Reality-Based Modeling for Simulation and Robot-Assisted Surgery

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Computer-assisted planning

Patient-specific Model

Preoperative

Update Model

Update Plan

Computer-Assisted Execution

Intraoperative

Atlas

Patient

Postoperative

Computer-Assisted Assessment

R. H. Taylor
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Computer-assisted planning

Preoperative

Update Model

Intraoperative

Update Plan

Surgical “CAD”

Patient-specific Model

Surgical “CAM”

Patient-Assisted Execution

Surgical “TQM”

Postoperative

R. H. Taylor
Reality-Based Modeling Process

Modeling Factors

Reality-Based Modeling Examples

Application: Needle Steering
Reality-Based Modeling Process

Modeling Factors

Reality-Based Modeling Examples

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.

Reality-Based Modeling Procedure

Considerations in the design of a data acquisition system:
- Bandwidth
- Resolution
- Degrees of freedom
- Geometry
- Size
- Material properties

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.

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.

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.

Reality-Based Modeling Procedure

Populating the Model

*Database*: Store data

*Input-output model*: Tune parameters

*Physics-based model*: Identify parameters
Reality-Based Modeling Procedure

Rendering (compute forces from the model)

Database: Interpolate/replay data

Input-output model: Invoke mapping

Physics-based model: Simulate physics

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.

Reality-Based Modeling Procedure

Human Perception and Performance:

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

Reality-Based Modeling Process

Modeling Factors

Reality-Based Modeling Examples

Application: Needle Steering
Reality-Based Modeling Examples

**Cutting with Scissors**

- **Database method:**

- **Input-output and Physics-based models:**

**Needle Insertion**

- **Database approach, Input-output model, and Physics-based models:**
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)
Cutting with Scissors

Modeling method 2:

Input-output deformation

Physics-based cutting

Rendering:

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

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”

Needle Insertion

Data acquisition:

Stiffness and puncture

Friction and damping

[Graphs and images showing force vs. deflection, velocity vs. time, and force vs. time plots]
Needle Insertion

Data acquisition:

Needle Insertion

Modeling:

Friction and damping

\[ f(x) = a_0 + a_1 x + a_2 x^2 \]

Total force

\[ f_{\text{needle}}(x) = f_{\text{stiffness}}(x) + f_{\text{friction}}(x) + f_{\text{cutting}}(x) \]
Reality-Based Modeling Process

Modeling Factors

Reality-Based Modeling Examples

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

Linear/Nonlinear Tissue Models: Palpation Task

\[ F = \begin{bmatrix} 1 & \kappa & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ \sigma = -pI + 2 \left\{ \left( \frac{\partial W}{\partial I_1} + I_1 \frac{\partial W}{\partial I_2} \right) B - \frac{\partial W}{\partial I_2} B^2 \right\} \]

\[ S_{ij} = \frac{\partial W}{\partial E_{ij}} \Rightarrow \sigma = \frac{1}{J} F S F^T \]

Presence of \( \sigma_{22} \neq 0 \) and \( \sigma_{11} \neq \sigma_{22} \) \( \Rightarrow \) Poynting Effect
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):
  \[ W = \frac{c}{2} (e^{Q} - 1) \]

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

Courtesy: U. Pittsburgh (Michael Sacks)
Factors Affecting Path Planning

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Square (S)</th>
<th>Circle (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary condition</td>
<td>Fixed edge (F)</td>
<td>Partially constrained (P)</td>
</tr>
<tr>
<td>(connective tissue)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tissue properties</td>
<td>Linear elastic (L)</td>
<td>Hyperelastic (H)</td>
</tr>
</tbody>
</table>

8 simulation cases:

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

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

CFH

CPL

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)
Urethra and pubic ligaments are not visible in MRI
Mesh generated using OOF
ABAQUS compatible simulation files
3.25 mm displacement to simulate needle insertion
Material Properties

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$E$ (kPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>$1.80 \times 10^6$</td>
<td>0.3</td>
</tr>
<tr>
<td>Fascia</td>
<td>4249.78</td>
<td>0.45</td>
</tr>
<tr>
<td>Fat</td>
<td>3.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Ligament</td>
<td>489.71</td>
<td>0.45</td>
</tr>
<tr>
<td>Muscle</td>
<td>29.85</td>
<td>0.45</td>
</tr>
<tr>
<td>Prostate</td>
<td>60.0</td>
<td>0.45</td>
</tr>
<tr>
<td>Urinary bladder (water)</td>
<td>$1.32 \times 10^4$</td>
<td>0.499</td>
</tr>
</tbody>
</table>

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 ($t = K\delta$)

- **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 \( (t = K \delta) \)
Modeling Sensitivity Studies

CohLig

Urinary bladder

Sphincter urethra muscle

CohUr
Traditional Modeling Approach

Detailed organ geometry and boundary conditions are not considered

From: Alterovitz et al. (UC Berkeley)
Results: $Crop$ and $NoCoh$

Displacement at node 3 for $Crop = 14 \times NoCoh$. 
Reality-Based Modeling Process

- Real Tissue
- Data Recorded
- Complex Tissue Model
- Simplifying Algorithm
- Tissue Model
- Rendering
- Haptic/Visual Display

Reality-Based Modeling Examples

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

Flexible Needle
Asymmetric Tip

Bevel Tip: Harnessing Asymmetry

Bevel Tip: Harnessing Asymmetry

Flexible Needle
Asymmetric Tip

Bevel Tip: Harnessing Asymmetry

Flexible Needle Asymmetric Tip

Needle Driving Apparatus

Steering Performance

Planning and Control

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

Steering angle and FEM model are used for planning


Cowan and Kallem, 2008 (JHU)
Reality-Based Modeling Process

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Reality-Based Modeling Examples

Application: Needle Steering
Acknowledgments

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http://haptics.lcsr.jhu.edu