Real-Time Deformable Models for Soft Tissue Simulation

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Importance of Soft Tissue Modeling

- Most medical procedures involve the deformation (and tearing or cutting) of anatomical structures
- The ability to simulate that behavior is an important element of the learning process
- Applications for more accurate soft tissue models are not limited to medical simulation

Soft Tissue Modeling: a grand challenge for medical simulation

- Soft tissue is very complex
- We do not understand yet all the aspects of soft tissue behavior
- We need tools to investigate tissue properties
- Once we have a better understanding we need to design appropriate mathematical models
- These models need to be optimized to provide real-time interaction

Soft Tissue Modeling

Biomechanical Properties	Mathematical Modeling	Real-time Modeling
In-vitro measurements	Constitutive Laws	Finite Element Methods
In-vivo measurements	Continuum Models	Spring-Mass Models
		Others

Validation, validation, validation

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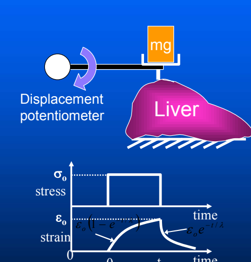
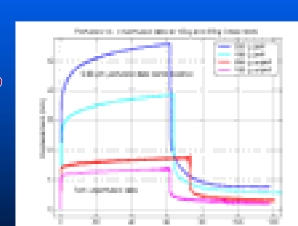
Viscoelastic Property Experiments





Creep Modulus $J(t) = \frac{\varepsilon(t)}{\sigma}$

Some references…

- *In vivo* property measurement
  - Ottensmeyer, M. “In vivo measurement of solid organ visco-elastic properties”. *Proceedings of Medicine Meets Virtual Reality*, J.D. Westwood, et al. (Eds.), Newport Beach, CA. IOS Press, pp 328-333, 2002.
  - Wellman, P.S. and Howe, R.D. “Extracting features from tactile maps”. *Proceedings of Medical Image Computing and Computer-Assisted Intervention (Lecture Notes in Computer Science Vol.1679),* 1999.
  - Brouwer, I. *et al*. “Measuring In Vivo Animal Soft Tissue Properties for Haptic Modeling in Surgical Simulation”, in *Proceedings of Medicine Meets Virtual Reality*, J.D. Westwood et al. (Eds.), 2001.
  - Kerdok, A. E., and Howe, R.D. “A Technique for Measuring Mechanical Properties of Perfused Solid Organs”, *ASME Summer Bioengineering Conference*, Key Biscayne, 2003.
  - Cespedes *et al*., Elastography: elasticity imaging using ultrasound with application to muscle and breast in vivo. *Ultrasonic Imaging*. 15(2):73-88, 1993.
  - Miller K, and Chinzei K. “Modeling of soft tissue deformation”. Journal Computer Assisted Surgery: Supplement, *Proceedings of Second International Symposium on Computer Aided Surgery*, 62-63, 1995.
- *In vitro* property measurement
  - Fung, Y. C. Biomechanics: Mechanical properties of living tissue. 2nd ed. New York: Springer-Verlag, 1993.
  - Duck FA. Physical Properties of Tissue, a comprehensive reference book. ISBN: 0-12-222800-6 Academy Press, Harcourt Brace Jovanovich, London, 1990.
  - Yamada H. Strength of Biological Materials. SBN: 683-09323-1, Williams & Wilkins Company, Baltimore, 1970.

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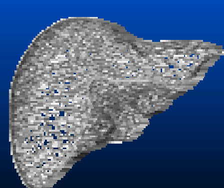
From Experimental Data to Predictive Models

- *First step:* build a database of experimental results
- *Second step*: define mathematical models that will fit the data and simulate tissue behavior across variable shapes and constraints

λ, μ →



Soft-Tissue Constitutive Laws

Constitutive laws need to account for tissue complexity

- Non-linear stress-strain relationship
  - *Forces are not linearly proportional to displacements*
- Large deformations
  - *Geometric non-linearities*
- Viscoelastic
  - *Properties are function of time*
- Non-homogeneous
  - *Properties vary throughout tissue thickness*
- Anisotropic
  - *Properties vary with direction*

Solving the Equations

- No close-form solution for the vast majority of constitutive laws
- Need to use numerical techniques that provide accurate results and account for boundary conditions and complex geometries
  - Continuum models
  - Approximated by Finite Element Models

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Real-time Soft Tissue Modeling

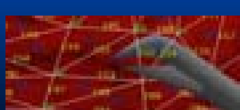
- A typical FEM computation on a non-linear model can take several minutes on a fast computer…
- … while the required update rates for interactive simulation typically range from 25 Hz (visual) to 300 Hz (haptics)
- An acceleration factor of more than 10,000 is needed to permit interactive manipulation of accurately simulated soft-tissue

Real-time Soft Tissue Modeling

- How to improve speed?
  - Get a faster computer…
  - Optimize the algorithms
  - Simplify the models
    - Linear vs. non-linear
    - Surface vs. volume
    - Static vs. dynamic
  - Use ad-hoc / heuristic techniques
    - Spring-mass models
    - Long Elements, Chain Mail, …
    - Hybrid models
    - Neural networks

Spring-Mass Models

- The surface or volume of the organ is discretized in a set of mass-points
- Each mass-point is “linked” to its neighbors by a one-dimensional “spring”
- When a “mass” moves away from its initial position, the spring force will act on the neighbors



Spring-Mass Models

- By solving Newton’s second law of motion we can compute the new location of all masses, i.e. the new shape of the object
  - Explicit methods (Euler, Runge Kutta, Midpoint, …)
  - Implicit methods (backward Euler, …)

Eye Surgery Simulation

Courtesy of LIFL

Some remarks regarding mass-spring models

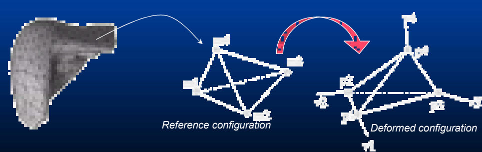
- Some good things…
  - Fast and easy to implement
  - Can handle geometric non-linearities
  - Easy to simulate cutting
  - Many publications on the topic
- … and not so good things
  - How to preserve volume?
  - Stability issues and jelly-like behavior
  - How to integrate soft-tissue properties into the model
  - Just another way of describing a FEM model for truss elements

Some references on spring-mass models for medical simulation

- Kuhnapfel, U. G. *et al.* “Endoscopic surgery training using virtual reality and deformable tissue simulation”. *Computers & Graphics*, 24:671--682, 2000.
- Meseure, P. *et al.* “A Physically-Based Virtual Environment dedicated to Surgical Simulation”, *Proceedings of the International Symposium on Surgery Simulation and Soft-Tissue Modeling*, 2003.
- Mollemans, W. *et al.* “Tetrahedral Mass Spring Model for Fast Soft Tissue Deformation”, *Proceedings of the International Symposium on Surgery Simulation and Soft-Tissue Modeling*, 2003.
- Anderson Maciel et al. “Deformable Tissue Parameterized by Properties of Real Biological Tissue”, *Proceedings of the International Symposium on Surgery Simulation and Soft-Tissue Modeling*, 2003.
- Neumann, P et al. “Virtual Reality Vitrectomy Simulator”, Proceedings of MICCAI’98, 1998, pp. 910-917

The Finite Element Method

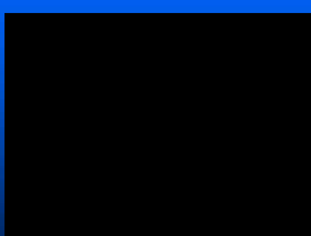
- Basic principles:
  - Discretize the geometry of the domain in a set of elements (i.e. tetrahedra),
  - Define the PDE for a reference element (i.e. tetrahedron), and then compute its expression on each element in the mesh,
  - Assemble the contribution of each element in the mesh to form (for instance) a linear system $Ku = F$

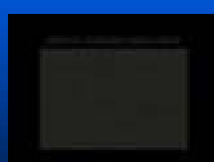


The Finite Element Method

- Basic principles (continued)
  - Compute the solution by using one of the numerous numerical techniques available for linear (or non-linear) systems of equations
  - Examples of numerical techniques
    - » Conjugate Gradient for linear systems
    - » Newton-Raphson method for non-linear systems
- For real-time applications, solving the system of equations is the bottleneck
- Performance can be improved by:
  - Applying new computation strategies (condensation, superposition, …)
  - Using multi-processing approaches

Example of real-time FEM model
(linear elastic model simulated at 300Hz)





Courtesy of INRIA (Cotin et al., 1999)

Some references on FEM in medical simulation

- Acceleration based on superposition principle and pre-computation: *Cotin, S., Delingette, H. "Real-Time Surgery Simulation with Haptic Feedback using Finite Elements". Proceedings of ICRA 1998: 3739-3744.*
- Similar idea but different formulation: *James, D., and Pai, D. "Multiresolution Green's function methods for interactive simulation of large-scale elastostatic objects". ACM Transactions on Graphics 2003. 22(1): 47-82.*
- Condensation technique: *Bro-Nielsen, M., and Cotin, S. "Real-time volumetric deformable models for surgery simulation using finite elements and condensation", Computer Graphics Forum (Eurographics '96), 15(3):57-66, 1996.*
- Adaptive meshing: *Wu, X., et al. "Adaptive Nonlinear Finite Elements for Deformable Body Simulation Using Dynamic Progressive Meshes". Computer Graphics Forum, 20(3), 2001.*
- Parallel computation: *Frank, A. et al. "Finite Element Methods for Real-Time Haptic Feedback of Soft-Tissue Models in Virtual Reality Simulators", in Proceedings of Virtual Reality 2001, pp 257-263.*

Some remarks regarding Finite Element models

- Advantages
  - This approach benefits from a solid background and established techniques, books and a vast literature.
  - It is easier to integrate tissue properties into the model
  - Numerical techniques for solving large linear (or non-linear) systems exist
  - Under some assumptions (linear elasticity, quasi-static), real-time computation is possible
  - Parallel computing techniques are available (domain decomposition, multi-resolution, …)

Some remarks regarding Finite Element models

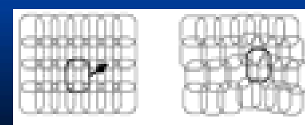
- Drawbacks
  - It is slow (and very slow for non-linear models) when not combined with real-time strategies
  - Real-time computation calls for assumptions that are not always compatible with requirements for medical simulation
  - Not always easy to implement
  - Not necessarily the best solution for any given problem…

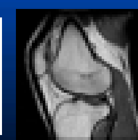
Other approaches to real-time soft tissue deformation

- Long (and radial) elements:
  - Balaniuk, R. *et al.* "Soft-tissue simulation using the Radial Elements Method", *Proceedings of the International Symposium on Surgery Simulation and Soft-Tissue Modeling*, 2003
  - Balaniuk, R. *et al.* "LEM – An approach for real-time physically-based soft tissue simulation", *Proceedings of ICRA,* 2001

Other approaches to real-time soft tissue deformation

- Chainmail:
  - Gibson, S. "*3D ChainMail: A Fast Algorithm for Deforming Volumetric Objects*", Symposium on Interactive 3D Graphics, pp. 149-154 (2000)
  - Schill, M. and Gibson, S. "*Biomechanical Simulation of the Vitreous Humor of the Eye Using an Enhanced ChainMail Algorithm*", Proc. Medical Image Computation and Computer Integrated Surgery, 1998, pp. 679-687



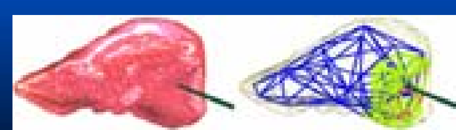


Other approaches to real-time soft tissue deformation

- Tensor-mass models:
  - Cotin, S. *"A Hybrid Elastic Model allowing Real-Time Cutting, Deformations and Force-Feedback for Surgery Training and Simulation".* The Visual Computer, 16(8):437-452, 2000
  - Picinbono, G. *"Real-Time Large Displacement Elasticity for Surgery Simulation: Non-Linear Tensor-Mass Model".* In Third International Conference on Medical Robotics, Imaging And Computer Assisted Surgery: MICCAI 2000, pages 643-652, 2000

Other approaches to real-time soft tissue deformation

- Adaptive sampling / mesh
  - Debunne, G. *et al. "Dynamic real-time deformations using space & time adaptive sampling".* Proceedings of SIGGRAPH 2001
  - Wu, X. et al. *"Adaptive Nonlinear Finite Elements for Deformable Body Simulation Using Dynamic Progressive Meshes"*, Proceedings of Eurographics 2001, pp. 349-358



Where is the research going?

- Derive new models from Biology not from Computer Graphics
  - Try to understand how things work in the real world before simulating it…
  - ... then define models based on experimental (*in vivo, in situ*) data
- Computations based on single processor approaches will soon reach their limits
  - Multi-resolution, multi-processor techniques
  - Clusters of PCs might be a way of dealing with simulation of complex anatomical structures

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Cross-Validation of Real-Time models is mandatory

- Mathematical models (constitutive laws) are a tradeoff between accurately "translating" the experimental data and remaining applicable to other geometries and constraints
- New data must be collected and compared with the results predicted by the model
- Real-time models usually require additional tradeoffs to provide fast computation: therefore validation is even more important.

Conclusion

- There is no ideal modeling technique for all simulations, only better, more stable, more accurate ways of doing things
- In any case, it is key to validate the results of the simulation by comparing them to the real world