### 3D Anatomical Modelling and Simulation Concepts

Prof. Nadia Magrenat-Thalmann – *MIRALab University of Geneva*
Jérôme Schmid – *MIRALab University of Geneva*
Dr. Hervé Delingette – *INRIA Asclepios*
Dr. Marco Agus – *CRS4 Visual computing group*
J.A. Iglesias Guitián – *CRS4 Visual computing group*

#### Schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:00 – 12:15</td>
<td><strong>Introduction</strong>&lt;br&gt;• Prof. Nadia Magrenat-Thalmann</td>
</tr>
<tr>
<td>12:15 – 13:05</td>
<td><strong>Anatomical modelling from medical data</strong>&lt;br&gt;• Prof. Nadia Magrenat-Thalmann and Jérôme Schmid</td>
</tr>
<tr>
<td>13:05 – 13:30</td>
<td><strong>Physically-based simulation of biological tissues (Part 1)</strong>&lt;br&gt;• Dr. Hervé Delingette</td>
</tr>
<tr>
<td>15:00 – 15:25</td>
<td><strong>Physically-based simulation of biological tissues (Part 2)</strong>&lt;br&gt;• Dr. Hervé Delingette</td>
</tr>
<tr>
<td>15:25 – 16:15</td>
<td><strong>Medical visualisation and applications</strong>&lt;br&gt;• Dr. Marco Agus and J.A. Iglesias Guitián</td>
</tr>
<tr>
<td>16:15 – 16:30</td>
<td><strong>Conclusion and discussion</strong></td>
</tr>
</tbody>
</table>
Introduction

Medical context and exemplary projects

Prof. Nadia Magnenat-Thalmann – MIRALab, University of Geneva, Switzerland

Anatomy related Projects

MIRALab research on medical simulation since 14 years

- Co-Me Interactive clinical visualization for hip joint examination, Swiss National project
- 3D Anatomical Human 3D anatomical functional models for the human musculoskeletal system, European Project
CO-ME

Subproject of the Swiss NCCR

www.co-me.ch

5 partners (MIRALab, HUG, MEM Center, EPFL, INSITIPAL Bern)

Goal

• Provide individualized functional hip joint models
• Support clinical diagnosis through a visualisation platform
  - Case study: prevention of hip osteoarthritis in patients subjected to hip degeneration (dancers)

Achievements

• Clinical MRI protocols (static & dynamic) for impingement evaluation
• Multi-organ automatic registration from MRI
• Biomechanical articulation model (particle systems & FEM)
• Measurement tools for orthopaedic surgery application
• Ontology-based visualisation platform for clinical use
Interactive clinical visualization for hip joint examination

WP1 - Acquisition and reconstruction
- Static & Dynamic MRI acquisition
- MoCap, EMG, body scanner
- Anatomical and kinematical modelling

WP2 - Functional hip joint simulation
- Soft-tissues and contact modelling
- Functional simulation and integration into virtual humans

WP3 - Hip joint model validation
- Discretization
- Mechanical testing
- Patient-specific 3D Mesh Models
- Material

WP4 - Clinical examination application
- Interactive clinical visualization for hip joint examination

Clinical Examination Application – Pipeline

Patient-specific 3D Mesh
- Discretization
- Models
- Mechanical Testing
- Material

Anatomy Analysis
- Hip joint center
- Range of motions
- Morphologies

Hip Motions
- Complete Scene
- Simulation
- Results
Analysis of Anatomical Information

- Patient-Specific 3D Mesh
- Analysis
- Anatomical Information

Simulation and Analysis

- Building joint
- Complete Scene
- Simulation
- Analysis

Extendable to Multi-level users
- Developer’s level
- End-user (surgeon) level

Internal / external Hip joint examination tools
Clinical study on young dancers (after local ethic committee approval):

- Measure maximum flexion angles
- Visualize and quantify impingements
- Assess possible hip subluxation during extreme motion

→ Prevention of osteoarthritis disease of young patients

Definition of the acquisition protocol:

- Acquisition time reduction → trade-off with resolution
- Use of radial acquisitions to better visualize femoro-acetabular conflicts
- Posture definition and feasibility study → Pilot experiments with volunteers

Goals

- **Develop** realistic functional musculoskeletal models of the lower limbs
  - Integrated model (anatomy + dynamics + physiology)

- **Unfold** new technologies and knowledge around virtual representations of human body
  - Combine knowledge on the human musculoskeletal system

- **Improve** the learning support for medical training
  - Dynamic atlases
8 Partners

MIRALab, University of Geneva
Istituti Ortopedici Rizzoli
University College of London
Institut National de Recherche en Informatique et en Automatique
Vrije Universiteit Brussel
Aalborg Universitet
Ecole Polytechnique Fédérale de Lausanne
Center for Advanced Studies, Research and Development in Sardinia

Main vision

An anatomical and functional atlas

Simulate in 3D the real and functional anatomy of the human body, focusing on the lower limb

Doctors will benefit of Virtual Reality last improvements for a new generation of medical training
Major innovations

To combine the knowledge of the musculo-skeletal system from the different medical disciplines using VR techniques

To detect anatomical anomalies and motion anomalies
- To scan in 3D any human articulation
- To allow doctor to fly through the articulation in motion without opening it
- To help doctor’s decision (Is a surgery necessary?)

In the near future: With 3D Anatomical Human, the different medical disciplines’s knowledges will be associated

- Basis for numerous future applications (surgical training, surgical planning, patient follow-up)
- Huge medical impact: virtual analysis, thus without surgical operation
- To dynamically learn and experiment
Scientific challenges

Medical imaging

3D models reconstruction

Realistic simulation of biological soft tissues

Motion analysis

Motion modeling

Knowledge management and dissemination

Medical imaging

Task Leader: UCL

MRI
  • No known harmful effects
  • 16 volunteers

Develop new protocols
  • Tissue-specific
  • Static and dynamic
  • Medically relevant
    - Movements
    - Postures
    - Joint loads
3D models reconstruction

Task leaders: MIRALab and INRIA

Two main tasks:
- Segmentation of musculo-skeleton structures from high resolution static MR images
- Tracking of those structures from low resolution MR images

Prerequisite
- Digital Atlas of the structures to be segmented

Digital Atlas
- Generated by compiling information
- Used as reference frame for segmenting new images

Advantages
- Labels are transferred
- Provide a standard system for morphometry
Soft tissue simulation

Task leader: IOR (U. Bologna)

To develop in-vitro testing procedures for soft tissues
To train researchers on consistent application of these procedures
To characterise passive behaviour of selected soft tissues
To define the constitutive relationships for soft tissues

International Institution for the Advancement of Medicine (IIAM) & others available to provide soft tissue

• BUT: problems with preservation during shipping (no freezing!)

Available animal specimens:

• Sacrificed for alimentary purposes
• Already sacrificed (at IOR) for other research activities
Soft tissue simulation

Mechanical properties of whole tendons
Tendon bundles
Bone-Ligament-Bone
Ligament bundles

Motion analysis

Task leader: Aalborg University

Dynamic information for biomechanical (forward and inverse) simulation

In-situ kinematical, dynamic and physiological measurements:
  • Internal motion from imaging modalities such as dynamic MRI
  • Posture/forces from optical motion capture (MoCap) and force plates
  • Profile of muscle actuation from electromyography (EMG)
Motion analysis: MoCap

Anatomical subject modelling

Joint simulation driven by optical motion capture

Motion acquisition

Motion simulation

Motion analysis: EMG

Profile of muscle actuation from electromyography (EMG)

To perform the active simulation of the musculoskeletal system

Muscle actuation patterns
Motion modelling

Task leader: EPFL

To build the kinematical skeleton from the reconstructed surface model

To provide an integrated framework for the lower limb forward and inverse functional simulation

Several levels of details

- for soft-tissues (muscle action lines to anisotropic muscles)
- simulation methods (idealized joints and contacts, and physical-based contacts)

Visualization and interaction

Task leaders: MIRALab and CRS4

A new visualisation/ interaction framework

- Effective visualization techniques
- Intuitive interaction techniques
- Level of details

To allow

- Training
- Virtual examination
Conclusion

An anatomical and functional atlas

Pluri-disciplinary research

Bridge complementary approaches for modeling and simulation

Increase the awareness of the use of virtual reality technologies

Data Acquisition: medical imaging

<table>
<thead>
<tr>
<th>Data</th>
<th>MRI</th>
<th>US</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>static</td>
<td>B-mode</td>
<td>static</td>
</tr>
<tr>
<td>Kinematics</td>
<td>Dynamic MRI</td>
<td>M-mode</td>
<td>Dynamic</td>
</tr>
<tr>
<td></td>
<td>(Cine) pc-MRI</td>
<td>Doppler</td>
<td></td>
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<tr>
<td></td>
<td>(Tagged) MRI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanics</td>
<td>MR Elastography</td>
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<tr>
<td>Physiology</td>
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</tr>
</tbody>
</table>

~ 1mm³

(uni.california)

~ 1mm³

~ 0.25mm³
Data Acquisition: ex. static MRI

Spin-echo T1, TR=578ms, TE=18ms
Gradient-echo T2*, TR=30ms, TE=14ms
Gradient-echo T1, TR=20ms, TE=7ms

MIRALab – HUG STATIC Protocol

#1,2,3: Axial 2D T1 Turbo Spin Echo (TSE), TR/TE= 578/18 ms, resolution=0.78x0.78mm
#4: Axial 3D T1 Gradient Echo, TR/TE= 20/7 ms, resolution=0.78x0.78mm
Data Acquisition: medical imaging

<table>
<thead>
<tr>
<th>Data</th>
<th>MRI</th>
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<tr>
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<td>Kinematics</td>
<td>Dynamic MRI</td>
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<td>Fluoroscopy</td>
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<td>(Cine) pc-MRI</td>
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<td>Mechanics</td>
<td>MR Elastography</td>
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<tr>
<td>Physiology</td>
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</tbody>
</table>

Data Acquisition: ex. Dynamic MRI

dMRI is used to assess real organs motion (e.g., bone motion)

- Can serve to diagnosis
- Can serve to validate approaches that estimate this motion

MIRALab – HUG DYNAMIC Protocol:
fast gradient echo sequence
# Data Acquisition: medical imaging

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<td>Kinematics</td>
<td>Dynamic MRI (Cine) pc-MRI</td>
<td>M-mode</td>
<td>Fluoroscopy</td>
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<tr>
<td></td>
<td>(Tagged) MRI</td>
<td>Doppler</td>
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<td>Mechanics</td>
<td>MR Elastography</td>
<td></td>
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<tr>
<td>Physiology</td>
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</tbody>
</table>

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# Data Acquisition: other modalities

<table>
<thead>
<tr>
<th>Data</th>
<th>Body scanner</th>
<th>Mocap</th>
<th>Plates</th>
<th>Mech. device</th>
<th>EMG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td></td>
<td>Laser</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinematics</td>
<td></td>
<td>Electromagnetic</td>
<td>Optical Mobile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamics</td>
<td></td>
<td>Pressure plates/soles</td>
<td>Force plates</td>
<td>Pressure sensors</td>
<td>Strain gauges</td>
</tr>
<tr>
<td>Mechanics</td>
<td></td>
<td></td>
<td></td>
<td>Uniaxial/ biaxial</td>
<td>Surface EMG Needle EMG</td>
</tr>
<tr>
<td>Physiology</td>
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</tbody>
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[papazoglou05]
3D body scanning

This modality digitalizes accurate skin models of the complete body.

3D body scanning is also used to extract the position of the markers for the motion capture.

Optical motion capture (MoCap)

This involves recording optical markers on the skin with digital cameras.

Then, the joint kinematics are reconstructed in 3D from the markers trajectories.
EMG

- Simultaneous acquisition with motion capture
- Electrodes positioning according to literature
- Movements: Isometric / isotonic contractions

- Surface EMG can only capture activity of muscles directly under the skin
- Needle EMG can capture internal muscles activity but is invasive

EMG signals (14 muscles)  EMG Gluteus Maximus during Gait  EMG electrodes placement with optical motion capture markers

Source: 3D Anatomical Human

Anatomical modelling from medical data

Introduction and introductive examples

Prof. Nadia Magnenat-Thalmann – MIRALab, University of Geneva, Switzerland
Section Overview

- Introduction anatomical modelling
- Direct segmentation
- Registration
- Examples

Anatomical Modelling

Virtual physiological human

- Integrate knowledge
- Drive experiments
- Diagnostic Therapy Follow-up
- Optimize measurements
Anatomical Modelling

Modelling and simulation at the macroscopic scale

Modelling/simulation level | Data | Scale | Medical outcome
---|---|---|---
Anatomy | Static, Kinematics | Organ | Diagnosis
Function | Dynamics, Mechanics | Joint | Treatment
Control | Physiology | Limb | Treatment

Example: musculoskeletal modelling (1/5)

Musculoskeletal system at macroscopic scale → mostly relevant to CG
Its functioning presents a nested nature with increasing complexity
Example: Musculoskeletal Modelling (2/5)

[Scheepers97]
- Anatomical concepts
- Anatomical constraints
  BUT
- Not patient-specific
- Unrealistic simplifications

Example: Musculoskeletal Modelling (3/5)

[Aubel and Thalmann2001]
- Anatomical Concepts (muscles, fat, bones)
- Anatomical constraints (e.g., attachements)
  BUT
- Not patient-specific
- Interactive modeling
- simplifications
Example: Musculoskeletal Modelling (4/5)

[Teran2005]

- Complex Anatomical Model (e.g., fiber direction, anisotropy, nonlinearity, fascia, etc.)
- Suitable for simulation (FVM)
- Patient-specific (Visible Human Dataset)

BUT

- Interactive (e.g., manual correction and editing)
- No medical validation

Example: Musculoskeletal Modelling (5/5)

[Blemker and Delp2005]

- Complex Anatomical Model (e.g., fiber direction)
- Patient-specific (MRI segmentation)
- Medical validation (comparison predicted and MRI-imaged muscles deformation)
- Suitable for simulation (FEM)

BUT

- Interactive (e.g., manual segmentation)
Anatomical modelling from medical data

Segmentation and registration

Jérôme Schmid – MIRALab, University of Geneva, Switzerland

Today, imaging becomes a routine clinical tool
But we measure much more than we can understand
→ Image analysis is required

Extraction of clinical information by image processing

3D digital images

Cancer: detection, localization
Radiotherapy: surgery, planning
Brain: changes over time, inter-subject differences

(Vandermeulen)
Image analysis

Acquisition: Measurement of physical properties

For computation, images are discretised (digitalised):
- In space, in time or in intensity

Image noise
- Due to the acquisition devices or methods (e.g., speckle noise in US, bias field in MRI)

Artifacts
- Due to Partial volume effects (PVE) (Multiple tissues contribute to a single voxel)
- Due to Patient movement, incorrect calibration (e.g., wave-speed in US)

Segmentation: Image partitioning
- non overlapping regions
- homogeneous regions
  - Distinct anatomical structure
  - Region of interest
  - Type of tissues (healthy/tumorous)

Direct segmentation

Pre-Processing:
- noise removal [perona90][Buades05]
- structures enhancement (contours,..)
- bias filtering

Region detection:
- contour detection/closing
- histogram analysis (Local and global [otsu79] thresholding, hysteresis, etc)
- texture analysis

Region classification:
- region growing
- region splitting
- fuzzy connectedness, Watershed

Model Reconstruction:
- Marching cubes [lorensen87]
- Constrained deformable models
Direct segmentation

• Usually direct segmentation is sensible to noise and not robust

• **Prior knowledge** can significantly improve it
  • Prior about structures to segment
    - Lines, curves: Hough transform [Duda72][Ballard87]
    - Tubular structures: scanning [Eberly94], tracing methods [Aylward96]

• Prior about intensity
  - Basic statistics (mean, variance)
  - PDF to be used in Bayesian approaches (e.g. Naïve Bayes classifier)
  - Neighbors relationships with Markov Random Fields
Problem: find a transformation $T$ that
- maximises the similarity between $T(J)$ and $I$
- is admissible in the application context

Equivalent to an Indirect segmentation

Reviews: [brown92], [mairitz98], [audette00], [cachier02], [Zitova03]

Registration outline

What is registered: Registration features

Registration criterion: Similarity measure

How to constrain the problem: Regularisation

How the registration is performed: Evolution
Registration features (1/3)

Iconic features
- photometric information: image intensities, gradient
- Regions of interest: voxel, template, intensity profile

Geometric features
- Points, curves, surfaces, volumes

Two approaches:
- Model extraction in the two datasets
  + geometric registration [audette00]
- Model extraction in the source dataset
  + iconic registration [brown92], [maintz98], [cachier02]

Registration features (2/3)

Three types of deformable models:

- **Continuous models** [kass88], [terzopoulos88], [cootes01]
  - Mapping between material parameters and spatial coordinates
    - For example, in 3D: \( u \in [0,1]^p \rightarrow [x(u),y(u),z(u)]^T \in \mathbb{R}^3 \)
    - Explicit mapping (snakes) or use of specific functions (parametric models)

- **Discrete models** [delingette94], [montagnat05], [lotjonen99], [szeliski96]
  - Explicit positions in space (vertices) + connectivity relationships

- **Implicit models** [osher88], [malladi95], [vemuri03], [cremers07]
  - Iso-value of a potential field
    - For example, in 3D: \( \{ \mathbf{p} \in \mathbb{R}^3 \mid F(\mathbf{p})=0 \} \)

Reviews: [McInerney96], [Jain98], [montagnat01], [nealen06]
# Registration features (3/3)

<table>
<thead>
<tr>
<th></th>
<th>Discrete</th>
<th>Continuous</th>
<th>Implicit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>Anatomical/ artificial landmarks</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Basis</td>
<td>Anatomical/ principal axis</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Curves</td>
<td>Polylines, 1-simplex models</td>
<td>2D snakes, splines</td>
<td>Level-sets</td>
</tr>
<tr>
<td>Surfaces</td>
<td>Triangle, 2-simplex meshes, mass-spring surfaces</td>
<td>3D snakes, splines, superquadrics</td>
<td>Level-sets</td>
</tr>
<tr>
<td>Volumes</td>
<td>Mass-spring networks (lattices), tetrahedral, 3-simplex meshes, particle systems</td>
<td>splines, superquadrics</td>
<td>Level-sets, superquadrics</td>
</tr>
</tbody>
</table>

## Registration outline

**What is registered:** Registration features

**Registration criterion:** Similarity measure

**How to constrain the problem:** Regularisation

**How the registration is performed:** Evolution
Similarity measure (1/4)

Geometric registration:

→ Minimise the distance btw geometric features

- Two points:
  - Euclidean distance: \( d = \left[ \sum (x_j - y_j)^2 \right]^{1/2} \)
  - p-order Minkowski distance: \( d = \left[ \sum (x_j - y_j)^p \right]^{1/p} \)

- Two meshes
  - Hausdorff distance: \( d = \max_{x \in X} \left\{ \min_{y \in Y} \{ d(x, y) \} \right\} \)
  - Probabilistic measures (e.g. Mahalanobis)

Similarity measure (2/4)

Iconic registration:

→ Align the source model to contours in the target image

- Maximise gradient magnitude: \( d = - \| \nabla I \| \)
- Align model and image gradient: \( d = \pm \nabla I \cdot n \)

→ Maximise the similarity btw icons

- Region of Interest (vertex neighbourhood):
  - Blocks → template matching \( [\text{spec01}] \)
  - Direction of expected changes
    - Intensity profile matching \( [\text{photogram00}] \)
    - (normalised) gradient profile matching \( [\text{context00}] \)
Similarity measure (3/4)

Intensity differences \[\text{horn81}\]

→ Assume intensity conservation: \[I \approx T(J)\]
  - Sum of absolute differences
  - Sum of squared differences

Intensity correlation \[\text{holden00}\]

→ Assume affine correlation btw intensities: \[I \approx \alpha T(J) + \beta\]
  - Normalised cross-correlation

Histogram correlation \[\text{viola95}, \text{wells96}, \text{maes97}, \text{roche00}, \text{woods92}\]

→ Assume functional relation btw intensities: \[I \approx \Phi(T(J))\]
  - Normalised mutual information
  - (bi-variate) Correlation ratio
  - Woods criterion

Use of
  - scalar measures (e.g. intensities, gradient magnitudes, gradient cosines, etc.)
  - vectorial measures (e.g. gradients)

Similarity measure (4/4)

<table>
<thead>
<tr>
<th>Feature Extraction Method</th>
<th>Different modalities</th>
<th>Different protocols</th>
<th>Large displacements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric [\text{audette00}]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depends on the feature extraction algorithm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gradient [\text{kass88}, \text{xu98}]</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Intensity differences [\text{horn81}, \text{thirion95}]</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity correlation [\text{holden00}]</td>
<td>+</td>
<td></td>
<td></td>
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<td>+</td>
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</tbody>
</table>

Eurographics 2009  Tutorial 6
Registration outline

What is registered: **Registration features**

Registration criterion: **Similarity measure**

How to constrain the problem: **Regularisation**

How the registration is performed: **Evolution**

---

Regularisation (1/5)

Noise
+ Local solutions
+ Aperture problem

→ The problem needs to be constrained through parameterisation and internal forces
Parameterisation

- Hypothesis about the form of the solution $T$
  - $\rightarrow$ Reduce the search space (DOF)
- Two approaches:
  - Standard approach: evolve parameters of a global transform
  - Pair & smooth approach: find a global transform from local pairs

- Coarse-to-fine approaches

  - Improve robustness and computational speed

Regularisation (2/5)

<table>
<thead>
<tr>
<th>Transform</th>
<th>DOF</th>
<th>General form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centred rigid</td>
<td>3</td>
<td>$\delta p = \begin{bmatrix} R - I &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 1 \end{bmatrix} p$</td>
</tr>
<tr>
<td>Rigid</td>
<td>6</td>
<td>$\delta p = \begin{bmatrix} R - I &amp; t &amp; 0 \ 0 &amp; 0 &amp; 1 \end{bmatrix} p$</td>
</tr>
<tr>
<td>Similarity</td>
<td>7</td>
<td>$\delta p = \begin{bmatrix} sR - I &amp; t &amp; 0 \ 0 &amp; 0 &amp; 1 \end{bmatrix} p$</td>
</tr>
<tr>
<td>Affine</td>
<td>12</td>
<td>$\delta p = \begin{bmatrix} A - I &amp; t &amp; 0 \ 0 &amp; 0 &amp; 1 \end{bmatrix} p$</td>
</tr>
<tr>
<td>Projective</td>
<td>15</td>
<td>$\delta p = \begin{bmatrix} A - I &amp; t &amp; xT \ 0 &amp; 0 &amp; v \end{bmatrix} p$</td>
</tr>
<tr>
<td>FFD (e.g. cubic splines)</td>
<td>$3N_xN_yN_z$</td>
<td>$\delta p = \sum_{i,j,k} \int f_{i,j,k}(p) \delta p_{i,j,k}$</td>
</tr>
<tr>
<td>Unstructured (e.g. RBF)</td>
<td>$3N$</td>
<td>$\delta p = \sum_i \sum_j w_i(p_j) \delta \parallel p - p_j \parallel + f(p)$</td>
</tr>
<tr>
<td>Constrained pairing</td>
<td>User-defined</td>
<td>Normals, image gradients (optical flow)...</td>
</tr>
<tr>
<td>Example-based</td>
<td>Sample size $N$</td>
<td>$\delta p = \sum_i \delta w_i(p_i)$</td>
</tr>
</tbody>
</table>

Regularisation (3/5)
Regularisation (4/5)

Internal constraints

→ Enforce shape continuity via energy minimisation

- Smoothing → Tikhonov differential stabilisers
  - Elastic energy (Laplacian smoothing)
    → curvature minimisation (1st order)
  - Bending energy
    → curvature averaging (2nd order)
  - To be applied to positions, velocities or forces

- Strain energy:
  - Matching to a reference local geometry

- Shape constraints:
  - Shape variations modelling (e.g. ASM)

- Volume preservation

\[ x \approx T(\bar{x} + \Phi \cdot b) \]

Regularisation (5/5)

- Physically-based
  - Minimisation of the strain energy
    - Space discretisation with FDM, FEM or FVM
    - Linear elasticity (small displacements), hyperelastic, fluid
  - Collision handling
  - Topological constraints

\[ T \]
Regularisation (5/5)

- Physically-based
  - Minimisation of the strain energy [christensen96], [bro-riisen96], [wang00], [veress06]
    - Space discretisation with FDM, FEM or FVM
    - Linear elasticity (small displacements), hyperelastic, fluid
  - Collision handling [park01]
  - Topological constraints [yang04]

- Pros / cons
  + One-to-one mapping, no negative volume
  + Validation of biomechanical models
  - High computational cost
  - Inter-patient registration ?
  - Image forces ?
  - Mechanical parameters ?

Registration outline

What is registered: Registration features

Registration criterion: Similarity measure

How to constrain the problem: Regularisation

How the registration is performed: Evolution
Explicit resolution \[\text{[arun87][pennec96]}\]

- Analytical solution for homogenous transform
- Example: affine transform:

\[
A^* = \sum_i (X_i - \mu_X) (Y_i - \mu_Y)^T \left[ \sum_i (X_i - \mu_X) (Y_i - \mu_Y)^T \right]^{-1}
\]

\[
t^* = \mu_Y - A^* \mu_X
\]

- Pair & smooth approach \[\text{[cachier02]}\]
- Iterative closest point \[\text{[kneb92]}\]

Evolution (2/4)

Energy minimisation = relaxation

- Global methods
  - Exhaustive or quasi-exhaustive methods (multigrid)
  - Simulated annealing \[\text{[snyder92]}\]
    - Allow energy increase according to the temperature
  - Evolutionary algorithm (genetic algorithms \[\text{[koza98]}\], differential evolution \[\text{[storn95]}\])
    - A fitness function is optimised through individual crossing/mutation
  - Dynamic programming \[\text{[amini90]}\]

→ The global minimum is reached at the price of computational cost
Evolution (3/4)

- Local methods = Oriented research
  - Bracketing: simplex (amoeba) method [valot65]
  - Gradient descent $\delta P = - \nabla E(P) \cdot dt$ [thirion95]
  - Powell’s method $\rightarrow$ conjugate directions [Press92]
  - Newton (2nd order development) $\delta P = - \nabla E(P) \cdot \nabla^2 E(P)^{-1} \cdot \nabla E(P)$ [vemuri97]
  - Levenberg-Marquardt = Newton + Gradient descent [Marquardt63]
  - Newton-Raphson (1st order development) $\delta P = - \| \nabla E(P) \|^2 E(P)$. $\nabla E(P)$

- Bayesian framework [staib92], [wang00], [chen00]
  - Maximisation of shape probability given the image

---

Evolution (4/4)

Dynamic evolution: Add velocity + damping

- Discrete models = lumped mass particles submitted to forces

- Newtonian evolution (1st order differential system):
  $\delta P = V \cdot dt$
  $\delta V = M^{-1} F(P,V) \cdot dt$

- Explicit schemes (Euler, RK) $\rightarrow$ Unstable for large time-step !!

- Semi-Implicit schemes (Euler, Verlet) $\rightarrow$ Unstable for large time-step !!

- Implicit schemes (Euler, BDF) $\rightarrow$ Unconditionally stable
  … But requires the inversion of a large sparse system
**GPU-assisted segmentation/ registration**

Main purpose of using GPU
- **Decrease computation time**
- **Visualize results during evolution**

→ **Interactivity**
→ **Control and tuning**

Level-set most popular [Lefohn03, hadwiger03, klar07]
But also MI-based approach [Shams07, Tessmann08]
watershed [Stoer00] ...

![Level-set example](image)

Review: [Hadwiger2004]

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**Examples (1/4)**

**Bones modelling** [gilles06, schmid08]
- **Dynamic evolution**
  - Implicit integration
  - CG resolution
- **Multi-resolution approach**
- **External forces**: intensity profiles
- **Internal forces**: Smoothing and PCA-based regularization

![Bones example](image)
Examples (2/4)

Muscles modelling \cite{gilles06, schmid08}
+ topological constraints (attachments)
+ radial forces
+ collision handling

Examples (3/4)

Tendons modelling \cite{schmid08}
+ tubular structures
+ semi-automatic tracing
Examples (4/4)

Multimodal data fusion (anatomy + kinematics) [Magnenat-Thalmann08][Charbonnier09]

MoCap system: Vicon MX, 120 Hz

Body scanner data → registered data → MRI segmented data → MoCap data → Simulation

Challenges:

- Link simulation and modelling domains
  - Biomechanical model validation
  - Parameterisation of segmentation methods
- Improve robustness wrt. image of anatomical variability
- Improve computation speed → real time user interaction
- Improve automation → reduce the number of user inputs

→ Integration in the clinical environment