Real-Time Soft Tissue Modeling

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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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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.
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  - Yamada H. Strength of Biological Materials. SBN: 683-09323-1, Williams & Wilkins Company, Baltimore, 1970.

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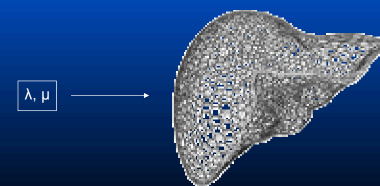
From Experimental Data to Predictive Models

- *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



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
  - More accurate than discrete models like spring-mass models
  - Other approaches exist that might be more appropriate for specific applications

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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

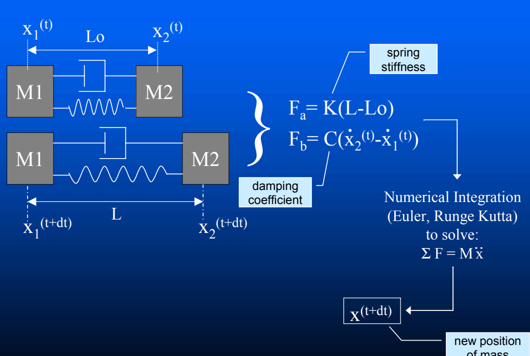
Real-time Soft Tissue Modeling

- 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 / discrete models
    - Spring-mass models
    - Long Elements, Chain Mail, …
    - Hybrid models
    - Neural networks

Spring-Mass Models

- Particle System
  - Collection of unconnected mass points
  - Particle motion influenced by force fields
- Spring-Mass Model
  - Basically same as a particle system
  - Structured, rather than free form
  - Mass points part of model
  - Use spring forces to connect masses
  - Each force object knows which points it acts on

Spring-Mass Models

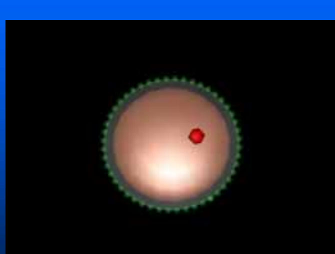


Spring-Mass Models

- Spring-mass models
  - 1-D elements linking a set of nodes distributed on the surface or in the volume of the "organ"
    - » Surface springs
    - » Volumetric springs

- Computation
  - Solve Newton's second law of motion
    - » Explicit methods (Euler, Runge Kutta, Midpoint, …)
    - » Implicit methods (backward Euler, …)

Eye Surgery Simulation



Courtesy of LIFL

Some references on spring-mass models for medical simulation

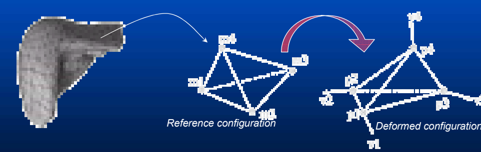
- Kuhnapfel, U. G. *et al.* "Endoscopic surgery training using virtual reality and deformable tissue simulation". *Computers & Graphics*, 24:671--682, 2000.
- Meseure, P. *et al.* "A Physically-Based Virtual Environment dedicated to Surgical Simulation", *Proceedings of the International Symposium on 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

Some remarks regarding mass-spring models

- Some good things…
  - Fast and easy to implement
  - Can handle geometric non-linearities
  - The use of 1D elements make it unrealistic to model volume (results depend on topology of the mesh…)
- … 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

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 value for each element in the mesh,



The Finite Element Method

- Basic principles (continued)
  - Assemble the contribution of each element in the mesh to form (for instance) a linear system $Ku = F$
  - The unknown vector u contains the values of the approximate solution at the mesh points (i.e. displacements)
  - The matrix K is assembled from the stiffness coefficients of each element
  - And the right-hand side F contains the external forces applied to the domain,

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 it is mainly this last step that needs to be accelerated
  - By applying new computation strategies (condensation, superposition, …)
  - By using multi-processing approaches

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.

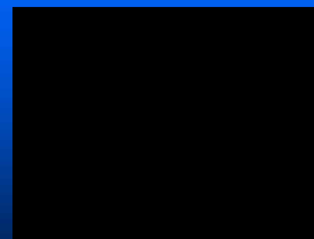
Some remarks regarding Finite Element models

- Advantages
  - This approach benefits from a solid background and established techniques, books and a vast literature.
  - It is a numerical technique for solving partial differential equations…
  - … so the results are less dependent on the initial mesh (as opposed to mass-spring models), and it is easier to integrate tissue properties into the model
  - Numerical techniques for solving large linear (or non-linear) systems exist (even though not necessarily fast enough)

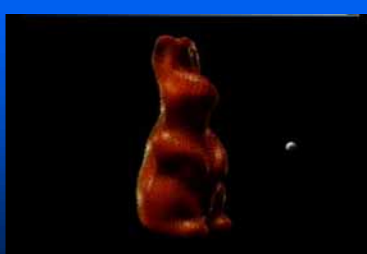
Some remarks regarding Finite Element models

- 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…

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



Multi-resolution Green's Function Method (D. James & D. Pai)



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.
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- 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*, March, 1998. pp. 679-687.

Other approaches to real-time soft tissue deformation

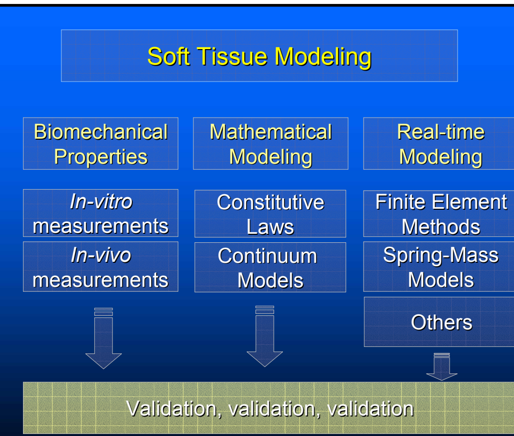
- Tensor-mass models:
  - Cotin, S. "A Hybrid Elastic Model allowing Real-Time Cutting, Deformations and Force-Feedback for Surgery Training and Simulation". *The Visual Computer*, 16(8):437--452, 2000.
  - Picinbono, G. "Real-Time Large Displacement Elasticity for Surgery Simulation: Non-Linear Tensor-Mass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

Where is the research going?

- The more accurate the models will be, the more computational power we will need
- Computations based on single processor approaches will soon reach their limits
- Clusters of PCs might be a way of dealing with Medical Simulation in the future



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.

Validate, validate, validate…

- 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

Conclusion

- Medical simulation has become a reality
- The medical community is expecting a lot from medical simulation
- Negative training must be avoided by developing realistic training systems based on real-world data.
- Do not forget to validate!