Modelling of soft tissue deformation

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Moscow, 2014

Characteristics of soft living tissues

- Non-uniformity, anisotropy

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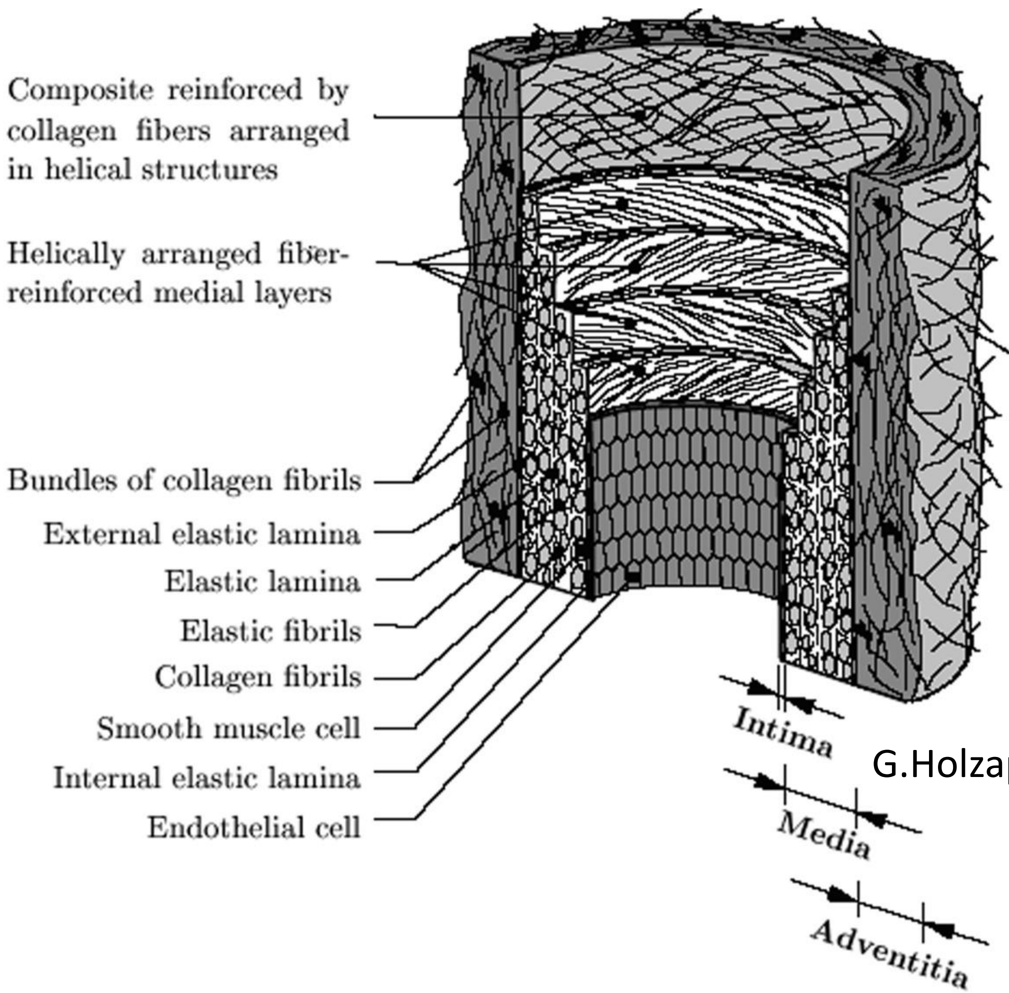

G.Holzapfel et al *Journal of Elasticity*, 2000

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- Material nonlinearity

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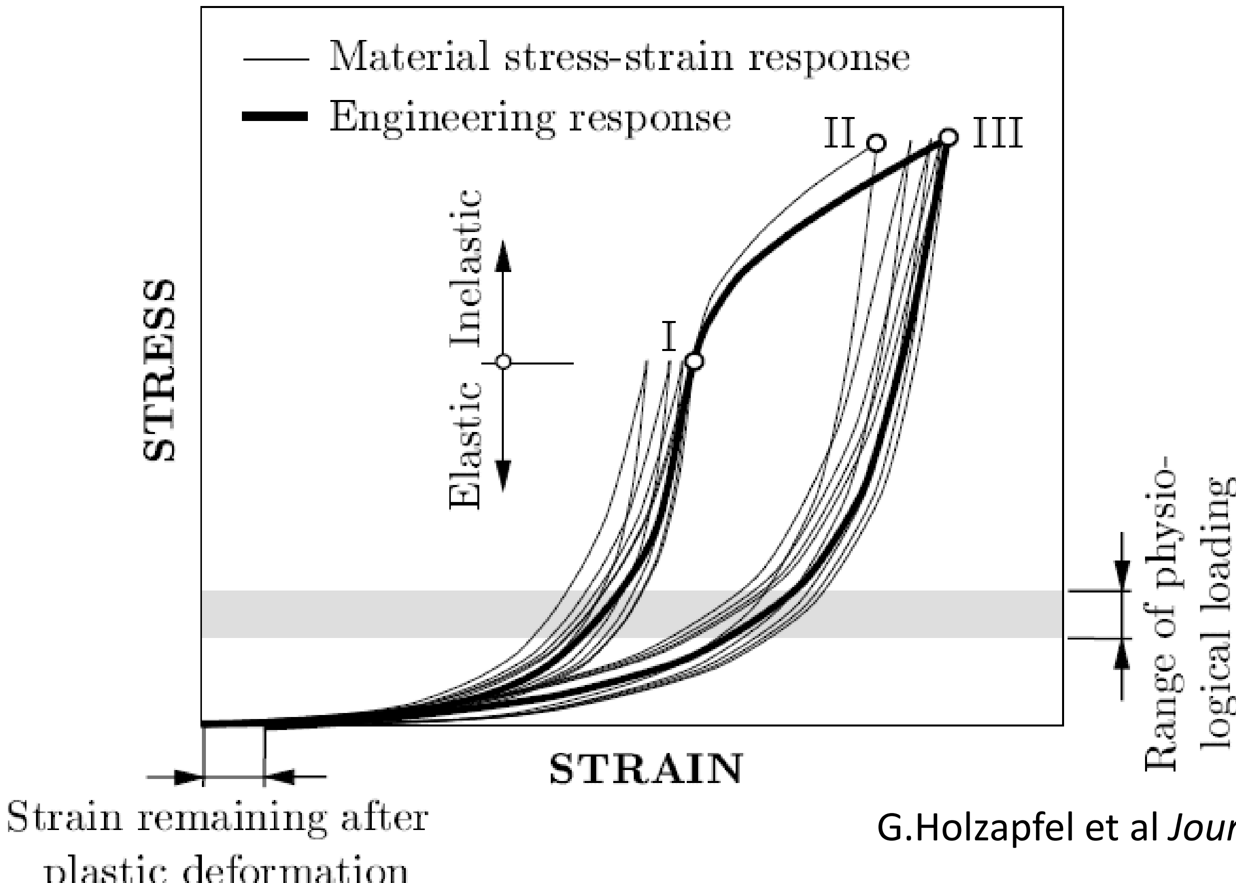

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Characteristics of soft living tissues

- Non-uniformity, anisotropy
- Material nonlinearity
- Quasi-incompressibility

Characteristics of soft living tissues

- Non-uniformity, anisotropy
- Material nonlinearity
- Quasi-incompressibility
- Undergoing large deformation

Approaches to living tissues simulation

- Mesh-based methods
  - Continuum Mechanics based methods (FEM, FVM, etc.)
  - Mass-Spring Models (MSMs)
- Meshless methods
  - Frame-based method elastic models

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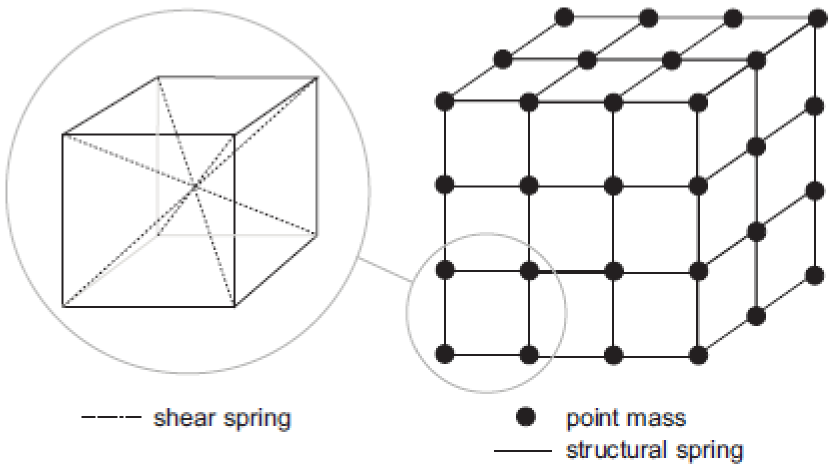
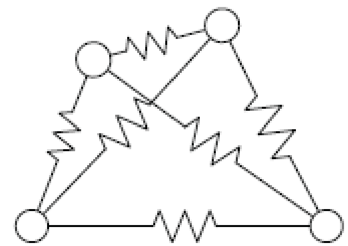
<u>References</u>:

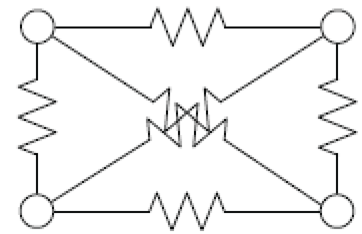
➢ A. Nealen et al *Computer Graphics Forum,* 2006

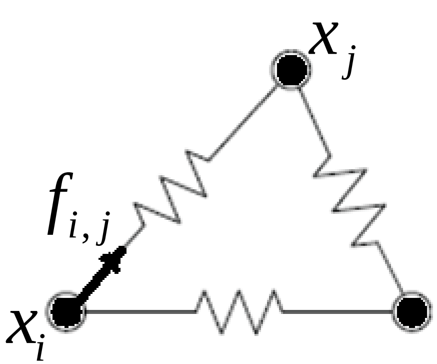
➢ B. Gilles et al *ACM Transactions on Graphics,* 2011

Mass-Spring Model (MSM)









$$m\ddot{x} = f(x)$$

Spring forces

$$f_{(i,j)} = k_{(i,j)} \left(\left\| x_j - x_i \right\| - l_0 \right) \frac{x_j - x_i}{\left\| x_j - x_i \right\|}$$

MSM: topology and spring stiffness

- Topology identification
- Spring stiffness estimation

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- Topology identification
  - different learning algorithms
  - tetrahedral mesh topology.
    - G. Bianchi et al *Proc. MICCAI '04*, 2004
- Spring stiffness estimation

MSM: topology and spring stiffness

- Topology identification
- Spring stiffness estimation
  - from Material Science
  - from discretized formulation of continuum
  - other optimization techniques

➢ G. San-Vicente et al *IEEE Transactions on Visualization and Computer Graphics*, 2012.

MSM: topology and spring stiffness

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  - **from discretized formulation of continuum**
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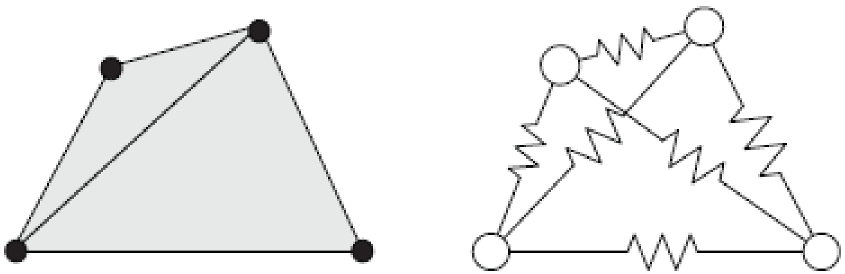
MSM: spring stiffness. Example.



l - edge length

E - Young's modulus

$\hat{l}_e$ - equivalent edge length

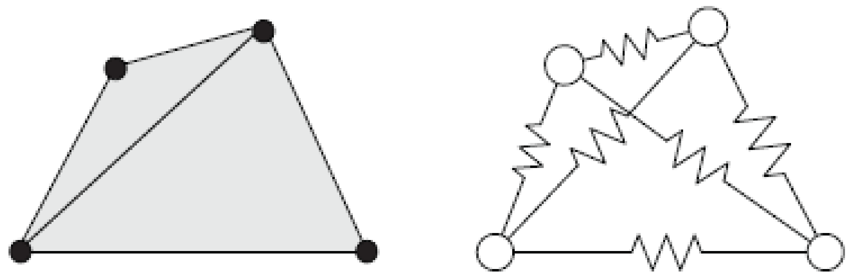
V_e - volume of element

For regular tetrahedral mesh $$k_{(i,j)} = \sum_e \frac{2\sqrt{2}}{25} lE$$

In case of irregular tetrahedral $$\hat{l}_e = \left(V_e \frac{12}{\sqrt{2}} \right)^{1/3}$$

- B. Lloyd et al *IEEE Transactions on Visualization and Computer Graphics*, 2007

MSM: spring stiffness. Example.



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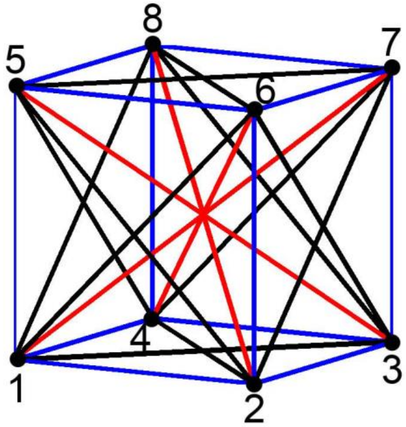
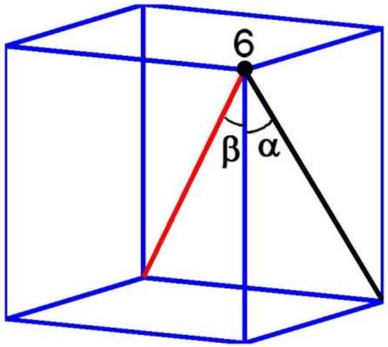
In case of irregular tetrahedral $$\hat{l}_e = \left(V_e \frac{12}{\sqrt{2}} \right)^{1/3}$$

! Limited to some specific values of Poisson's ratio; valid for small deformations

MSM: cubical mesh

- Topology cubical mesh





- Spring stiffness - fitting procedure

➢ G. San-Vicente, (2011) "Designing deformable models of soft tissue for virtual surgery planning and simulation using the Mass-Spring Model". PhD thesis.

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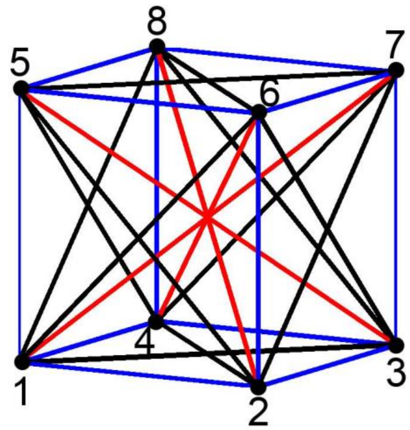

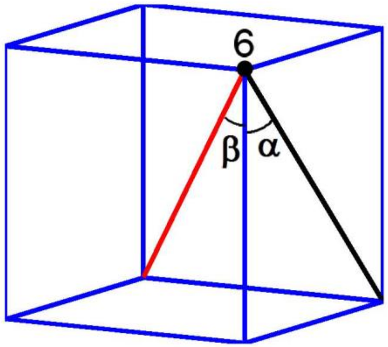

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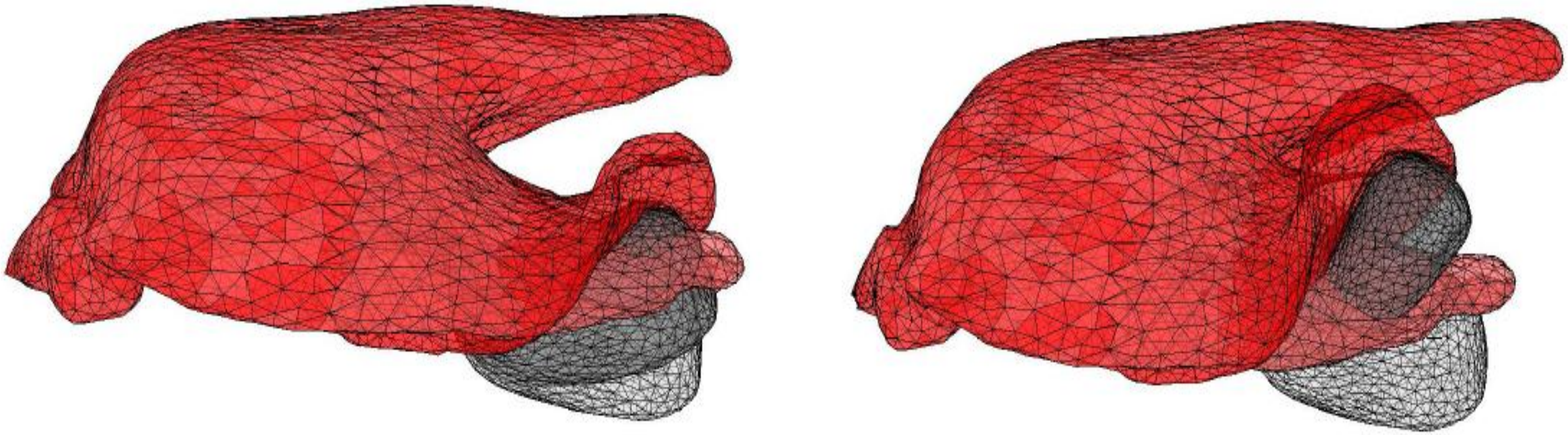
! Material nonlinearity; but regular cubical mesh, fitting procedure

MSM: examples

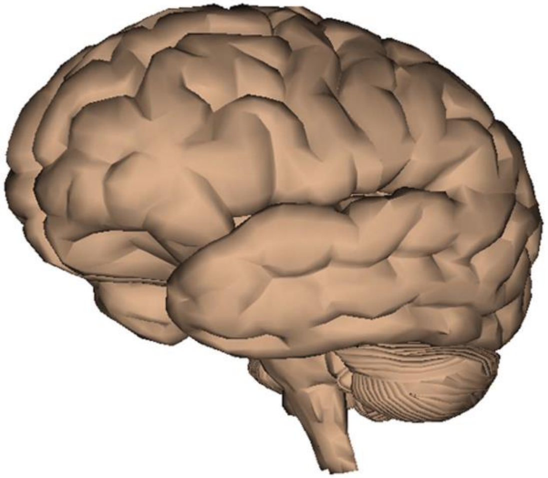
Porcine liver and gallbladder deformation:
Y. Duan et al *Lecture Notes in Computer Science*, 2013

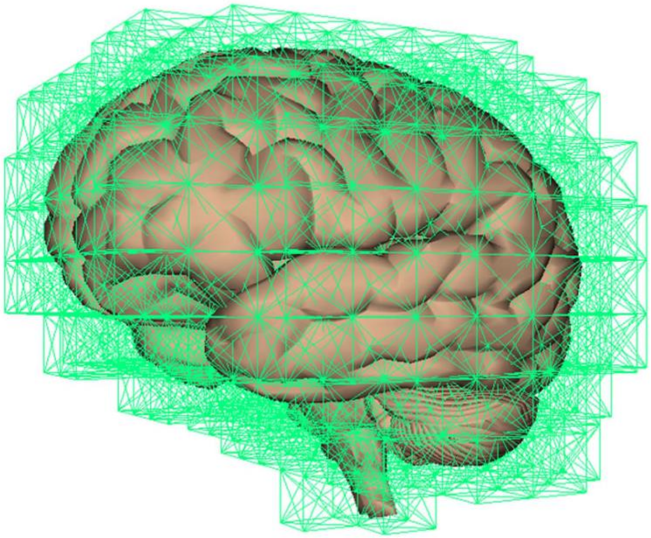


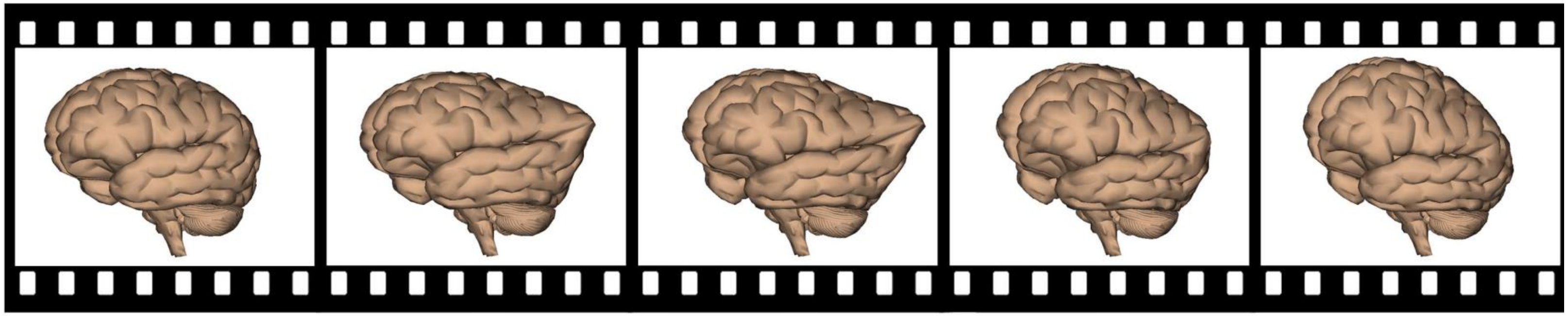
MSM: examples

Brain model deformation:

G. San-Vicente et al *IEEE Transactions on Visualization and Computer Graphics*, 2012







MSM: pros and cons

Pros:

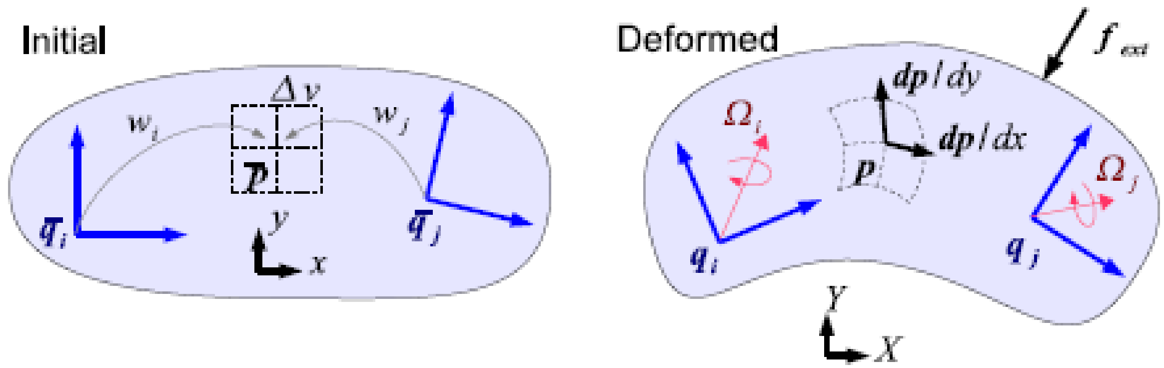
- Easy to construct
- Allowing real-time simulations
- Ability to deal with large deformations
- Computationally attractive

Cons:

- **Spring stiffness estimation**
- Topology identification
- Difficult to express constraints such as incompressibility and anisotropy

Frame-based elastic models

- Interpolating rigid transformations - skinning



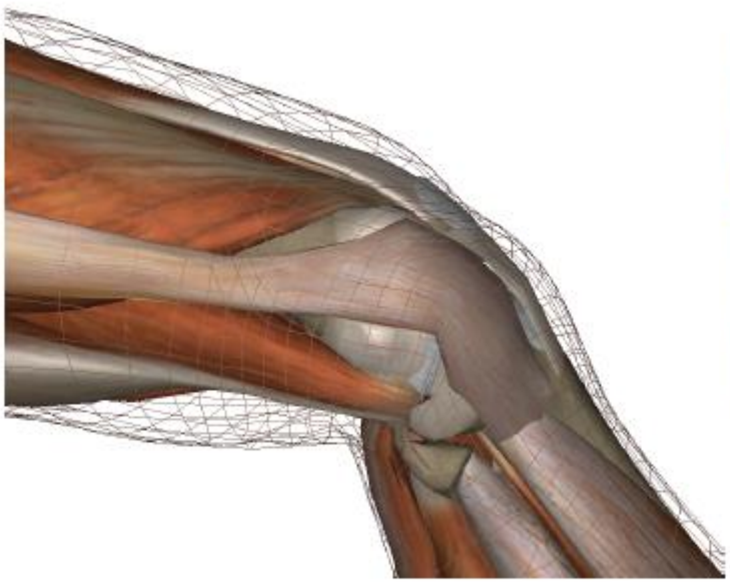
- Continuum mechanics + skinning

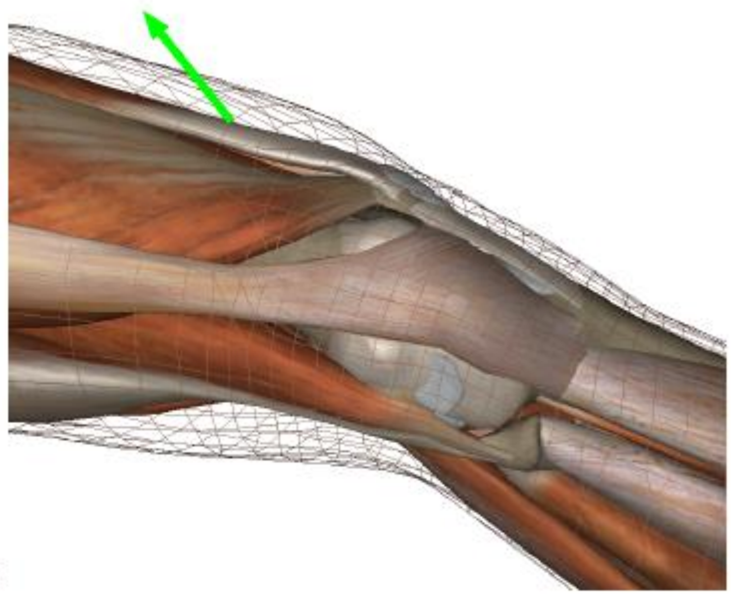
Position		Strain		Energy
$\mathbf{q}$	$\xrightarrow{\partial}$	$\mathbf{E}$	$\xrightarrow{\text{Material}}$	W
$\int \uparrow$				$\downarrow \nabla$
$\mathbf{\Omega}$	$\xleftarrow{\int}$	$\dot{\mathbf{\Omega}}$	$\xleftarrow{\text{Mass}}$	$\mathbf{\Gamma}$
Velocity		Acceleration		Force

F-B elastic models: examples

Interactive knee simulation using 10 frames. Pulling the quadriceps lifts the tibia.

F. Faure et al *ACM Transactions on Graphics*, 2011





F-B elastic models: pros and cons

Pros:

- Robust to large deformations
- Computationally attractive
- Material nonlinearity
- Small number of moving frames to model complex materials and geometry

Cons

- Weight functions choice
- Optimal placement of frames

Conclusions

- Real-time simulation -> alternative approaches
- Computationally attractive
- Robust to large deformations
- But approximate simulation
- Need to be further developed
- SOFA-framework

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- Computationally attractive
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Project : Abdominal cavity expansion during laparoscopic surgery (CO2-pneumoperitoneum).
(jointly with Vassilevski Yu., Simakov S., Danilov A., Mynbaev O.)