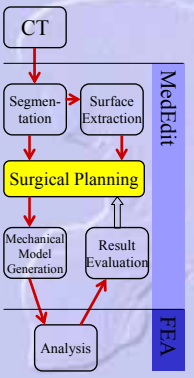
## System Overview – Surgical Planning




- Repositioning
- Implants

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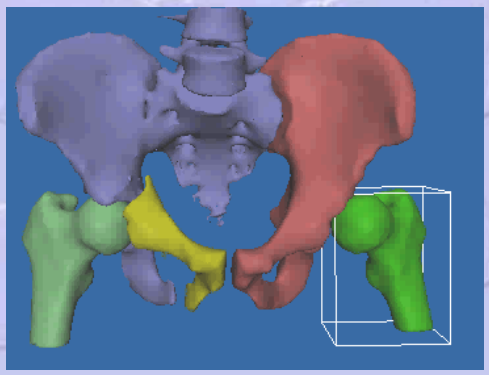
## Surgical Planning - Translation



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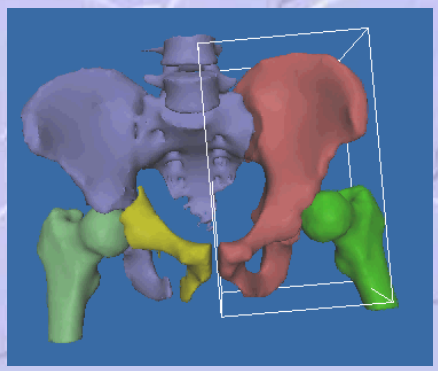
## Surgical Planning - Rotation



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## Heptic device

http://www.sensable.com/index.htm

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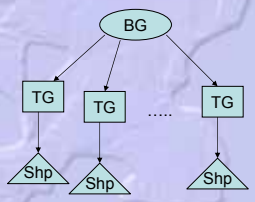
## Surgical Planning

- Treat bone surfaces as objects in 3D space
- Transformations
  - Translation
  - Rotation
- Implants
  - Screw
  - Fixation Plate

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## Surgical Planning

- 3D object positioning requires learning
- The model is 3D but the screen and the mouse is 2D
- Automatic tool is needed
- Collision detection can help

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## Collision Detection

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## Surgical Planning – Fixation Screw

- Screw parameters
  - Length
  - Insertion depth
  - Shank diameter
  - Tip length
  - Head length/diameter
  - Thread length
  - Major / minor diameters
  - Pitch

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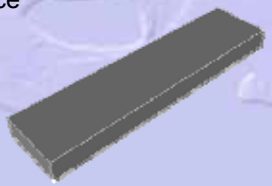
## Surgical Planning – Fixation Plate

- Fixation plate
  - Width
  - Height
  - Length
  - Follow surface



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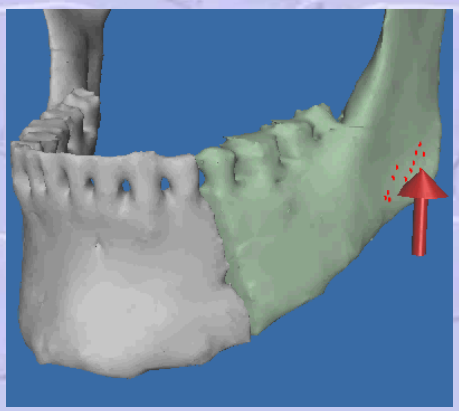
## Surgical Planning



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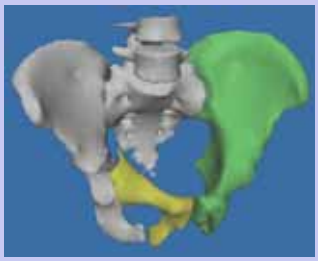
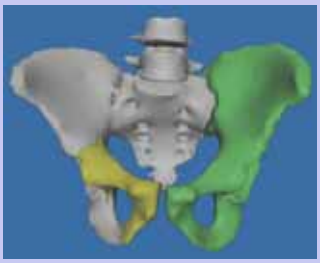
## Surgical Plan – Example I.





Original

After bone repositioning

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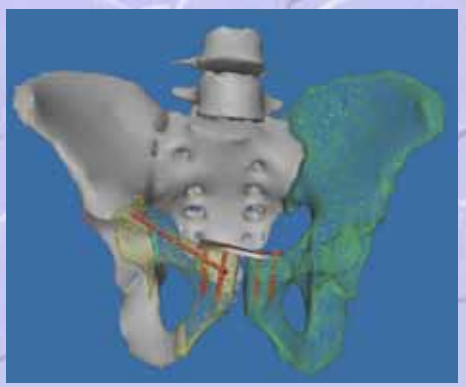
## Surgical Plan – Example I.



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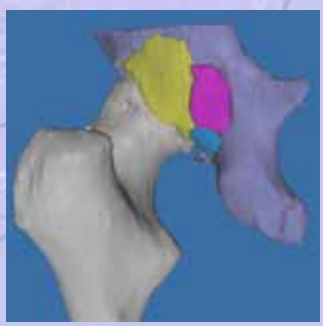
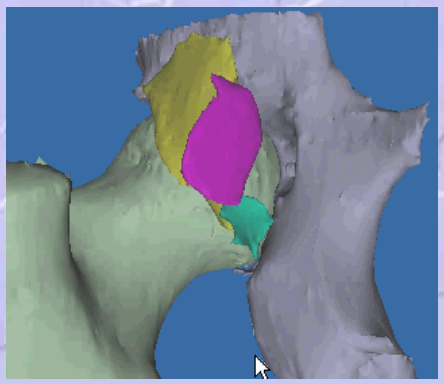
## Surgical Plan – Example II.



## Surgical Plan – Example II.



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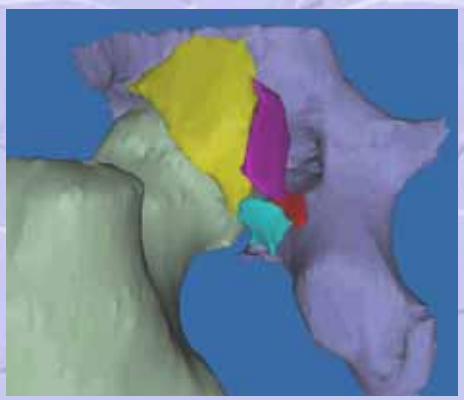
## Surgical Plan – Example II.



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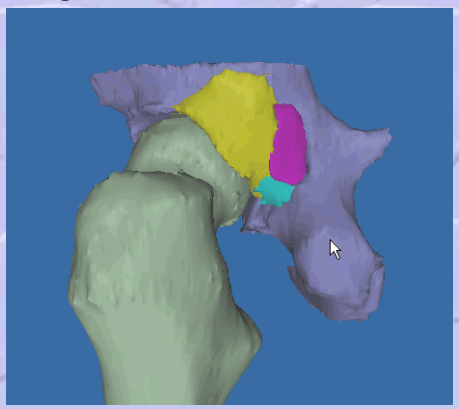
## Surgical Plan – Example II.



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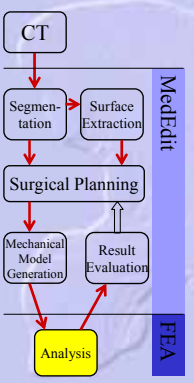
## Finite Element Analysis




- History
- Basic concept
- Material properties
- Mesh, element library
- How an enginier works

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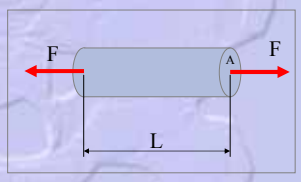
## Stress

- Stress is a measure of the internal distribution of force per unit area within a body that balances and reacts to the loads applied to it.

*F*: force,
*A*: crossectional area

$$\sigma = F / A$$

- Unit: N / $m^2$ = Pa

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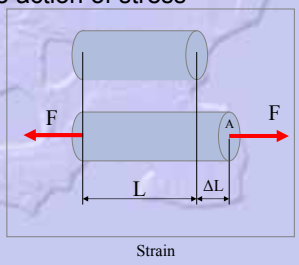
## Strain

Strain is the geometrical expression of deformation caused by the action of stress

$$\varepsilon = \Delta L / L$$

*L*: original length
*ΔL* : change in length

Unit: no unit

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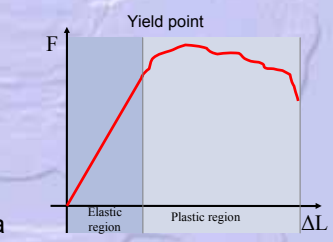
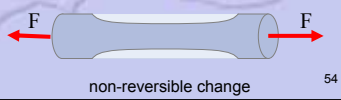
## Deformation

- Elastic region: the deformation is proportional to the force
- Plastic region: the material undergoes a non-reversible change




non-reversible change

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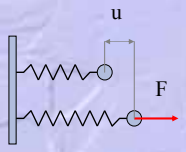
# Hooke's law

- *Hooke's law (1676): F*, is proportional to *u* by a constant factor, *k*

F = ku




*Where, k is the spring constant, u stretching distance*

- Elastic materials: *E* is the elastic modulus.

$\sigma = E\varepsilon$

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# Hooke's law

- Generalised to 3D by Cauchy

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix} = \begin{bmatrix}C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{bmatrix} \begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{zx}\\ \varepsilon_{xy}\end{bmatrix}$$

Stress — Stiffness matrix — Strain

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# Hooke's law

- *Izotropic material*: the material properties are independent of direction (2 elastic constants)

- *Ortotropic material: 2-3 orthogonal planes of symmetry, where material properties are independent of direction within each plane*
- Anisotropyc (21 elastic constants)

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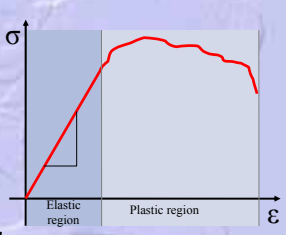
# Young's modulus

- Modulus of elasticity
- The slope of the stress-strain curve

$E = \sigma / \varepsilon$

- SI unit: Pa




| Material | E (GPa) |
|---|---|
| Diamond | 1200 |
| Steel | 210 |
| Iron | 196 |
| Aluminium | 69 |

| | |
|---|---|
| Bone | 1.1 |
| Cancelous bone | 0.01 |
| Rubber | 0.01 |

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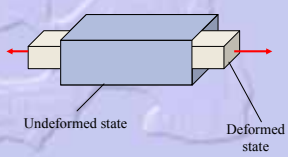
# Poisson's ratio

- Defined as the ratio of the contraction strain normal to the applied load divided by the extension strain in the direction of the applied load
- $n = - \varepsilon_{trans} / \varepsilon_{longitud}$
- $-1 <= n < 0.5$




| | |
|---|---|
| Rubber | 0.495 |
| Steel | 0.28 |
| Bone | 0.3 |
| Cork | 0.0 |

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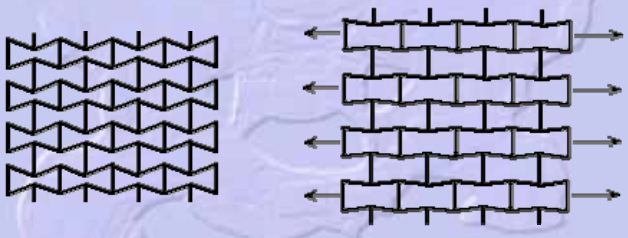
# Negative Poisson's Ratio Materials



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# Finite Element Method

- If we can not solve the original problem, let's brake it into smaller, but well known pieces and solve it that way!

$K = 2r\pi$ $K_n = nK_{ij}$ $K_{ij}=K_{45}=2r\sin(\pi/n)$

$\pi_n = K_n/2r = n$

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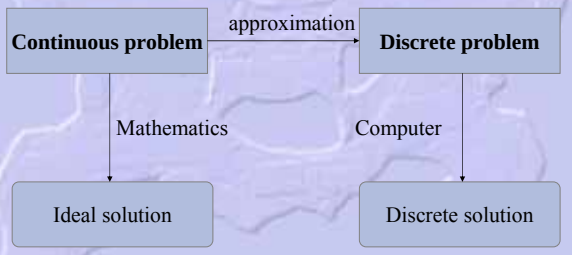
# FEA theory

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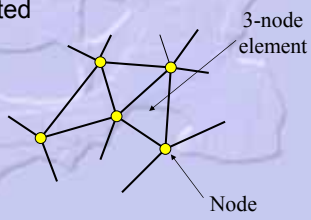
# Finite Element Mesh

- The model is a mesh of springs
  - **Nodes** define the geometry
  - **Elements** define which nodes are connected

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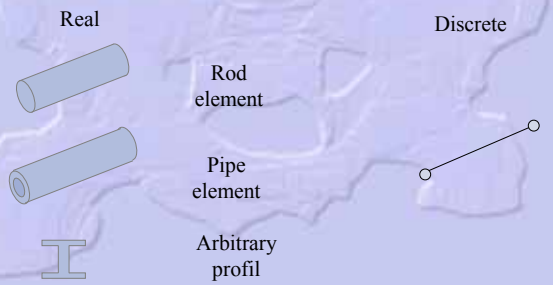
# Element library I.

- Primitive elements

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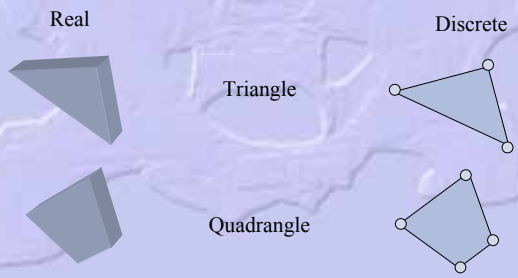
# Element library II.

- Shell elements: 2D, but with thickness

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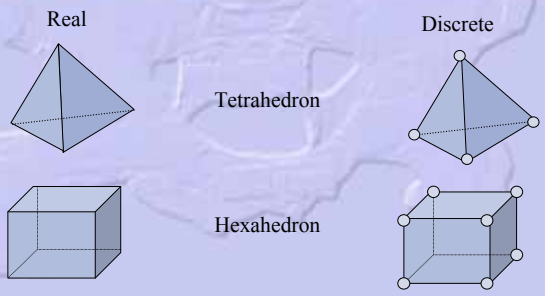
# Element library III.

- 3D elements

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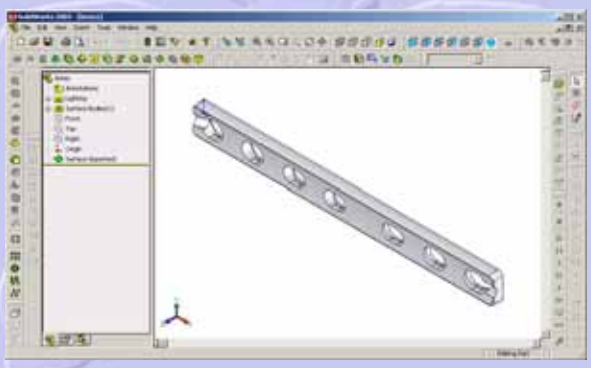
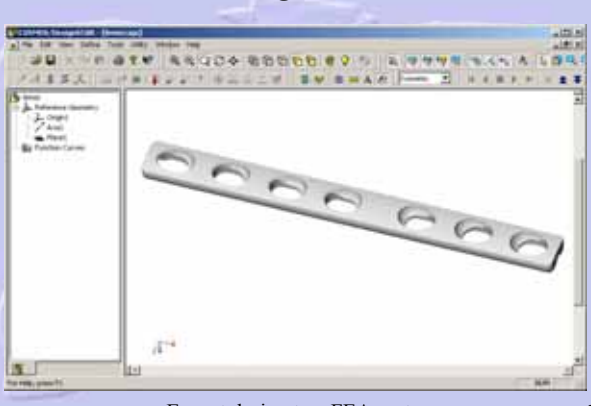
## How an engineer works



Desig in a CAD system

67

## How an engineer works



Export design to a FEA system

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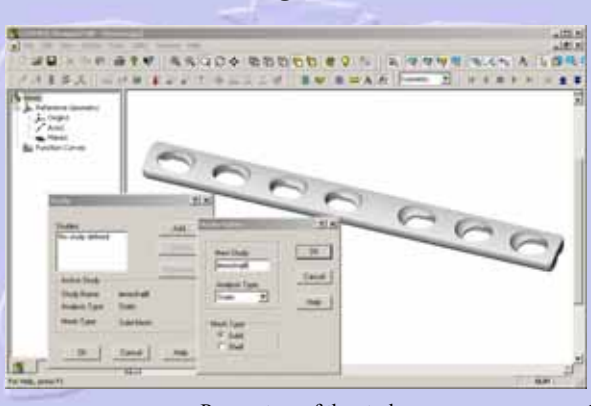
## How an engineer works



Parameters of the study

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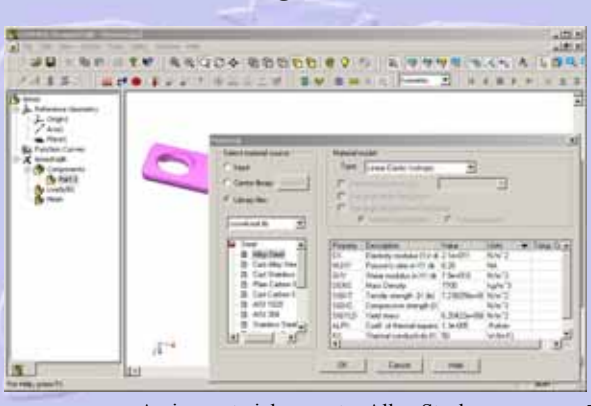
## How an engineer works



Assign material property: Alloy Steel

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## How an engineer works

Define fixed points

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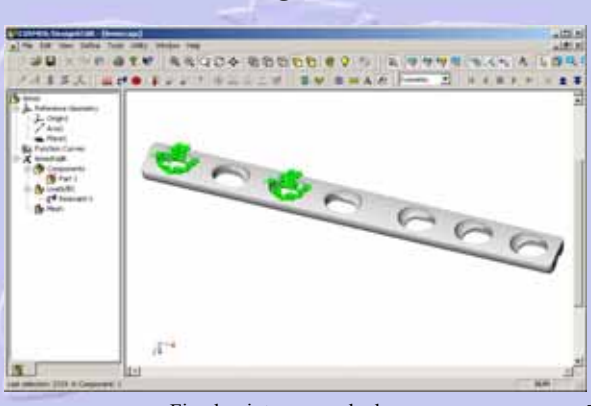
## How an engineer works



Fixed points are marked green

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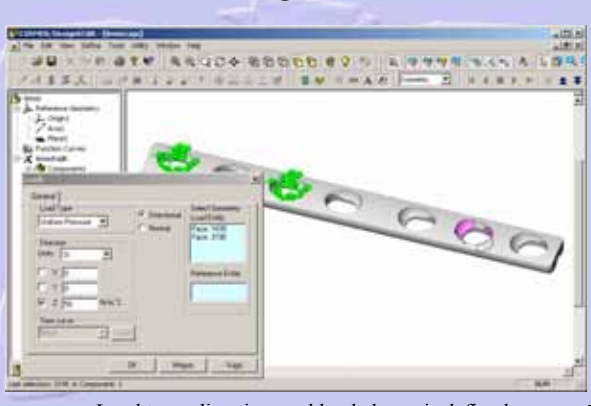
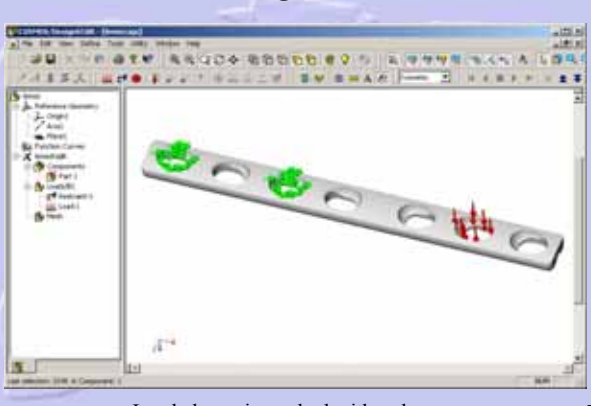
## How an engineer works



Load type, direction, and loaded area is defined

73

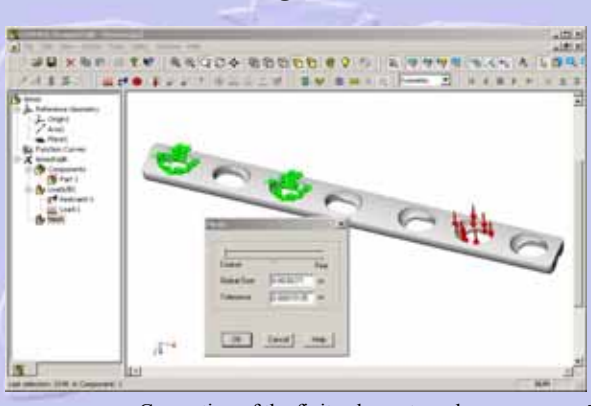
## How an engineer works



Loaded area is marked with red arrows

74

## How an engineer works



Generation of the finite element mesh

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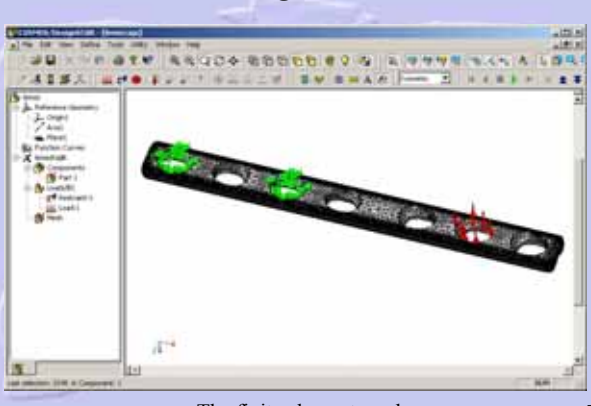
## How an engineer works



The finite element mesh

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## How an engineer works

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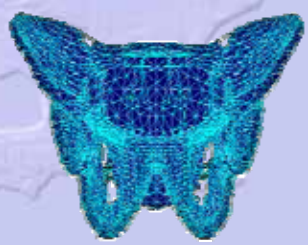
## Irregular objects

- There is no CAD model of the patients broken bone
- **No automatic mesh generation**
- Fixed points and loaded areas



CAD-pelvis

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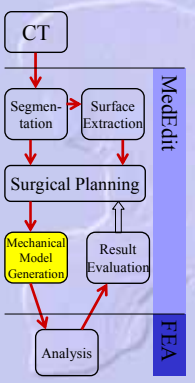
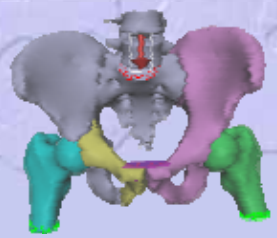
## Mechanical Model Generation




- UI for Load and boundary conditions
- Direct mesh generation



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## Mechanical Model

- Geometrical model
  - Nodes
  - Finite elements (shell, tetra, hexa)
  - Material properties (Young's modulus, Poisson' ratio)
  - Load
  - Boundary conditions
  - Connections between objects

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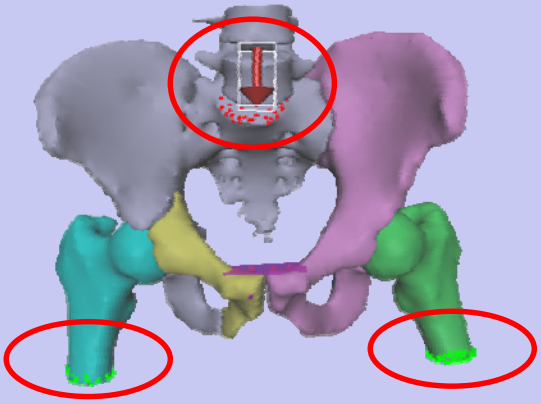
## Load and boundary conditions



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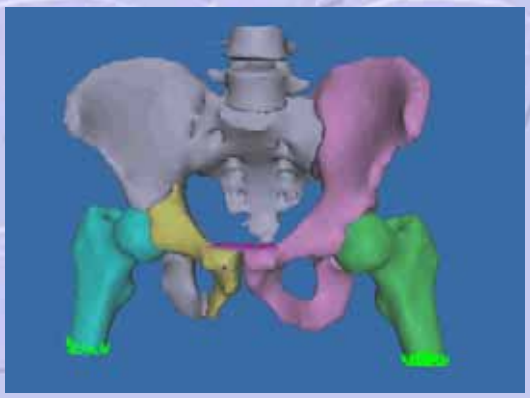
## Load



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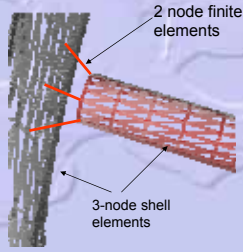
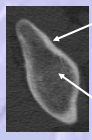
## Mechanical Model

- Based on the geometry → 3-node shell el.
- Relation between objects → 2-node el.

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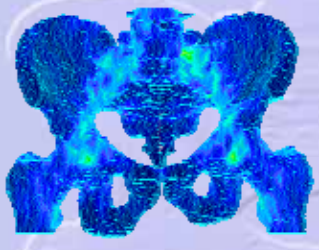
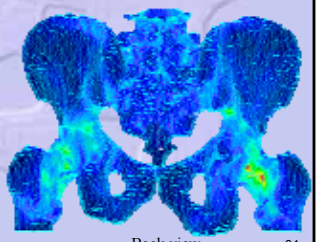
## Result of the Analysis



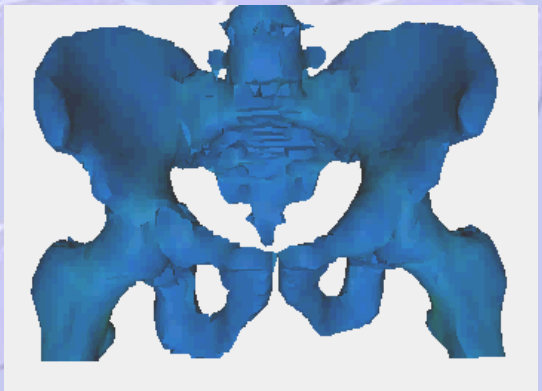
Front view



Back view

84

## Result of the Analysis



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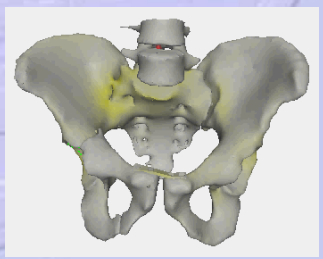
## Example I. - Pelvis



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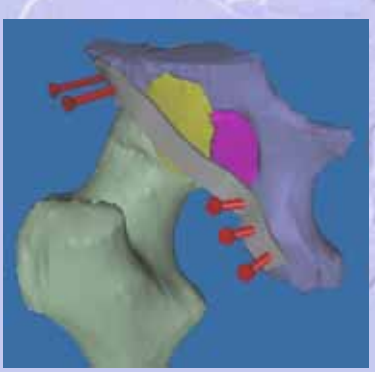
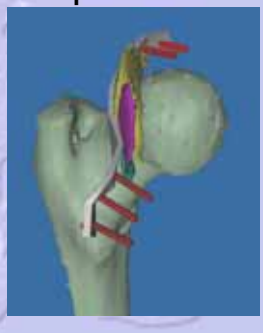
## Example II. - Hip





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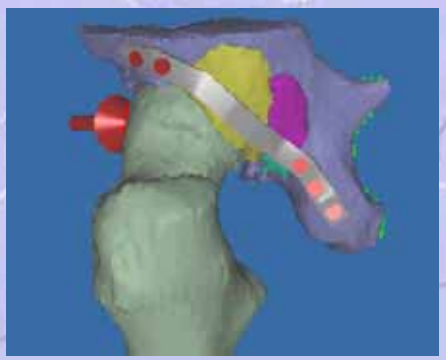
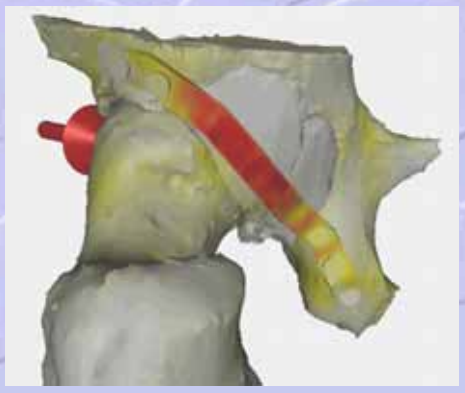
## Example II.



88

## Example II.



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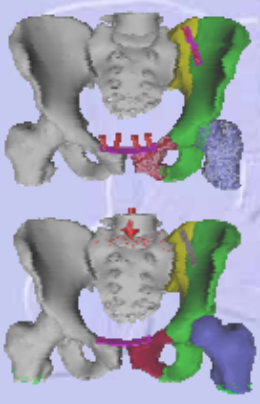
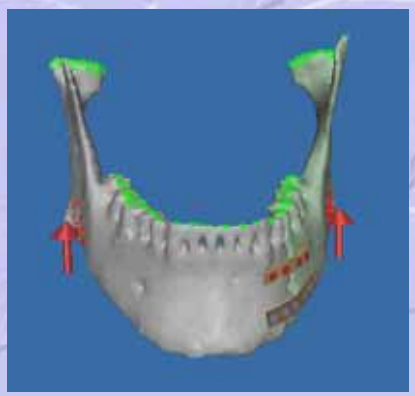
## Example III. - Pelvis



90

## Example IV. - Jaw



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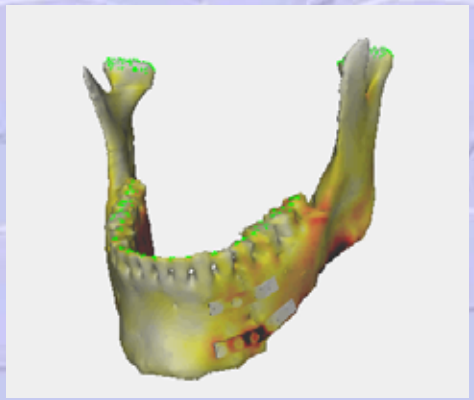
## Example IV. - Jaw



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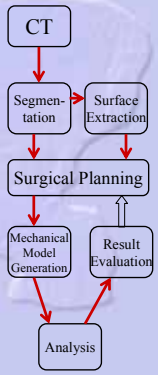
## Conclusion

- Results match to the clinical expectations
- Quantitative comparative measurements still pending
- Possible Applications
  - Clinical practice
  - Education
  - Real-time navigation in operating room
  - Research

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