Modelling of Joints and Soft Tissues Workshop 2003
Verbier, Switzerland

Anatomy-based Kinematical Joint Model with Connective Soft Tissues

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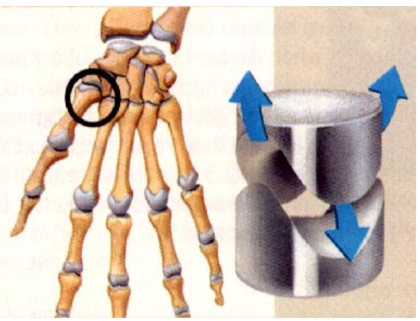
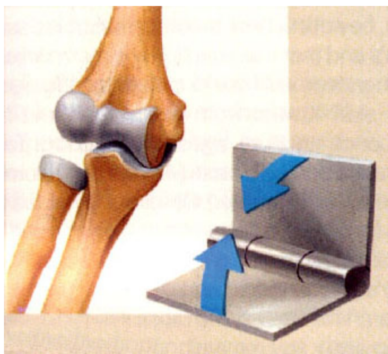
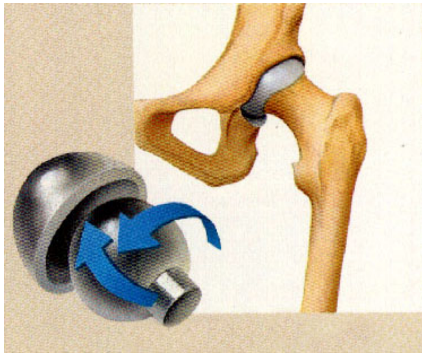
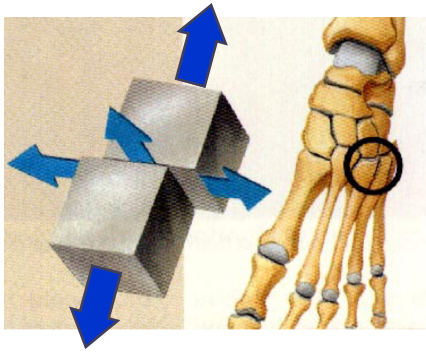
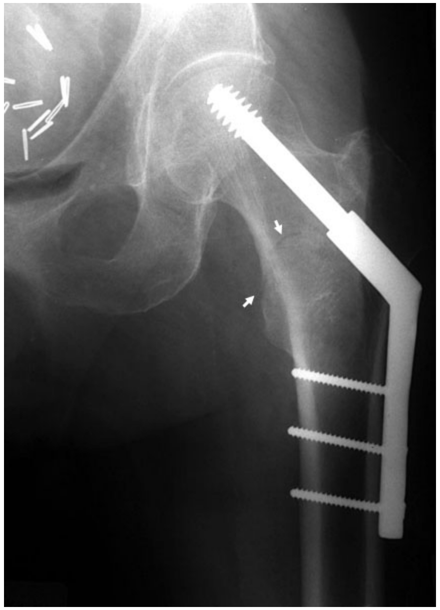
Outline

1. The problem of joint modeling
2. Context of this work (medical applications)
3. Our approach
    1. Kinematics (motion)
    2. Soft tissues (deformation)
4. Results & evaluation
5. Expected medical outcome

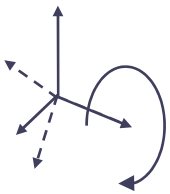
Problem

- Modeling joints
  - Where the motion takes place
  - Clinical interest

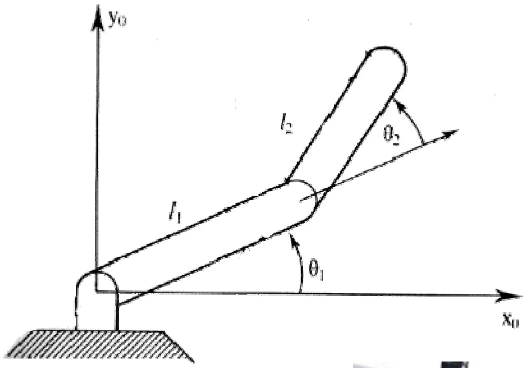
Usual approach

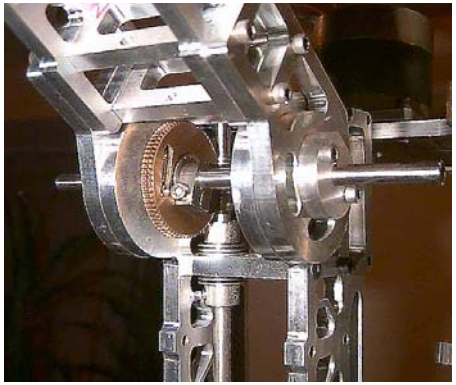
- Simplified – Idealized joint

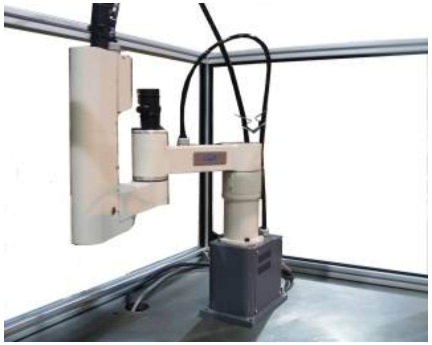


$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_x \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

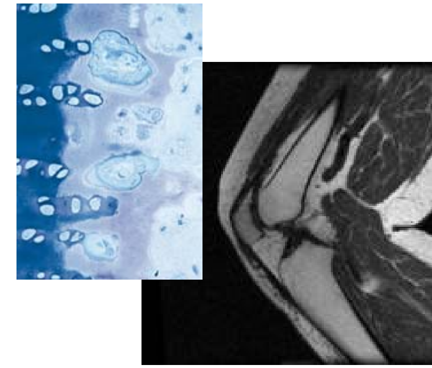
- From robotics works



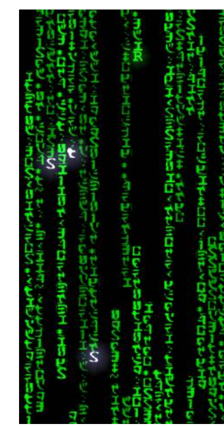




Ideal Approach



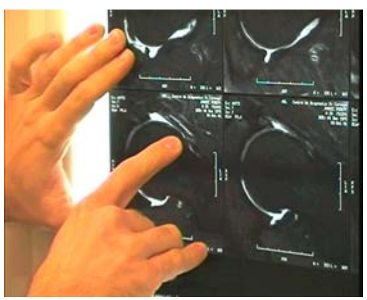
- Model everything
  - From cells to tissues to organs
- Complex
  - We cannot run the “Matrix” in nowadays’ machines

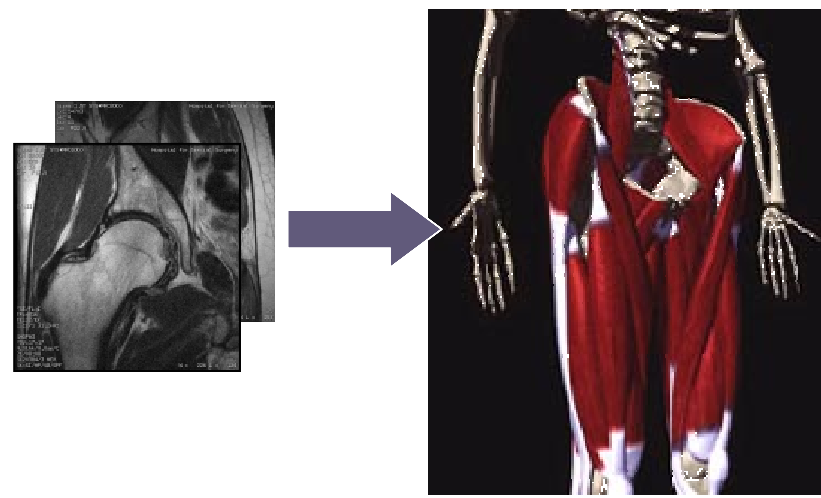


- Must simplify
  - Application driven simplification

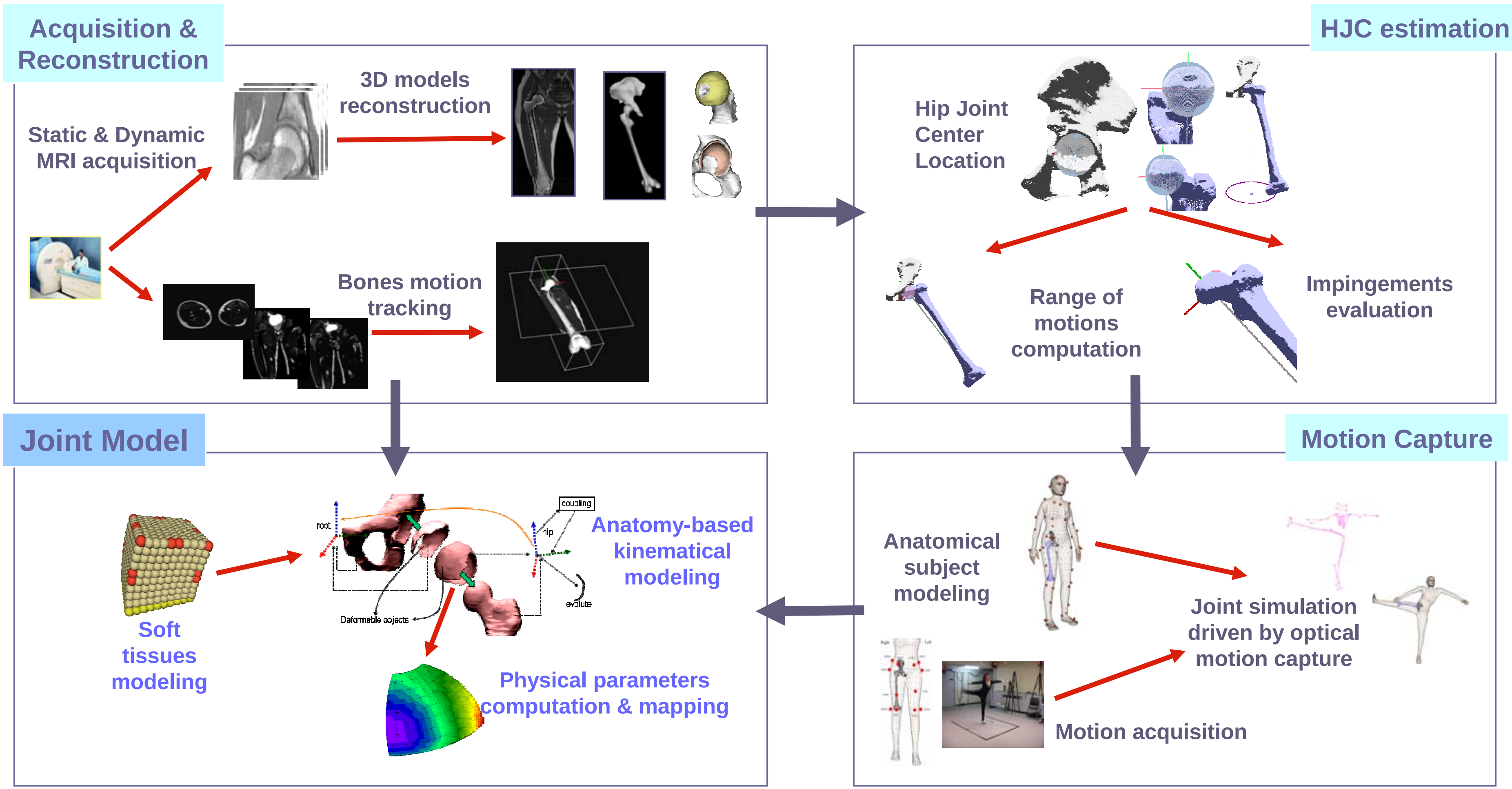
Context and overview

- CO-ME project
  - **<u>Co</u>**mputer Aided and Image Guided **<u>Me</u>**dical Interventions
  - Project #10:
    - A generalized approach towards individualized functional modeling of human articulations





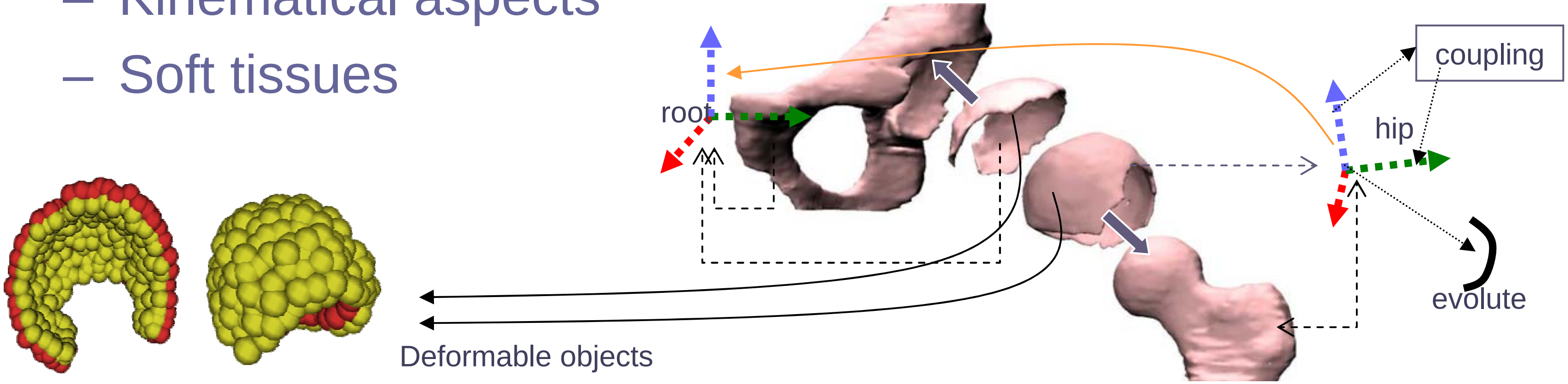
Context and overview



Our approach

- Compromise (simplify according to the application)

- Medical applications: problem split in 2
  - Kinematical aspects
  - Soft tissues



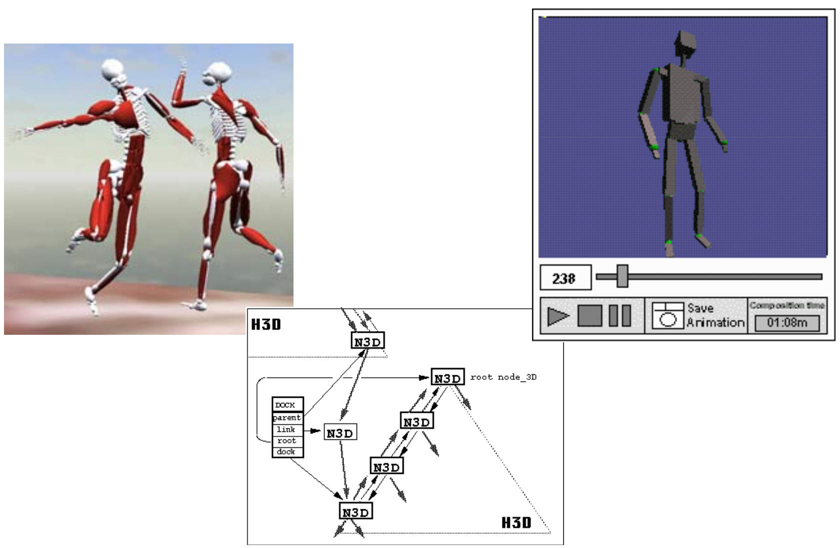
Kinematical aspects

Joint motion model

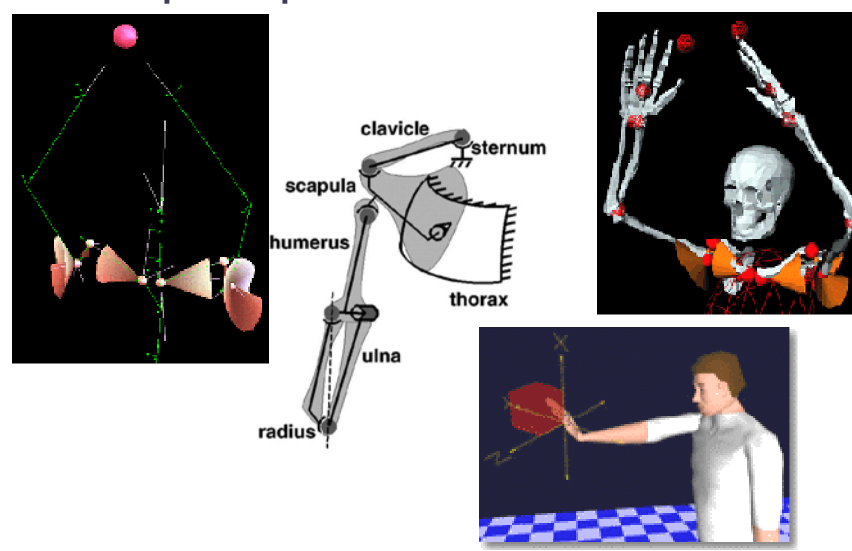
Related work

Two classes of works

General mechanisms to keep body structure



Simulation of specific complex parts

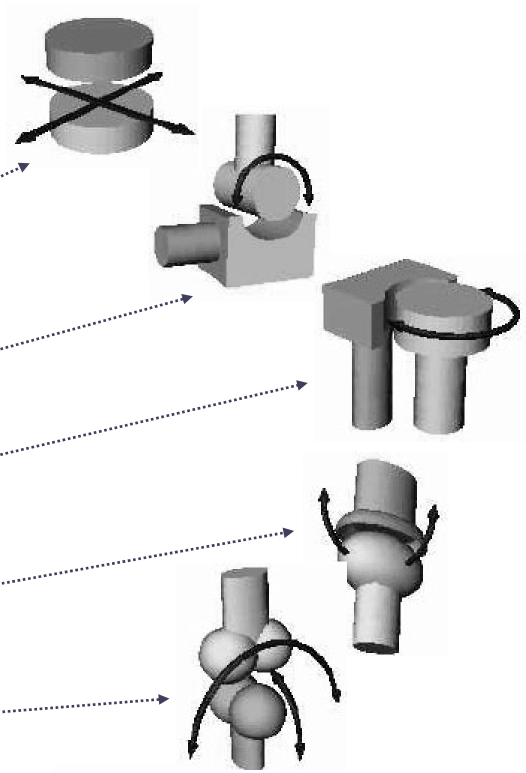


Anatomy-based kinematical model

- Take anatomy into consideration
- Allow producing and constraining any type of motion
  - + normalized parameterization
  - + range of motion control
  - + axes coupling
  - + axes displacements
- Can be setup from captured data
- Simple motion specification (unified parameter)

Types of joints - anatomy

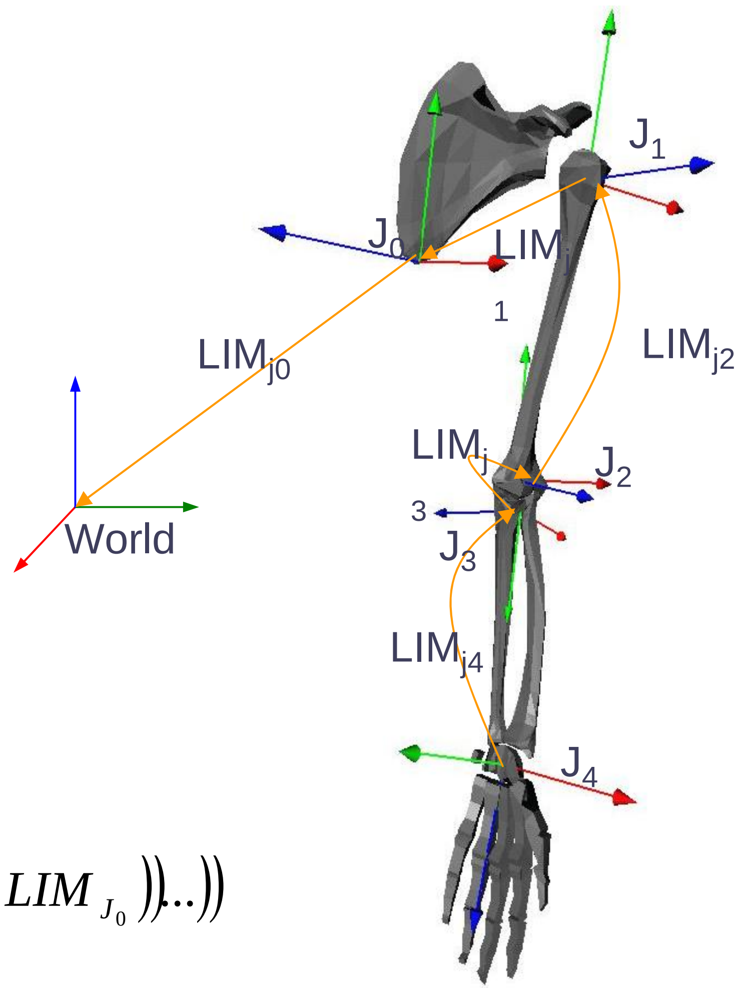
- Synarthroses
- Anphiarthrose
- Diarthroses
  - 2 DOF { Planar
  - 1 DOF { Hinge, Pivot
  - 2 DOF { Ellipsoid, Saddle
  - 3 DOF { Ball-and-socket



- Axes are not fixed
- Joints are coupled

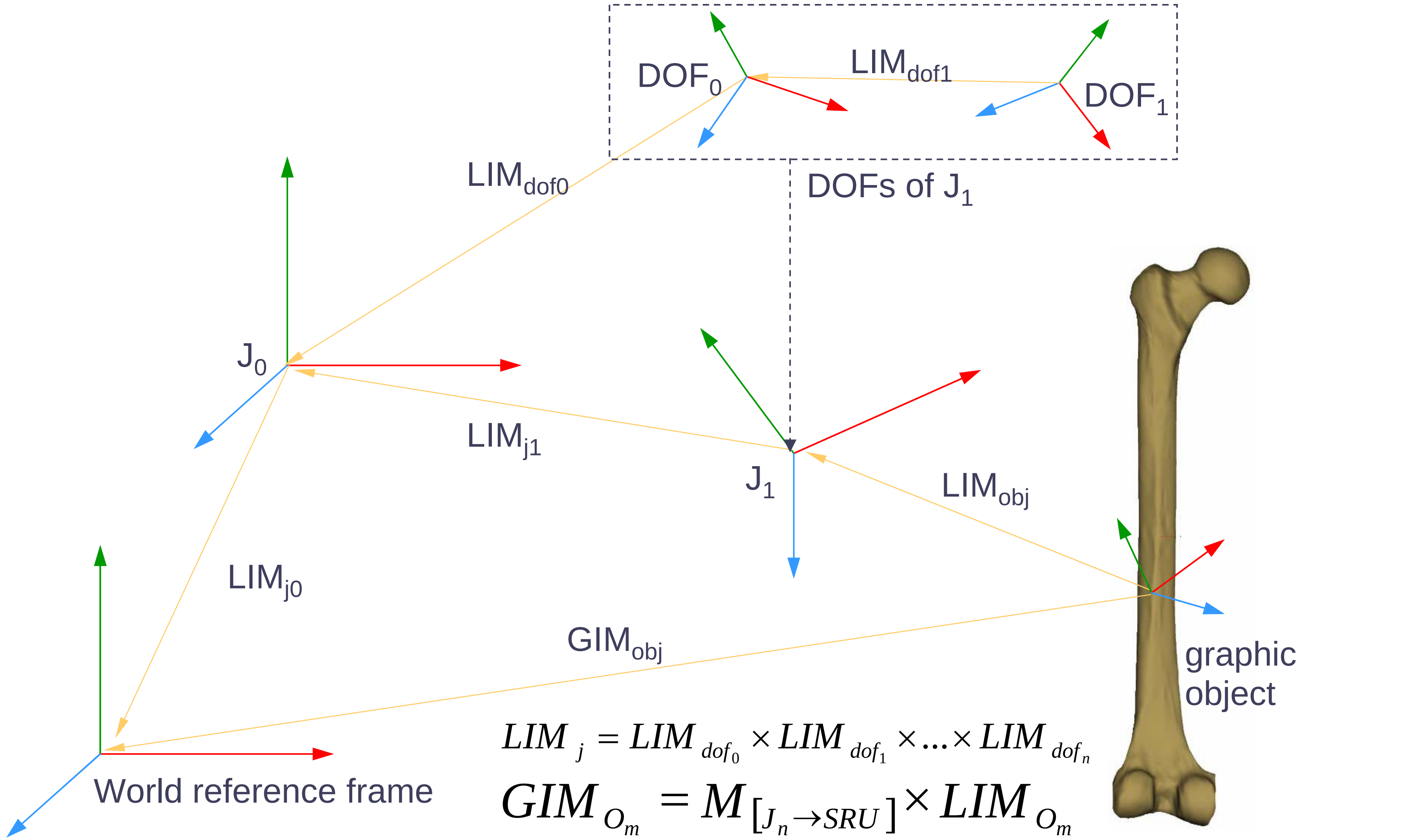
The Joint Model – Basic topology

LIM = Local Instance Matrix



$$M_{[J_n \rightarrow World]} = \left(LIM_{J_n} \times \left(LIM_{J_{n-1}} \times \ldots \times \left(LIM_{J_2}\left(LIM_{J_1} \times LIM_{J_0}\right)\right)\ldots\right)\right)$$

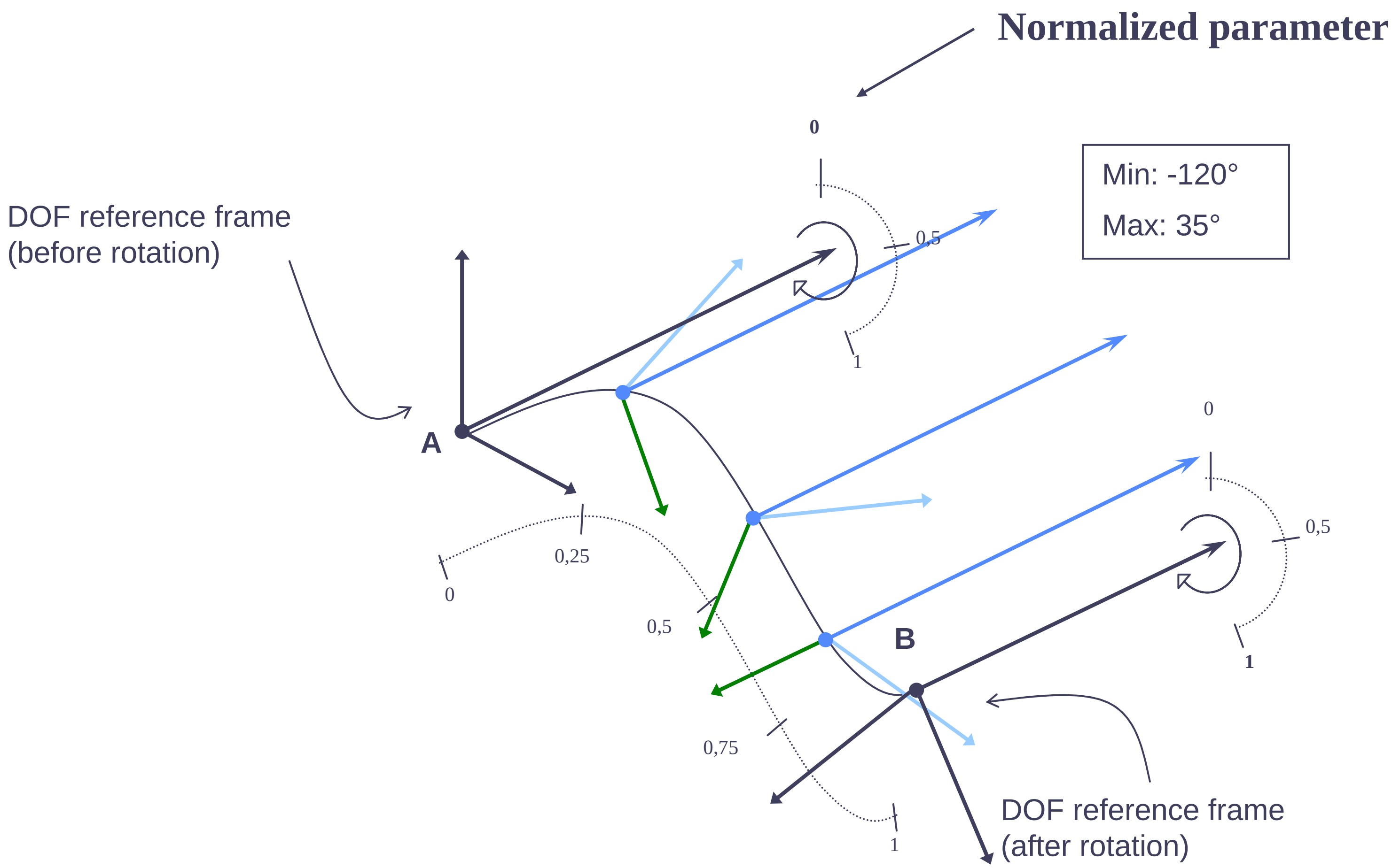
The Joint Model – Isolating DOFs



$$LIM_j = LIM_{dof_0} \times LIM_{dof_1} \times \ldots \times LIM_{dof_n}$$

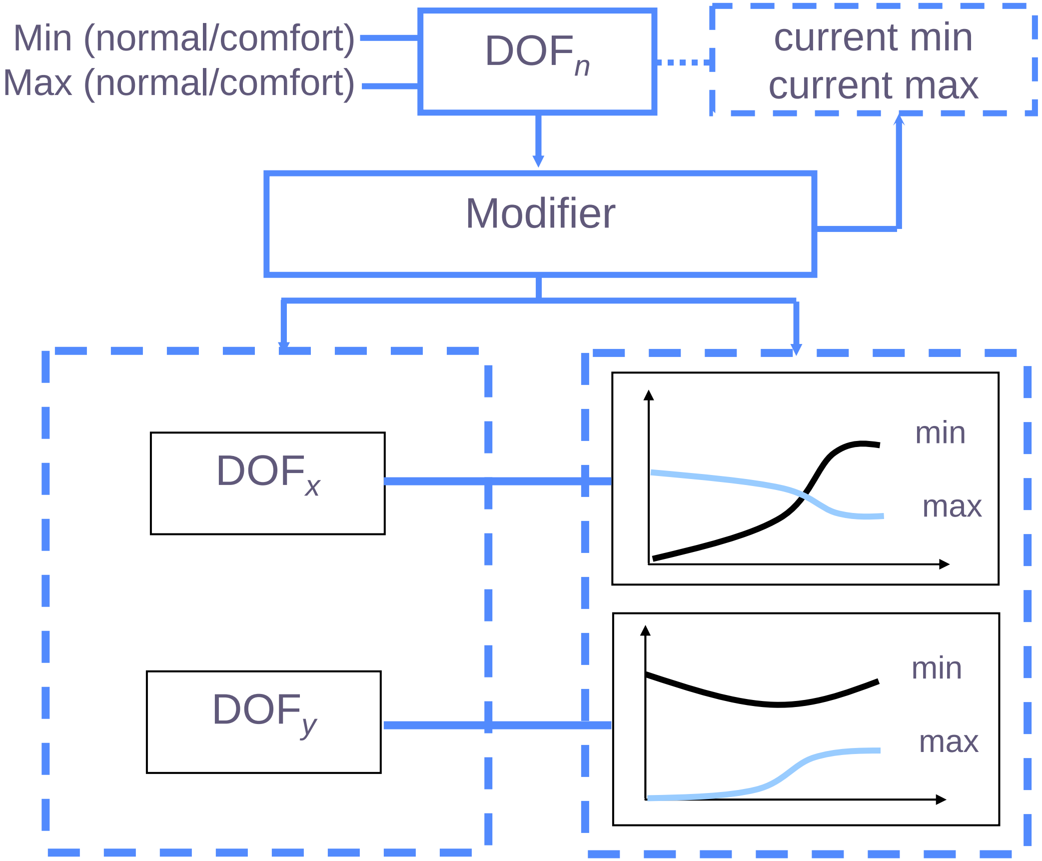
$$GIM_{O_m} = M_{[J_n \rightarrow SRU]} \times LIM_{O_m}$$

The Joint Model – 1 DOF

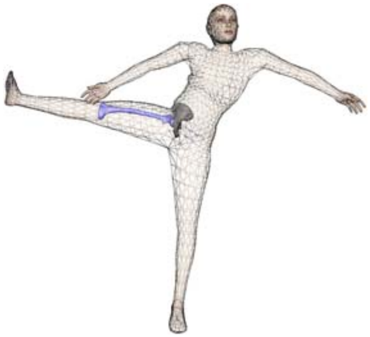


The Joint Model – Range modifiers

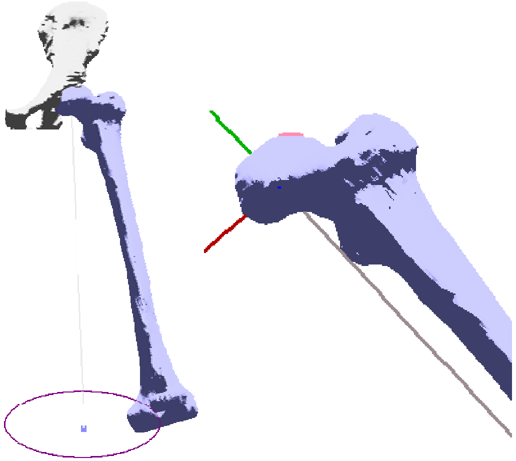
- Coupling between joints



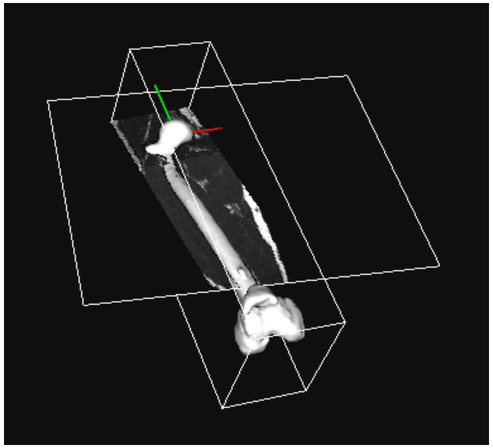
Anatomy-based configuration

Optical motion capture



Hip Joint Center and range of motions



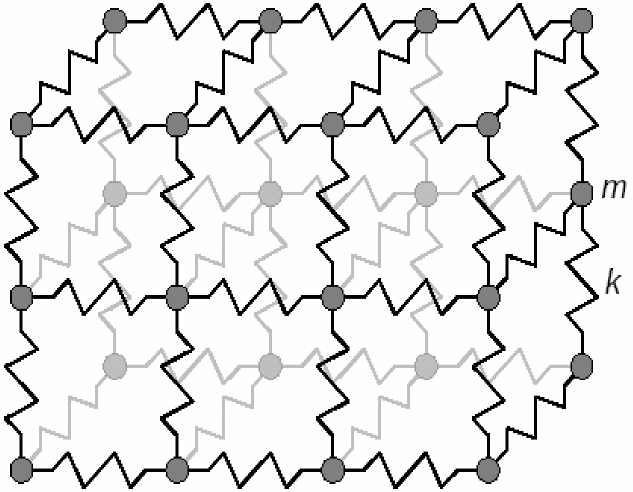
Dynamic MRI data

Deformation aspects

Soft tissues model

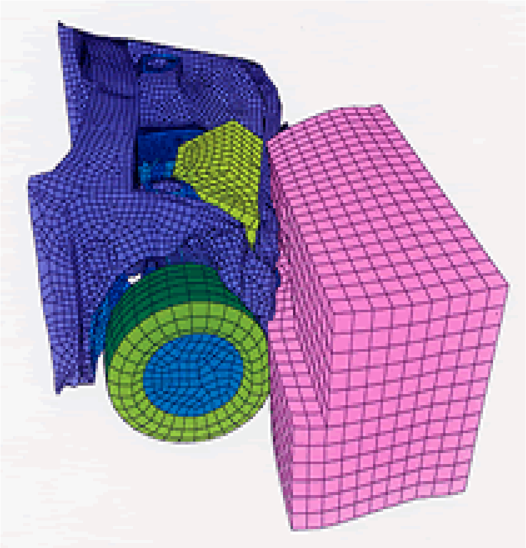
Literature review: modeling methods

- Mass-spring systems
  - Lattice of masses connected by springs
  - Advantages
    - Easy to construct/implement
    - Real-time animation
  - Limitations
    - Difficult to tune mechanics
    - Convergency problem
      (time step vs. stiffness)

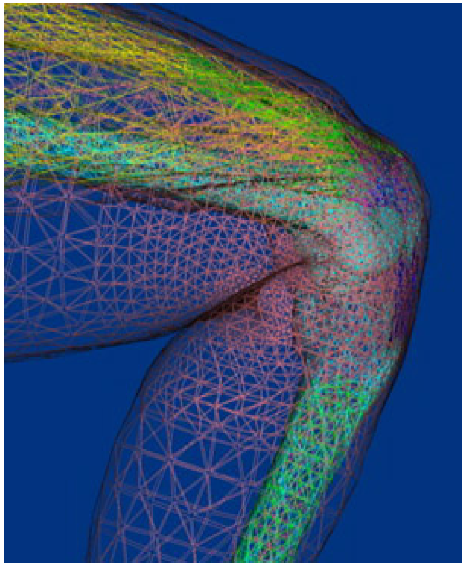


Literature review: modeling methods

- Finite element method
  - Deformable object is considered as a continuum subdivided into elements
  - Advantages
    - Mechanical behavior is more realistic than mass-spring methods
    - Mechanical properties can be specified in the model
  - Limitations
    - computationally less efficient than mass-spring methods (especially for soft biological tissues)



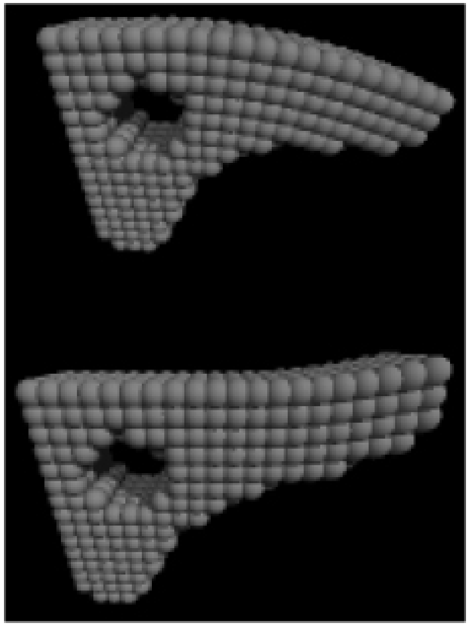
Related work



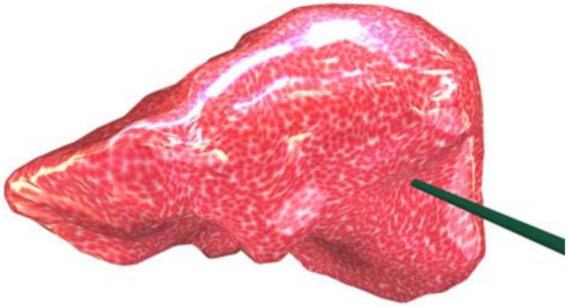
Simulation of deforming elastic solids in contact

- Simulation of human motion from scanned data (visible human)
- Lowered computations
  - Precomputed material depth
- Solving method
  - Implicit finite element

G. Hirota, et al., An Implicit Finite Element Method for Elastic Solids in Contact. Computer Animation 2001.



J. JANSSON and J. S. M. VERGEEST "A discrete mechanics model for deformable bodies". Computer-Aided Design. Amsterdam, 2002.



Time and space adaptive sampling

- Adaptive level of detail
  - Refining the resolution with larger deformation
- Fast solving method
  - Local explicit finite element

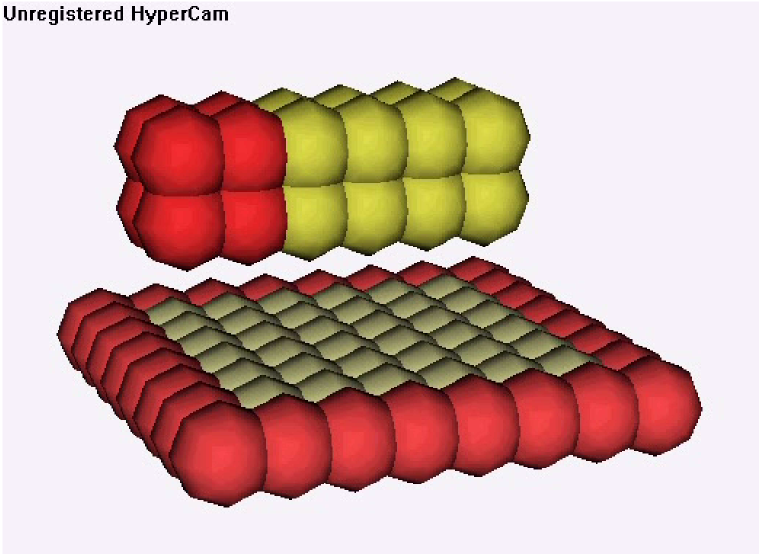
G. Debunne, et al., Dynamic Real-Time Deformations Using Space & Time Adaptive Sampling, SIGGRAPH 2001.

Soft tissues model

Molecular model based on *

A generalized mass-spring model where mass points are spherical mass regions.

$$E = \{e_1, e_2, \cdots e_n\} \quad C = \{C_{e_1}, C_{e_2}, \cdots C_{e_n}\} \quad C_e = \{C_1, C_2, \cdots C_n\}$$



$$\vec{F}_e = \vec{F}_G + \vec{F}_L + \vec{F}_C + \vec{F}_{collision}$$

$$\vec{F}_G = m_e \vec{g}$$

$$\vec{F}_C = \vec{F}_b + \vec{F}_d + \vec{F}_f$$

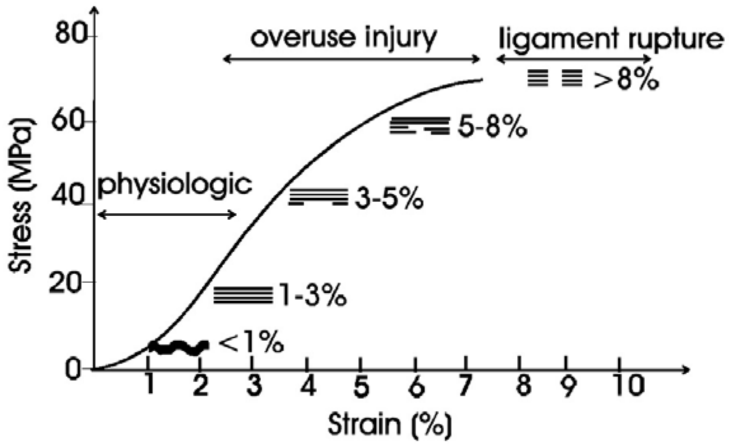
$$\vec{F}_L = -\Pi r_e^{\,2} \rho \left|\vec{V}_e\right|^2 \frac{\vec{V}_e}{\left|\vec{V}_e\right|}$$

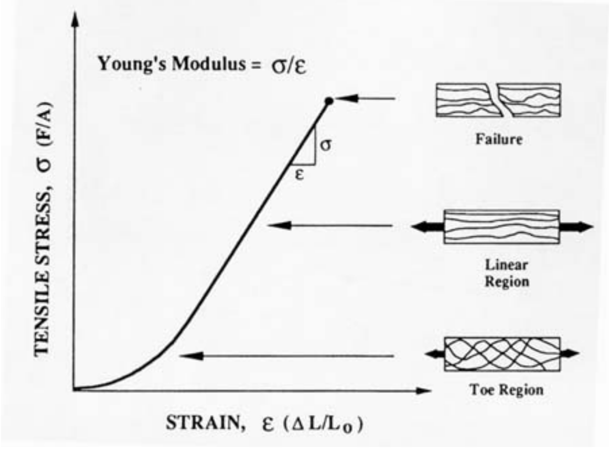
$$\begin{cases} \vec{F}_b = \sum_{i=0}^{|C_e|} -k_c\left(\left|\vec{P}_e - \vec{P}_p\right| - l_c\right) \dfrac{\vec{P}_e - \vec{P}_p}{\left|\vec{P}_e - \vec{P}_p\right|} \\ \vec{F}_d = \sum_{i=0}^{C_e} -b_c\left(\vec{V}_\parallel\right) \\ \vec{F}_f = \sum_{i=0}^{C_e} -\left|\mu_e \vec{F}_N\right| \dfrac{\vec{V}\perp}{\left|\vec{V}\perp\right|} \end{cases}$$

* J. JANSSON and J. S. M. VERGEEST “A discrete mechanics model for deformable bodies”. Computer-Aided Design. Amsterdam, 2002.

Bio-tissues behavior

- Ligament, cartilage, tendon, muscle.
- Viscoelastic
- Anisotropic
- Non-linear
- Heterogeneous
- Sensitive to: age, gender, activity…





Configuring springs: trivial approach

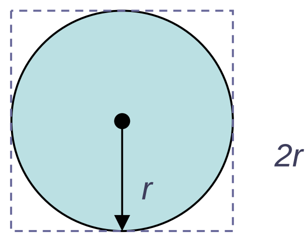
Input:

- Young's modulus of material (E)
- Spheres distribution
  - r = radius
  - l_0 = nominal distance between centers

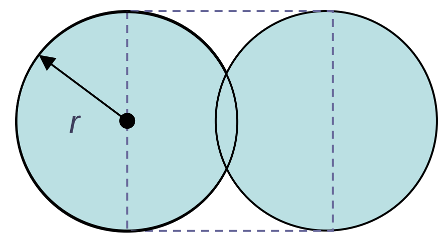
Output:

k = Hooke's constant

$$k = \frac{E(2r)^2}{l_0}$$

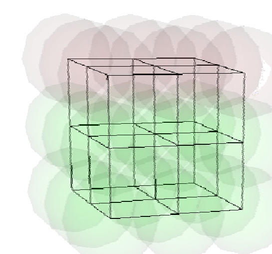


cross-sectional area = $(2r)^2$



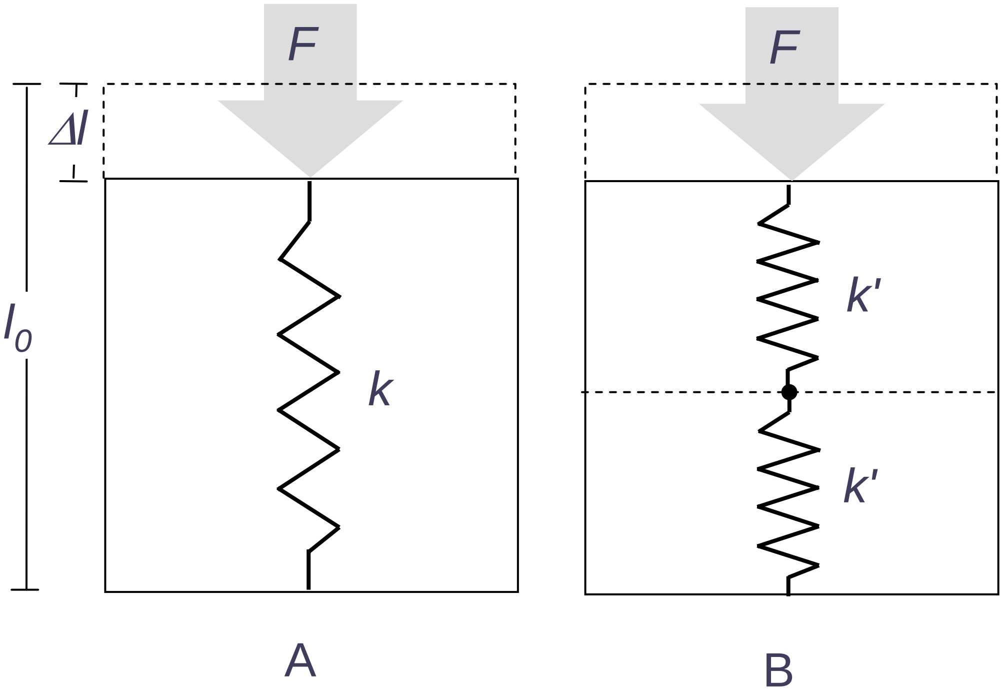
l_0

This approach works straight forward when applied to objects which springs have only right angles.



Iterative approach

- Pre-processing phase
  - Iteratively approximate value of spring constants

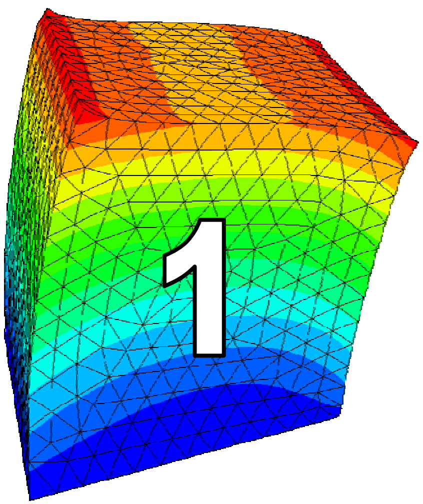


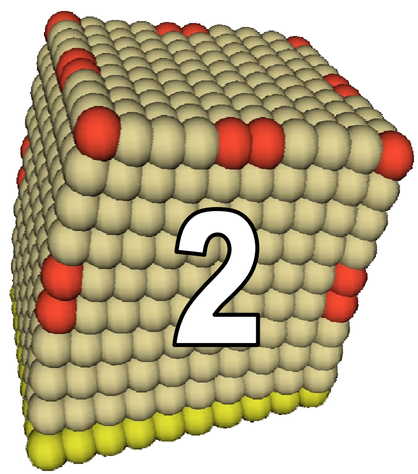
$$E = \frac{F \cdot l_0}{\Delta l \cdot A}$$

- Estimate effective E at a time step
  - A given force
  - Rest elongation
  - Current elongation variation
  - Cross sectional area
- Adapt k values
  - Minimize difference between effective and target E

Comparing with FEM analysis

- Same dimensions
- Same Young's modulus
- Same force applied
- Very similar deformation





1 - FEM static analysis by IMES - Center of Mechanics/ETHZ

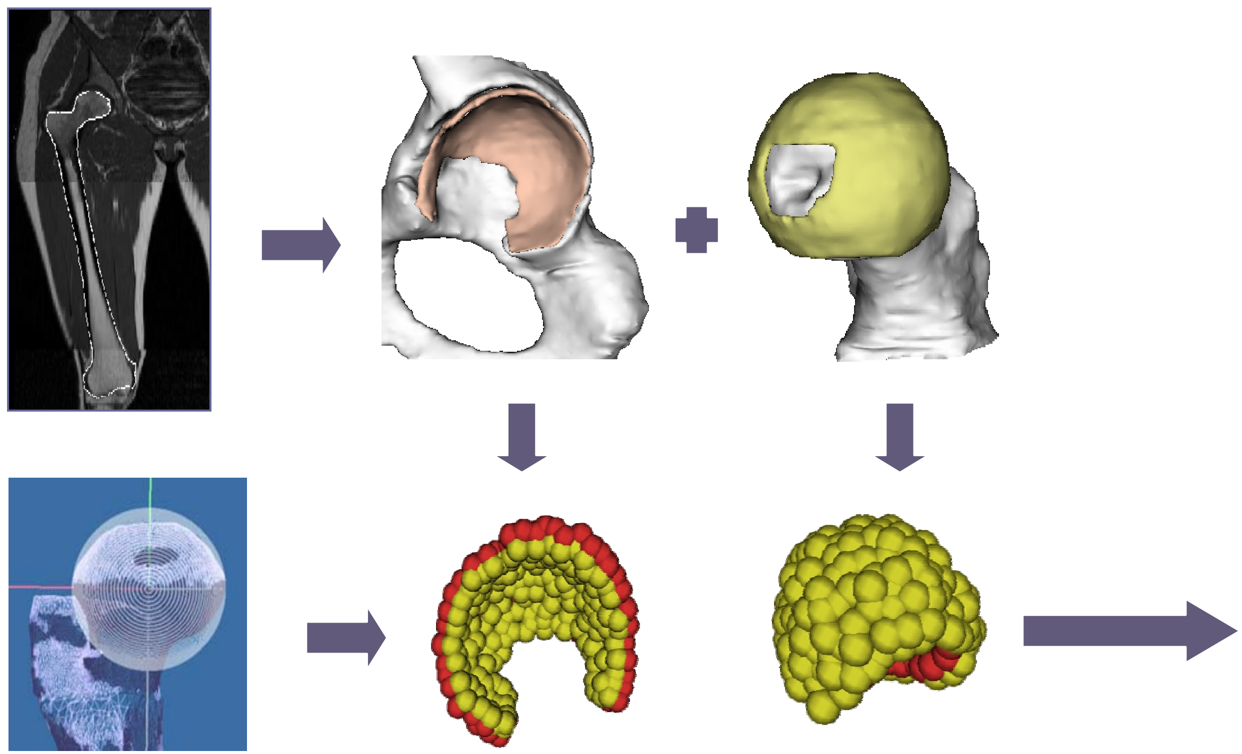
2 - Our reproduction using the same physical parameters and applying the same forces

Results and Evaluation

- Case study
  - Hip joint

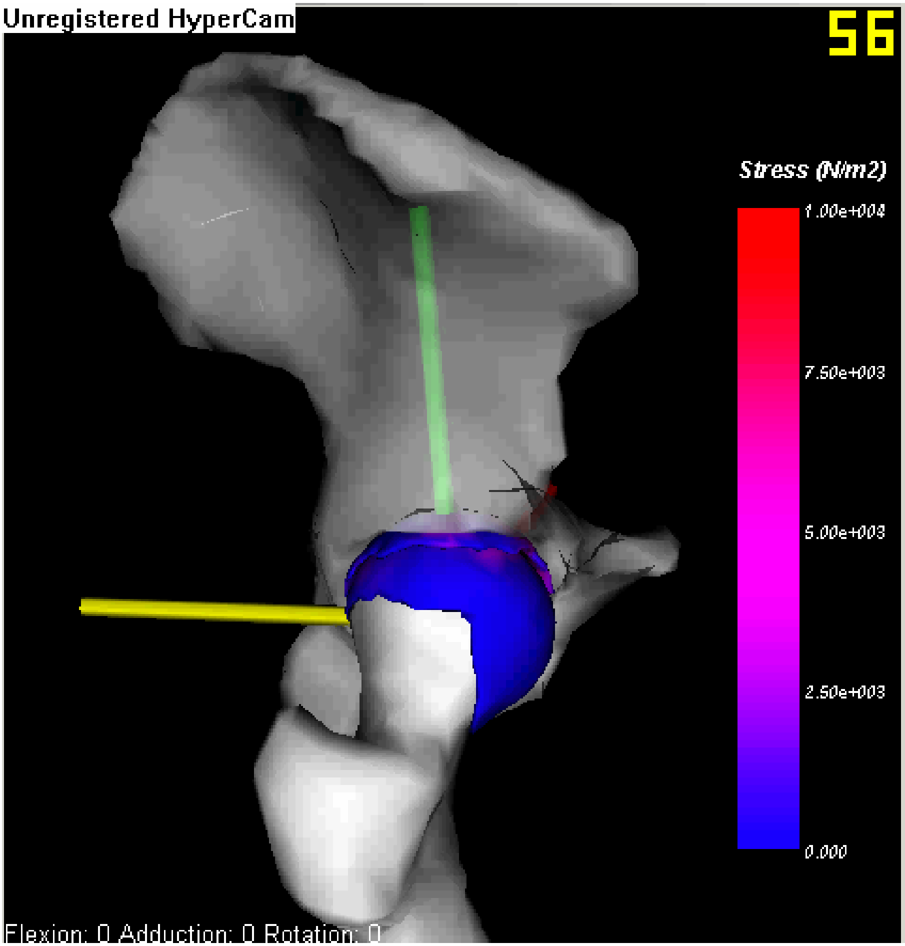
MRI acquisition and 3D models reconstruction

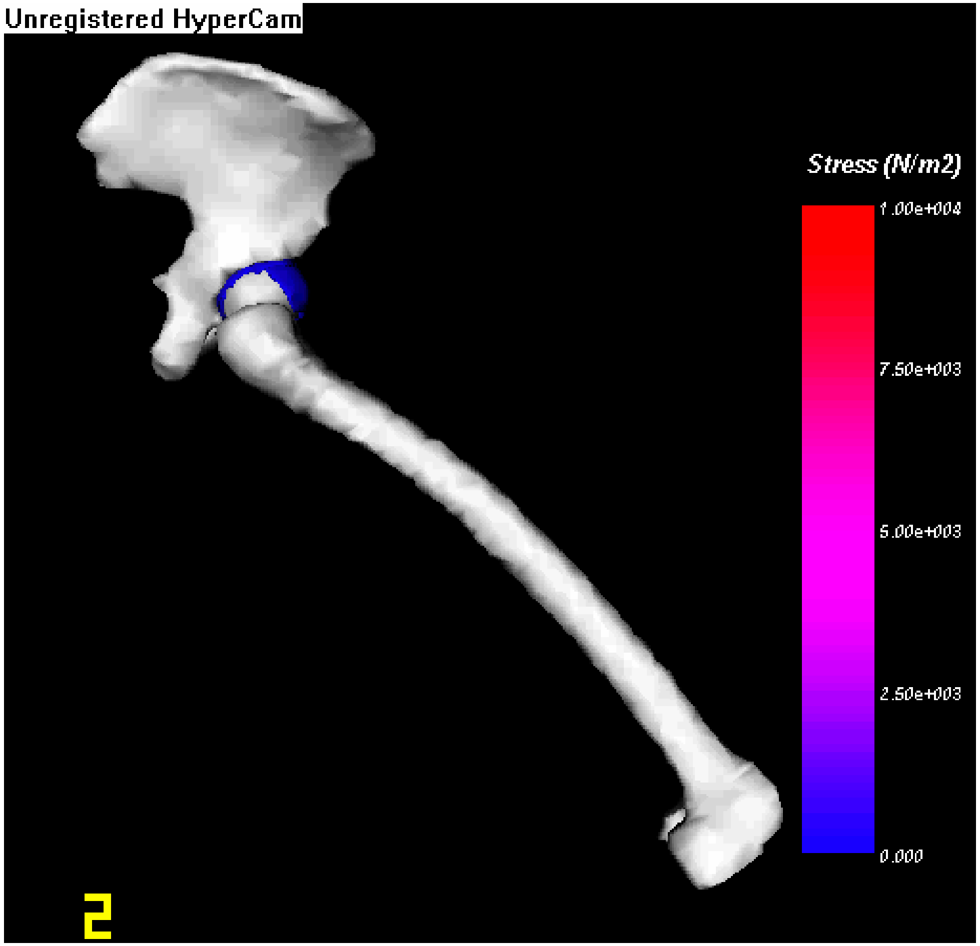
Hip Joint Center



Discretization and kinematical model

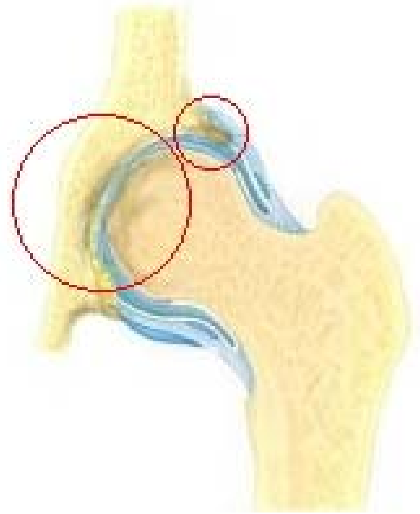
Results – stress on hip joint cartilage

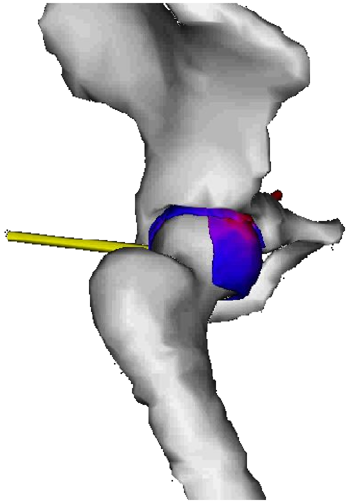




Outcome

- Challenges:
  - Understanding the role of different structures
    - Correlate pain and stress
  - Help on diagnosis
  - Surgery planning
    - validate customized treatments before application





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CO-ME
Computer Aided and Image Guided
Medical Interventions

EPFL
École Polytechnique
Fédérale de Lausanne