Anatomically-Based Human Body Deformations

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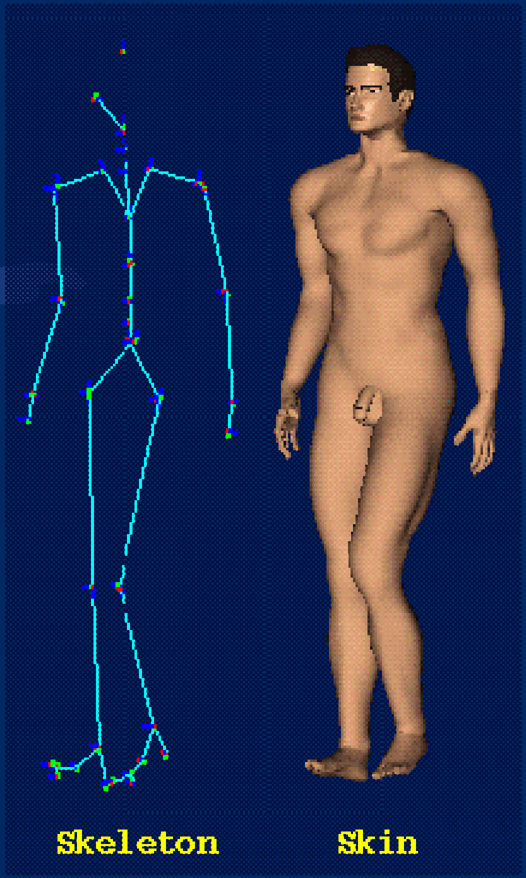
Statement of the Problem

Given a moving articulated structure (skeleton)

Automatically generate fast realistic deformations of the geometric envelope (skin)



State of the Art

1. Surface models
   - *Algorithmic [Thalmanns 88] [Komatsu 88]*
   - *Skinning [Lander 98]*
   - *Keyshapes interpolation [Lewis 00] [Sloan 01]*

2. Multi-layered models
   - *Geometric deformation [Chadwick 89] [Shen 96]*
   - *Lagrangian approaches [Hirota 01]*

Overview of our Approach

- Multi-layered model focusing on the body excluding its extremities
- We explicitly model and deform each major anatomical layer

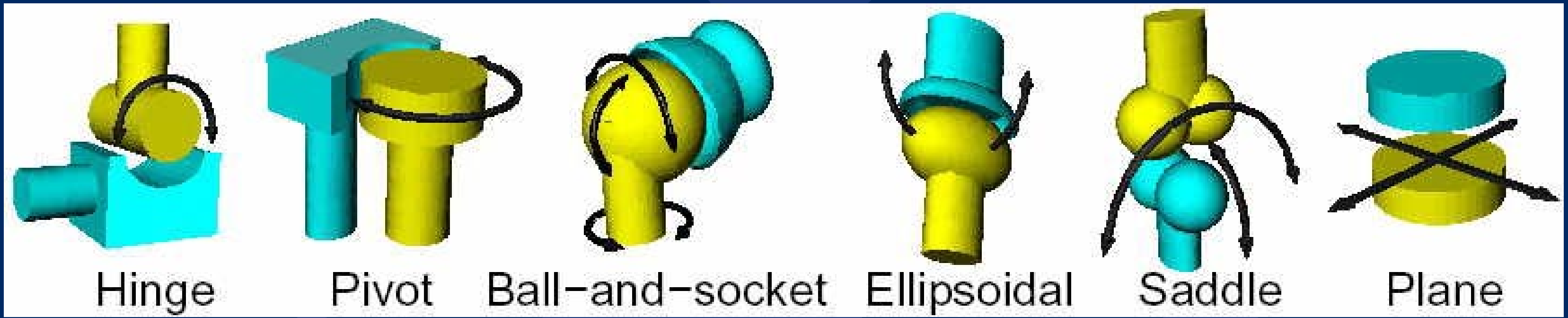
Why Model Anatomical Layers?

- That's how we are built
- New applications & links with other disciplines: biomechanics, medicine, anatomy
- Dynamics jiggles of the skin can be simulated accurately only if the inner material is here

Outline

1. Introduction
2. Joint Models
3. Muscle Layer
4. Fatty Tissues
5. Skin Layer
6. Conclusion

Joint Models



- Revolute (Hinge and Pivot)
- Knee (Hinge coupled with a Pivot)
- Swing (Ellipsoidal and Saddle)
- Ball-and-socket

Knee Joint

Successive rotations about two orthogonal axes:

$$R = R_z(\gamma)R_x(\alpha)$$

Twist limit is functionally dependent on the flexion

Ball-and-socket Joint

- Intuitive parameterization
- A single singularity (when swing vector has norm π)
- Easy specification, visualization and enforcement of limits

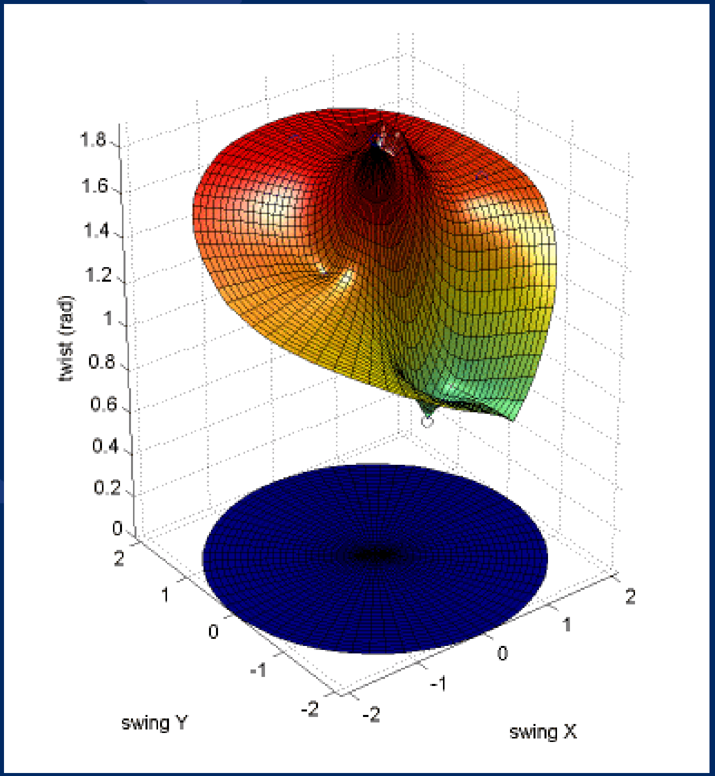
$$R = R^{twist} R^{swing}$$

$$R^{swing} = \begin{bmatrix} s_x & s_y & 0 \end{bmatrix}$$

$$R^{twist} = R_z(\tau)$$

Coupled Limits of Ball-and-socket

- Directional limits as a spherical polygon
- Twist restricted by 2 surfaces in the swing plane



Outline

1. Introduction
2. Joint Models
3. Muscle Layer
   - ~ *Anatomy & previous work*
   - ~ *Action lines*
   - ~ *Surface mesh*
   - ~ *Examples*
4. Fatty Tissues
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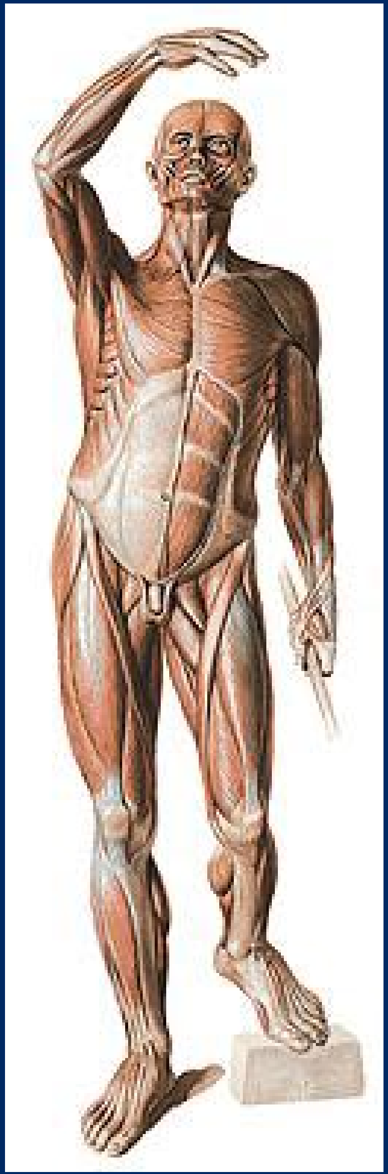
Myology

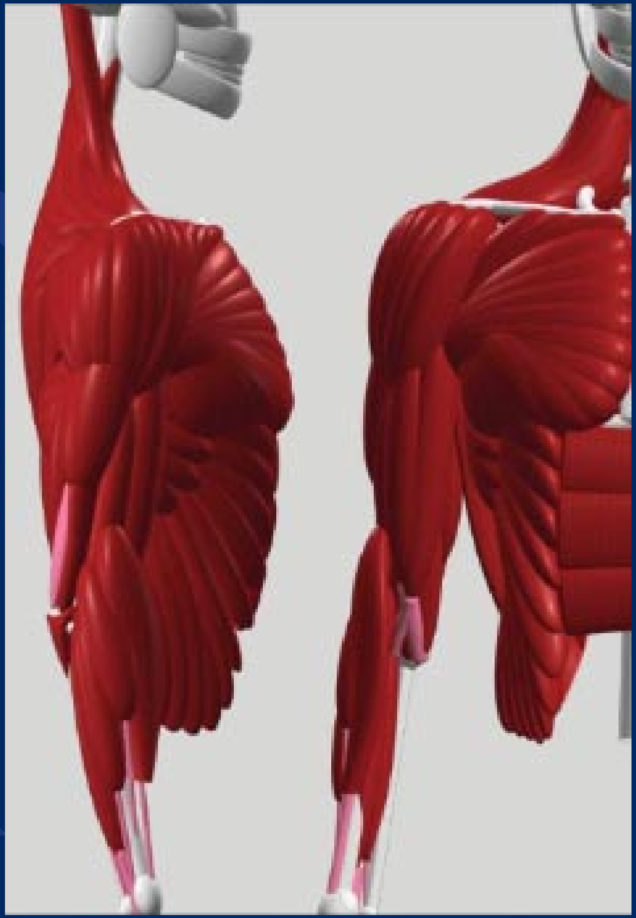


- A muscle consists of:
  - ~ *A contractile central part – the belly*
  - ~ *Stiff tendinous ends that connect the belly to the bones*
- Various shapes:
  - ~ *Fusiform muscles in the limbs*
  - ~ *Short muscles around joints*
  - ~ *Flattened muscles on torso*
  - ~ *Multiple bellies, tendons, etc.*

Previous Muscle Models (1)

Scheepers *et al.* (Siggraph'97)

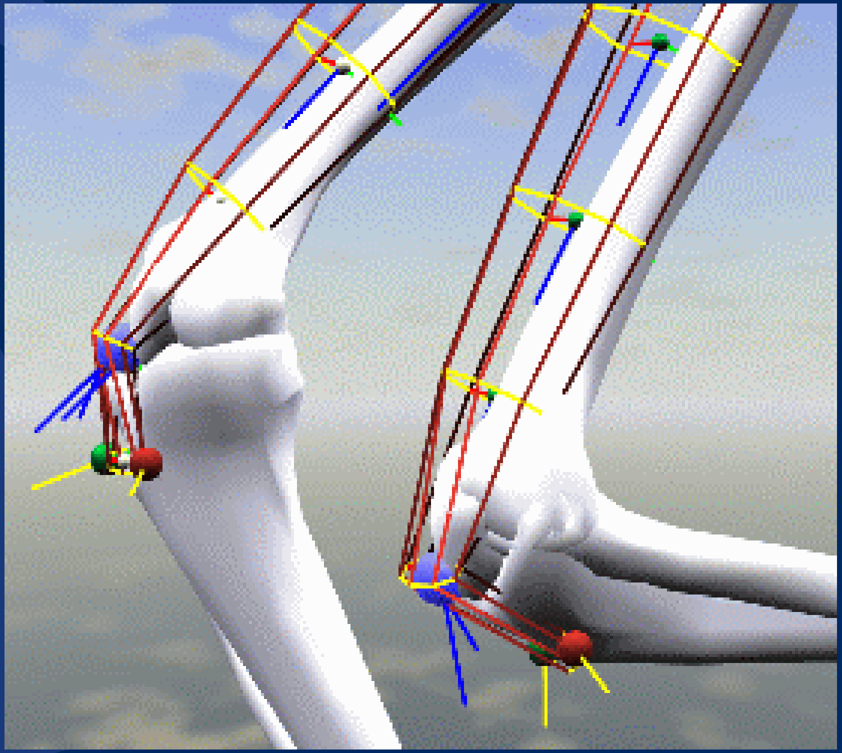
- ~ *Single ellipsoid for fusiform muscle*
- ~ *Multiple ellipsoids along two spline curves for multi-belly muscles*
- ~ *B-spline muscle model otherwise*



Previous Muscle Models (2)

Whilelms & Van Gelder (Siggraph'97)

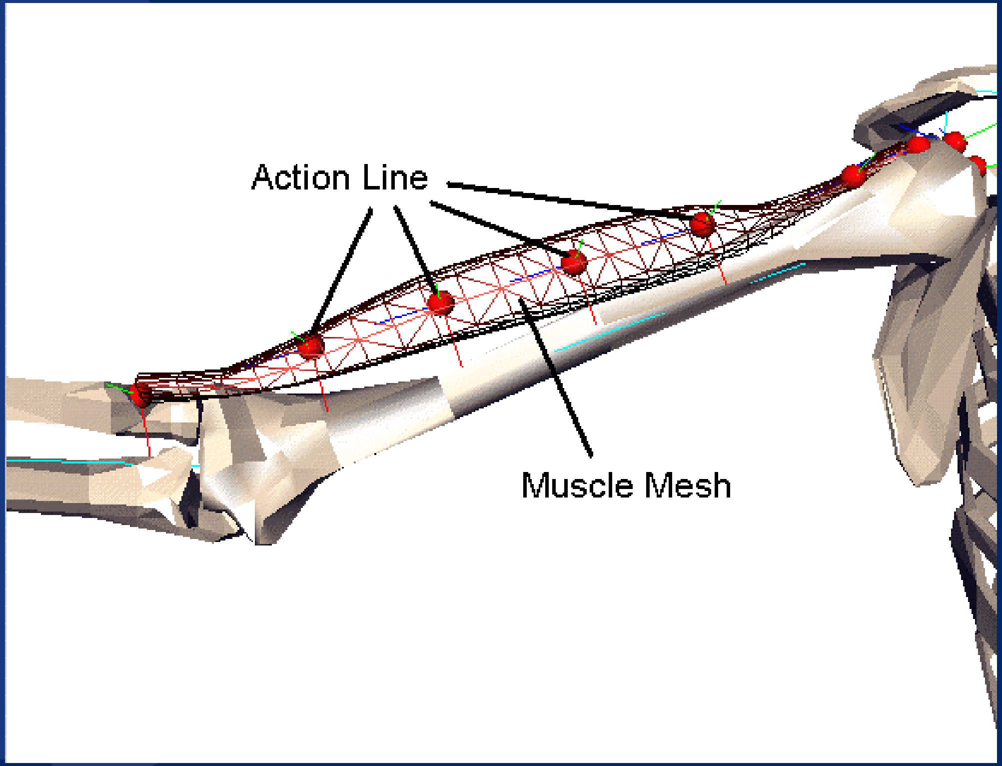
- *~ Generalized cylinder*
  - More accurate
  - Can wrap around joints



Two-layered Muscle Model

- Action Line(s)
  - ~ *Nodes connected by lines or cubic curves*
  - ~ *Each node has a local frame*

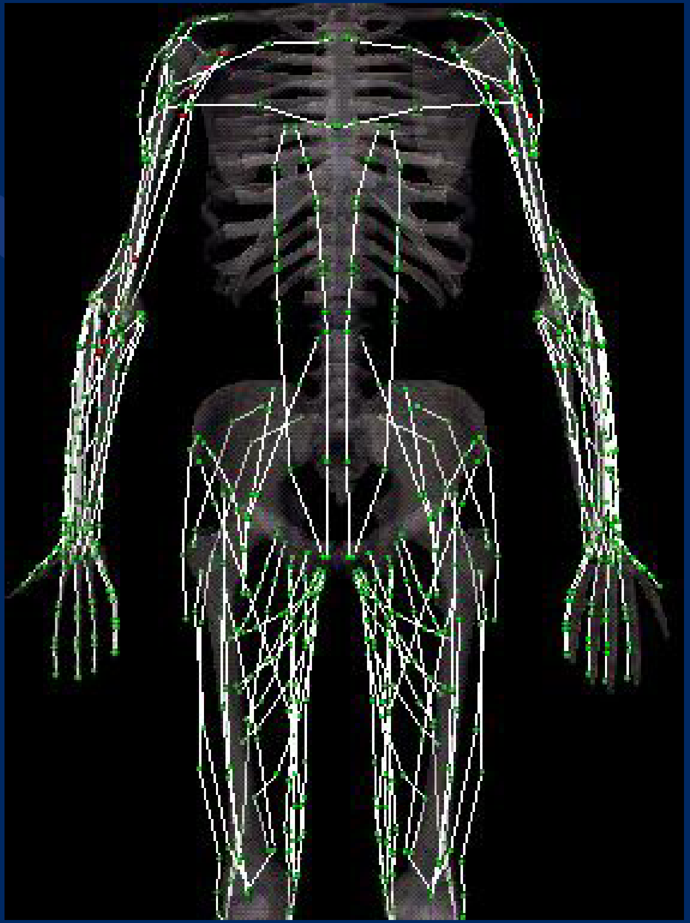
- Surface Mesh
  - ~ *A triangle mesh or any other vertex-based representation*



Action Lines

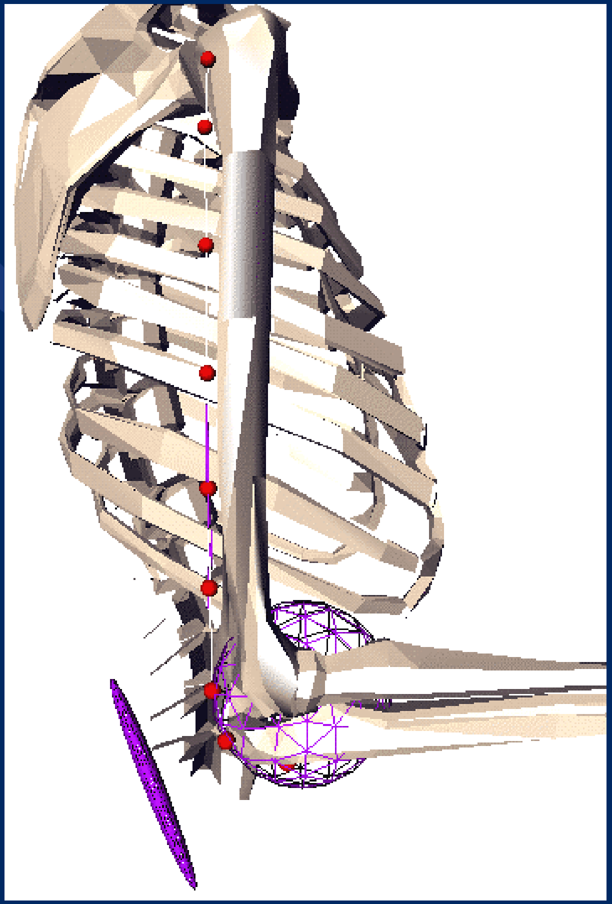
- High number of muscles:
  - ~ *Specification of an AL must be easy*
  - ~ *Reusable, duplicable*

- Two paradigms for controlling the action lines:
  - ~ *Relaxation of 1D mass-spring systems*
  - ~ *Purely geometric deformations*

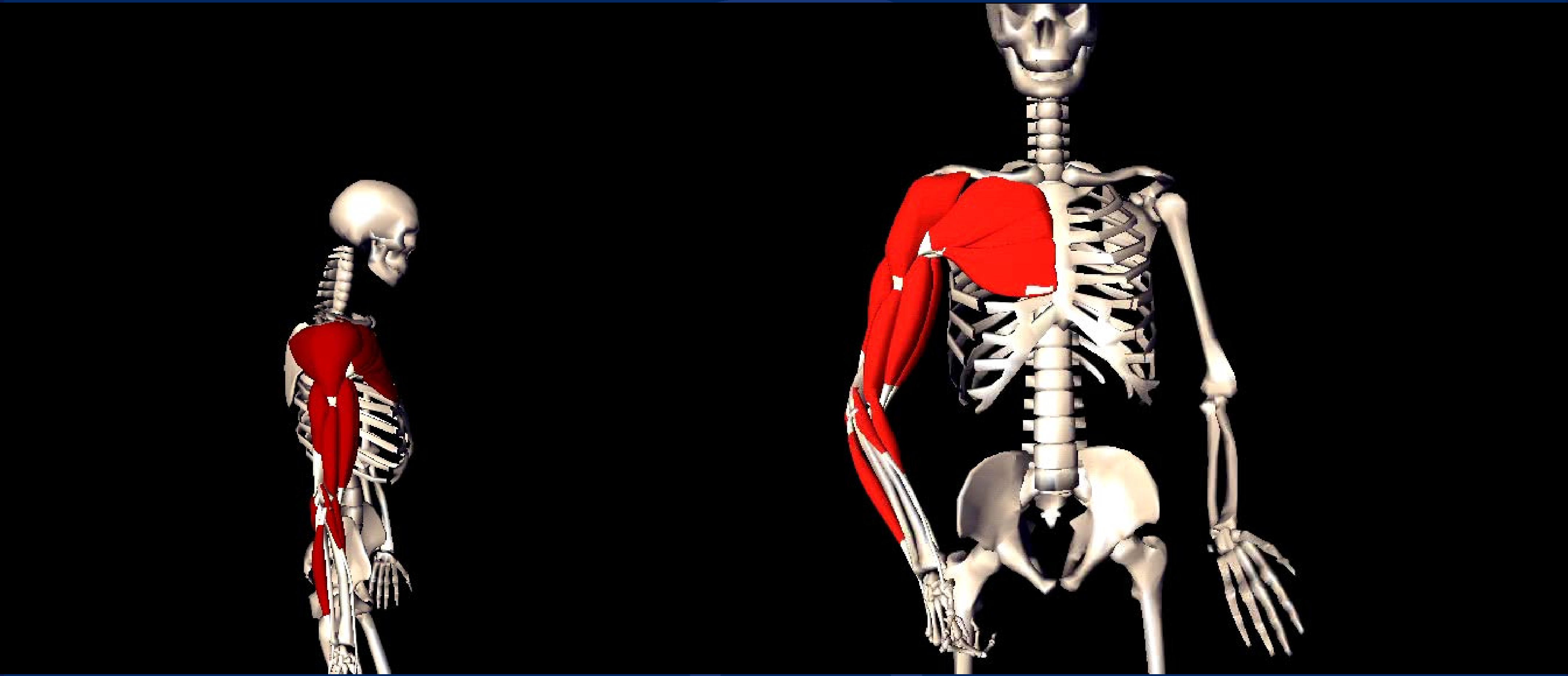


Elastic Polyline

- Springs are hyper elongated to avoid compression
- Action line is bent into the required shape, for any posture, using ellipsoidal force fields



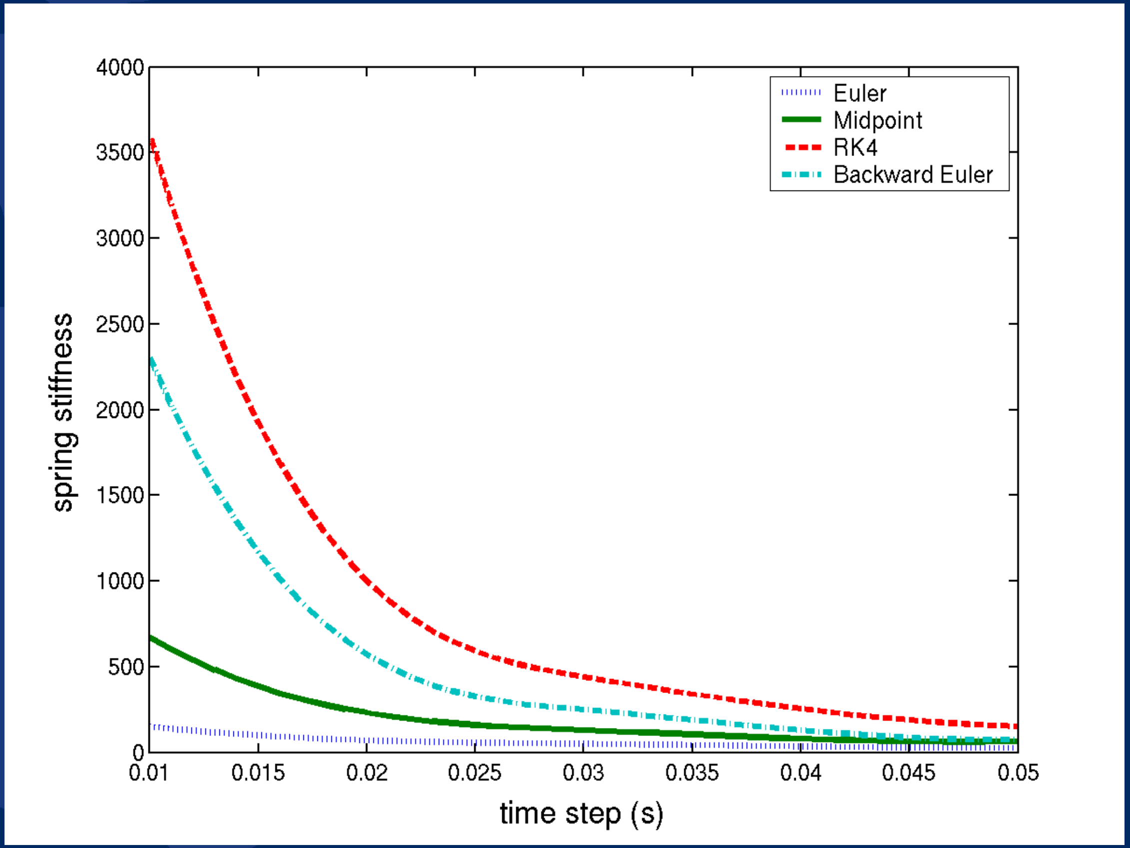
Examples: Captured Tennis Motions



Elastic Relaxation

- Integration scheme
  - ~ *Backward Euler*
  - ~ *Midpoint*
  - ~ *RK(4)*

- Adaptive time step
  - ~ *Adaptive RK(5) based on residual [Press 92]*
  - ~ *Adaptive RK(4) based on kinetic energy variation*



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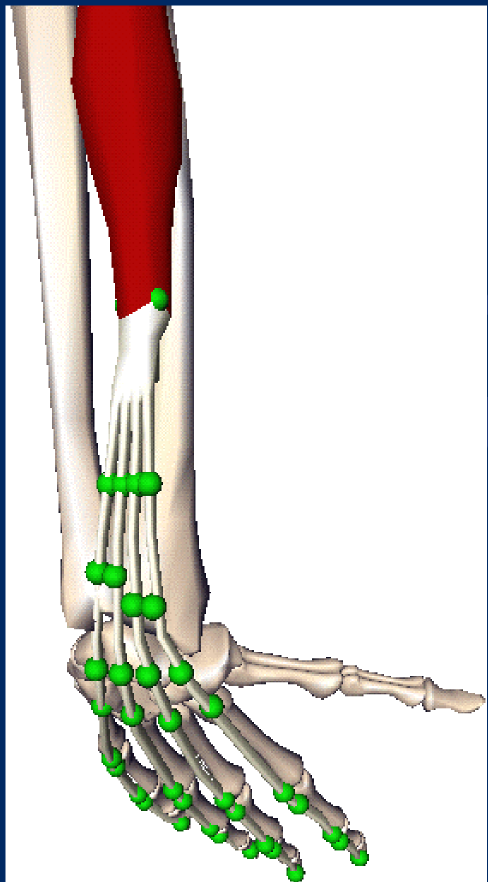
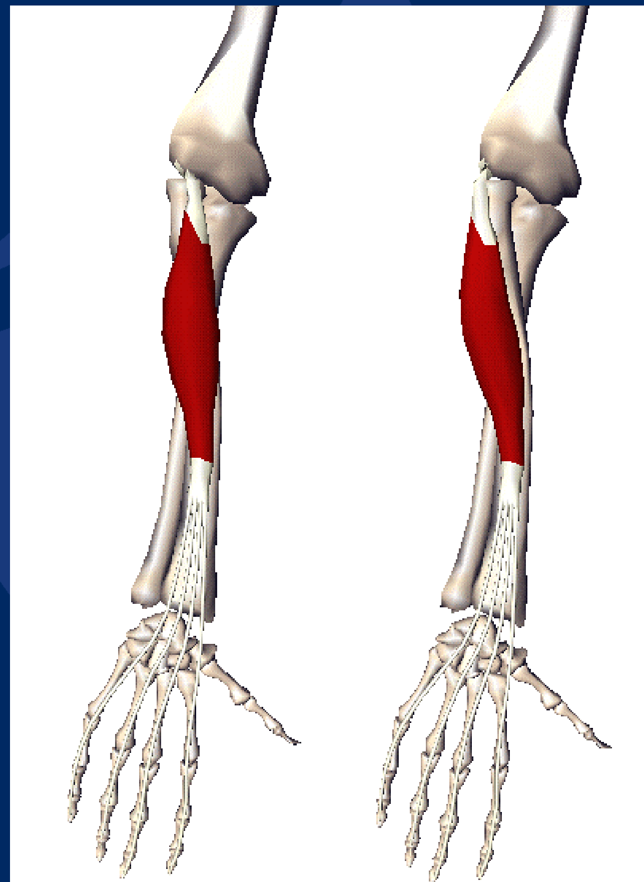
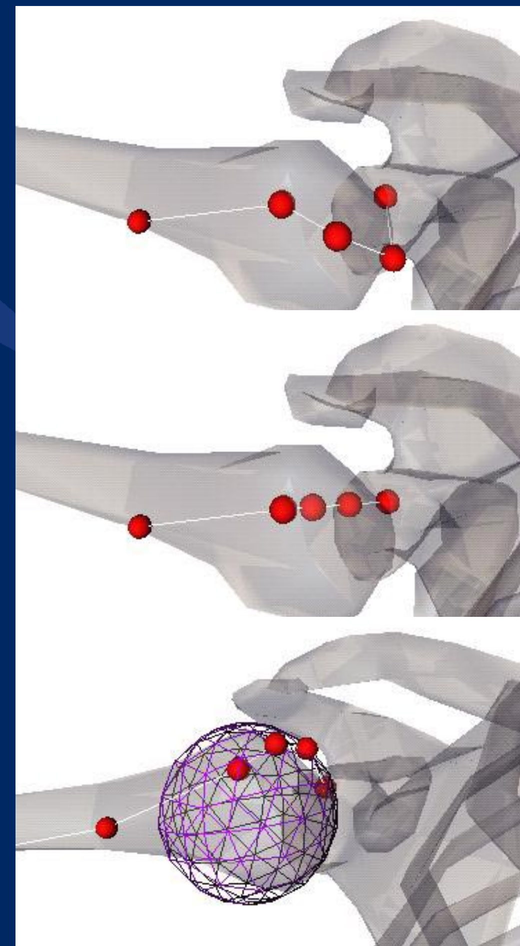
Geometric Deformation

- Nodes deform as a function of the underlying skeletal state
- Possible delay w.r.t. joint angles
- Some nodes are parameterized by the segment between two enclosing nodes
- Ellipsoidal deflective surfaces

Geometric Deformation (2)

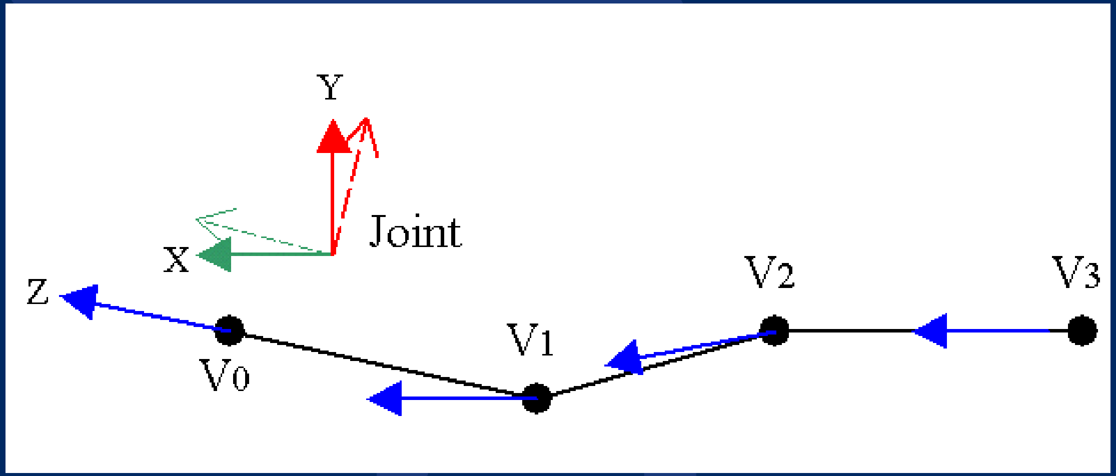




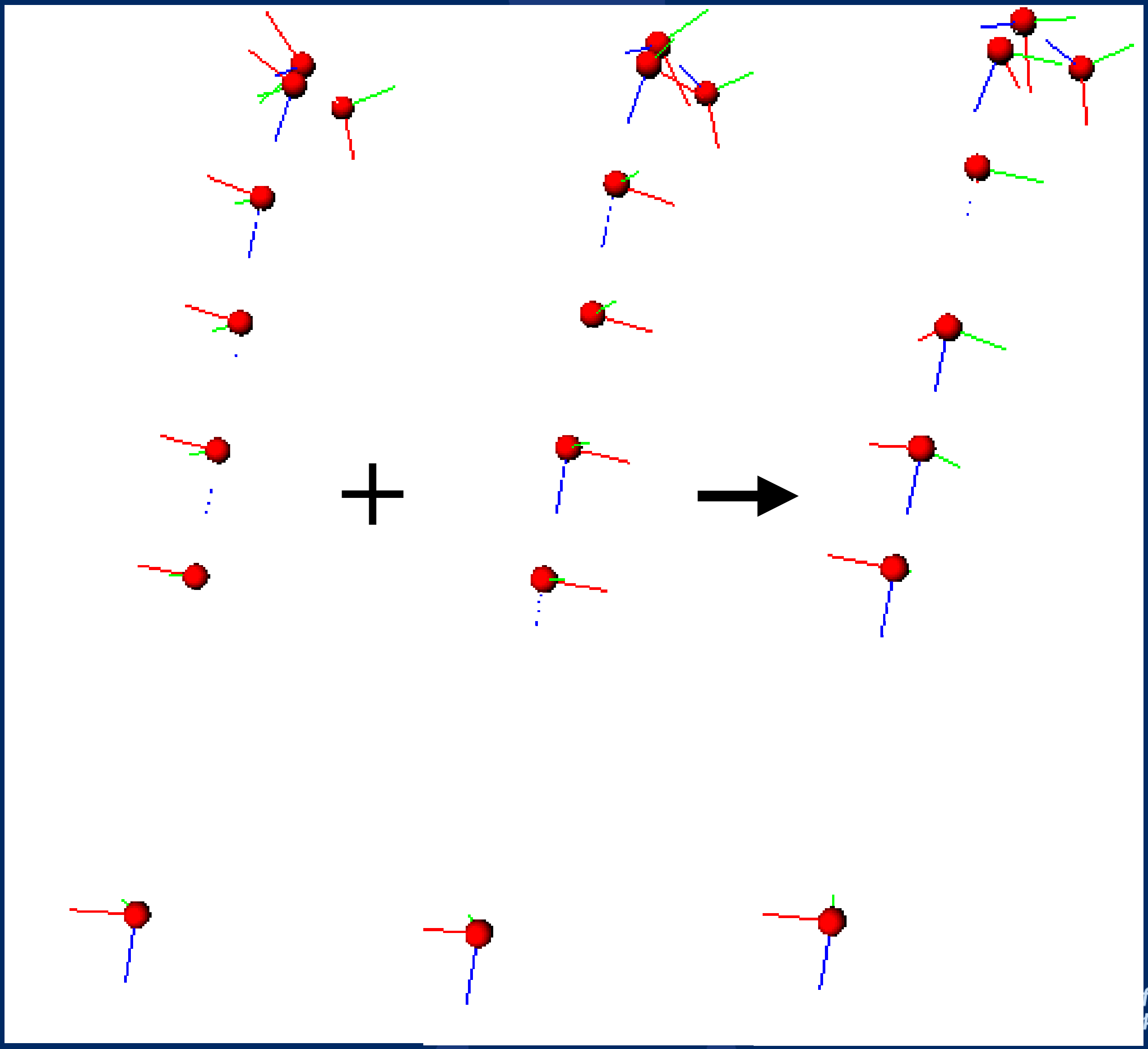


Local Frames

- Z-axis is set to normal of bisecting plane
- X- and Y-axes constructed for end nodes first



Frame Interpolation



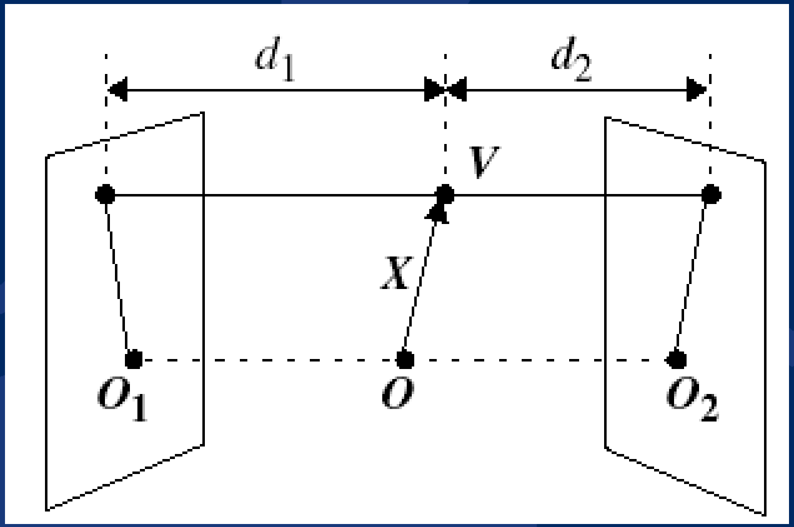
Frame Interpolation (2)

Function that returns an orientation (quaternion) with a fixed direction v:

$$f(\theta, v) = (\cos(\theta/2), v\sin(\theta/2)) \times b(v)$$

1. *Upward (resp. downward) propagation of orientations*
2. *Extract θ_u and θ_d for each node*
3. *Frame-to-frame coherence (2π modulo)*
4. *Linearly interpolate θ_u and θ_d (distance or user-defined ratio)*

Surface Mesh



Each vertex parameterized by an action line [Sun 99]:

- ~ *Parameterization* (*s,t*) = (*Action Line segment, ratio in* [0..1])
- ~ *Local coords computed w.r.t. an ultra local frame*

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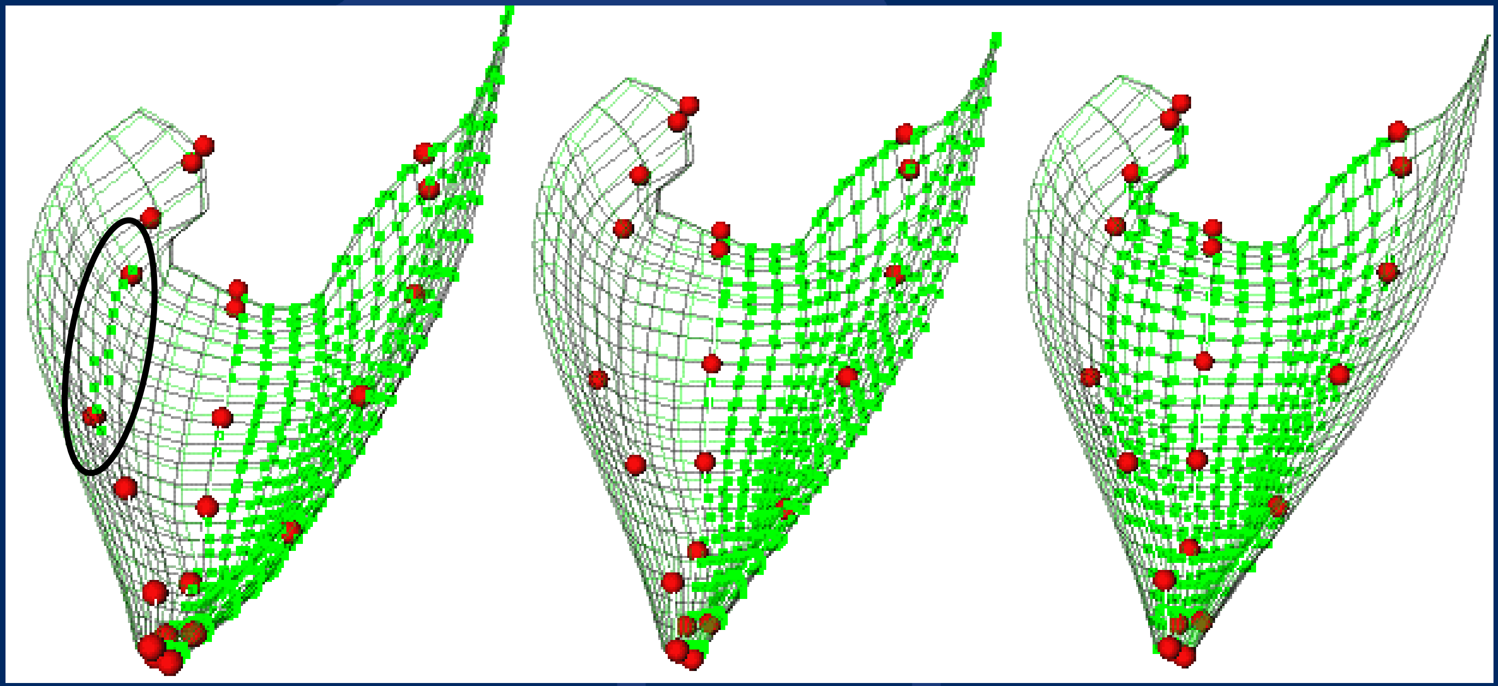
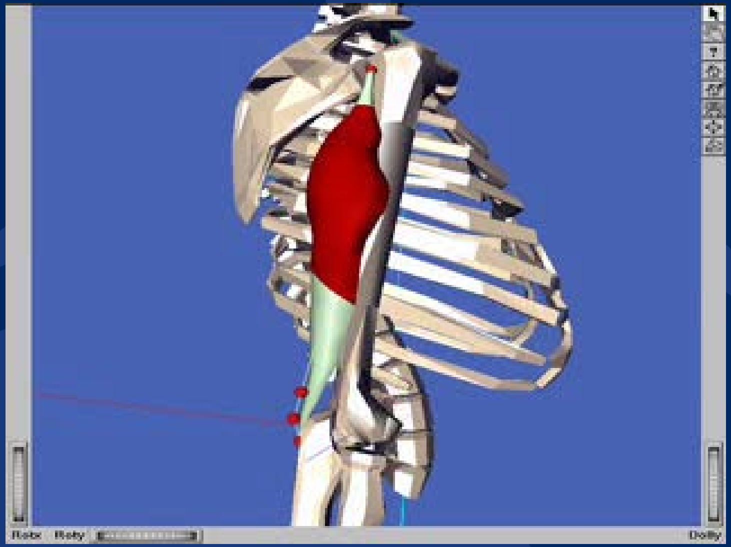
Vertex Mapping

- Incremental algorithm to determine the zone of influence for each AL
- Automatic identification of border vertices



Isotonic Contraction



Automatic mesh scaling as a response to the change in length of the AL

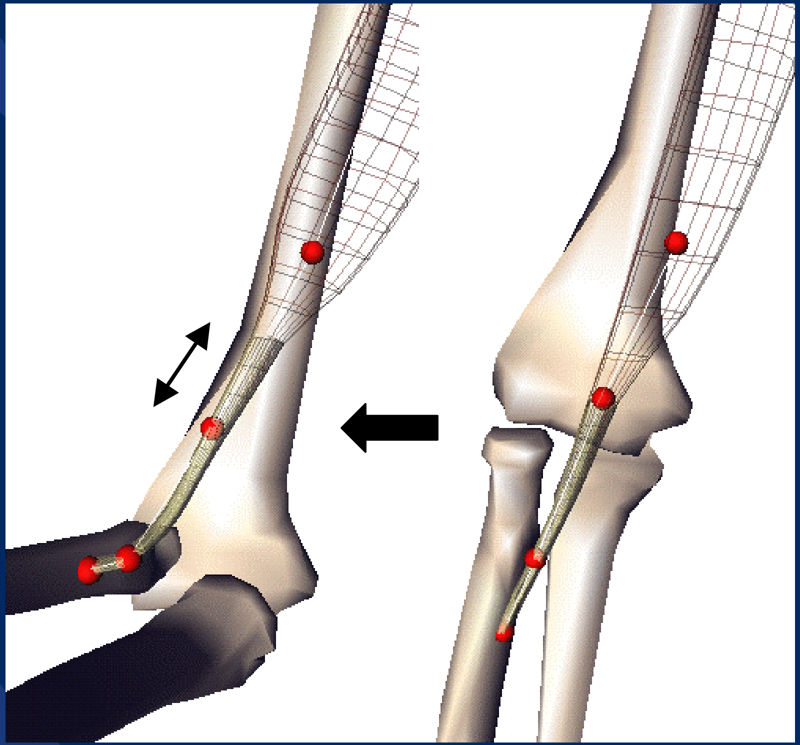
Isotonic Contraction (2)

- Cubic interpolation of the elongation values of AL segments
- Individual scaling value computed using vertex parameterization (*s = segment*, *t = ratio*):

$$s = \sqrt{e(s,t)}$$

Elongation of AL Segments

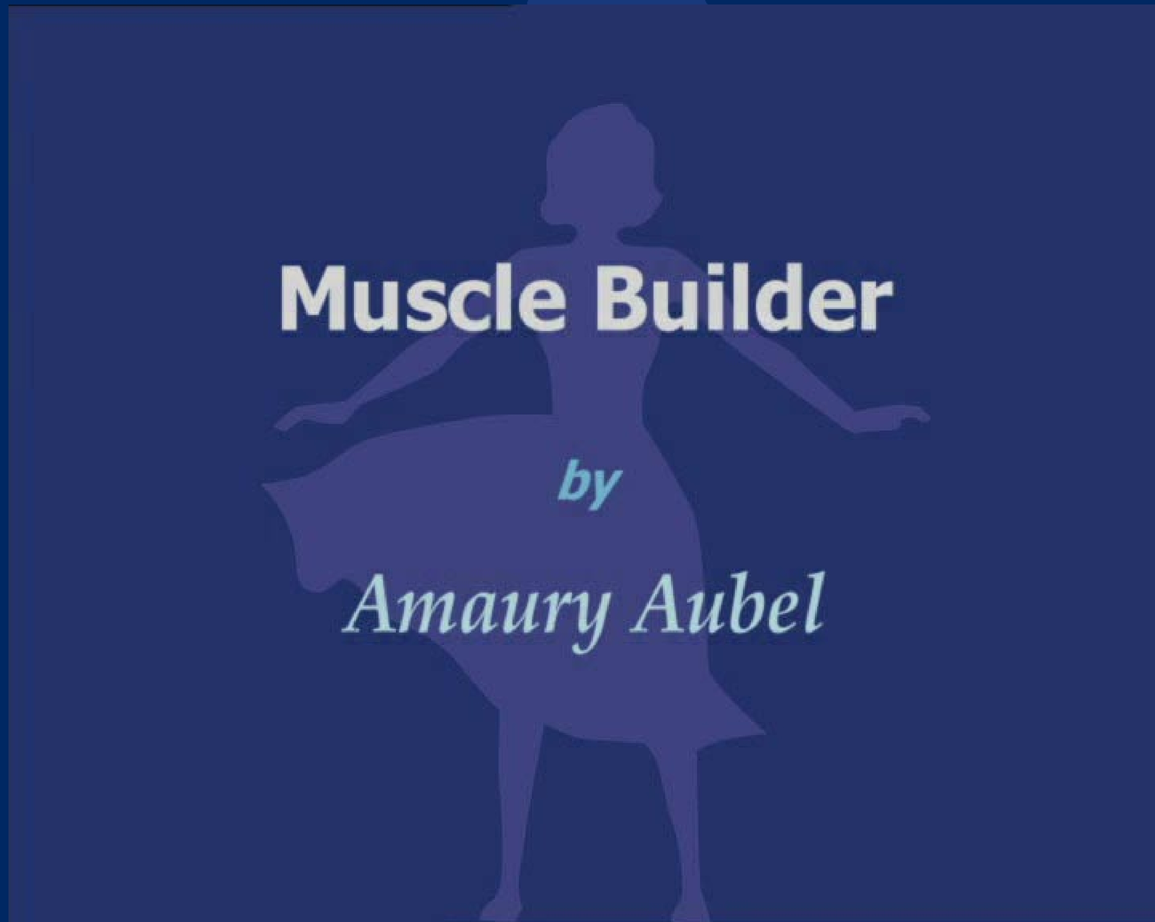
- Elastic Polyline
  - ~ *Spring stiffness reflects material type*
- Geometric Deformation
  - ~ *Dynamic reparameterization of nodes*



Isometric Contraction

Local frames provide a convenient way to simulate isometric contractions

Example



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Fat and Skin

- Fatty tissues play an important role (often underestimated in CG) on the surface form
- The skin and fat layers appear to move elastically as a whole over the muscles

Mechanical Model

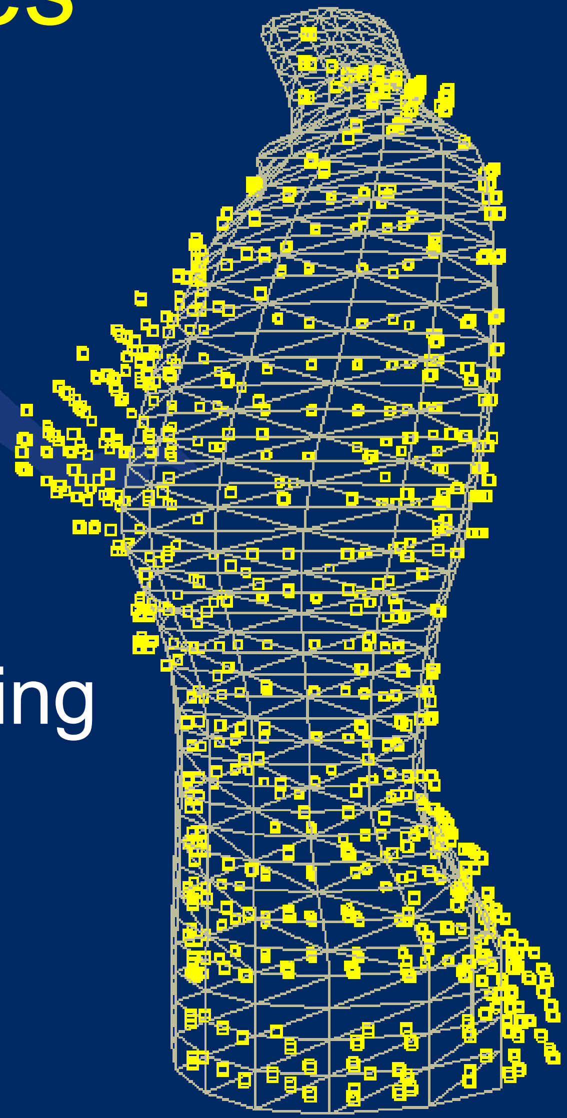
Lamé equation for a homogeneous isotropic linearly-elastic material:

$$\rho a = \mu \Delta d + (\mu + \lambda) \nabla \left(div(d) \right) + f_{ext}$$

Finite Differences

- Lamé equation discretized over time and space with finite differences [Debunne 99]

- Skin mesh anchored to voxels using local frames



Breast Simulation

~1000 voxels

time step = 0.001 s

1 s (animation) ~ 5 mn (computation)

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Previous Work

- Elastic surface
  - ~ *Turner & Thalmann CGI'93*
  - ~ *Whilhelms & Van Gelder Siggraph'97*
- Skinning + Ray-Casting
  - ~ *Shen & Thalmann CGI'96*
  - ~ *Leclercq et al. CAS'01*

Skin Deformation Overview

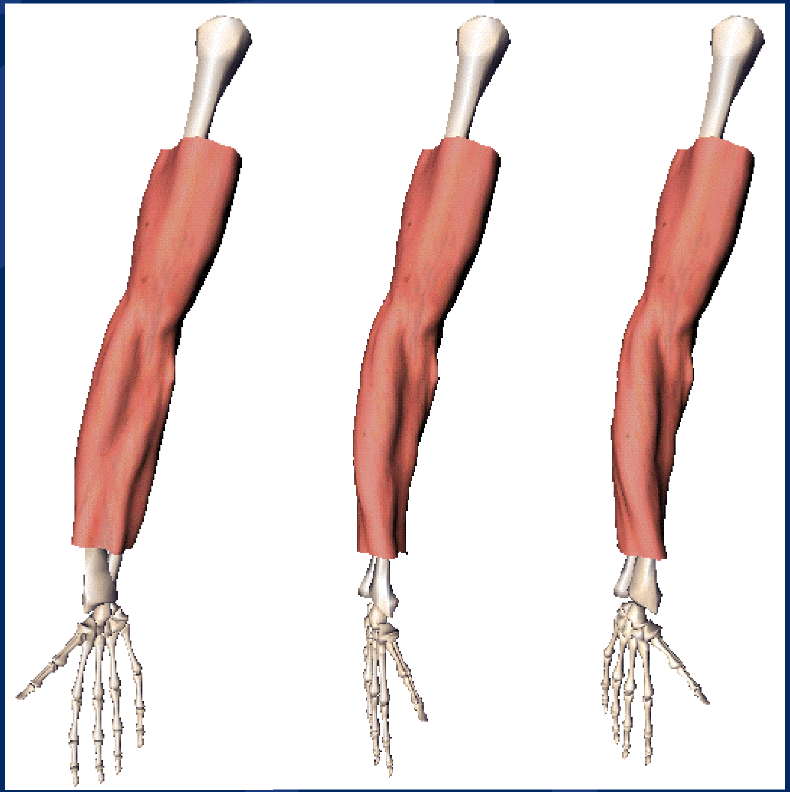
For each animation frame

1. *A technique related to skinning is applied to position the skin vertices w.r.t. the skeleton*

2. *A ray is cast from each vertex to the underlying components so as to maintain a fixed initial distance*

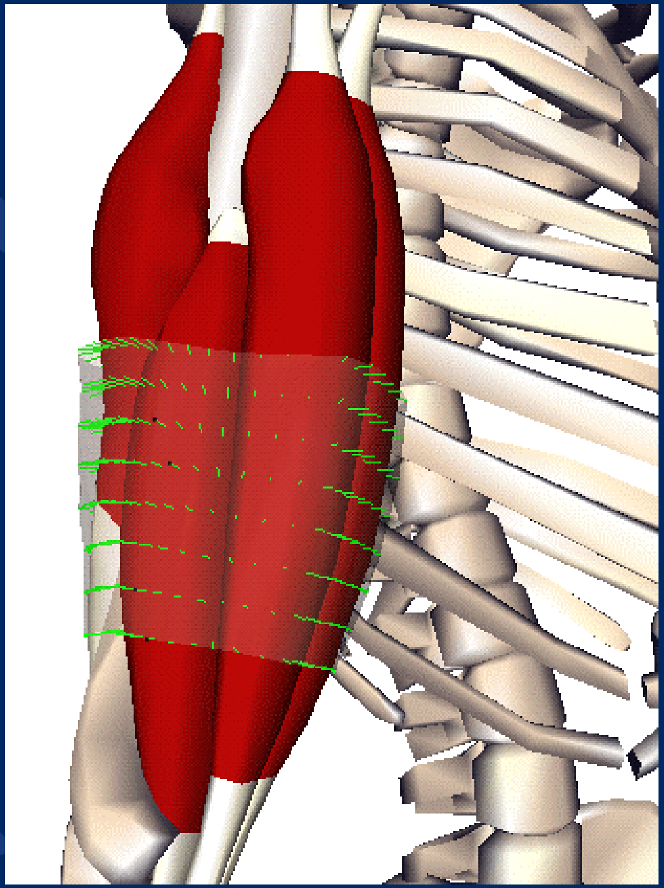
Vertex Positioning

- Construction of a local frame for each vertex
- Orientation by linear interpolation of quaternions

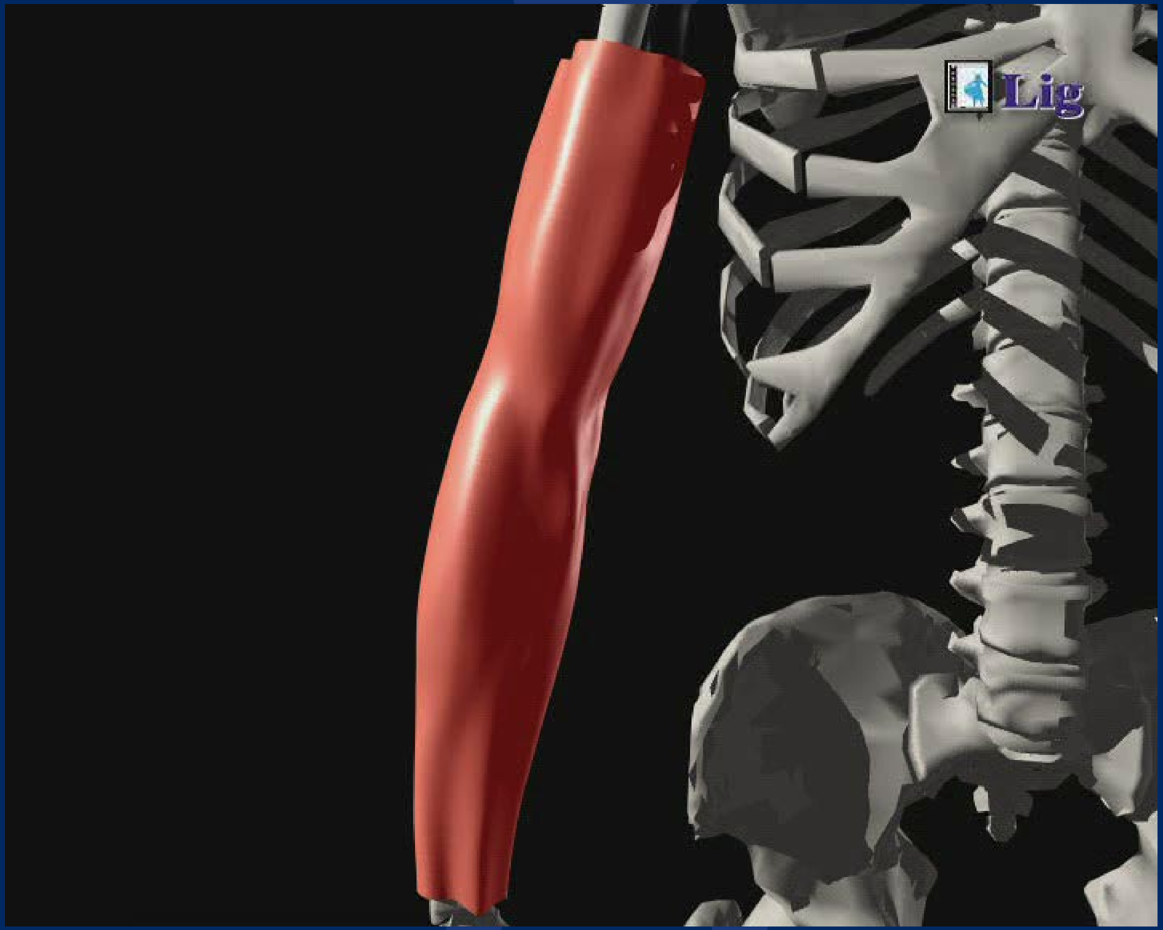


Ray-Casting

- Ray cast along vertex normal
- Height field
- Shrinkwrap to simulate various levels of contraction



Example



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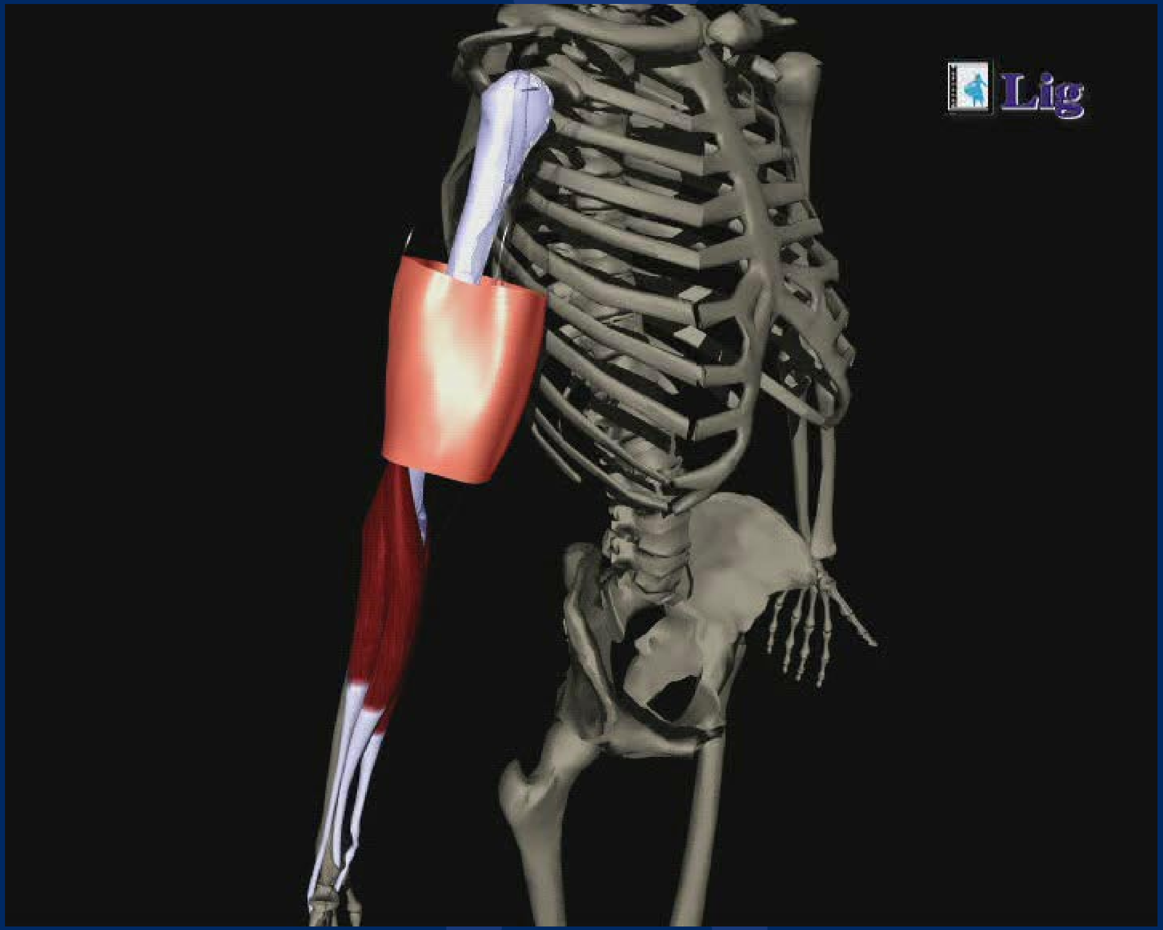
Filtering the Height Field

- Median filter in the spatial domain to discard outliers
- Median filter in the temporal domain to avoid hysteresis
- Smoothing filter (subdivision, Gaussian filter…) before rendering

Example



Conclusion

- Joint models with coupled limits
- Simple, fast, general muscle model that unifies approaches in computer graphics and biomechanics
- Skin deformed by a geometric algorithm that takes muscle movement into account

Questions?