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

Viscoelastic Property Experiments

\[ f(t) = \frac{\sigma(t)}{\varepsilon(t)} \]

Displacement potentiometer

Liver...
Some references...


In vitro property measurements


In vivo measurements


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.

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.

Soft Tissue Constitutive Laws

- Constitutive laws need to account for tissue complexity:
  - Non-linear stress-strain relationship
  - Large deformations
  - Anisotropic
  - Non-homogeneous
  - Properties vary with time
  - Properties vary with direction
  - Geometric non-linearities
  - Viscoplastic

Soft Tissue Modeling

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

Validation, validation, validation
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
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 $Ku = F$.

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

**Example of real-time FEM model**

- Linear elastic model simulated at 300Hz

**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.
  - Parallel computing techniques are available (domain decomposition, multi-resolution, …).

- **Drawbacks**
  - Performance can be improved by:
    - Applying new computation strategies
    - Using multi-processing approaches
  - Real-time computation calls for assumptions that are not always compatible with requirements for medical simulation
  - Not necessarily the best solution for any given problem…

Some references on FEM in medical simulation

- Similar ideas but different formulation: James, D. and Pol, D. "Multiresolution finite element method for interactive simulation of large-scale elastostatic objects": ACM Transactions on Graphics 2003, 22(1), 47-82.
Other approaches to real-time soft tissue deformation

- Long (and radial) elements:

- Tensor-mass models:

- Other approaches to real-time soft tissue deformation

  - Chainmail:

- Adaptive sampling / mesh

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 vitro) 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

Soft Tissue Modeling

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

Validation, validation, validation
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.