Reality-Based Modeling for Simulation and Robot-Assisted Surgery

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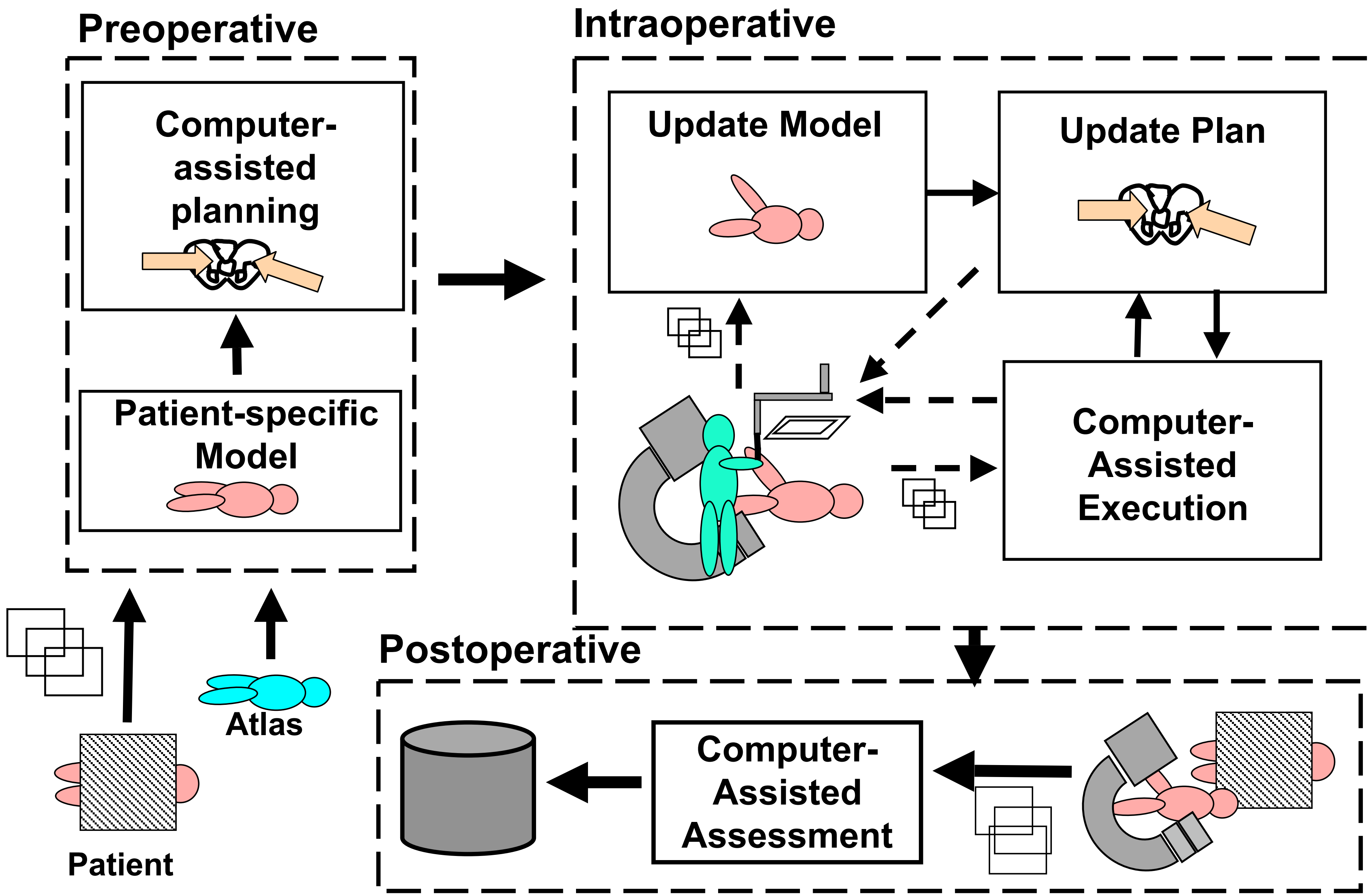
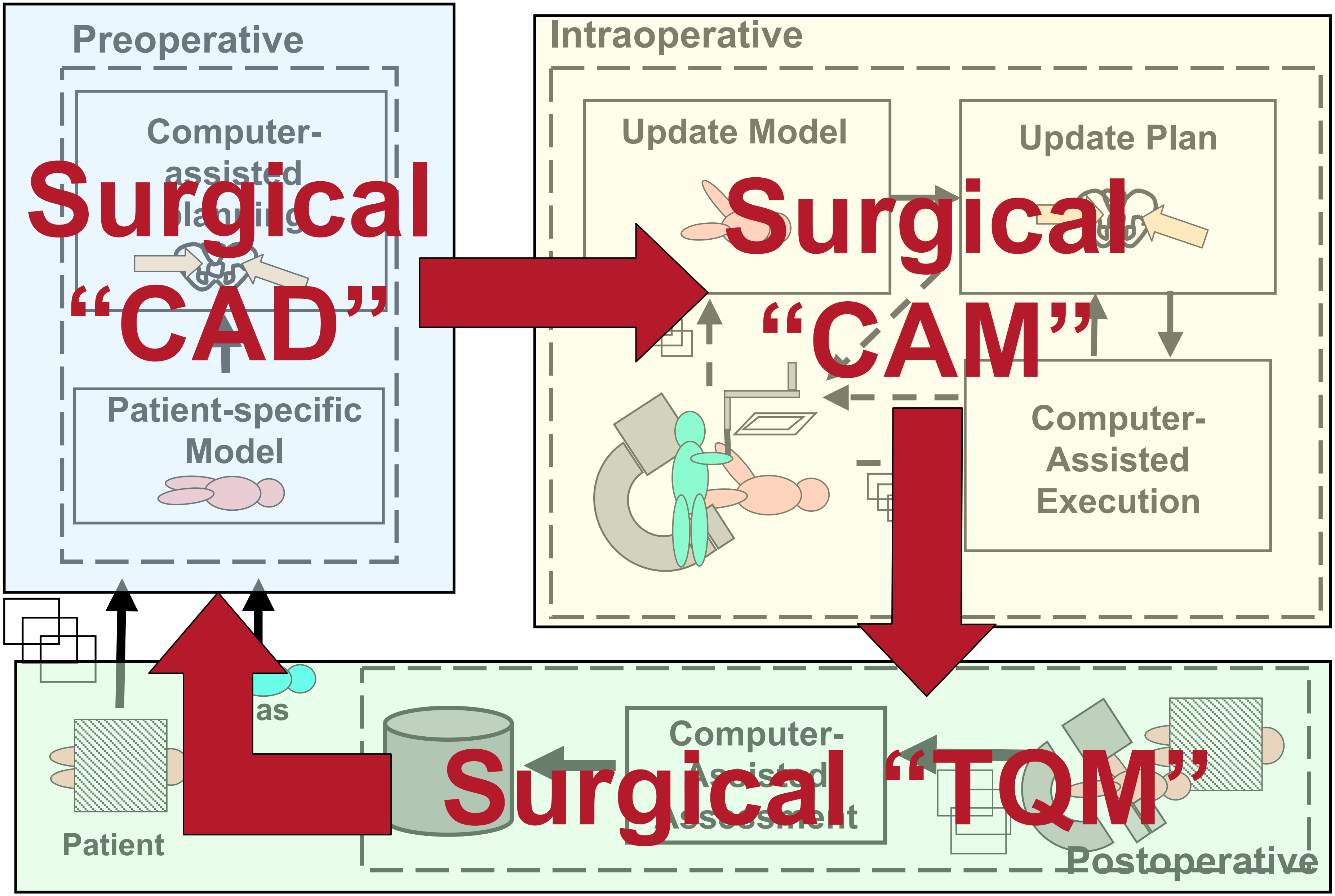
NSF Engineering Research Center for
Computer-Integrated Surgical Systems and Technology



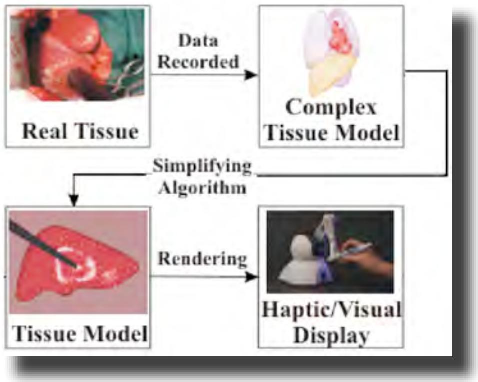
Preoperative
Computer-assisted planning
Patient-specific Model
Atlas
Patient
Intraoperative
Update Model
Update Plan
Computer-Assisted Execution
Postoperative
Computer-Assisted Assessment

R. H. Taylor

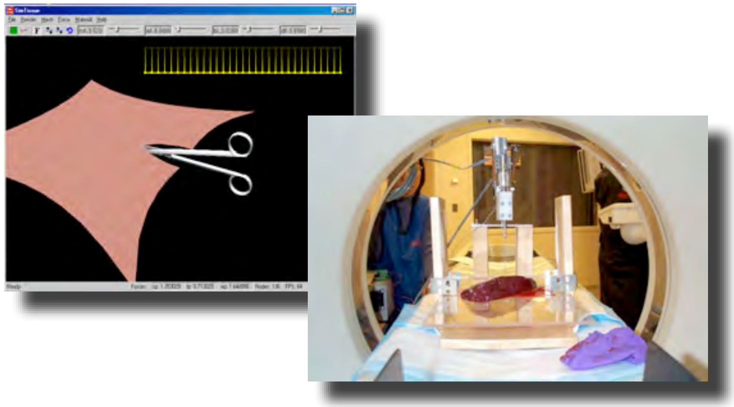

Preoperative
Computer-
assisted
Surgical
“CAD”
Patient-specific
Model
Intraoperative
Update Model
Update Plan
Surgical
“CAM”
Computer-
Assisted
Execution
Patient
Computer-
Surgical “TQM”
Postoperative

R. H. Taylor

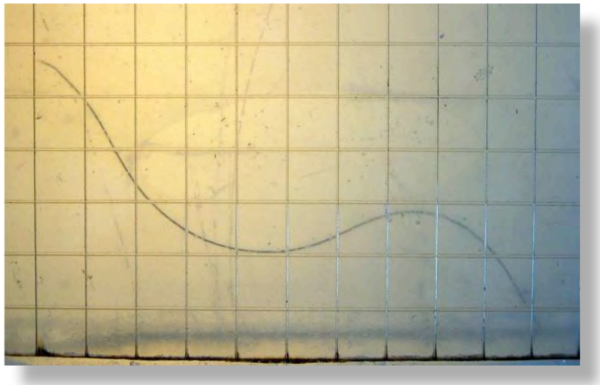
Reality-Based Modeling Process



Reality-Based Modeling Examples

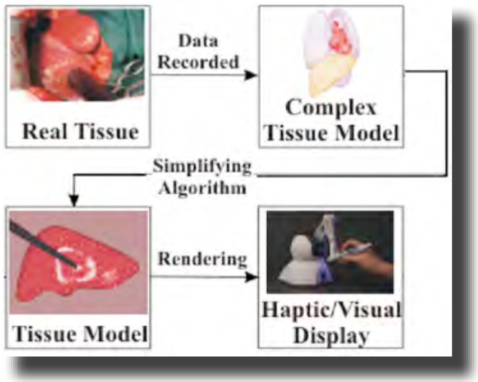


Modeling Factors

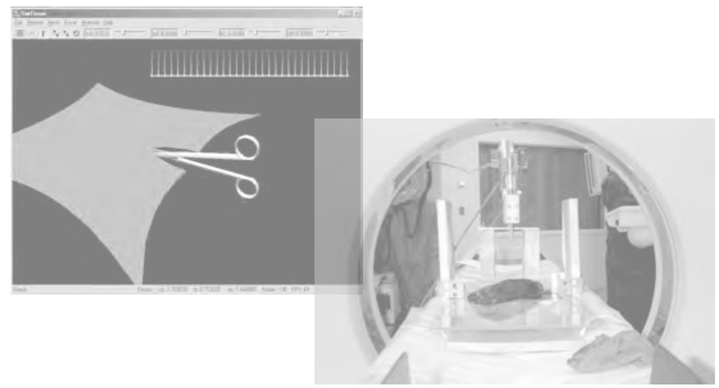


Application: Needle Steering

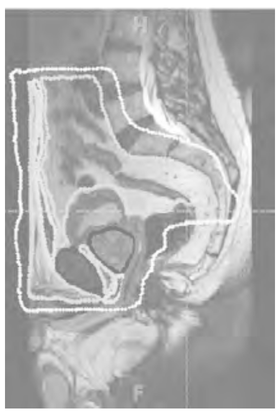
Reality-Based Modeling Process



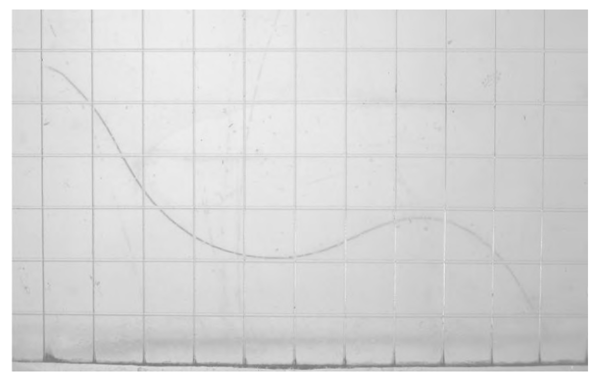
Reality-Based Modeling Examples



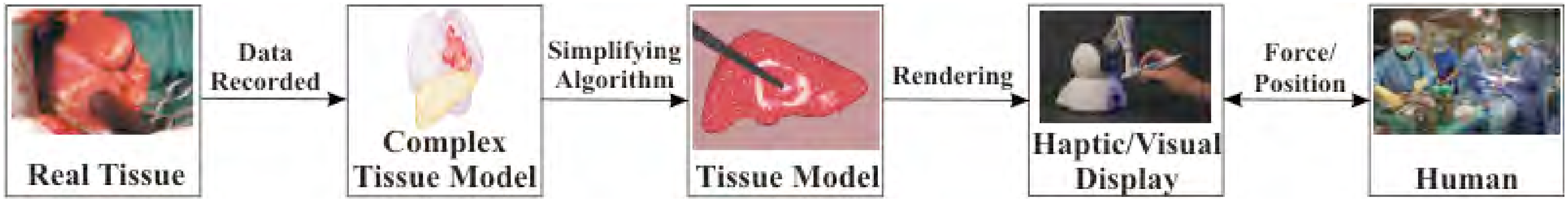
Modeling Factors



Application: Needle Steering



Reality-Based Modeling

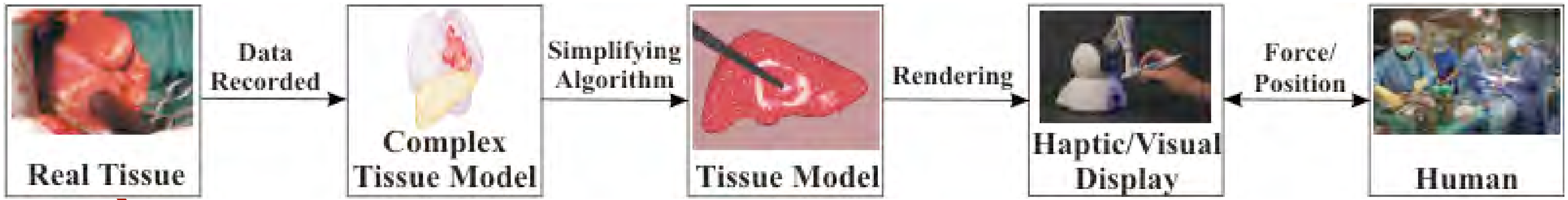


Each stage of the modeling and display process acts a “filter” in which information about force-motions relationships are lost or transformed.

This talk addresses the ***mechanical*** and ***haptic*** components of reality-based modeling and display.

S. Misra, K. T. Ramesh, and A. M. Okamura. Physically valid surgical simulators: Linear versus nonlinear tissue models. In Medicine Meets Virtual Reality, 2008. In press.

Reality-Based Modeling Procedure



Considerations in the design of a data acquisition system:

Bandwidth

Resolution

Degrees of freedom

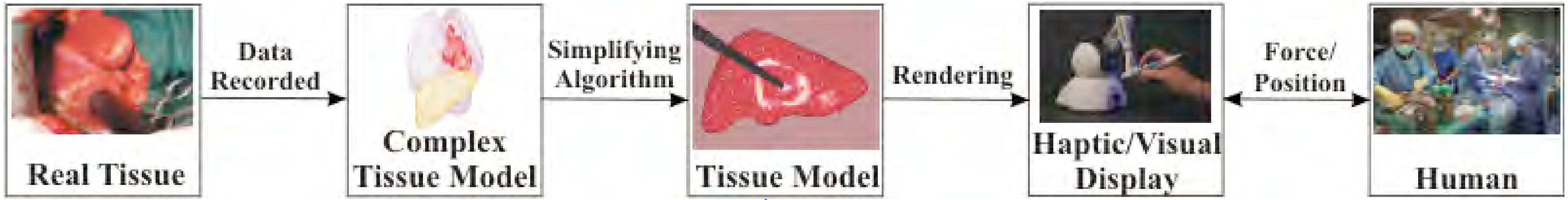
Geometry

Size

Material properties

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Procedure

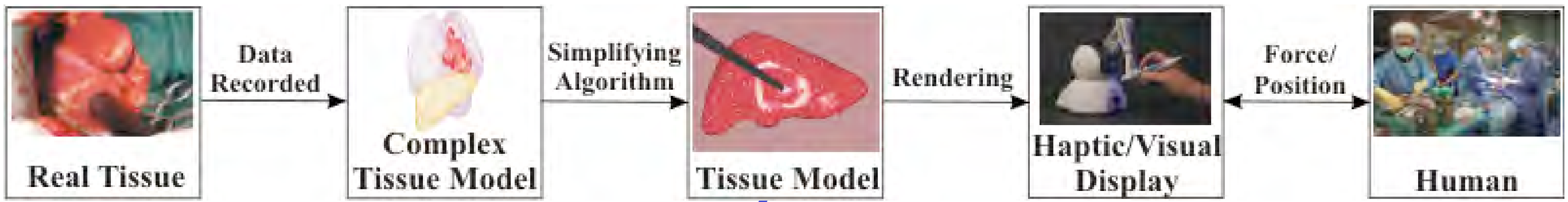


Database model:

Recordings of a movement variable, such as position or force, are played back during haptic rendering, similar to audio recordings played on a stereo.

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Procedure

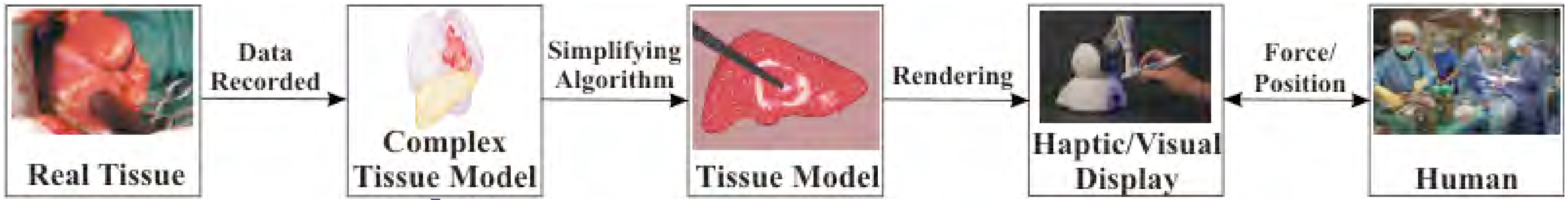


Input-output model:

Simple phenomenological models are fit to recorded data and the haptic response is tuned as needed to provide the desired feel.

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Procedure

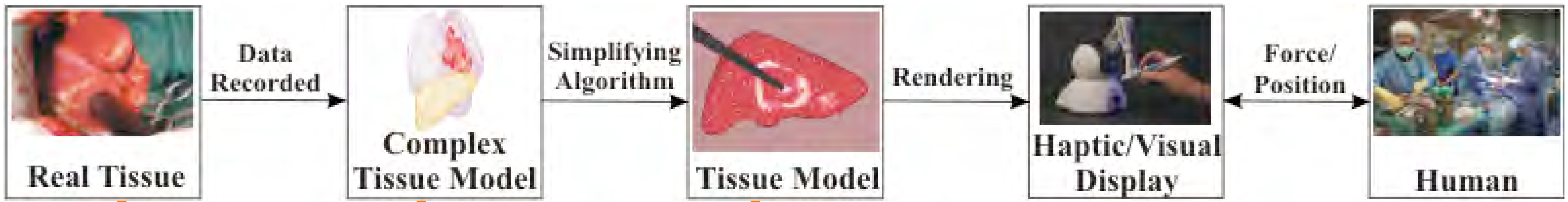


Physics-Based Model:

Constructed from a fundamental understanding of the mechanical principles underlying the recorded haptic interaction; numerical values for the model's physical parameters can be selected either by fitting the model's response to the recorded data or by derivation from basic material properties.

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Procedure



Populating the Model

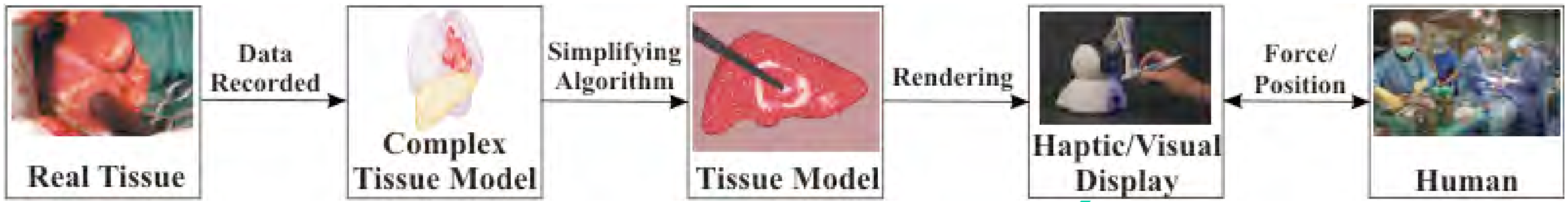
Database: Store data

Input-output model: Tune parameters

Physics-based model: Identify parameters

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Procedure



Rendering (compute forces from the model)

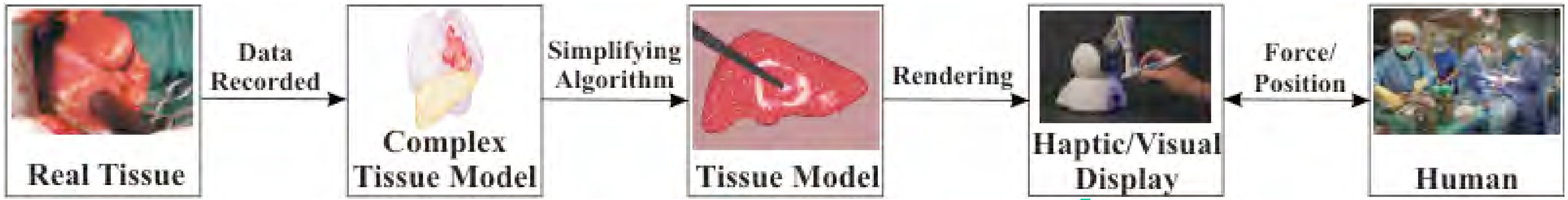
Database: Interpolate/replay data

Input-output model: Invoke mapping

Physics-based model: Simulate physics

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Procedure



Rendering (generating desired forces)

The haptic device selected to render the desired forces much have a sufficient resolution, bandwidth, output stiffness, stability, configuration, number of degrees of freedom, and workspace for the chosen virtual environment.

A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

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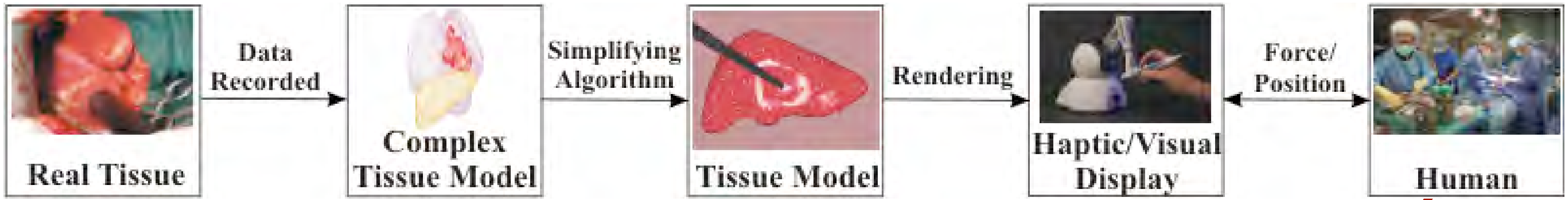
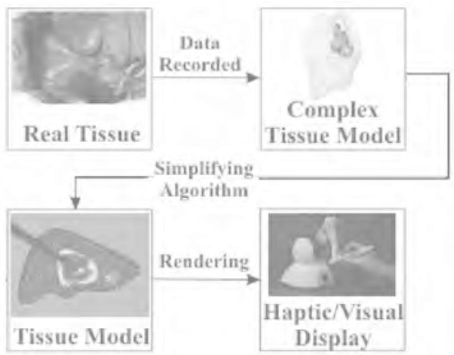


Human Perception and Performance:

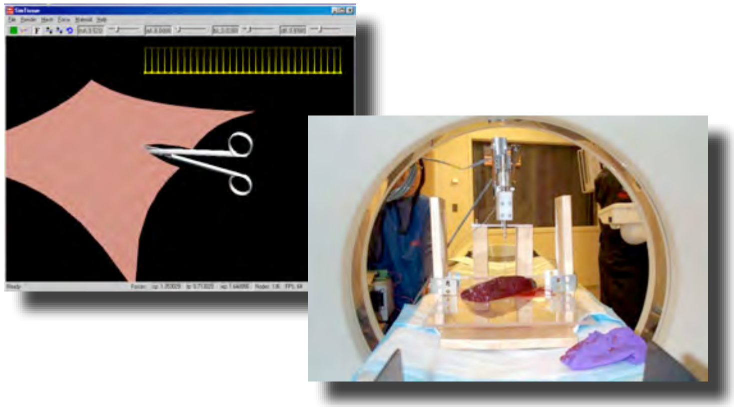
The realism of a haptic virtual environment can be objectively evaluated through experiments on human perception and performance.

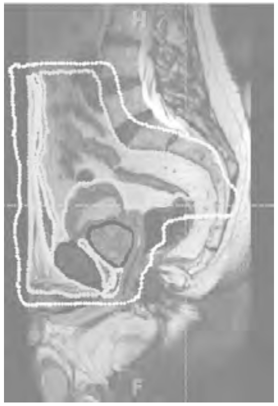
A. M. Okamura, K. J. Kuchenbecker, and M. Mahvash. Measurement-based modeling for haptic display. In M. C. Lin and M. Otaduy, editors, Haptic Rendering: Foundations, Algorithms, and Applications. AK Peters, 2008. In press.

Reality-Based Modeling Process

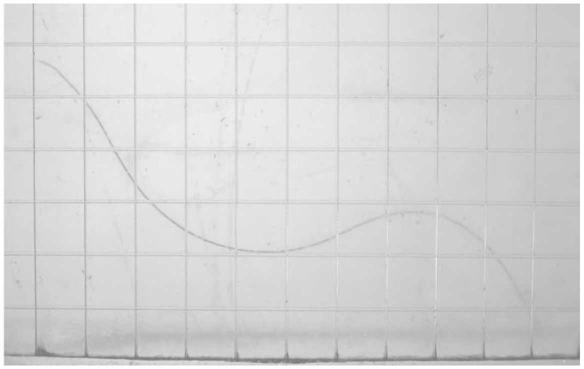


Reality-Based Modeling Examples





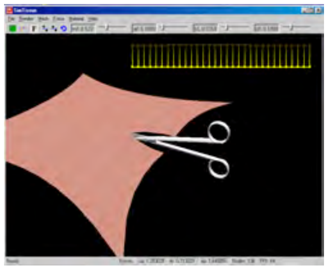
Modeling Factors



Application: Needle Steering

Reality-Based Modeling Examples

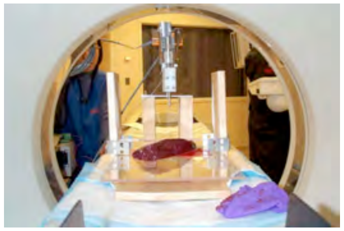
Cutting with Scissors



Database method:
S. Greenish, V. Hayward, T. Steffen, V. Chial, and A. M. Okamura, “Measurement, Analysis and Display of Haptic Signals during Surgical Cutting”, Presence, 11(6):626-651, 2002.

Input-output and Physics-based models:
M. Mahvash, L. Voo, D. Kim, K. Jeung, and A. M. Okamura, “Modeling the Forces of Cutting with Scissors”, IEEE Transactions on Biomedical Engineering, in press, 2008.

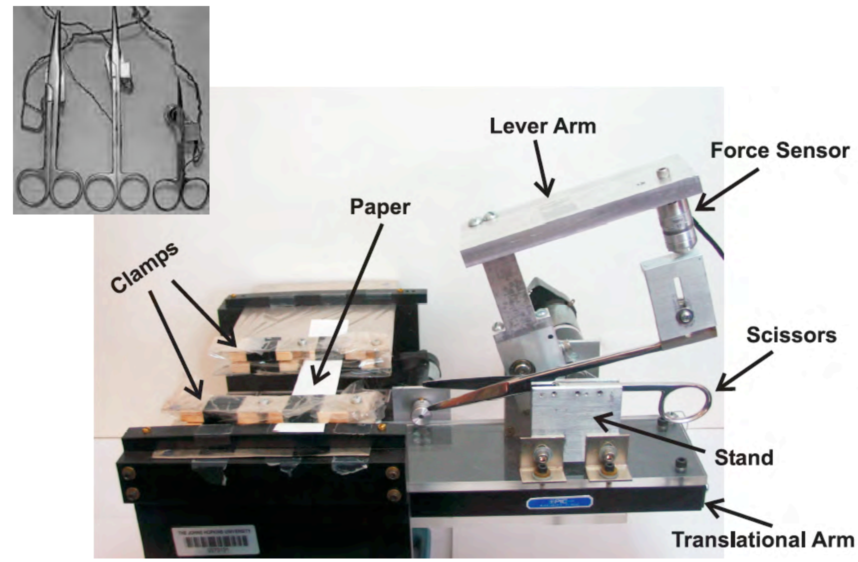
Needle Insertion



Database approach, Input-output model, and Physics-based models:
A. M. Okamura, C. Simone, and M. D. O'Leary, “Force Modeling for Needle Insertion into Soft Tissue,” IEEE Transactions on Biomedical Engineering, 51(10):1707-1716, 2004.

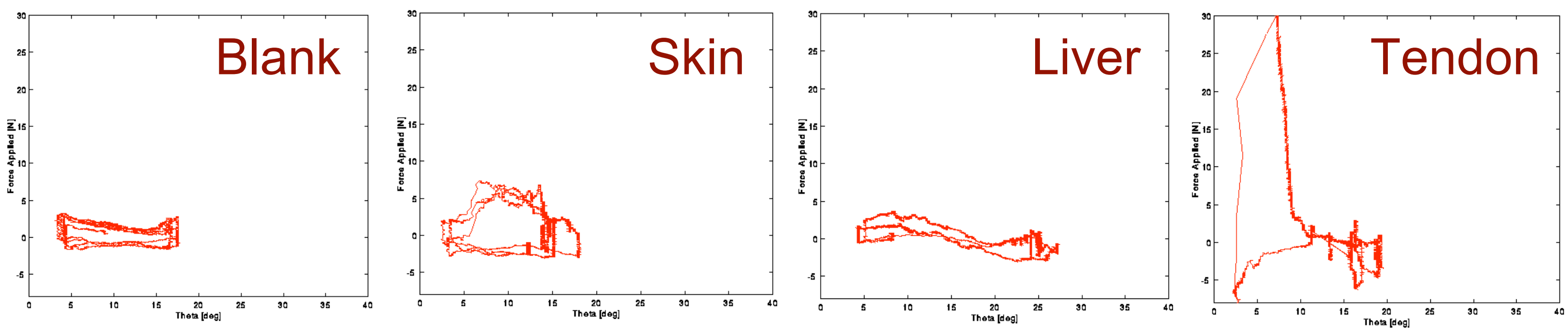
Cutting with Scissors

Data acquisition:
Scissors instrumented with a force and positions sensors were used to cut sheep, rat, and chicken tissues



Modeling method 1:
Database (haptic recordings)

Force



Scissor Angle

Cutting with Scissors

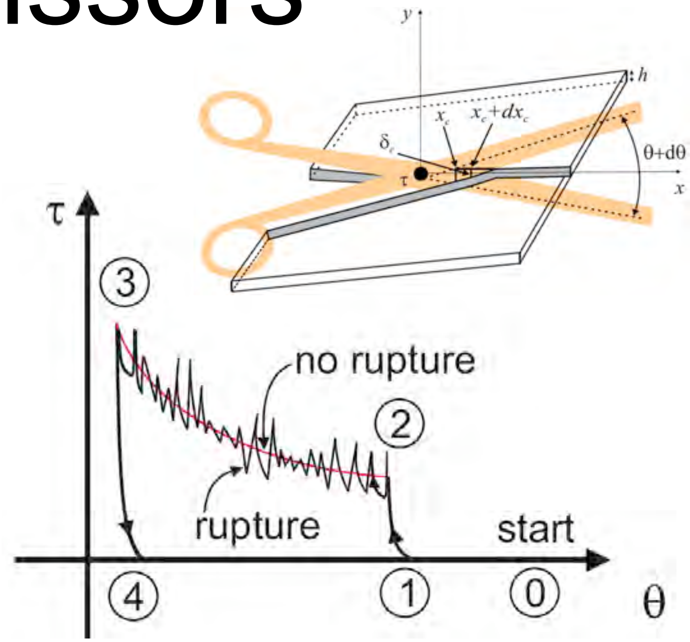
Modeling method 2:

Input-output deformation

$$f_u = \frac{\tau}{R} = \frac{x_c}{R} g(\delta)$$

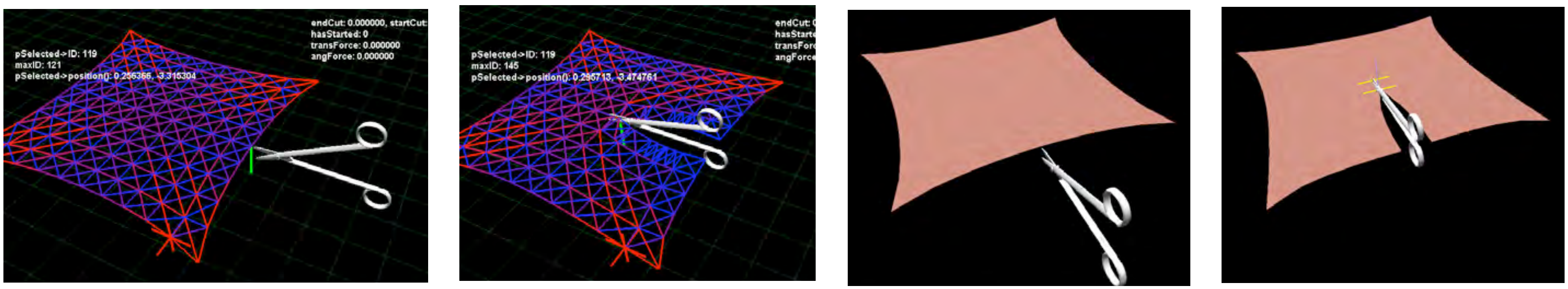
Physics-based cutting

$$\tau = -J_c \, h \, \frac{dx_c}{d\theta}$$



Rendering:

Compute forces from database or models and integrate with a mass-spring-damper mesh

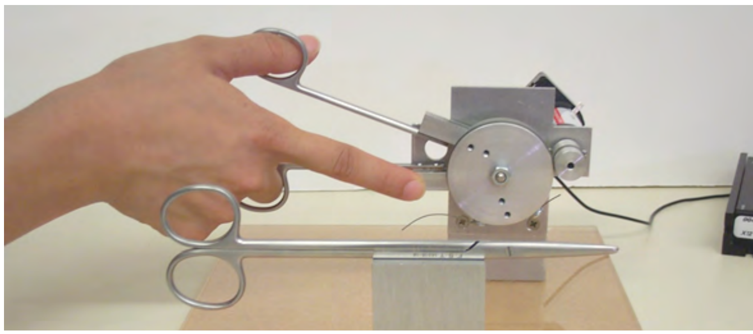


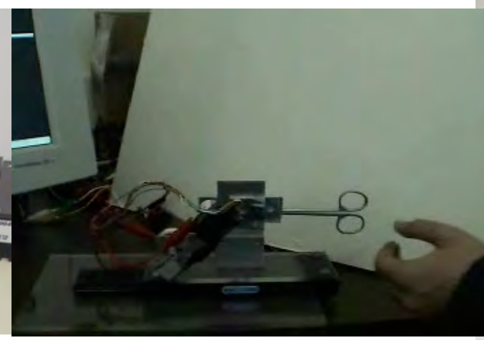
D. Weiss and A. M. Okamura. Haptic rendering of tissue cutting with scissors in a virtual environment. In 12th Medicine Meets Virtual Reality Conf., 2004.

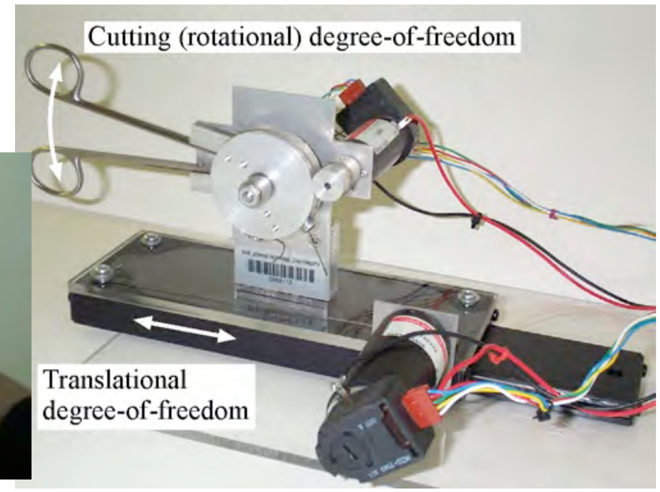
Cutting with Scissors

Rendering:

2-degree-of-freedom haptic scissors







Human:

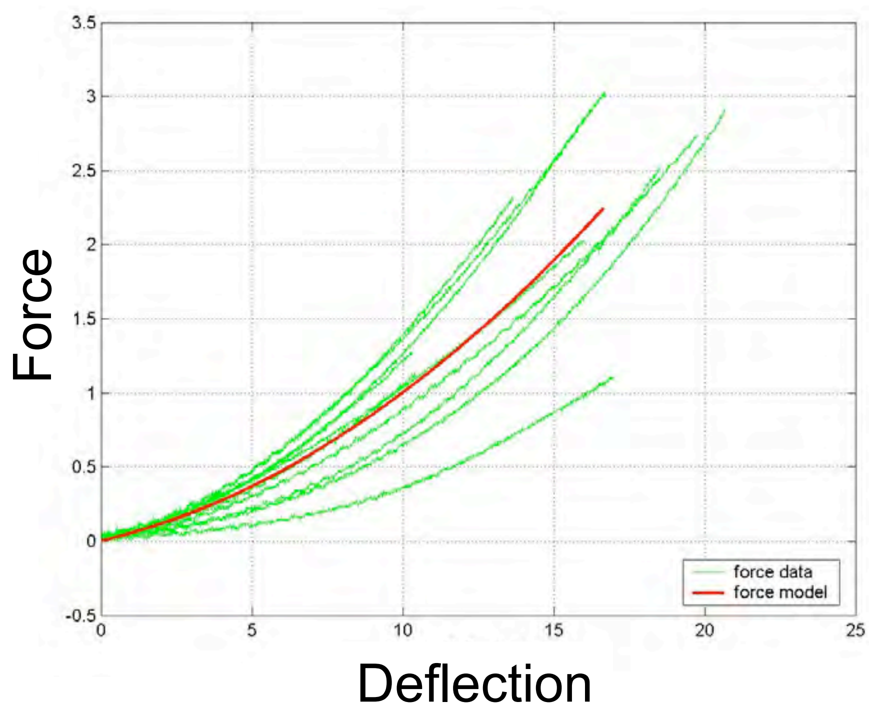
- ❑ Turing test: 2 of 6 subjects thought VE was real
  4 of 6 subjects thought real scissors were real
- ❑ Subjects ranked the stiffness of real and VE tissues similarly
- ❑ Database and input-output models compared for realism were not distinguishable... Perhaps the database approach is “good enough”

A. M. Okamura, R. J. Webster III, J. T. Nolin, K. W. Johnson, and H. Jafry. The haptic scissors: Cutting in virtual environments. In Proceedings of the IEEE International Conference on Robotics and Automation, pages 828–833, Taipei, Taiwan, September 2003.

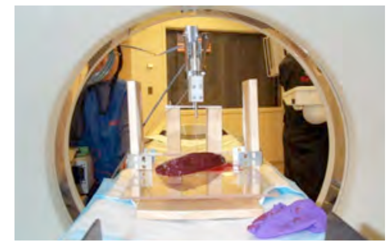
Needle Insertion

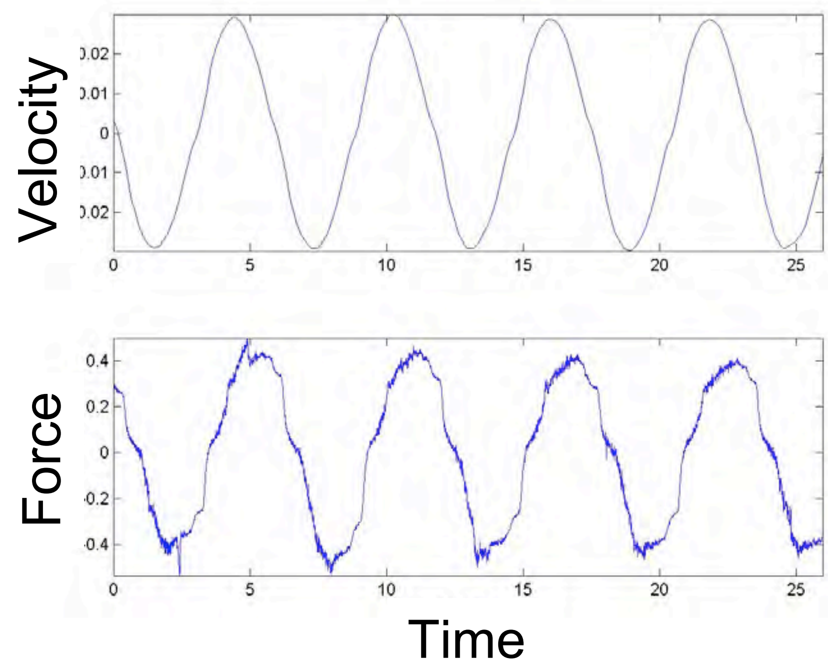
Data acquisition:

Stiffness and puncture



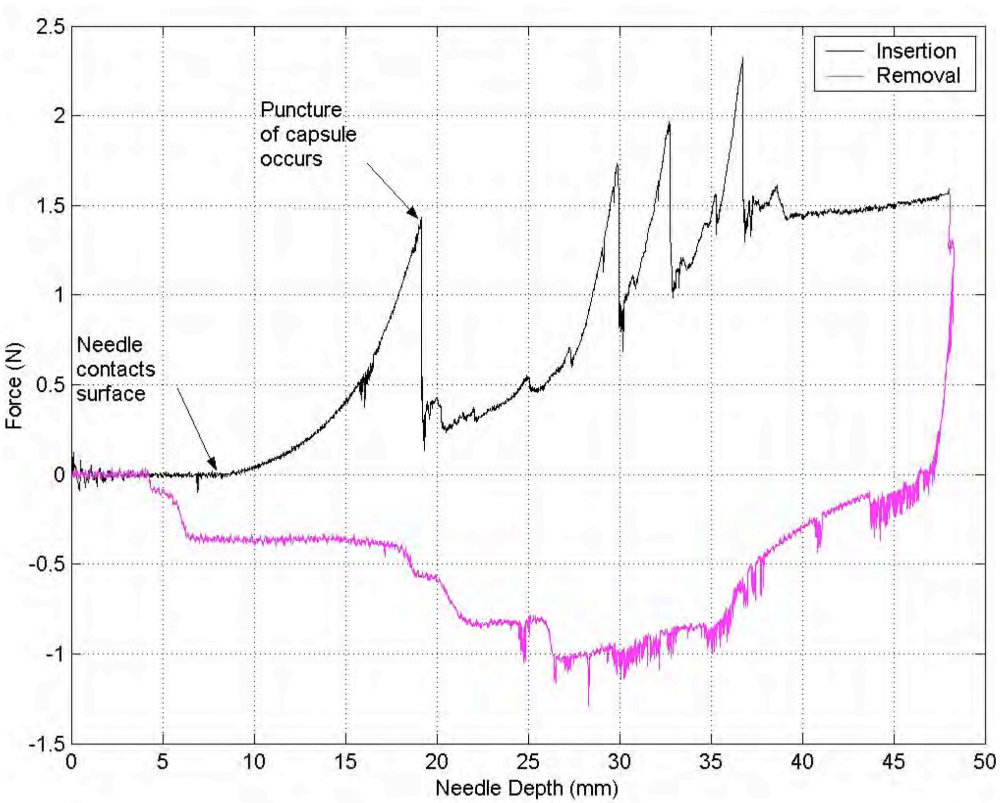
Friction and damping

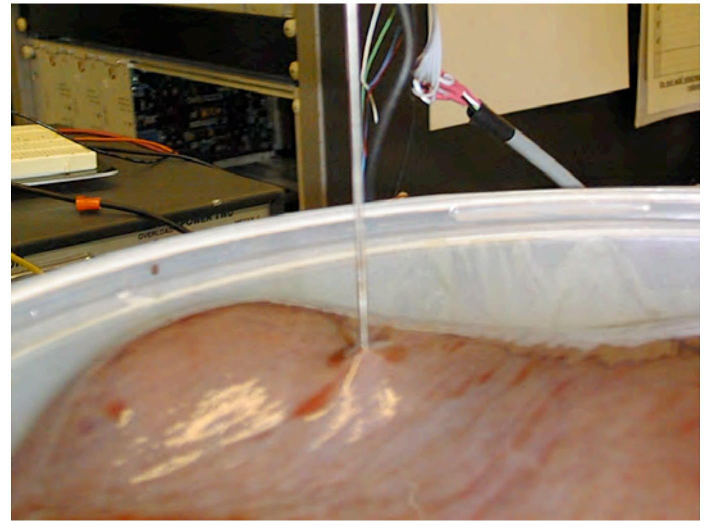


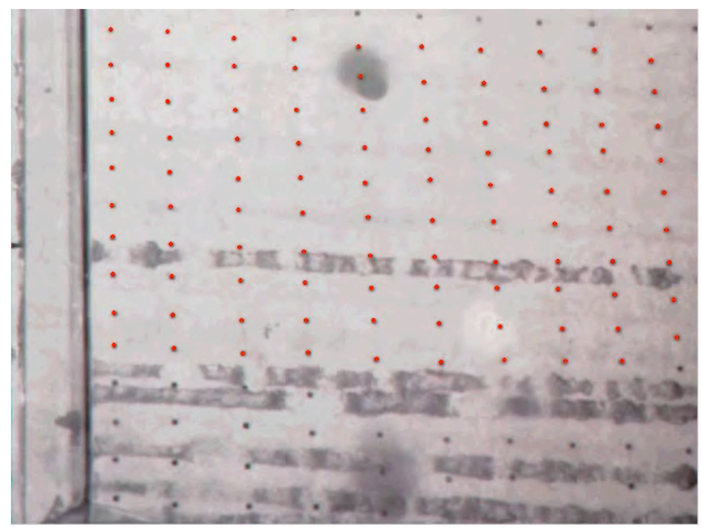


Needle Insertion

Data acquisition:





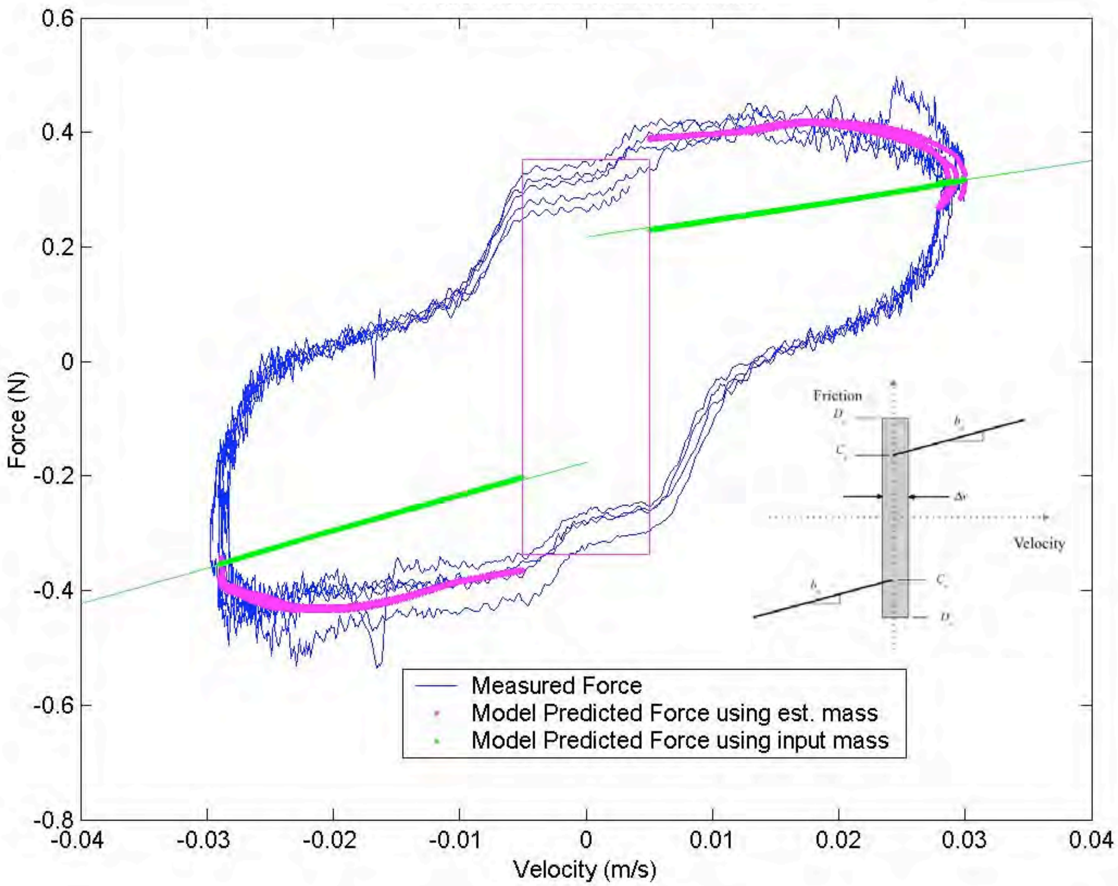


J. R. Crouch, C. M. Schneider, J. Wainer, and A. M. Okamura. A velocity-dependent model for needle insertion in soft tissue. In Proceedings of the Eighth International Conference on Medical Image Computing and Computer Assisted Intervention – MICCAI 2005, Lecture Notes in Computer Science, volume 3750, pages 624–632, 2005.

Needle Insertion

Modeling:

Friction and damping

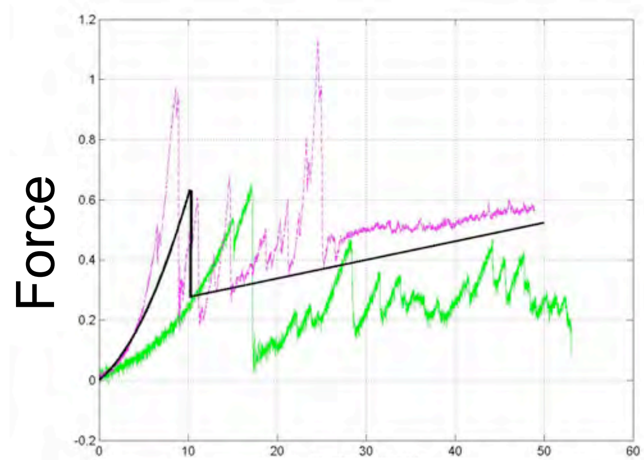


Stiffness

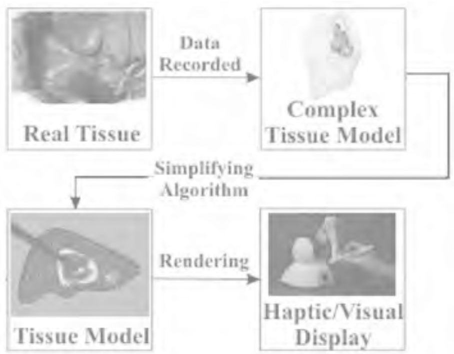
$$f(x) = a_0 + a_1 x + a_2 x^2$$

Total force

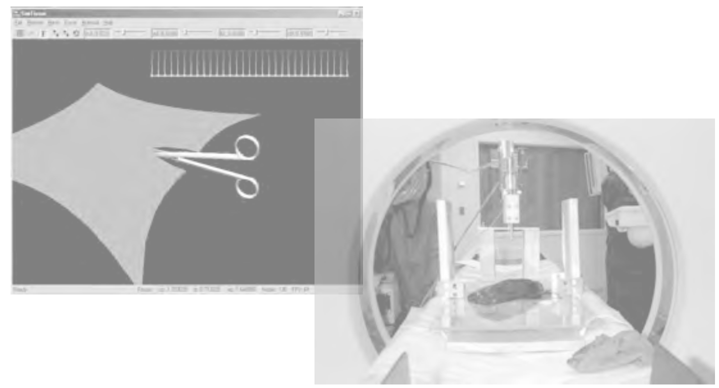
$$f_{needle}(x) = f_{stiffness}(x) + f_{friction}(x) + f_{cutting}(x)$$



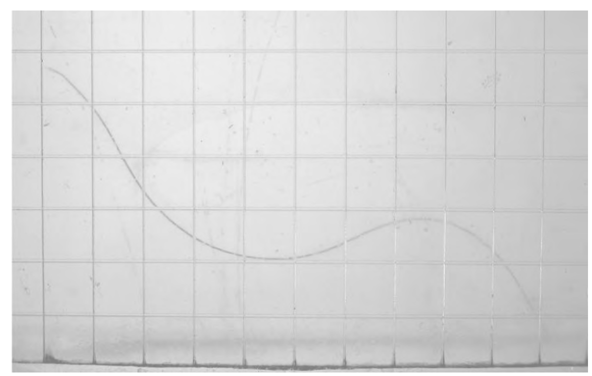
Reality-Based Modeling Process



Reality-Based Modeling Examples



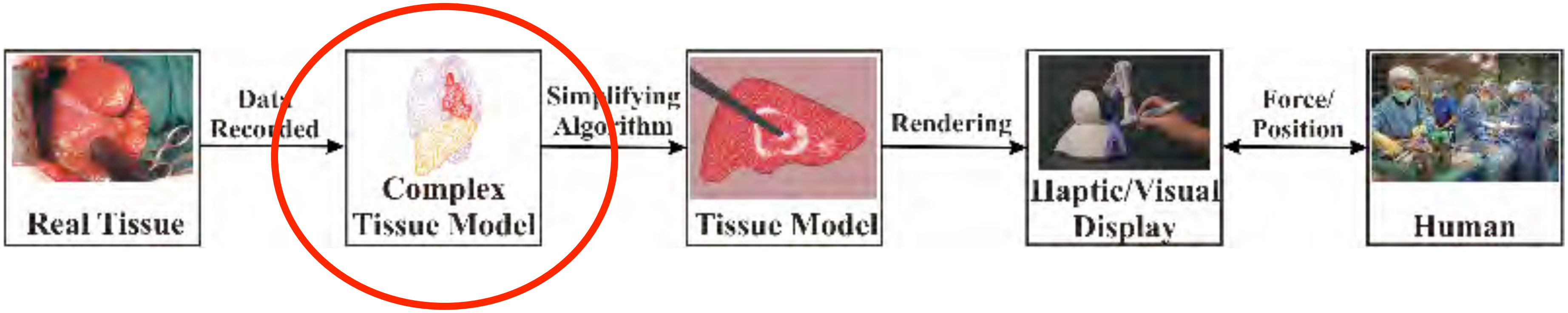
Modeling Factors



Application: Needle Steering

Modeling Factors

- Tool-tissue interaction **modeling factors** that affect fidelity of surgical simulators

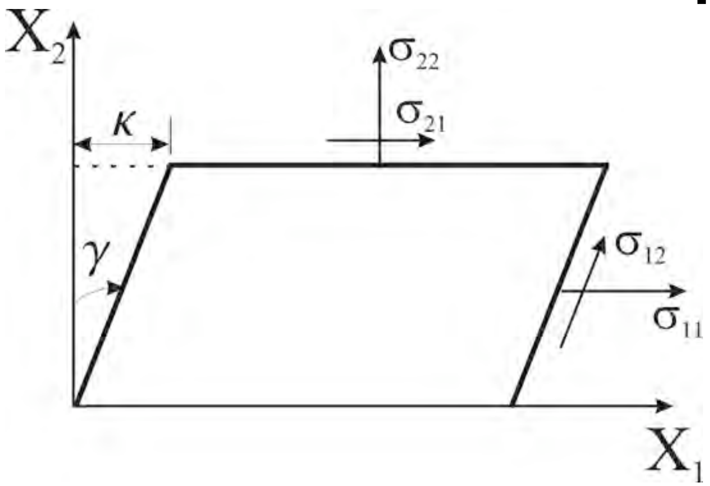


- Comparison of **linear versus nonlinear elasticity models** tissue models for surgical simulation

- Importance of **organ geometry and boundary constraints** for surgical planning

S. Misra, K. T. Ramesh, and A. M. Okamura. Physically valid surgical simulators: Linear versus nonlinear tissue models. In Medicine Meets Virtual Reality, 2008. In press.

Linear/Nonlinear Tissue Models: Palpation Task



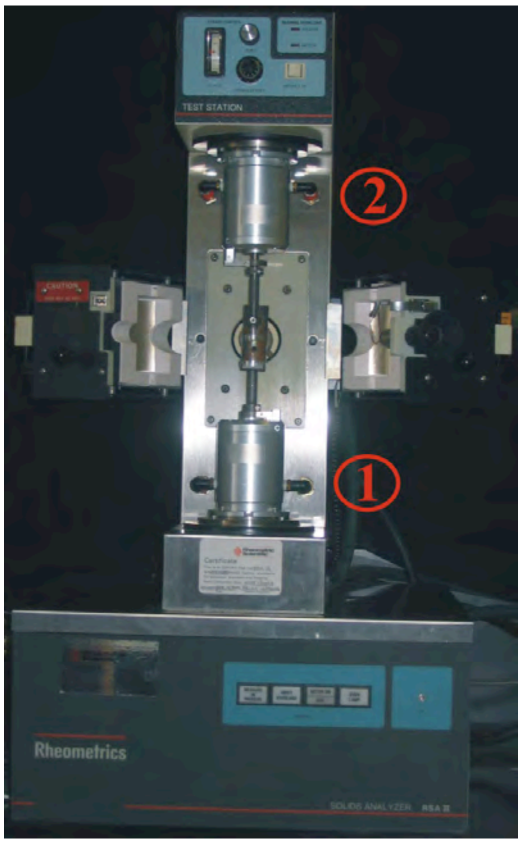
$$\mathbf{F} = \begin{bmatrix} 1 & \kappa & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

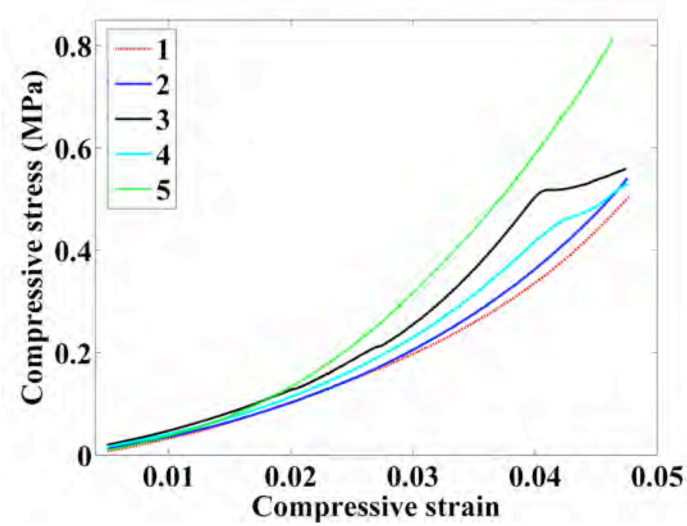
$$\sigma = -p\mathbf{I} + 2\left\{\left(\frac{\partial W}{\partial I_1} + I_1\frac{\partial W}{\partial I_2}\right)\mathbf{B} - \frac{\partial W}{\partial I_2}\mathbf{B}^2\right\}$$

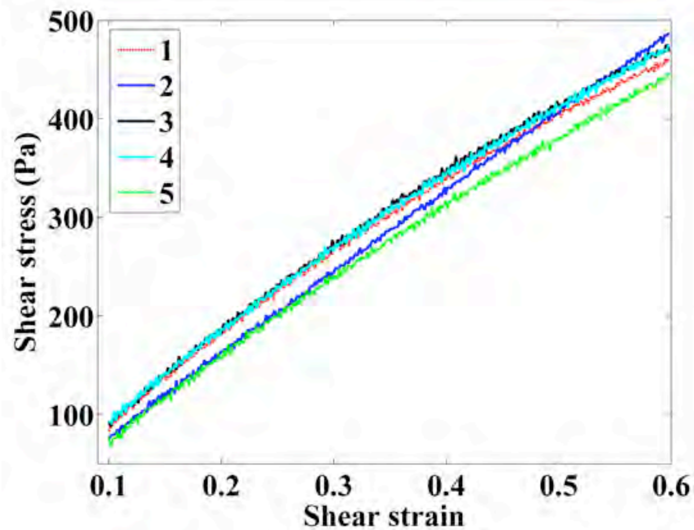
$$S_{ij} = \frac{\partial W}{\partial E_{ij}} \Rightarrow \sigma = \frac{1}{J}\mathbf{FSF}^T$$

Presence of $\sigma_{22} \neq 0$ and $\sigma_{11} \neq \sigma_{22} \Rightarrow$ **Poynting Effect**

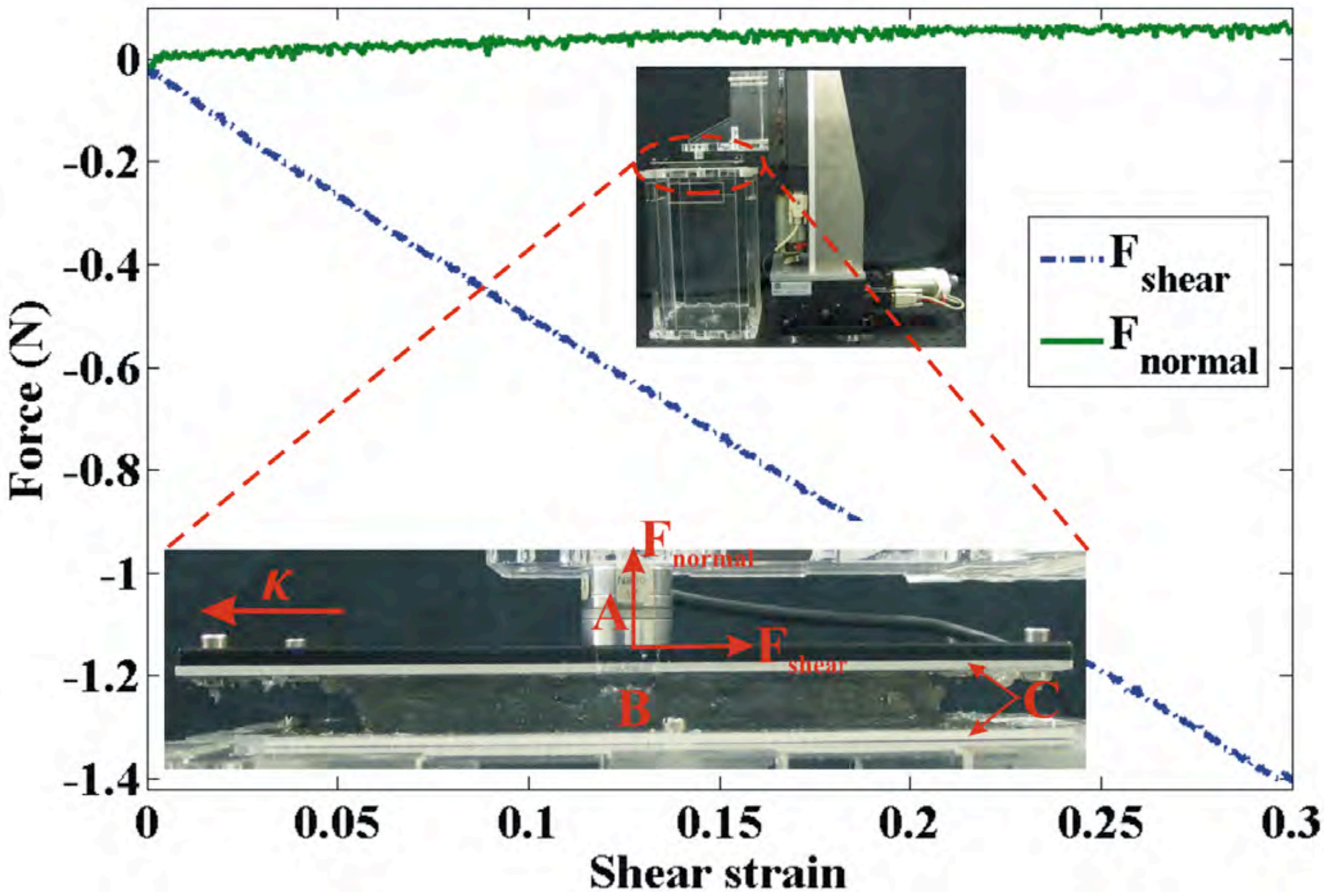
Linear/Nonlinear Tissue Models: Sylgard 527 Gel







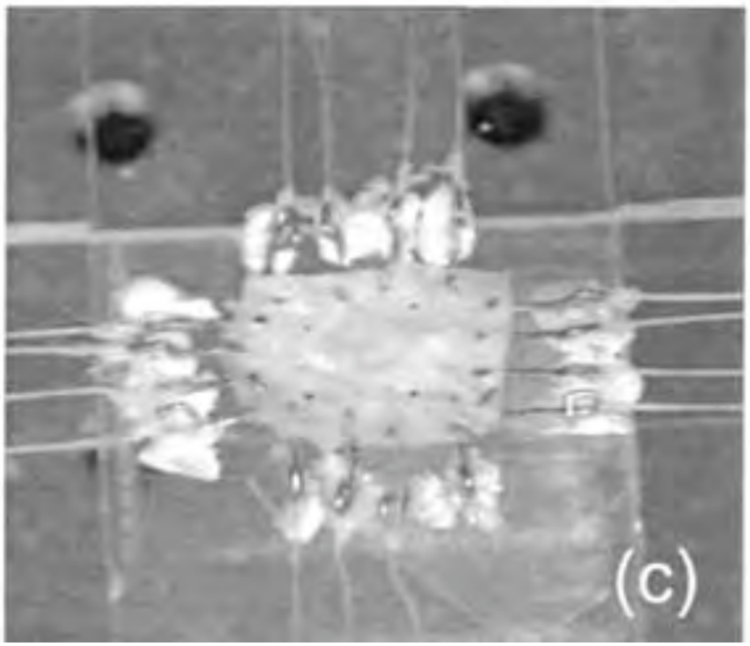
Linear/Nonlinear Tissue Models: Sylgard 527 Gel

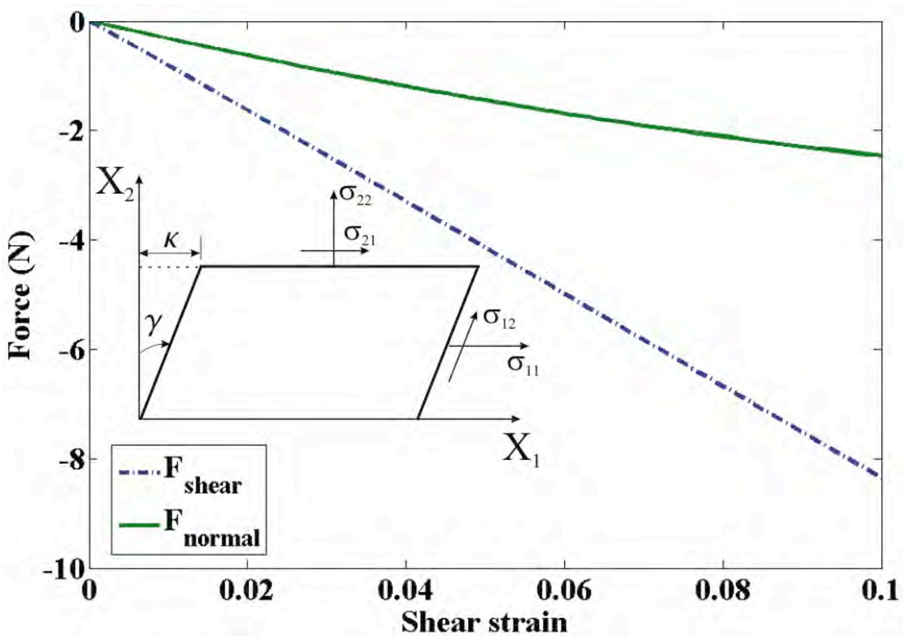


- Normal forces generated are less than the absolute human perception threshold for force discrimination

Linear/Nonlinear Tissue Models: Myocardial Tissue

- Exponential Model (with fiber anisotropy): $W = \frac{c}{2}\left(e^{Q} - 1\right)$





Courtesy: U. Pittsburgh (Michael Sacks)

- Normal forces generated are **greater** than the absolute human perception threshold for force discrimination

Factors Affecting Path Planning

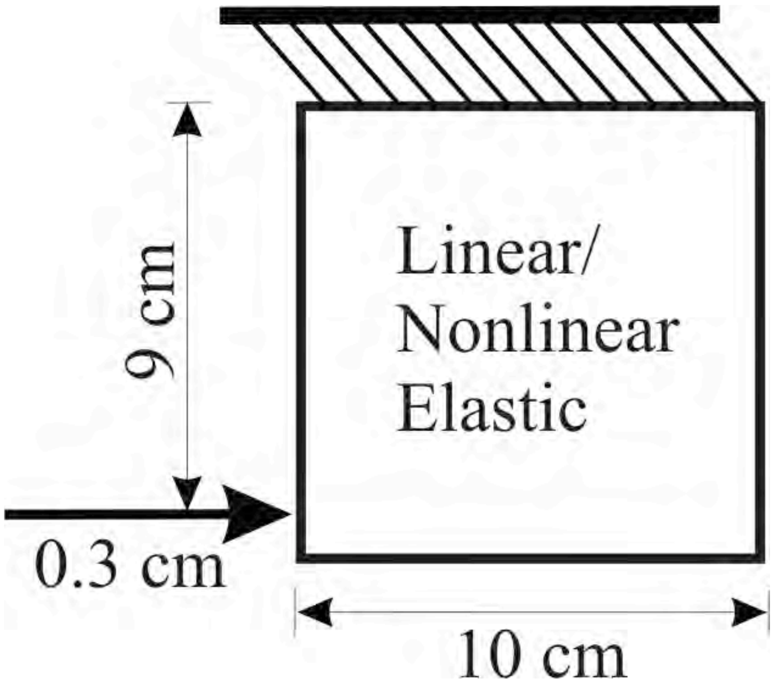
Geometry	Square (*S*)	Circle (*C*)
Boundary condition (connective tissue)	Fixed edge (*F*)	Partially constrained (*P*)
Tissue properties	Linear elastic (*L*)	Hyperelastic (*H*)

8 simulation cases:

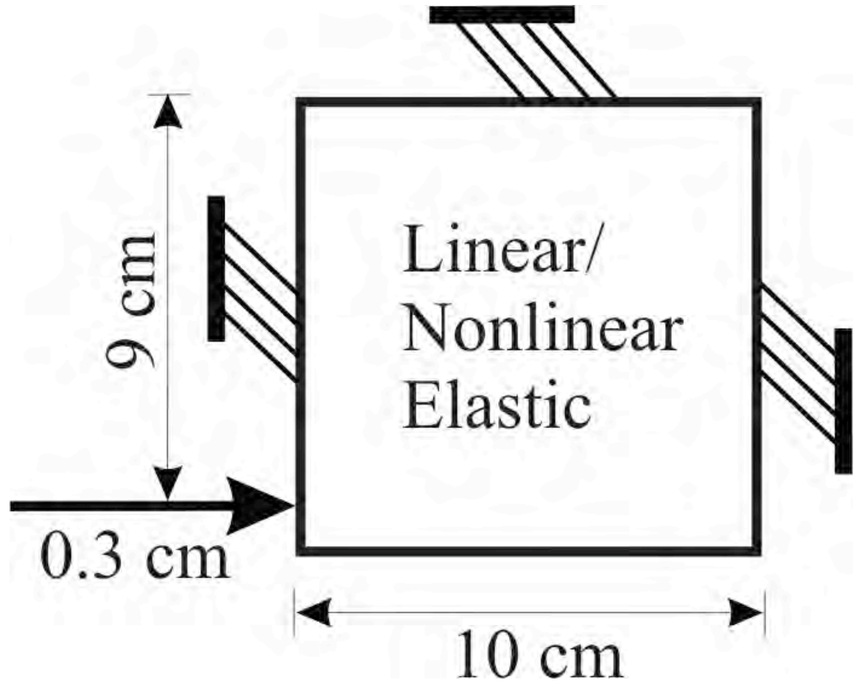
SFL, *SFH*, *SPL*, *SPH*, *CFL*, *CFH*, *CPL*, *CPH*

S. Misra, K. J. Macura, K. T. Ramesh, A. M. Okamura, “The Importance of Organ Geometry and Boundary Constraints for Planning of Medical Interventions”, 2008. Submitted.

Simulation Cases: Square

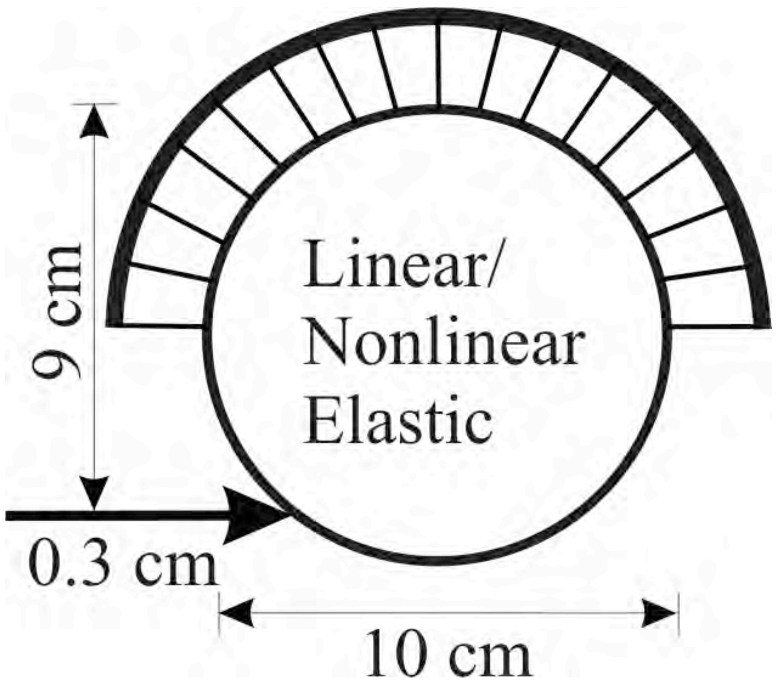


SFL and *SFH*

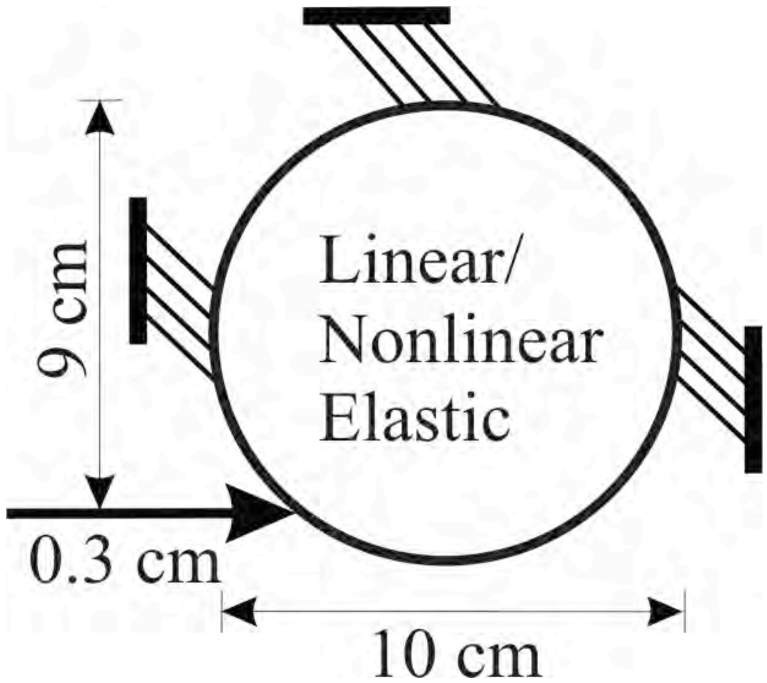


SPL and *SPH*

Simulation Cases: Circle

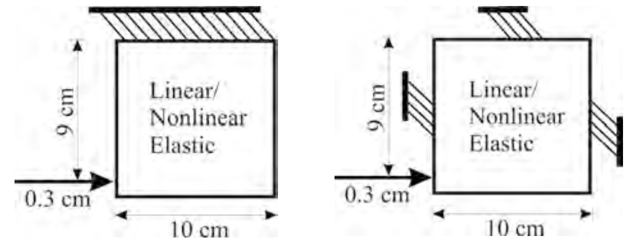


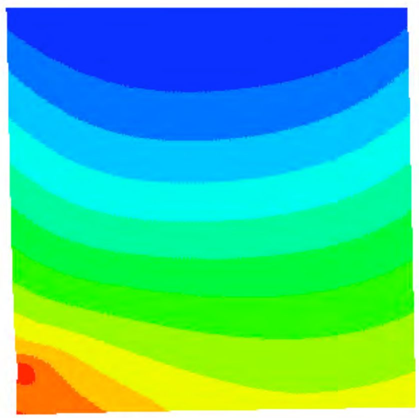
CFL and *CFH*



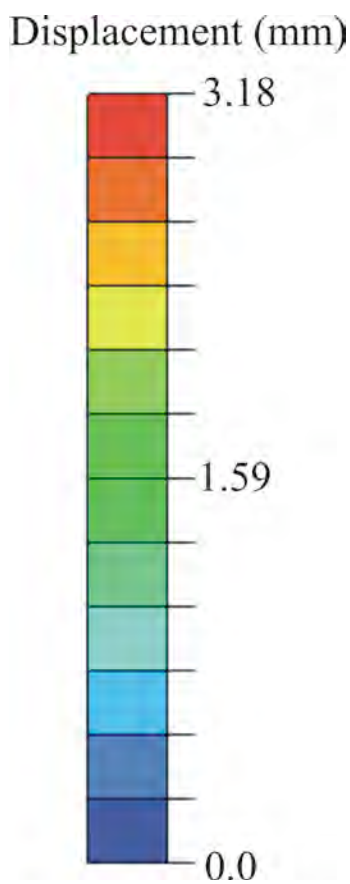
CPL and *CPH*

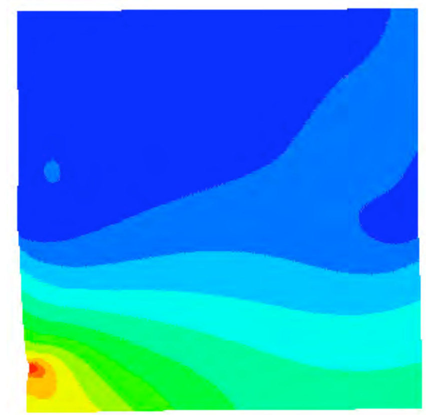
Nodal displacement: Square



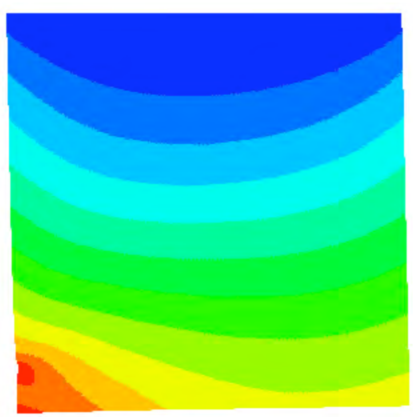


SFL

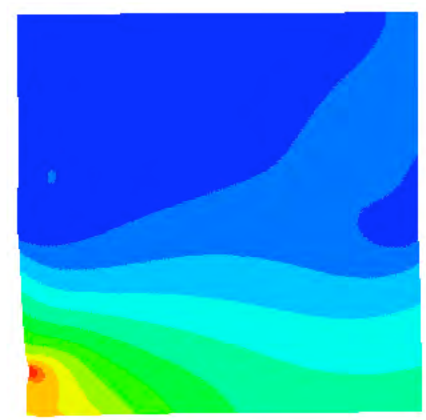




SPL

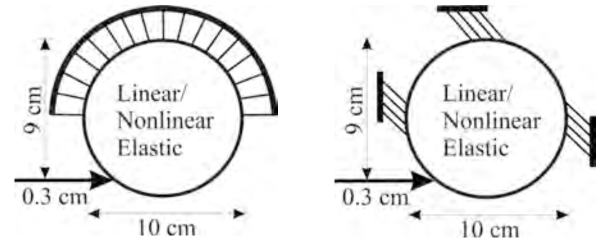


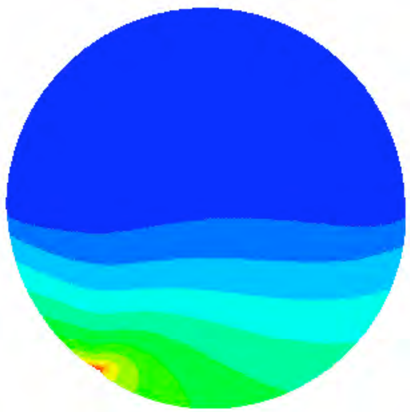
SFH



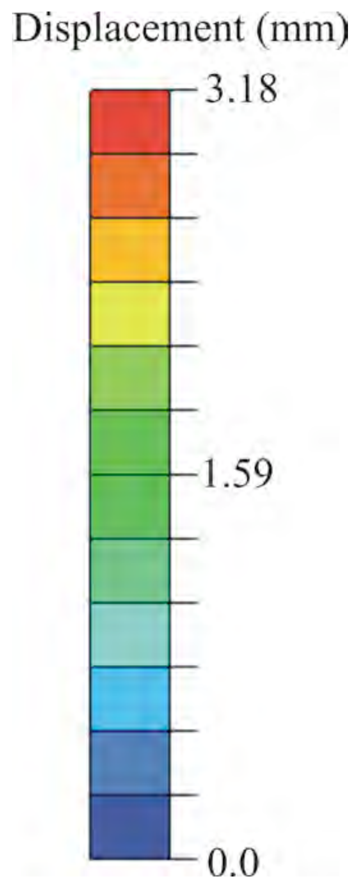
SPH

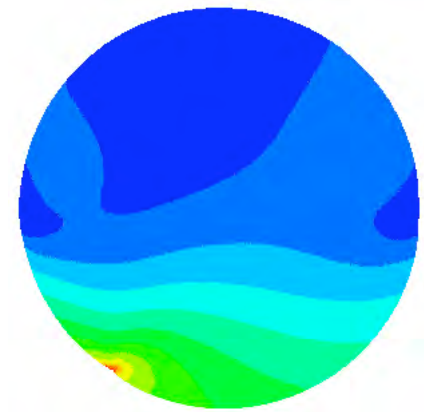
Nodal displacement: Circle



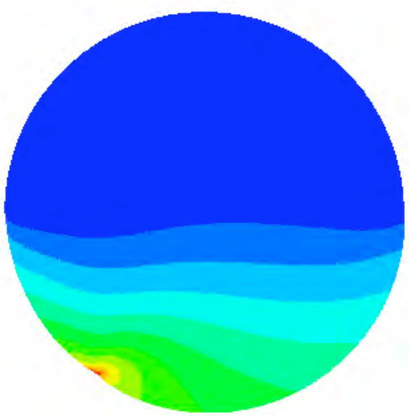


CFL

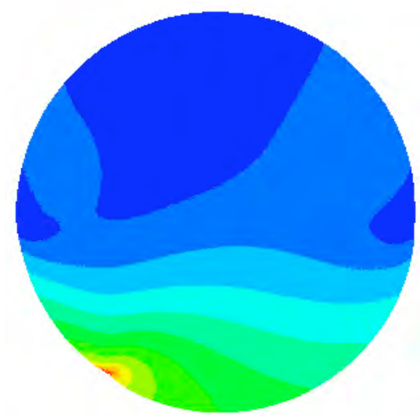




CPL

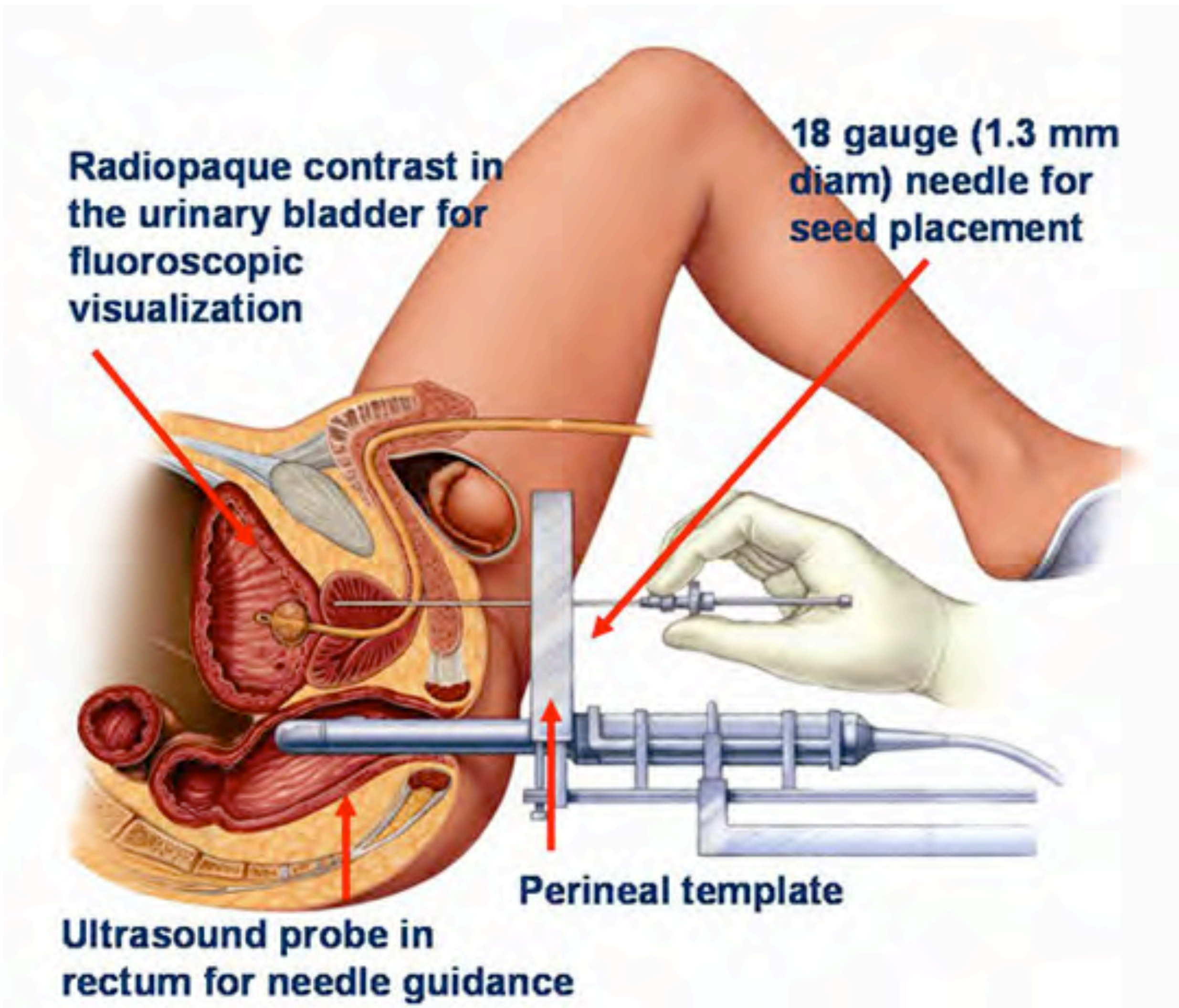


CFH



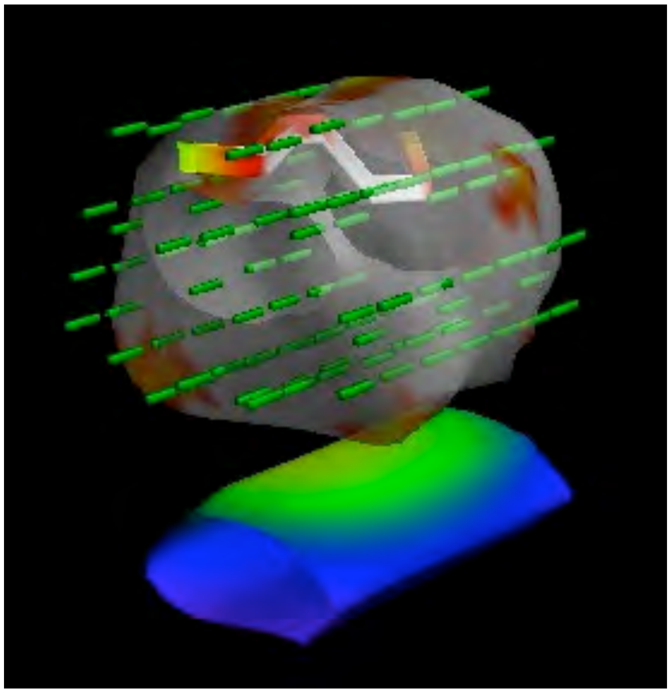
CPH

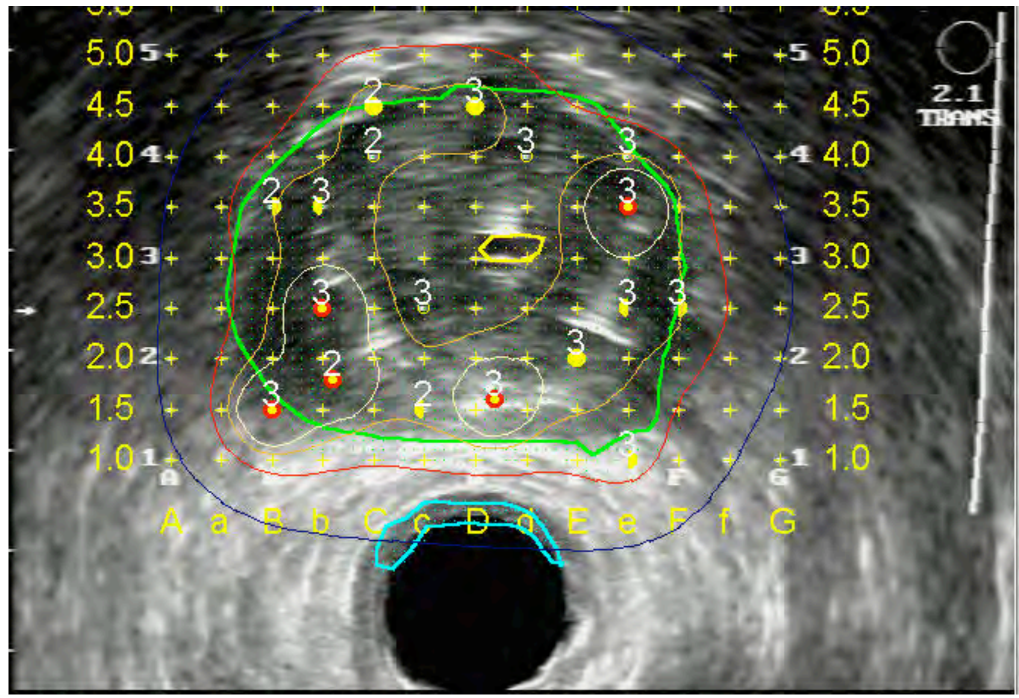
Prostate Brachytherapy



From: http://www.prostatebrachytherapyinfo.net

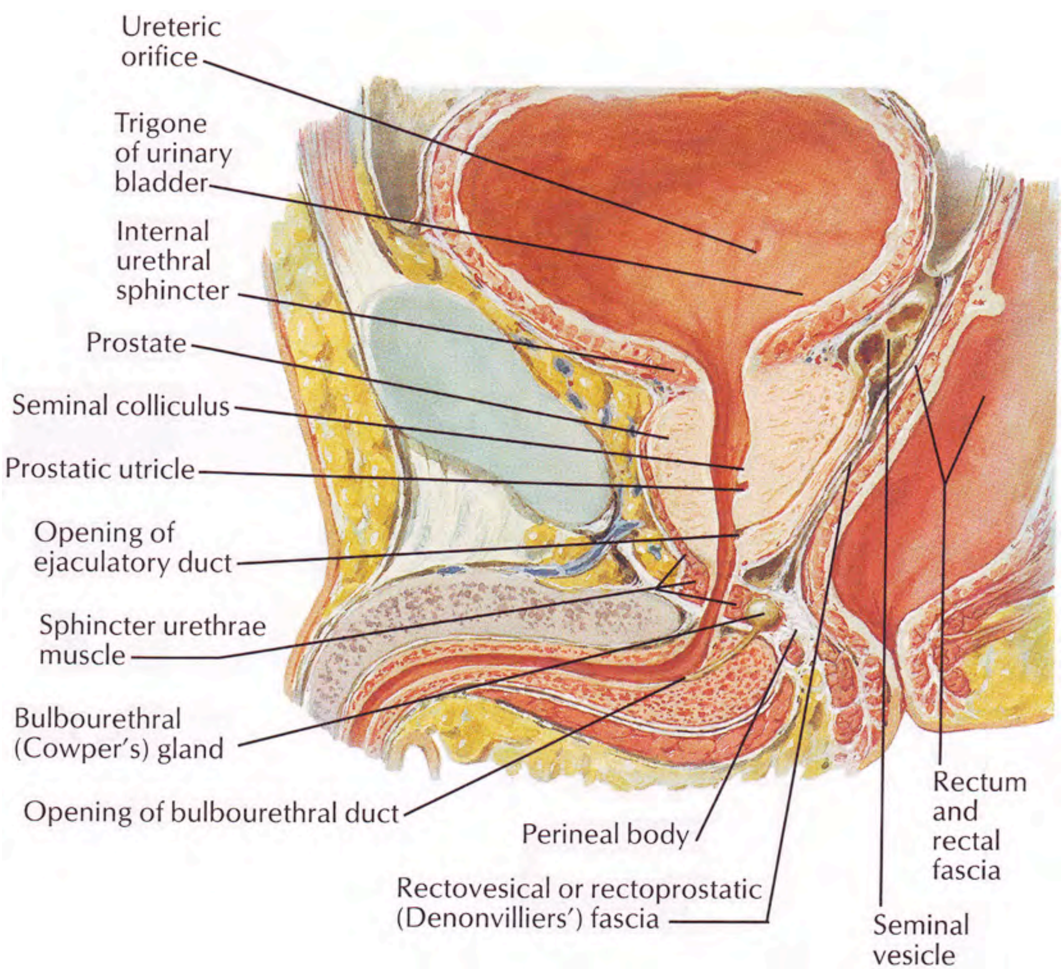
Prostate Brachytherapy: Surgical Planning





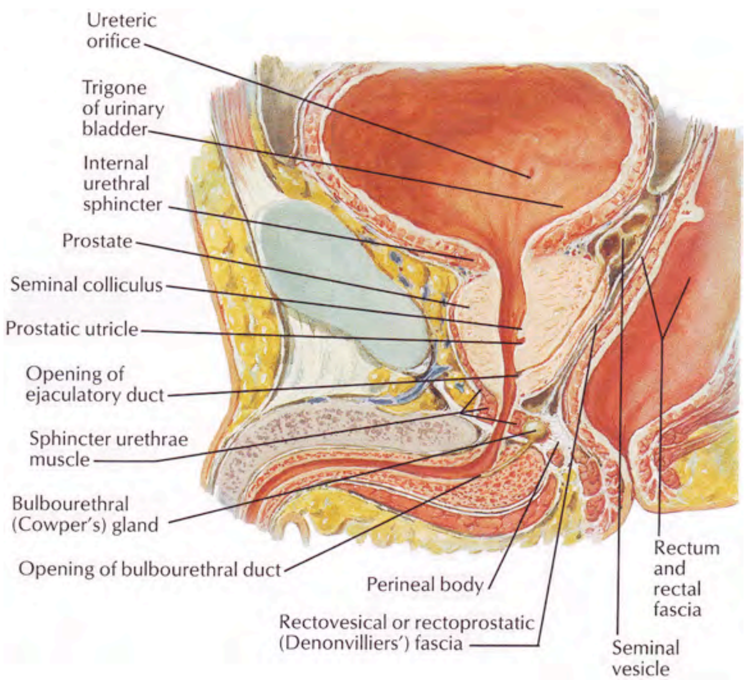
From: http://www.dktech.de

Prostate Anatomy (Sagittal View)



From: Atlas of Human Anatomy, Frank H. Netter

Prostate Anatomy (Sagittal View)



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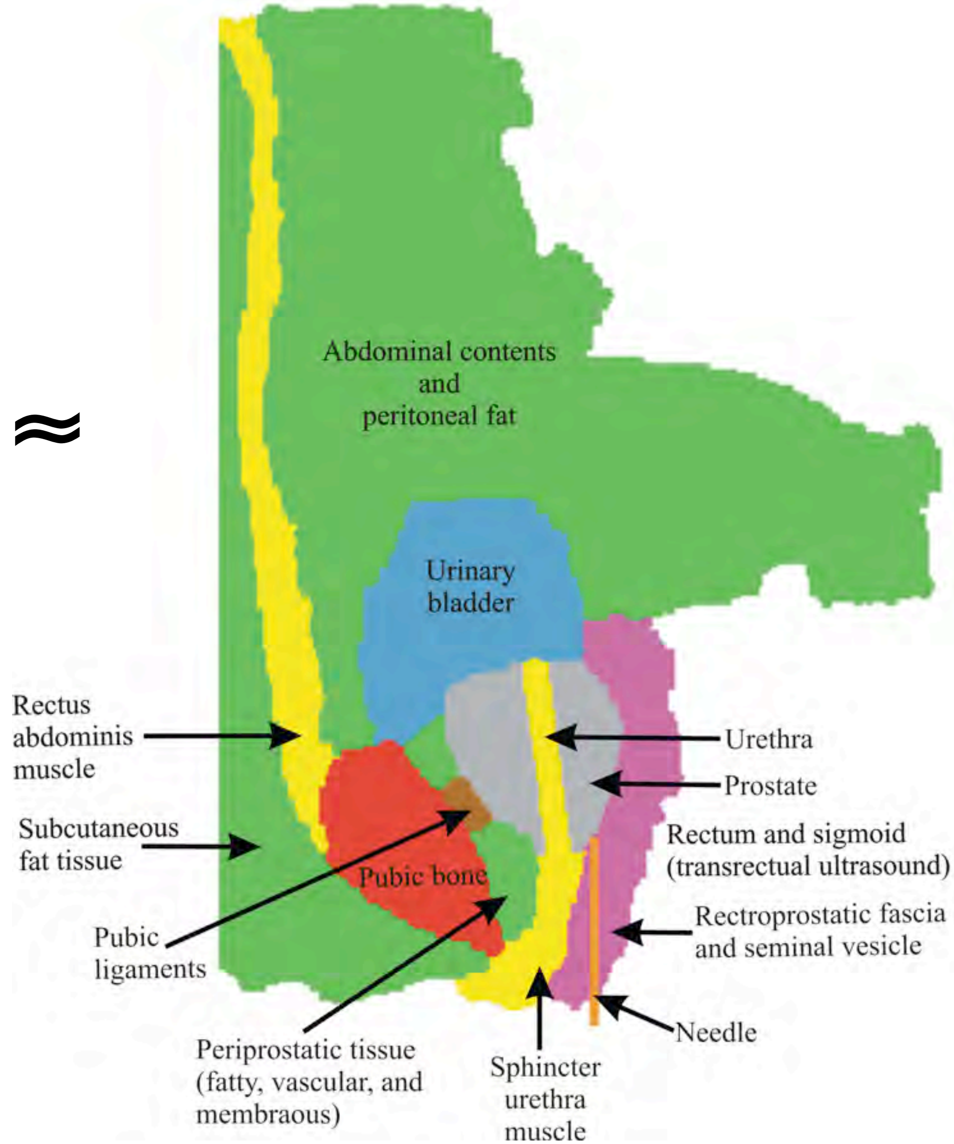
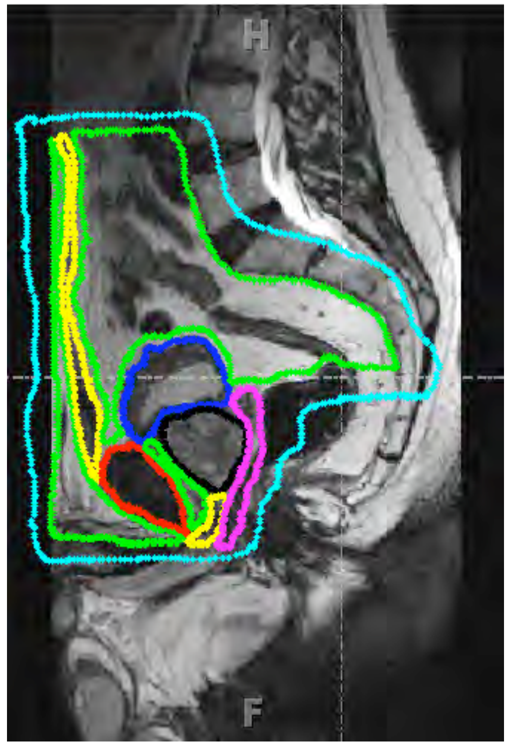


MRI Segmentation: Random Walker Algorithm

MRI

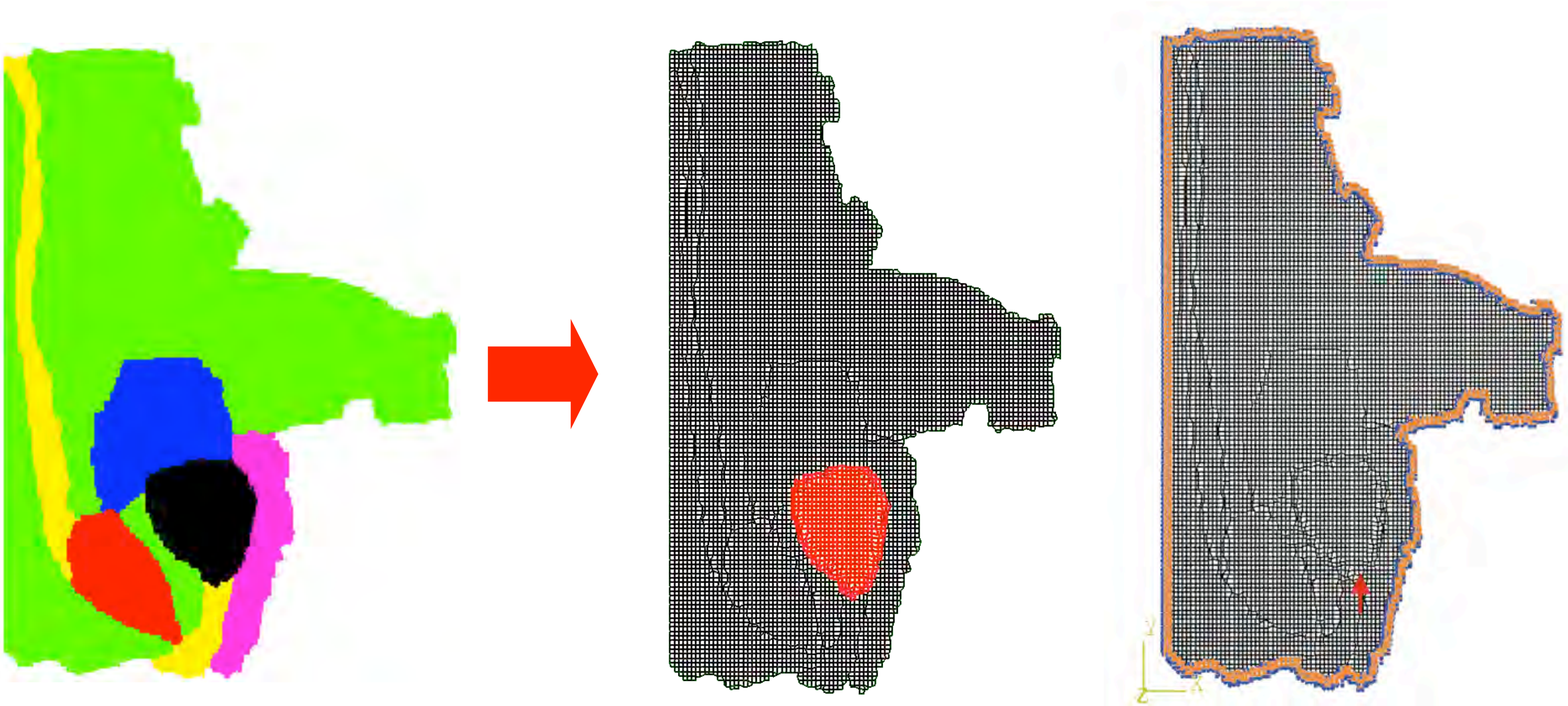


Anatomy identification

Segmented image

Urethra and pubic ligaments are not visible in MRI

FE Mesh



- ❑ Mesh generated using OOF
  ABAQUS compatible simulation files
- ❑ 3.25 mm displacement to simulate needle insertion

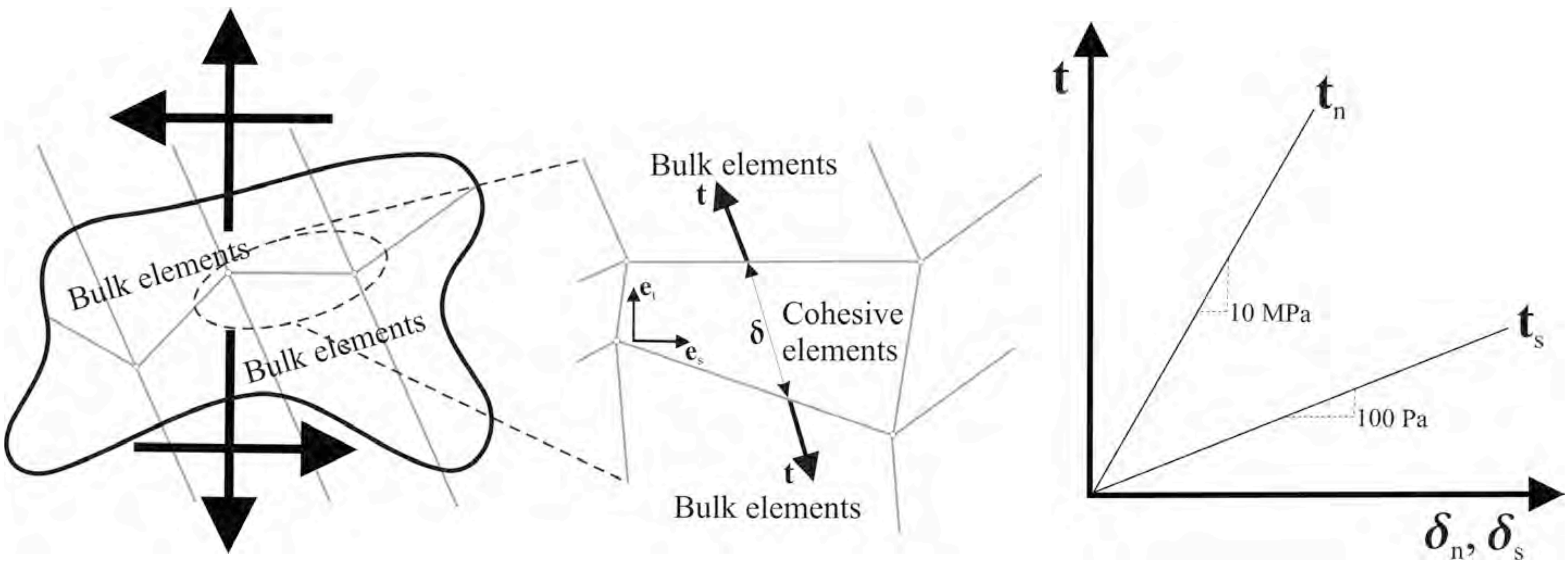
Material Properties

Tissue	E (kPa)	ν
Bone	1.80×10^6	0.3
Fascia	4249.78	0.45
Fat	3.25	0.45
Ligament	489.71	0.45
Muscle	29.85	0.45
Prostate	60.0	0.45
Urinary bladder (water)	1.32×10^4	0.499

Material properties obtained from
Strength of Biological Materials (H. Yamada)

Cohesive Zone Model

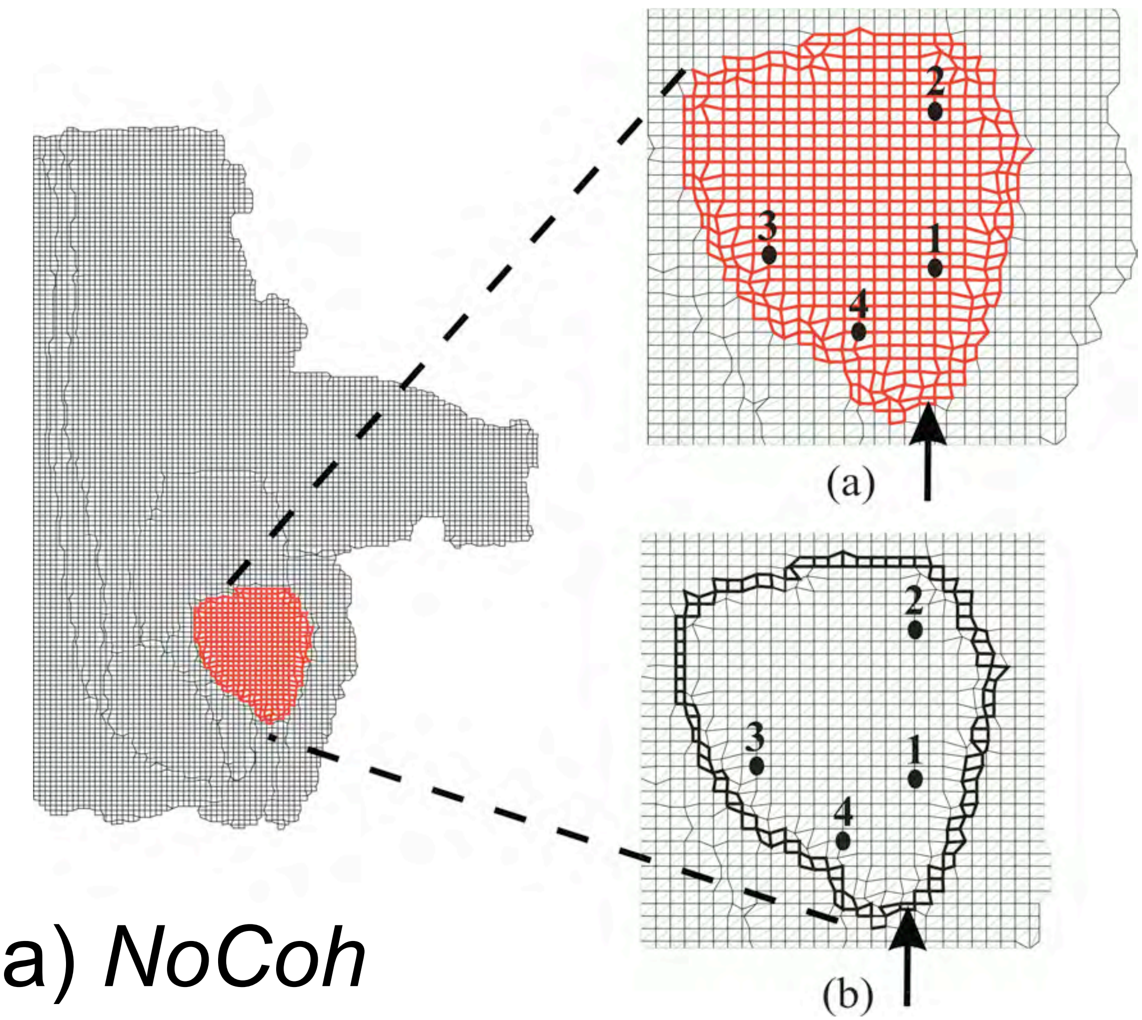
- To simulate the relative contact between the prostate and its surrounding structures
  - Tensile stiffness = 10 MPa , Shear stiffness = 100 Pa



Modeling Sensitivity Studies

- ***NoCoh***: No cohesive zone or relative slip model employed
- ***Coh***: Cohesive zone model between the prostate and surrounding organs ($\mathbf{t} = \mathbf{K}\delta$)
- ***CohUr***: Cohesive zone model around the prostate and urethra passing through the prostate
- ***CohLig***: Cohesive zone model around the prostate and pubic ligaments attached to the prostate
- ***Crop***: Simpler model which was a cropped version of our original mesh

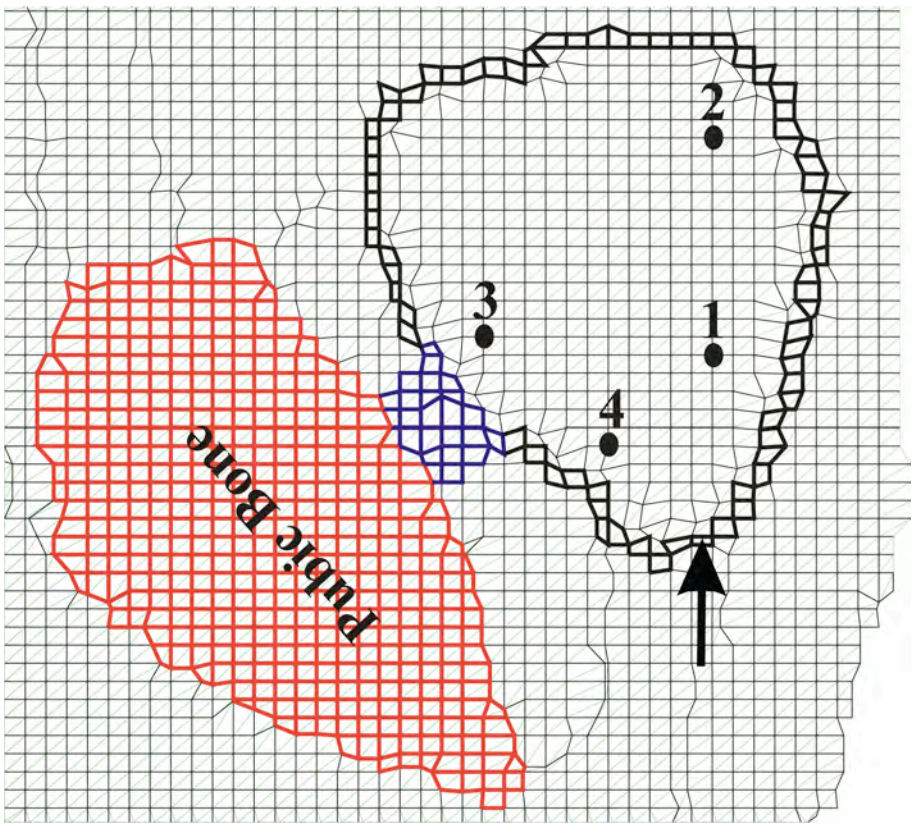
Modeling Sensitivity Studies



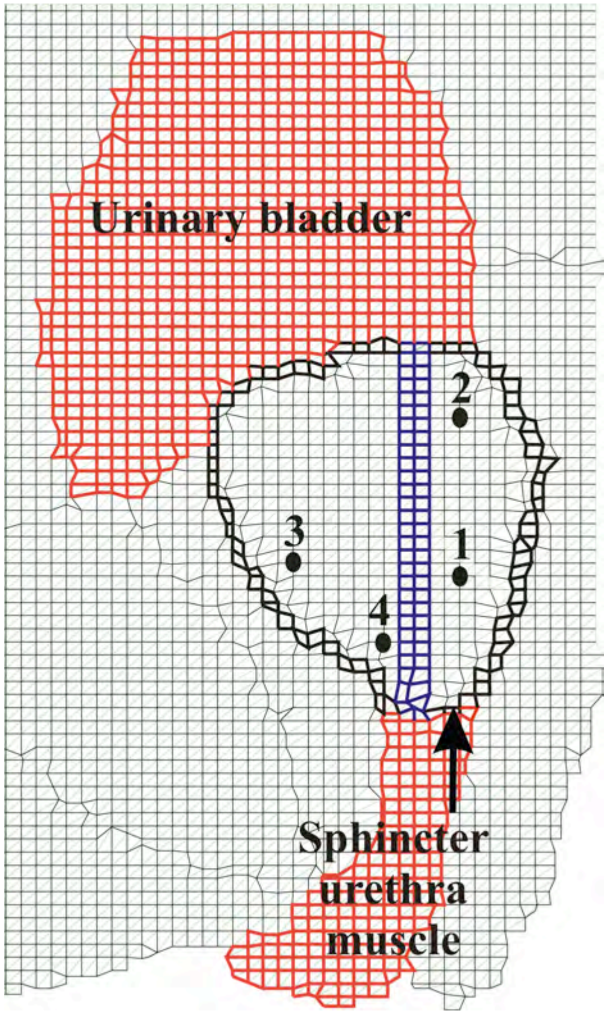
(a) *NoCoh*

(b) *Coh* ($\mathbf{t} = \mathbf{K}\delta$)

Modeling Sensitivity Studies



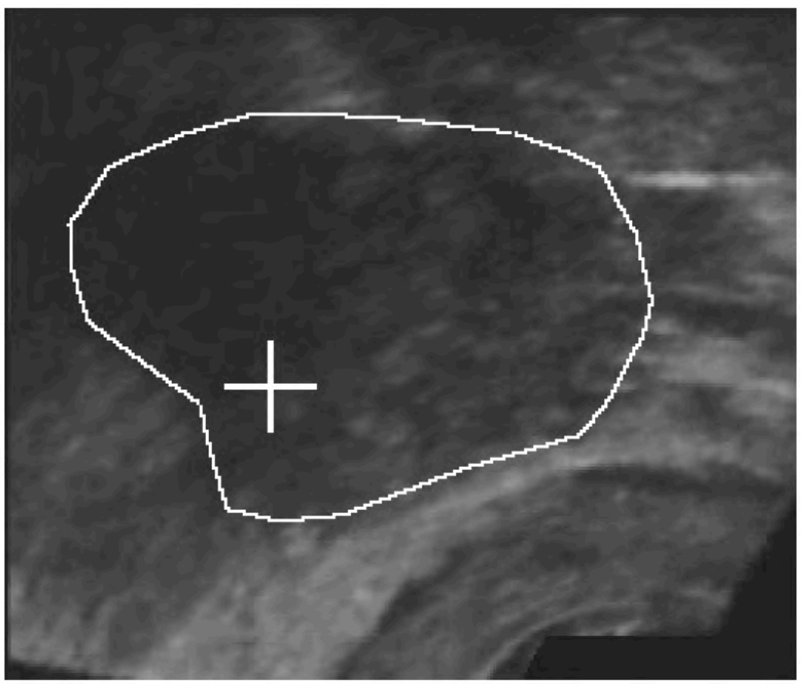
CohLig



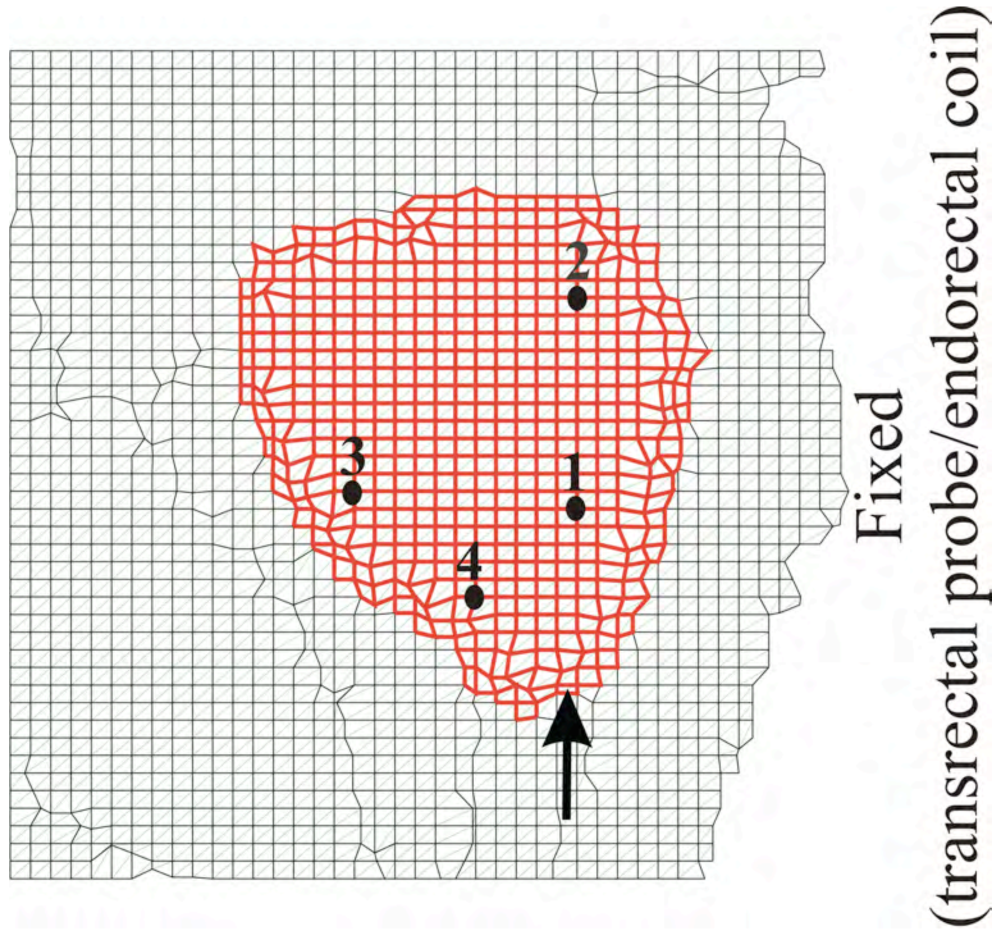
CohUr

Traditional Modeling Approach

Detailed organ geometry and boundary conditions are not considered

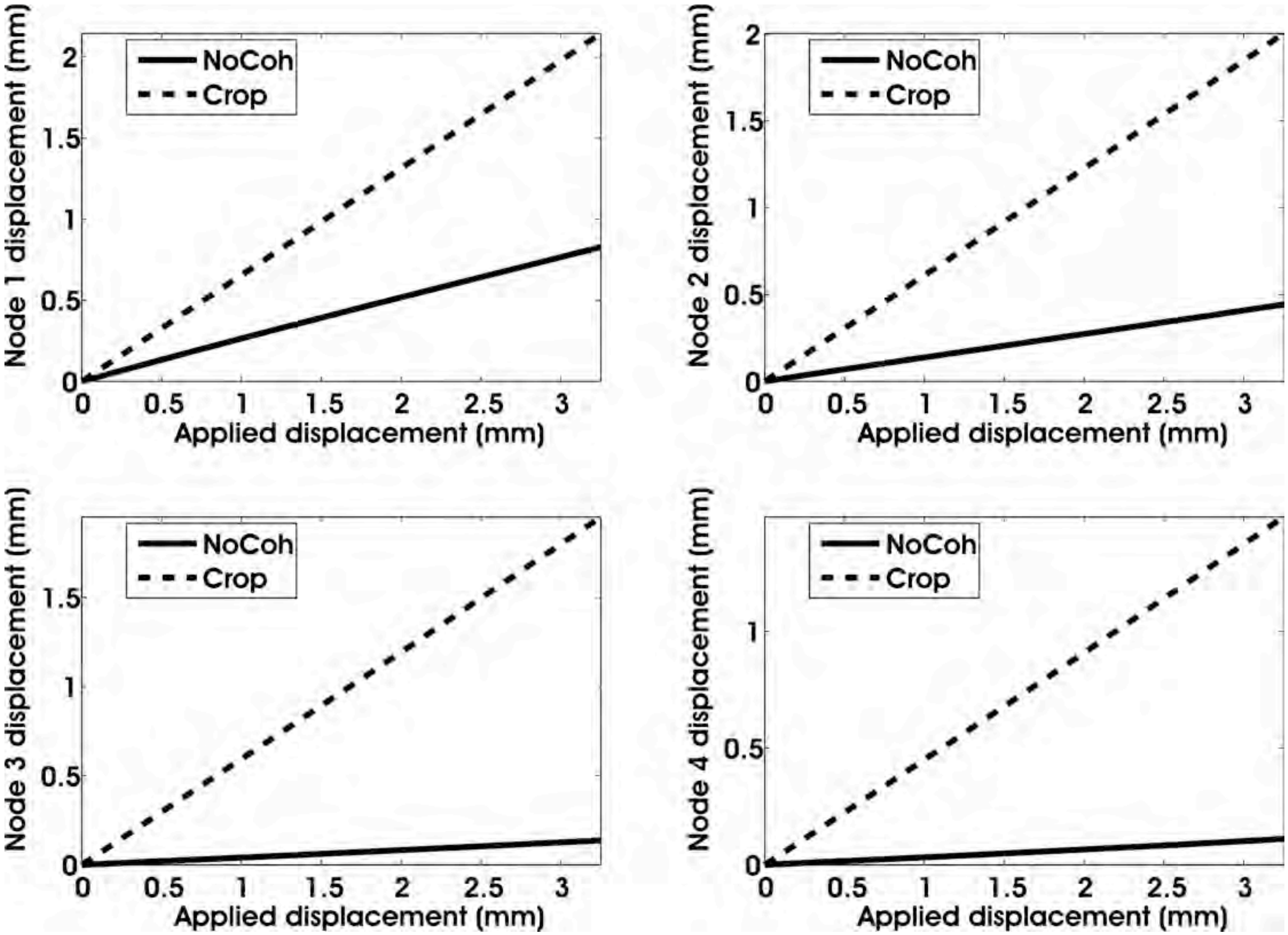


From: Alterovitz et al. (UC Berkeley)



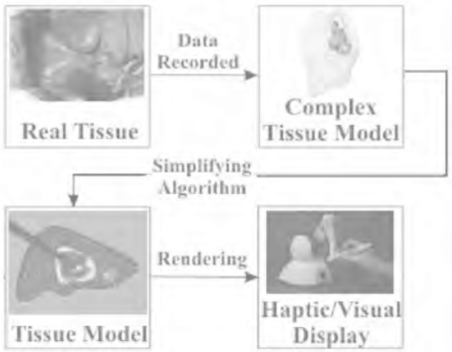
Crop

Results: *Crop* and *NoCoh*

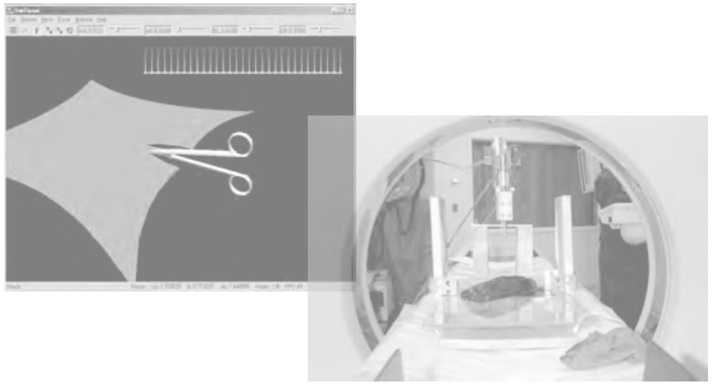


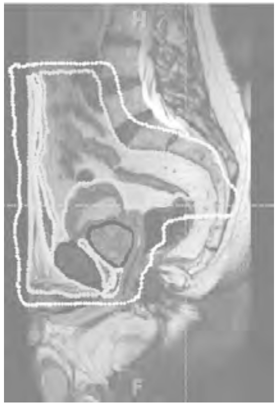
Displacement at node 3 for *Crop* = 14 × *NoCoh*.

Reality-Based Modeling Process

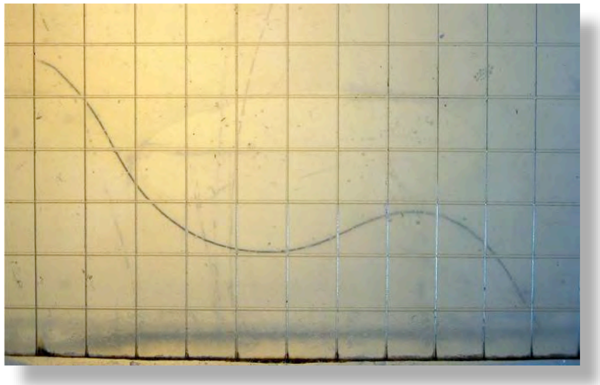


Reality-Based Modeling Examples





Modeling Factors



Application: Needle Steering

Needle Steering

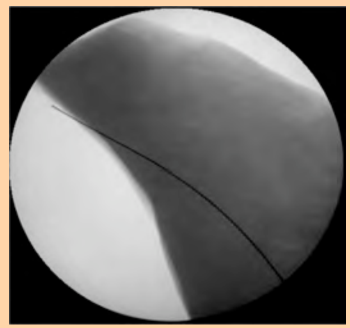
is an exciting new application of tissue models for planning and control. Steering techniques include:

Insertion point selection

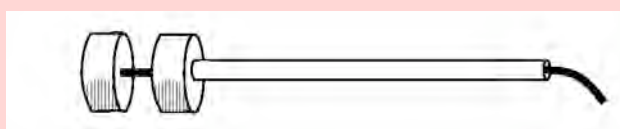
Alterovitz et al. 2003 (UC Berkeley)

Bevel tip

Webster, et al. 2004 (JHU)

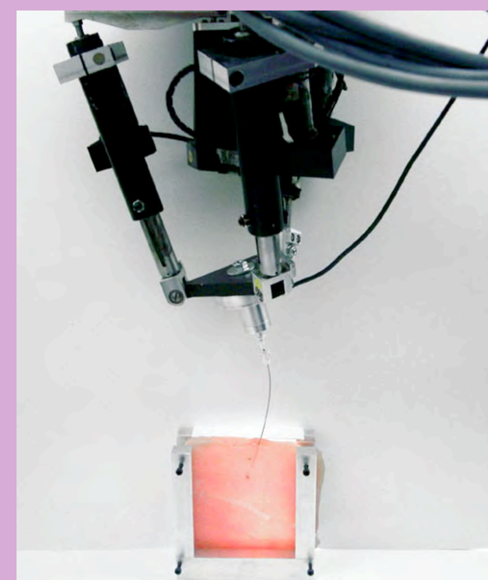


Pre-bent elements



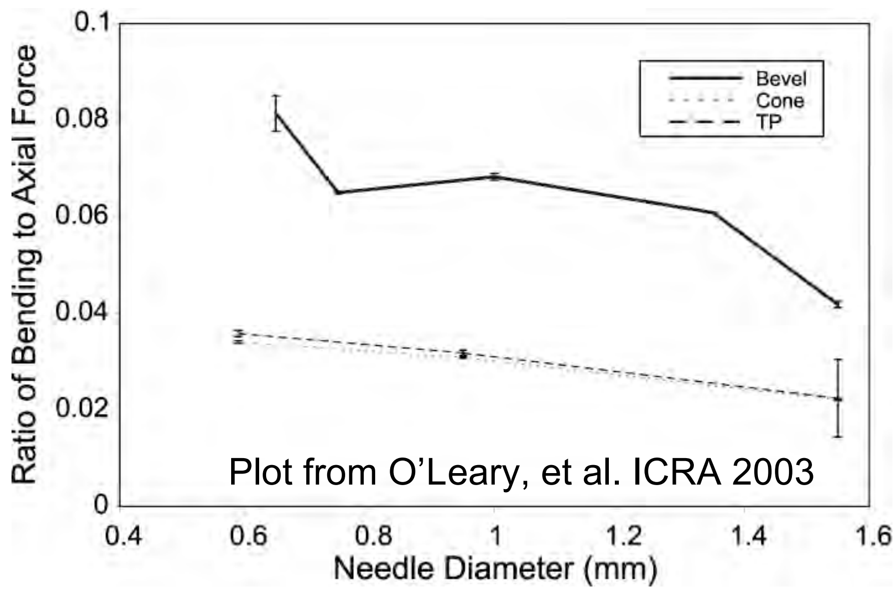
Ebrahimi, et al. 2003 (UBC)

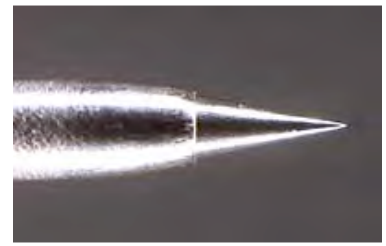
Needle deformation

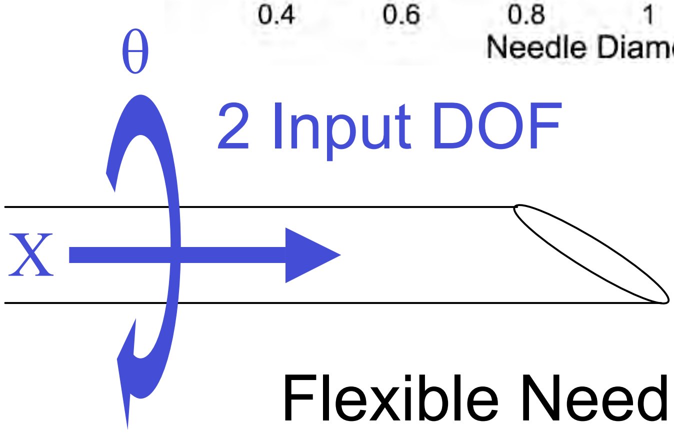


Glozman, et al. 2004 (Technion)
DiMaio, et al. 2003 (UBC)

Bevel Tip: Harnessing Asymmetry







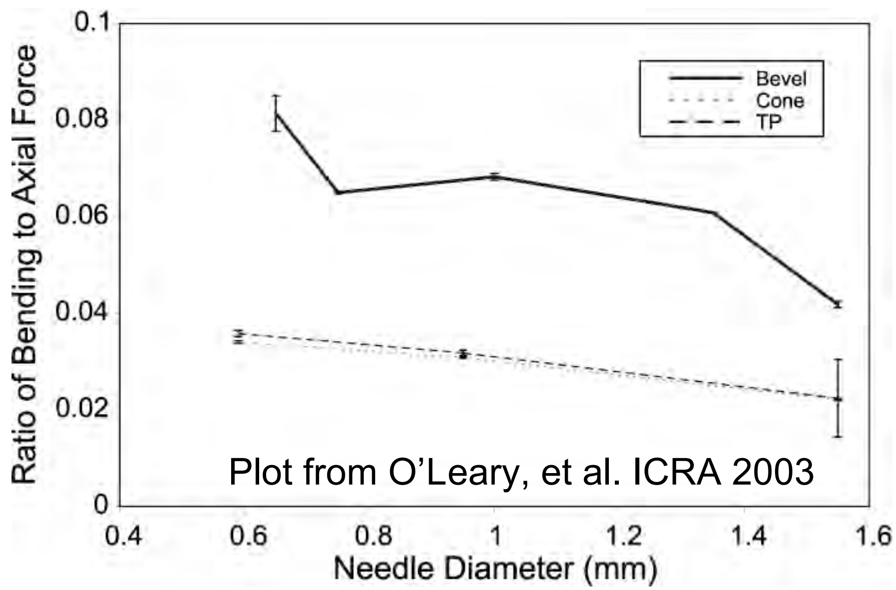
2 Input DOF

Flexible Needle
Asymmetric Tip

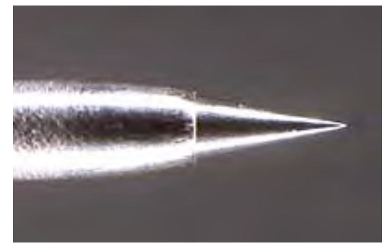
R. J. Webster III, J. S. Kim, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. Nonholonomic modeling of needle steering. International Journal of Robotics Research, 25(5-6):509–525, 2006.

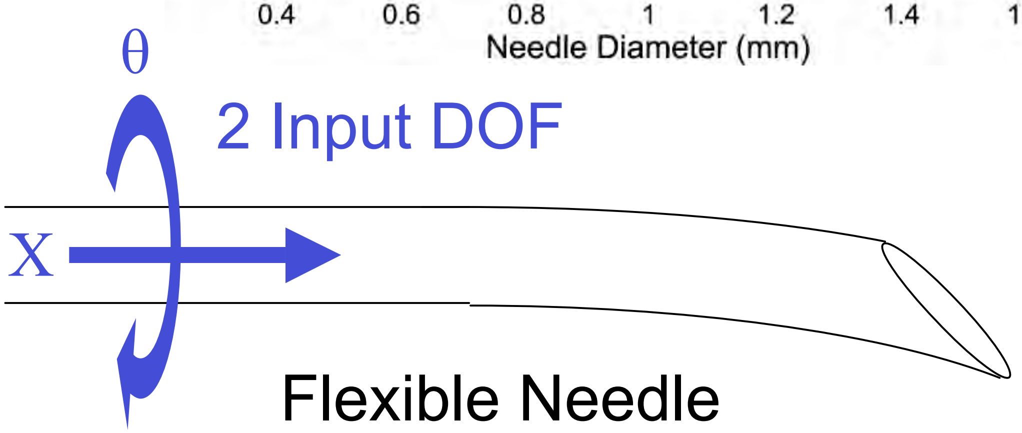
Target
6-DOF
Pose

Bevel Tip: Harnessing Asymmetry



Plot from O'Leary, et al. ICRA 2003



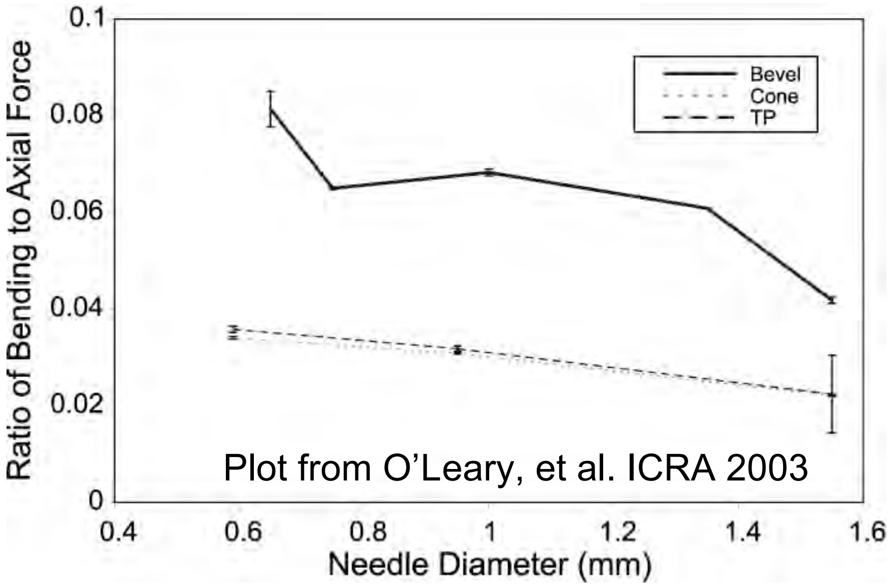


Flexible Needle
Asymmetric Tip

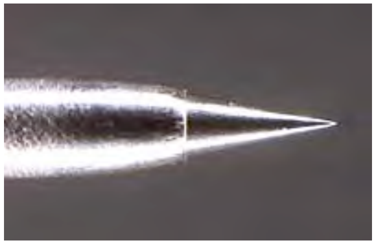
R. J. Webster III, J. S. Kim, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. Nonholonomic modeling of needle steering. International Journal of Robotics Research, 25(5-6):509–525, 2006.

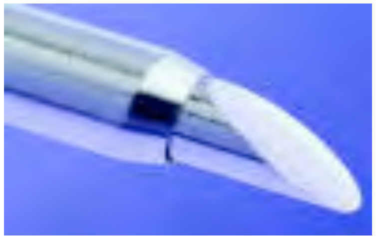
Target
6-DOF
Pose

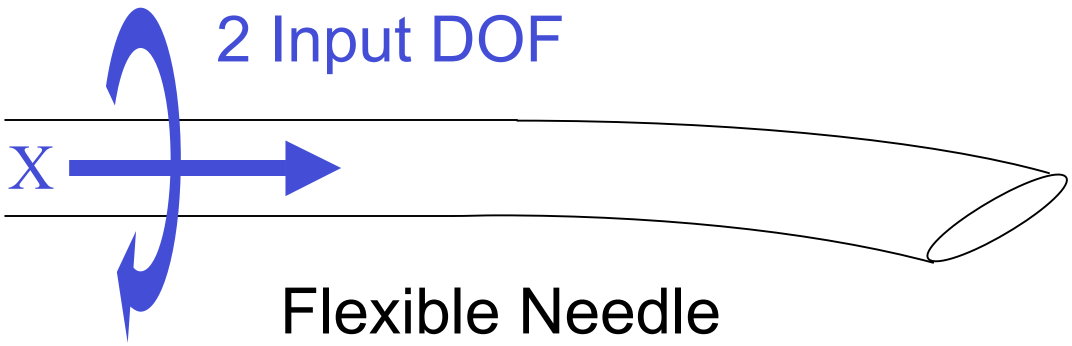
Bevel Tip: Harnessing Asymmetry



Plot from O'Leary, et al. ICRA 2003







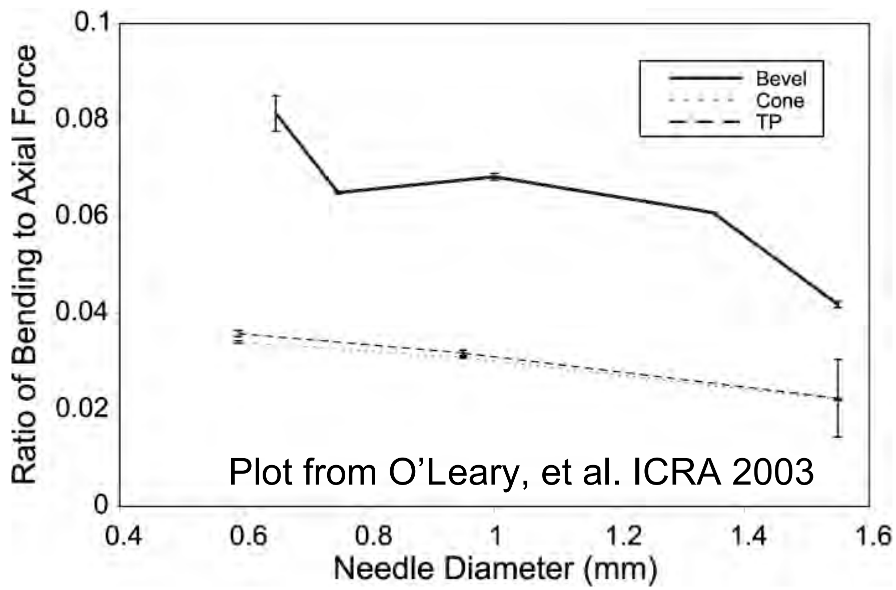
2 Input DOF

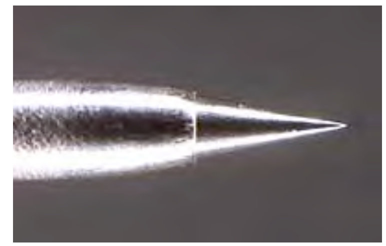
Flexible Needle
Asymmetric Tip

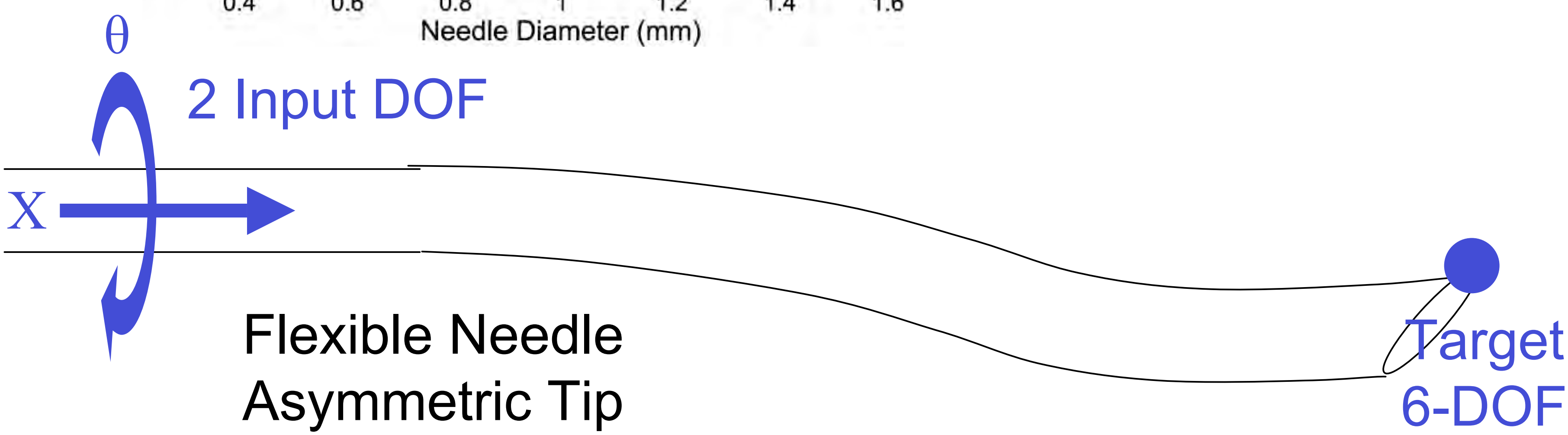
Target
6-DOF
Pose

R. J. Webster III, J. S. Kim, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. Nonholonomic modeling of needle steering. International Journal of Robotics Research, 25(5-6):509–525, 2006.

Bevel Tip: Harnessing Asymmetry

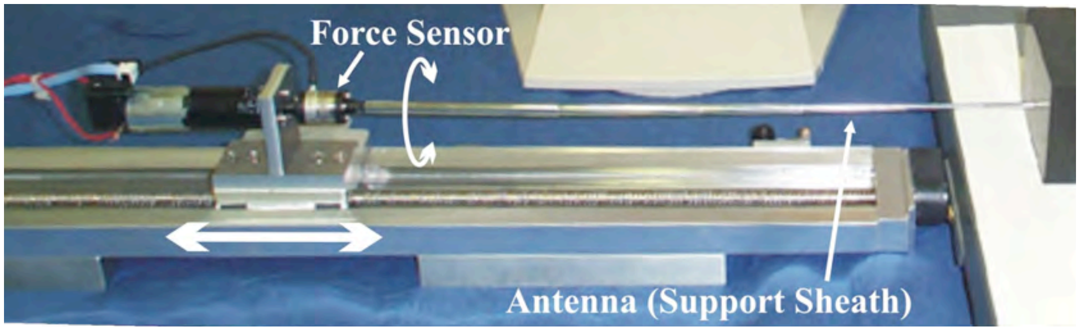


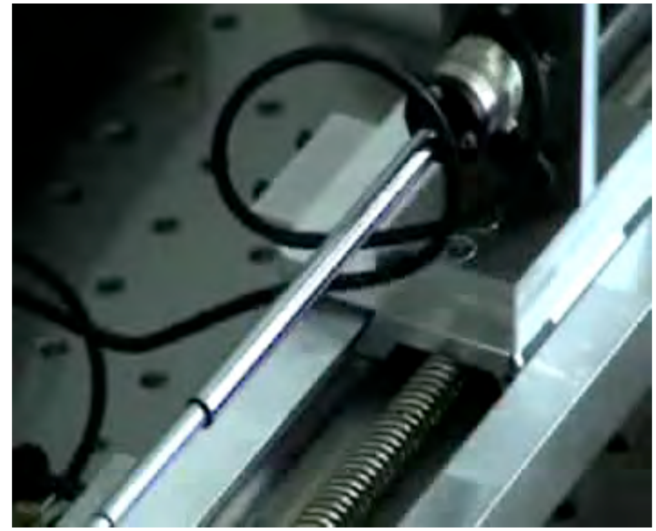


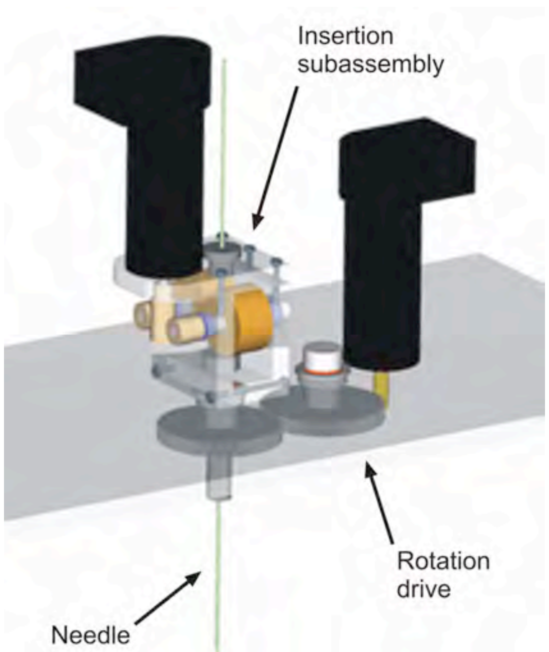


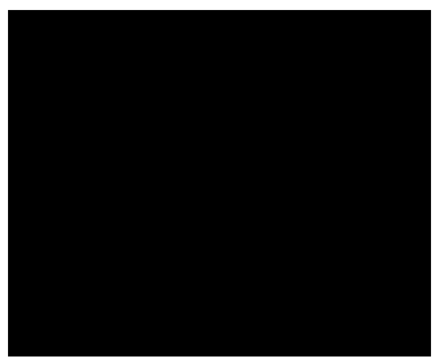
R. J. Webster III, J. S. Kim, N. J. Cowan, G. S. Chirikjian, and A. M. Okamura. Nonholonomic modeling of needle steering. International Journal of Robotics Research, 25(5-6):509–525, 2006.

Needle Driving Apparatus



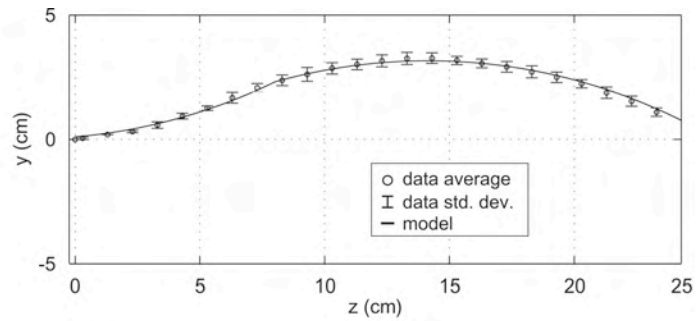




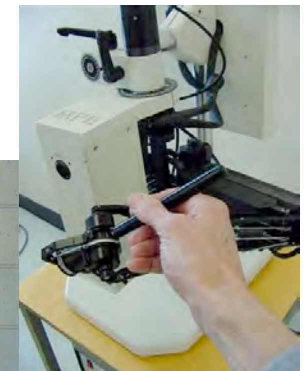


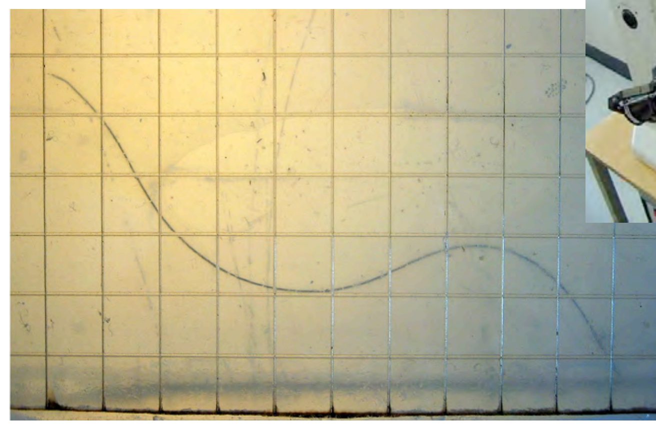
R. J. Webster III, J. Memisevic, and A. M. Okamura. Design considerations for robotic needle steering.
In IEEE International Conference on Robotics and Automation, pages 3599–3605, 2005.

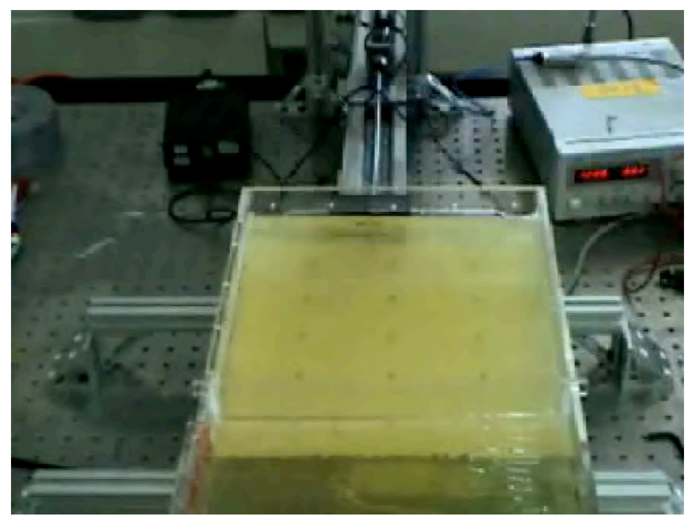
Steering Performance



J. M. Romano, R. J. Webster III, and A. M. Okamura. Teleoperation of steerable needles. In IEEE International Conference on Robotics and Automation, pages 934–939, 2007.

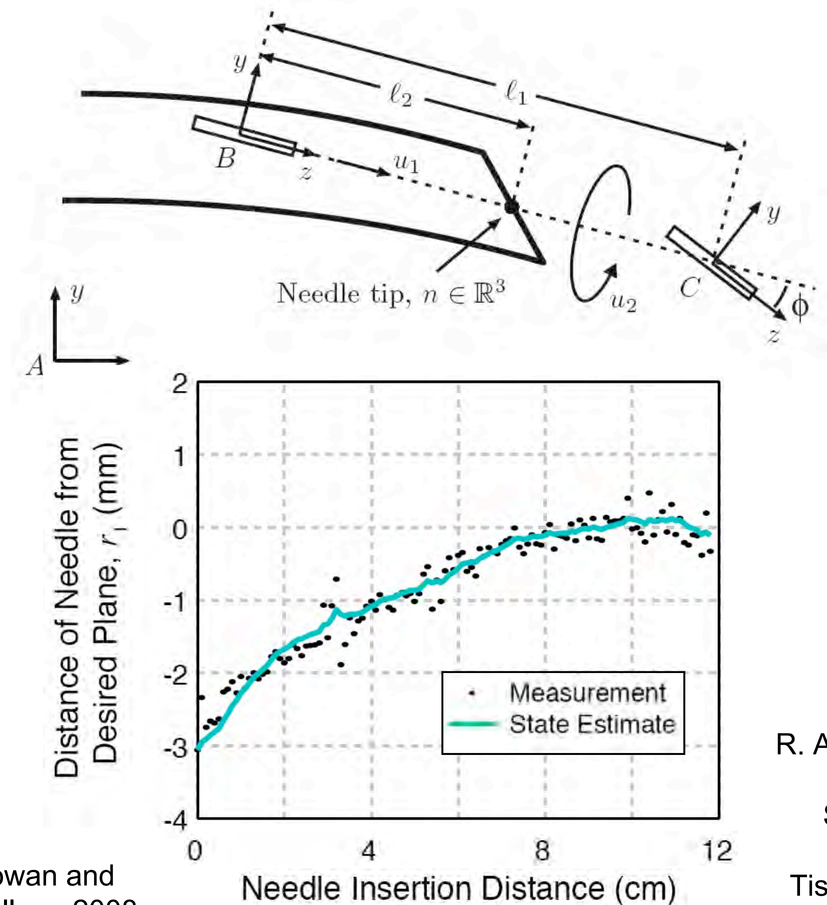






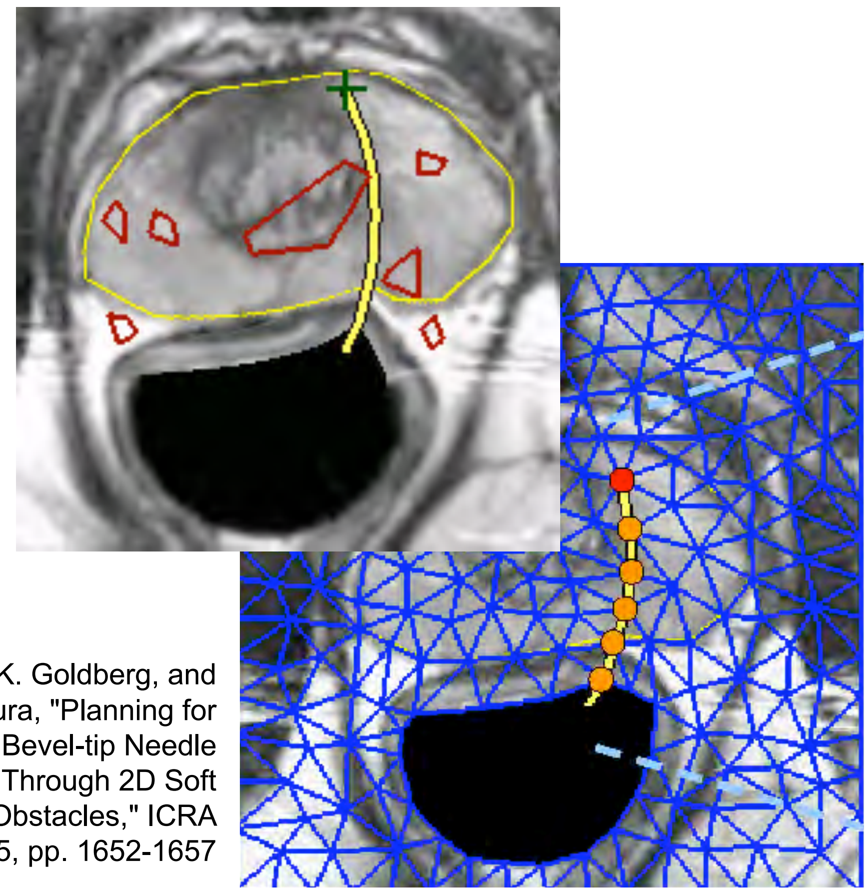
Planning and Control

Nonholonomic “bicycle” model is used in vision-based control



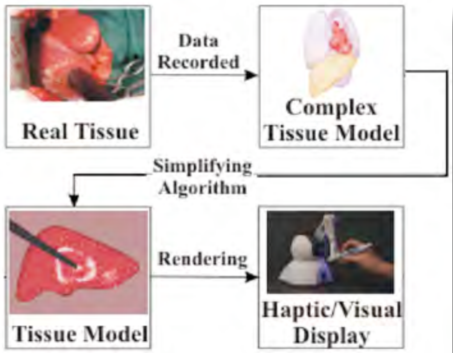
Cowan and Kallem, 2008 (JHU)

Steering angle and FEM model are used for planning

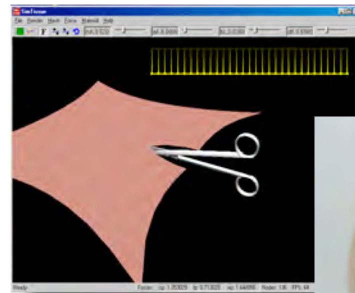


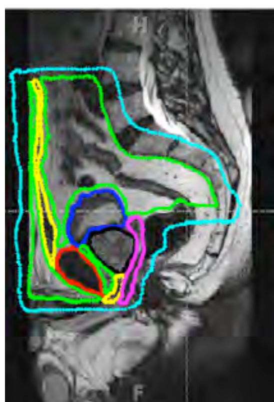
R. Alterovitz, K. Goldberg, and A. Okamura, "Planning for Steerable Bevel-tip Needle Insertion Through 2D Soft Tissue with Obstacles," ICRA 2005, pp. 1652-1657

Reality-Based Modeling Process

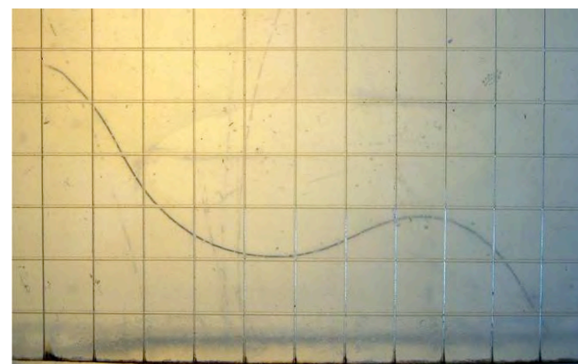


Reality-Based Modeling Examples





Modeling Factors



Application: Needle Steering

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