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
1. The problem of joint modeling
Usual approach

• Simplified – Idealized joint

• From robotics works

1. The problem of joint modeling
**Ideal Approach**

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

1. The problem of joint modeling
Context and overview

• CO-ME project
  – Computer Aided and Image Guided Medical Interventions
  – Project #10:
    • A generalized approach towards individualized functional modeling of human articulations

2. Context of this work
2. Context of this work
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

3. Our approach – related work
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
- Amphiarthrosis
- Diarthroses
  - Planar
  - Hinge
  - Pivot
  - Ellipsoid
  - Saddle
  - Ball-and-socket

2 DOF
- Axes are not fixed
- Joints are coupled

3. Our approach – kinematical model
The Joint Model – Basic topology

LIM = Local Instance Matrix

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

3. Our approach – kinematical model
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The Joint Model – Range modifiers

- Coupling between joints

3. Our approach – kinematical model
Anatomy-based configuration

Optical motion capture

Hip Joint Center and range of motions

Dynamic MRI data

3. Our approach – kinematical model
Deformation aspects

Soft tissues model

3. Our approach – deformation 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)

3. Our approach – deformation model
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)

3. Our approach – deformation model
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


Time and space adaptive sampling
- Adaptive level of detail
  - Refining the resolution with larger deformation
- Fast solving method
  - Local explicit finite element


3. Our approach – deformation model
Soft tissues model

Molecular model based on *

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

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

\[ \vec{F}_e = \vec{F}_G + \vec{F}_L + \vec{F}_C + \vec{F}_{\text{collision}} \]

\[ \vec{F}_G = m_e \ddot{g} \]

\[ \vec{F}_C = \vec{F}_b + \vec{F}_d + \vec{F}_f \]

\[ \vec{F}_L = -\Pi r_e^2 \rho \frac{\vec{V}_e^2 \vec{V}_e}{\vec{V}_e} \]

\[ \vec{F}_b = \sum_{i=0}^{C_{d}} -k_c (|\vec{P}_e - \vec{P}_p| - l_c) \frac{\vec{P}_e - \vec{P}_p}{|P_e - P_p|} \]

\[ \vec{F}_d = \sum_{i=0}^{C_{d}} -b_c \left( \vec{V}_e \right) \]

\[ \vec{F}_f = \sum_{i=0}^{C_{d}} -\mu_c \frac{\vec{V}_e}{|\vec{V}_e|} \]


3. Our approach – deformation model
Bio-tissues behavior

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

3. Our approach – deformation model
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

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

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

3. Our approach – deformation model
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 \( E \)

3. Our approach – deformation model
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

3. Our approach – deformation model
Results and Evaluation

• Case study
  – Hip joint

MRI acquisition and 3D models reconstruction

Hip Joint Center

Discretization and kinematical model

4. Results and evaluation
Results – stress on hip joint cartilage

4. Results and evaluation
Outcome

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

5. Medical outcome
Acknowledgement