Modeling Realistic Tool-Tissue Interactions with Haptic Feedback: A Learning-based Method

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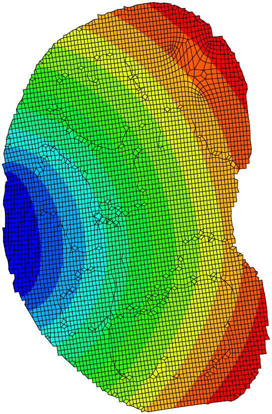
Deformation Modeling



S. Misra, K. T. Ramesh, and A. M. Okamura. **Modeling of tool-tissue interactions for computer-based surgical simulation: a literature review**. Accepted to *Presence: Teleoperators and Virtual Environments*, 2008.

Simbionix. **LAP Mentor Product Brochure** Available via web, http://www.simbionix.com/LAP_Mentor.html

Finite Element Models

Idea

- Model tissue as a set of elements with PDEs defining boundary conditions.
- Solve matrix equations based on continuum mechanics

Characteristics

- Accurate
- Slow

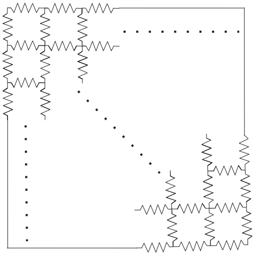
Mass-Spring-Damper Meshes

Idea

- Model tissue as point masses connected by springs and dampers.
- Dynamics solved in closed form using Hooke's law.

Characteristics

- Limited to linear deformations
- No volume conservation
- Fast



Our Approach

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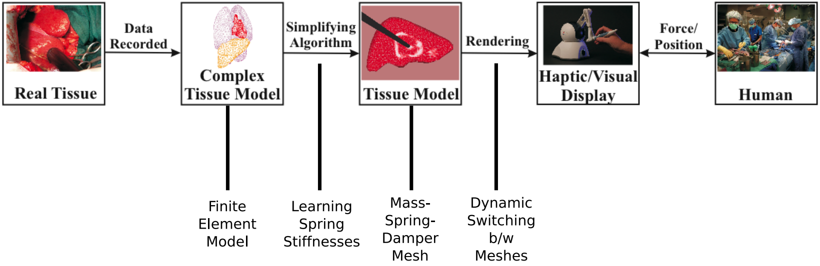
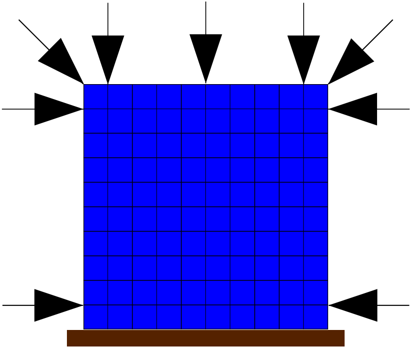
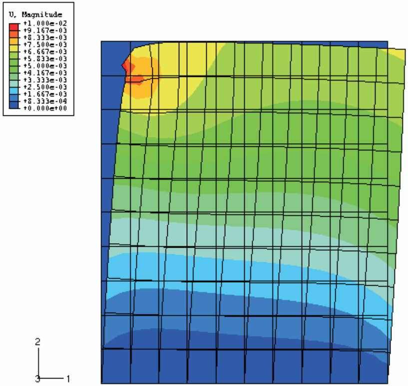


Finite Element Modeling

- Started with directly-measured porcine brain tissue parameters
  K. Miller, K. Chinzei, G. Orssengo, and P. Bednarz. **Mechanical properties of brain tissue in-vivo: experiment and computer simulation**. *Journal of Biomechanics*, 33(11):1369 1376, 2000.
- Used ABAQUS with several different loading conditions





Comparison Model

Van Gelder/Mollemans Heuristic

$$k_c = \frac{E_2 \sum_e area(T_e)}{|c|^2} \qquad m_i = \sum_j \frac{1}{4} \rho_j V_j$$

- A. Van Gelder. **Approximate simulation of elastic membranes by triangulated spring meshes**. *Journal of Graphics Tools*, 3(2):2141, 1998.
- W. Mollemans, F. Schutyser, J. Cleynenbreugel, and P. Suetens. **Tetrahedral mass spring model for fast soft tissue deformation**. In *International Symposium on Surgery Simulation and Soft Tissue Modeling*, pages 145–154, 2003.

Parameter Learning

Our approach

- Optimized all spring stiffnesses for each loading condition
- Used Simultaneous Perturbation Stochastic Approximation (SPSA)

Previous work

- Simulated Annealing – Deussen et al. (1995), Morris (2006)
- Genetic Algorithms – Bianchi (2003), (2004)

SPSA

Pseudocode

for k=1:n

$\delta = 2round(rand(p, 1)) - 1$

$\theta_{\pm} = \theta \pm c_k \delta$

$y_{\pm} = Loss(\theta_{\pm})$

$\hat{g} = \frac{y_{+} - y_{-}}{2c_k\delta}$

$\theta = \theta + a_k \hat{g}$

end

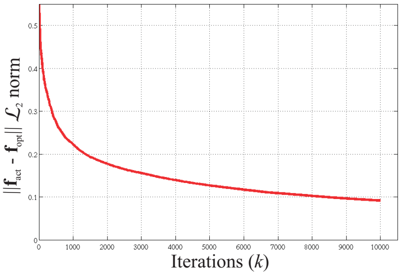
Variables

δ	Perturbation vector
$\theta_{\pm}$	Positive & negative samples
$y_{\pm}$	Loss function at samples
$\hat{g}$	Gradient estimate
c_k	Perturbation step-size
a_k	Update step-size

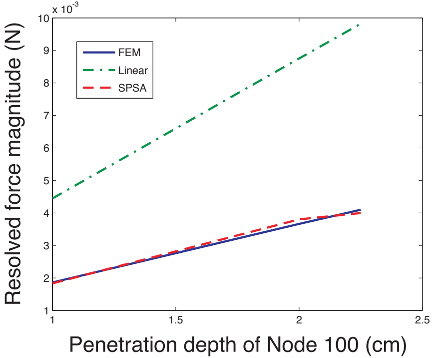
Adapted from Spall, J.C. **An Overview of the Simultaneous Perturbation Method for Efficient Optimization**, *Johns Hopkins APL Technical Digest*, vol. 19, pp. 482–492, 1998.

Results

Sample learning curve



Deformation of a sample node for all 3 models



Implementation System

- Phantom Omni
- SenseAble OpenHaptics Toolkit
- Boost matrix/vector libraries

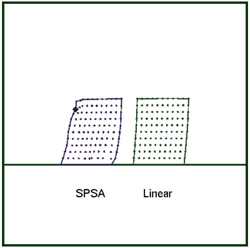
Implementation Method

Notation and Data Structures

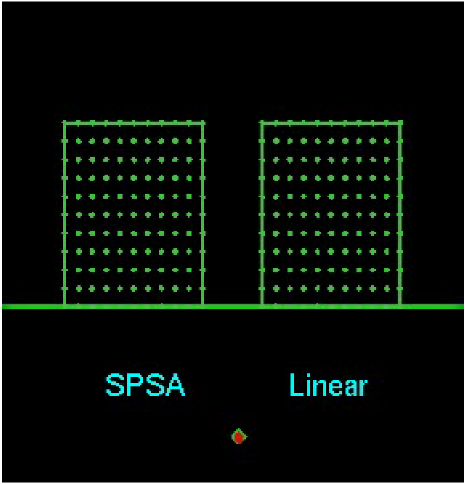
$\mathbf{x}_t$	Mesh node positions	$\mathbf{B}$	Damping
$\mathbf{M}$	Mesh node masses	$\mathbf{f}_t$	Contact force
$\mathbf{K}$	Spring elasticities	τ	Time-step

Dynamics

$$\ddot{\mathbf{x}}_t = \mathbf{M}^{-1}\left(\mathbf{K}_t \Delta \mathbf{x}_t + \mathbf{B}\dot{\mathbf{x}}_t + \mathbf{f}_t\right)$$
$$\dot{\mathbf{x}}_t = \dot{\mathbf{x}}_{t-1} + 0.5\tau\left(\ddot{\mathbf{x}}_{t-1} + \ddot{\mathbf{x}}_t\right)$$
$$\mathbf{x}_t = \mathbf{x}_{t-1} + 0.5\tau\left(\dot{\mathbf{x}}_{t-1} + \dot{\mathbf{x}}_t\right)$$
$$\mathbf{K}_t = \gamma K(\mathbf{f}_t) + (1-\gamma)\mathbf{K}_{t-1}$$



Implemented Display



Conclusions

Contributions

- Method to learn spring stiffness for high-fidelity modeling
- Enabled fast piece-wise linear approximation of nonlinear deformations

Future Work

- Extension to 3D
- Learning more mesh parameters
- Online mesh structure redefinition

Thanks

- Thanks for listening.
- Thanks to NIH Grant R01 EB002004 for continued support.

- Questions?