3D Anatomical Modelling and Simulation Concepts

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

Schedule

- **12:00 – 12:15 Introduction**
  - *Prof. Nadia Magnenat-Thalmann*
- **12:15 – 13:05 Anatomical modelling from medical data**
  - *Prof. Nadia Magnenat-Thalmann and Jérôme Schmid*
- **13:05 – 13:30 Physically-based simulation of biological tissues (Part 1)**
  - *Dr. Hervé Delingette*
- **15:00 – 15:25 Physically-based simulation of biological tissues (Part 2)**
  - *Dr. Hervé Delingette*
- **15:25 – 16:15 Medical visualisation and applications**
  - *Dr. Marco Agus and J.A. Iglesias Guitián*
- **16:15 – 16:30 Conclusion and discussion**

Introduction

Medical context and exemplary projects

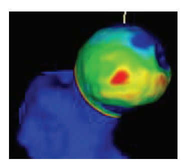
Prof. Nadia Magnenat-Thalmann – *MIRALab, University of Geneva, Switzerland*

Anatomy related Projects

MIRALab research on medical simulation since 14 years

2001

- Co-Me *Interactive clinical visualization for hip joint examination, Swiss National project*



2006

- 3D Anatomical Human
  3D anatomical functional models for the human musculoskeletal system, European Project

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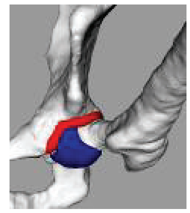
CO-ME

Subproject of the Swiss NCCR

www.co-me.ch

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



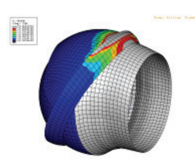
Goal

- 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)

CO-ME

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



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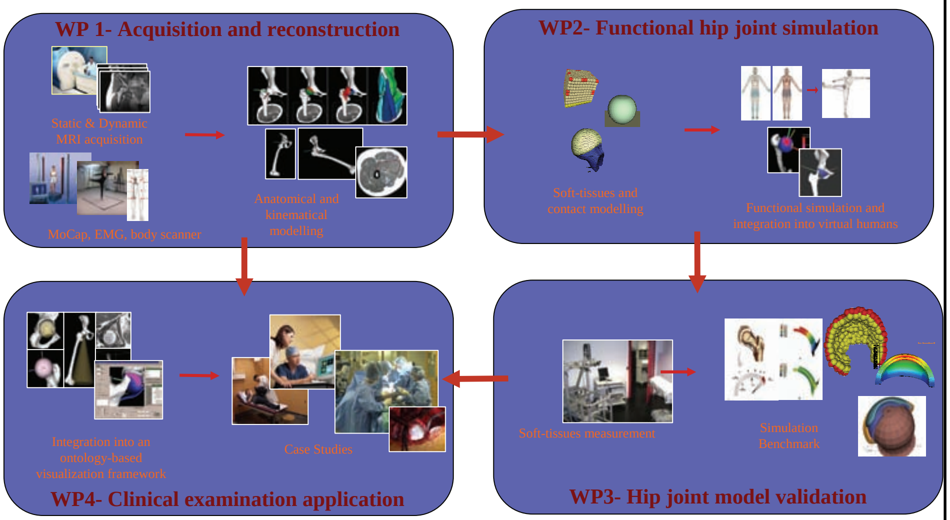
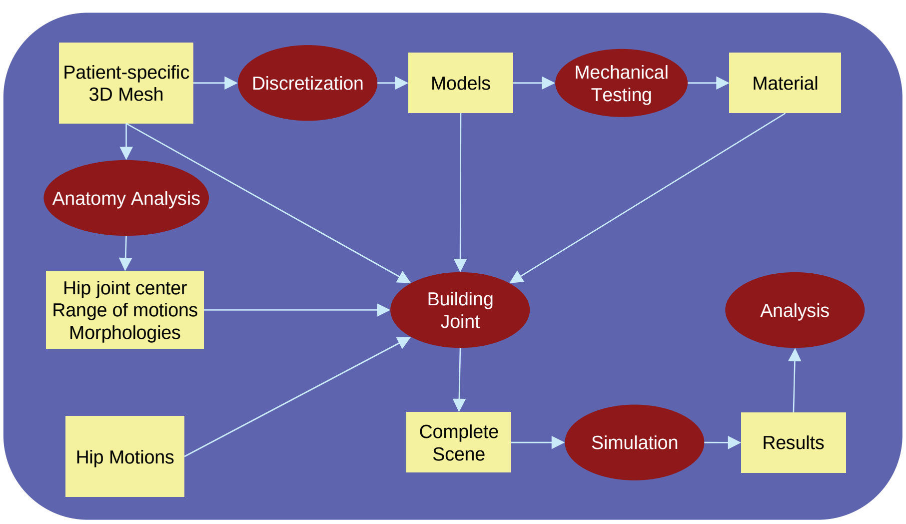
Interactive clinical visualization for hip joint examination

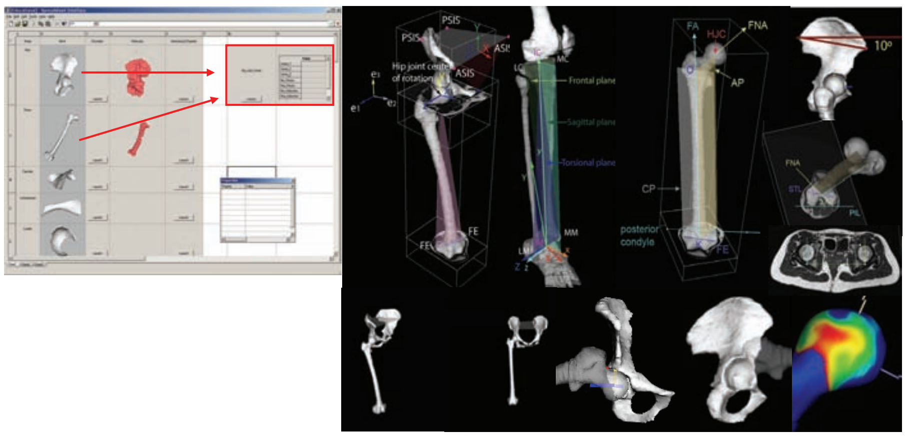


Clinical Examination Application – Pipeline



Analysis of Anatomical Information

Patient-Specific 3D Mesh → Analysis → Anatomical Information



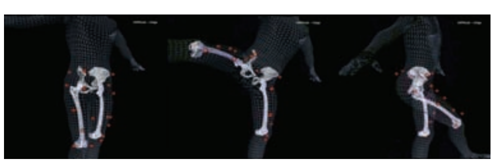
Simulation and Analysis

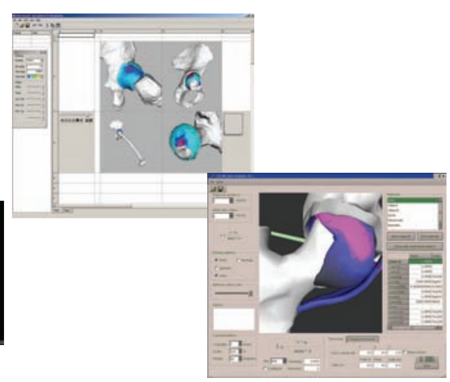
Building joint → Complete Scene → Simulation → Analysis

Extendable to Multi-level users

- Developer's level
- End-user (surgeon) level

Internal / external Hip joint examination tools

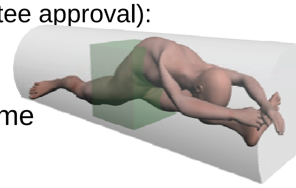




MRI Quantification of Maximum Hip Motions

Clinical study on young dancers (after local ethic committee approval):

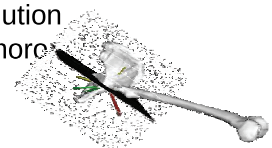
- Measure maximum flexion angles
- Visualize and quantify impingements
- Assess possible hip subluxation during extreme motion



→ 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 volonteers



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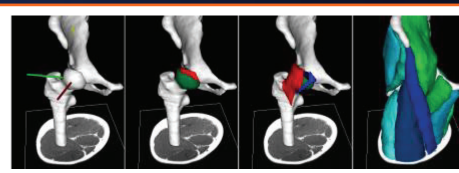
3D Anatomical Human

Marie Curie RTN

3dah.miralab.unige.ch



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

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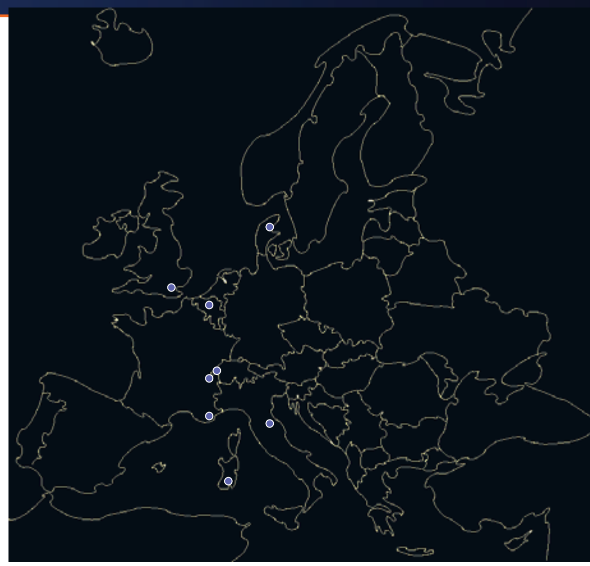
8 Partners

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



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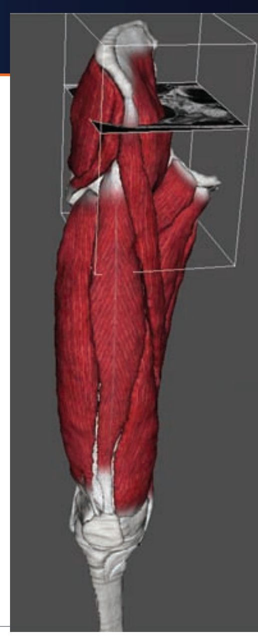
Main vision

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



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Major innovations

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

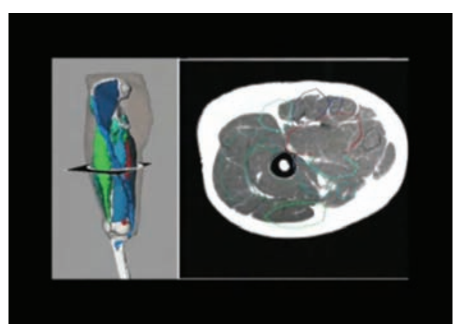
To detect anatomical anomalies and motion anomalies

- 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?)

Major innovations

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

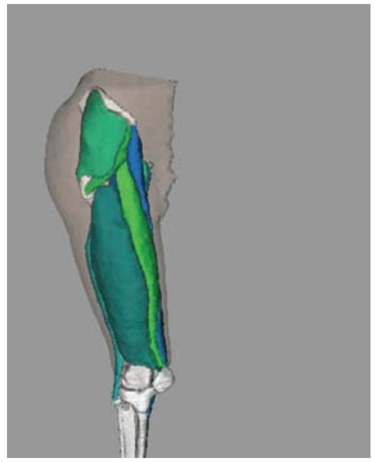
3D models reconstruction

Realistic simulation of biological soft tissues

Motion analysis

Motion modeling

Knowledge management and dissemination



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Medical imaging

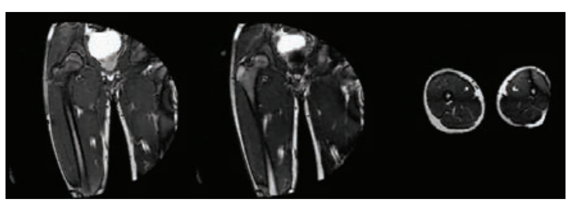
Task Leader: UCL

MRI

- No known harmful effects
- 16 volunteers

Develop new protocols

- Tissue-specific
- Static and dynamic
- Medically relevant
  - Movements
  - Postures
  - Joint loads



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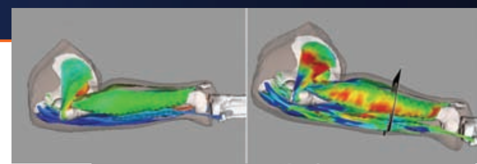
3D models reconstruction

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

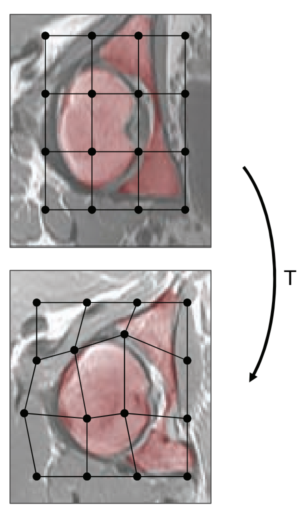
Prerequisite

- Digital Atlas of the structures to be segmented

3D models reconstruction

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

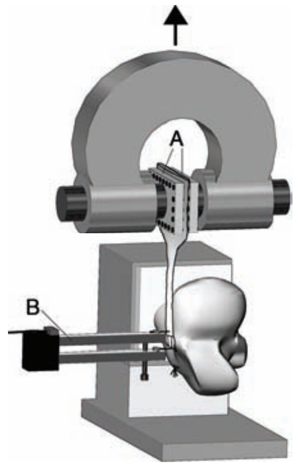
Task leader: IOR (U. Bologna)

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



Soft tissue simulation

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

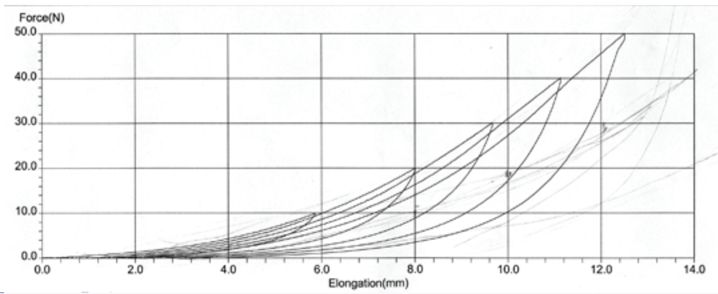
Soft tissue simulation

Mechanical properties of whole tendons

Tendon bundles

Bone-Ligament-Bone

Ligament bundles



Motion analysis

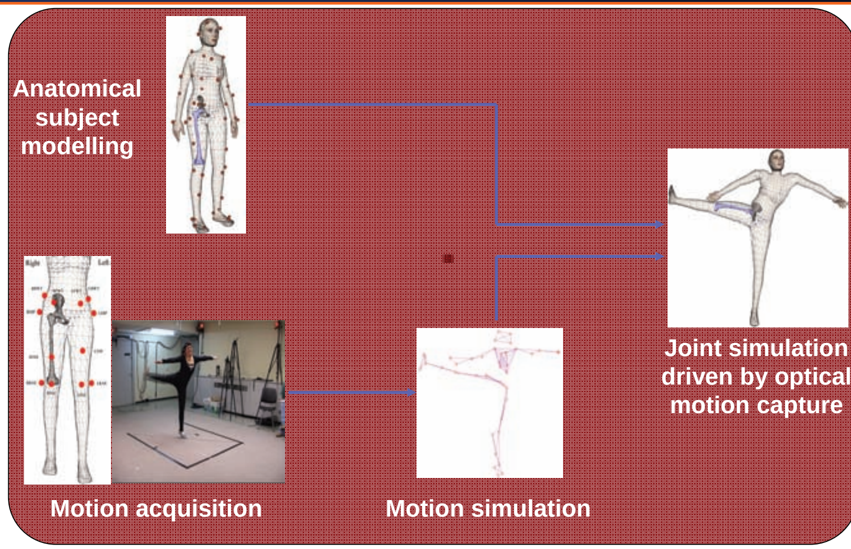
Task leader: Aalborg University

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



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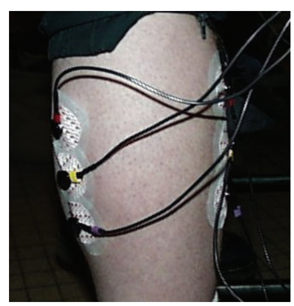
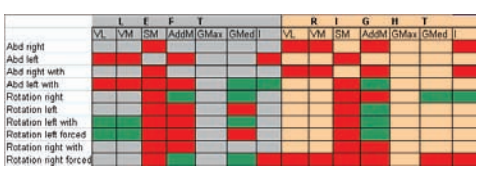
Motion analysis: EMG

Profile of muscle actuation from electromyography (EMG)

To perform the active simulation of the musculoskeletal system





Muscle actuation patterns

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Motion modelling

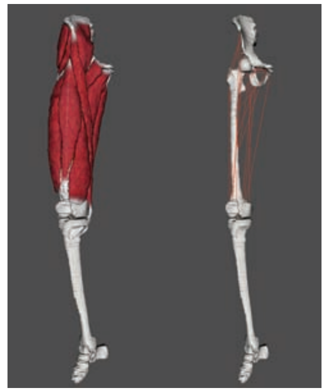
Task leader: EPFL

To build the kinematical skeleton from the reconstructed surface model

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

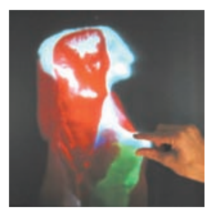
Several levels of details

- 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

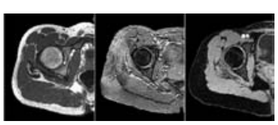
Bridge complementary approaches for modeling and simulation

Increase the awareness of the use of virtual reality technologies

Data Acquisition: medical imaging

Data	MRI	US	CT
Static	static	B-mode	static
Kinematics	Dynamic MRI (Cine) pc-MRI (Tagged) MRI	M-mode Doppler	Dynamic
Dynamics			
Mechanics	MR Elastography		
Physiology			

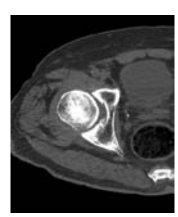
~ $1mm^3$



[heemskerk05]

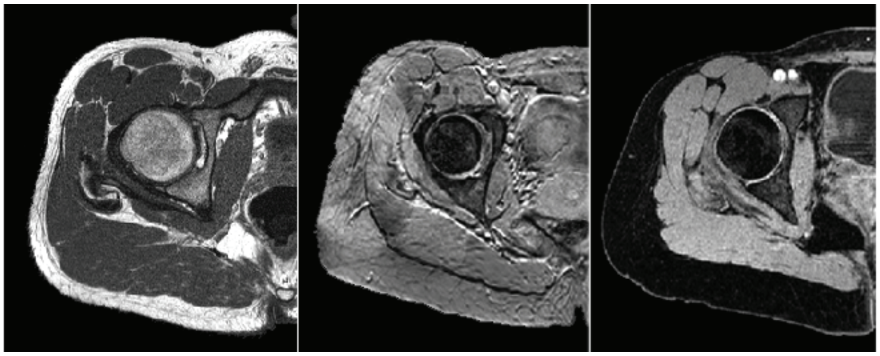
[Univ. california]

~ $1mm^3$



~ $0.25mm^3$

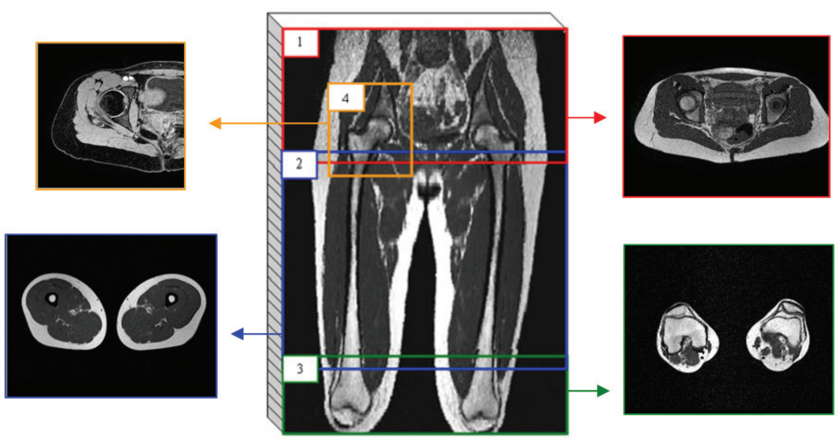
Data Acquisition: ex. static MRI



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

Data Acquisition: ex. static MRI

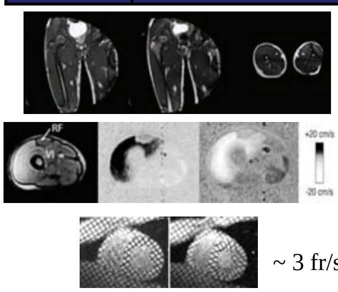
MIRALab – HUG **STATIC Protocol**



#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

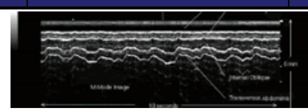
Data Acquisition: medical imaging

Data	MRI	US	X-rays / CT
Static	static	B-mode	CT
Kinematics	Dynamic MRI (Cine) pc-MRI (Tagged) MRI	M-mode Doppler	Fluoroscopy
Dynamics			
Mechanics	MR Elastography		
Physiology			

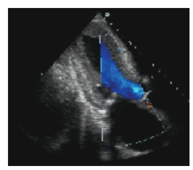


[delp02]

~ 3 fr/s

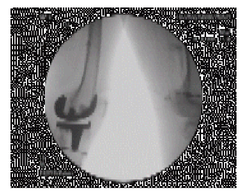


[Bunce04]



[anaesthesiaUK]

~ 60Hz



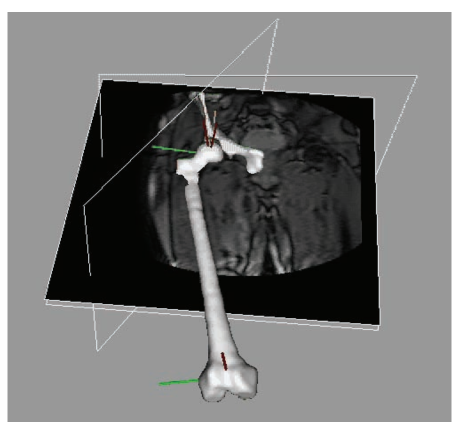
[ETHZ]

~ 50Hz

Data Acquisition: ex. Dynamic MRI

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

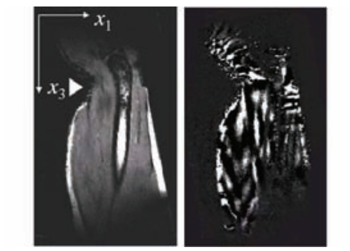
- Can serve to diagnosis
- Can serve to validate approaches that estimate this motion



MIRALab – HUG **DYNAMIC Protocol: fast gradient echo sequence**

Data Acquisition: medical imaging

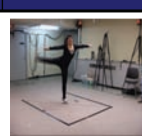
Data	MRI	US	X-rays / CT
Static	static	B-mode	CT
Kinematics	Dynamic MRI (Cine) pc-MRI (Tagged) MRI	M-mode Doppler	Fluoroscopy
Dynamics			
Mechanics	MR Elastography		
Physiology			

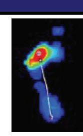


[papazoglou05]

Data Acquisition: other modalities

Data	Body scanner	Mocap	Plates	Mech. device	EMG
Static	Laser				
Kinematics		Electromagnetic Optical Mobile			
Dynamics			Pressure plates/soles Force plates	Pressure sensors Strain gauges	
Mechanics				Uniaxial/ biaxial	
Physiology					Surface EMG Needle EMG

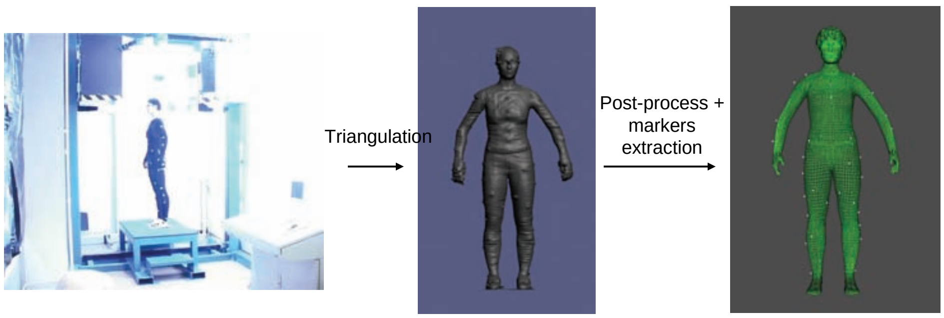






3D body scanning

This modality digitalizes accurate skin models of the complete body

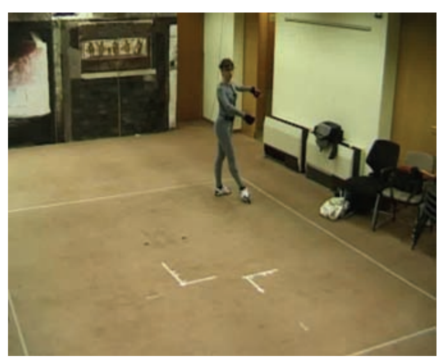
3D body scanning is also used to extract the position of the markers for the motion capture



Optical motion capture (MoCap)

This involves to record optical markers on the skin with digital cameras

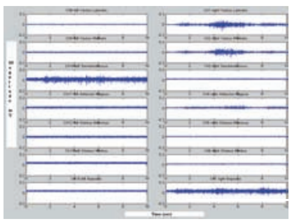
Then, the joint kinematics are reconstructed in 3D from the markers trajectories



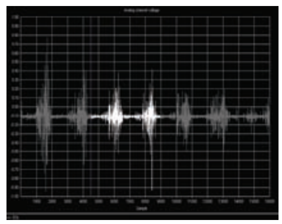
EMG

- 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

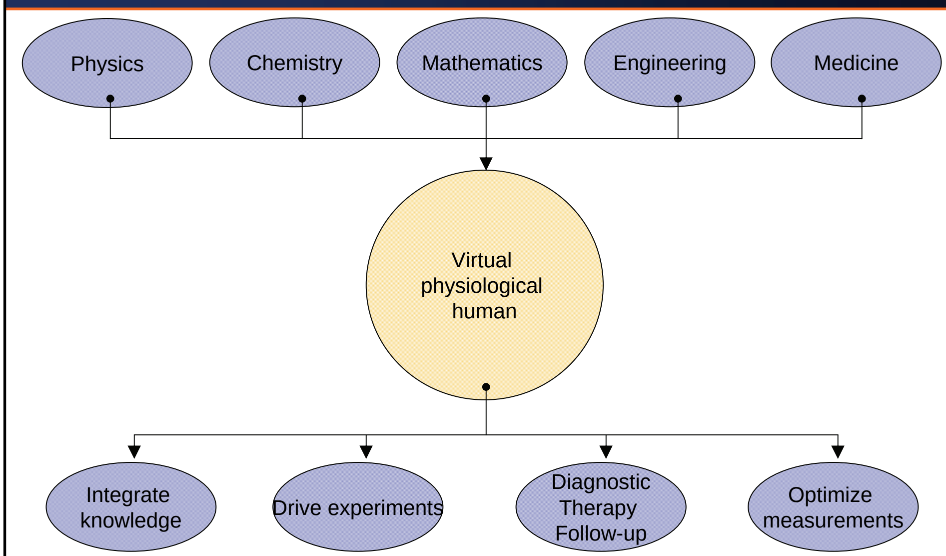
Introduction and introductive examples

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

Section Overview

- **Introduction anatomical modelling**
- **Direct segmentation**
- **Registration**
- **Examples**

Anatomical Modelling



Anatomical Modelling

Modelling and simulation at the macroscopic scale

Parameterisation/ validation

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

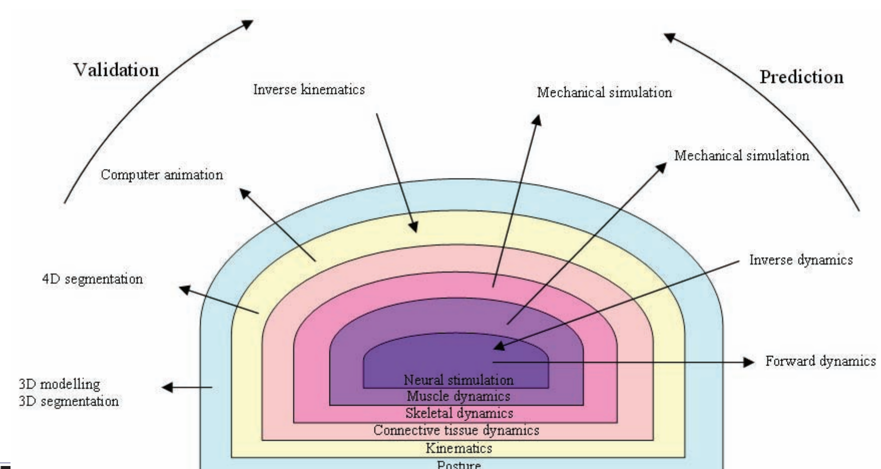
Complexity ↓

Prediction

Example: musculoskeletal modelling (1/5)

Musculoskeletal system at macroscopic scale → mostly relevant to CG

Its functioning presents a nested nature with increasing complexity



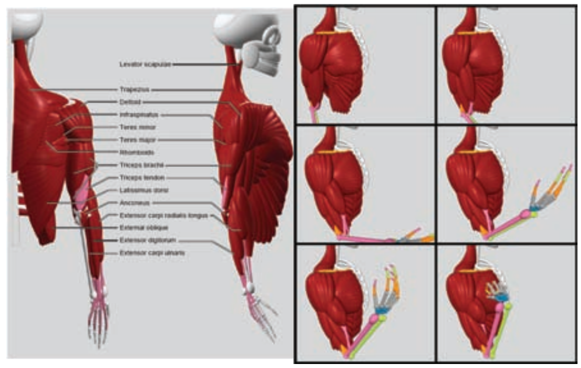
Example: Musculoskeletal Modelling (2/5)

[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

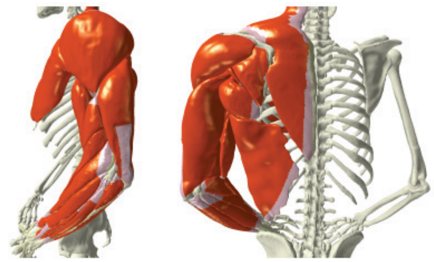
Example: Musculoskeletal Modelling (4/5)

[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



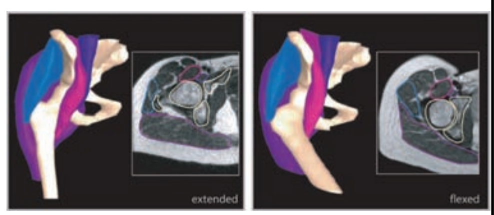
Example: Musculoskeletal Modelling (5/5)

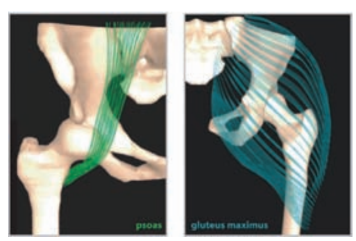
[Blemker and Delp2005]

- 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

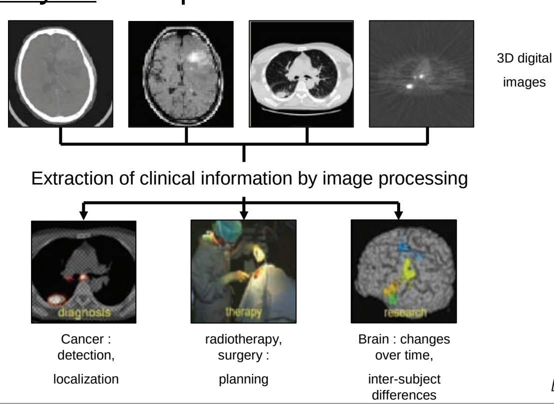
Jérôme Schmid – *MIRALab, University of Geneva, Switzerland*

Image analysis

Today, imaging becomes a routine clinical tool

But we measure much more than we can understand

→Image analysis is required



[Vandermeulen]

Image analysis

Acquisition: Measurement of physical properties

For computation, images are discretised (digitalised) :

- In space, in time or in intensity

Image noise

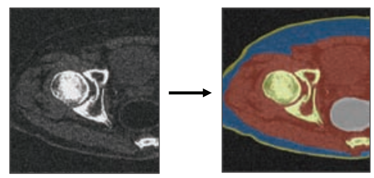
- Due to the acquisition devices or methods (e.g., speckle noise in US, bias field in MRI)

Artifacts

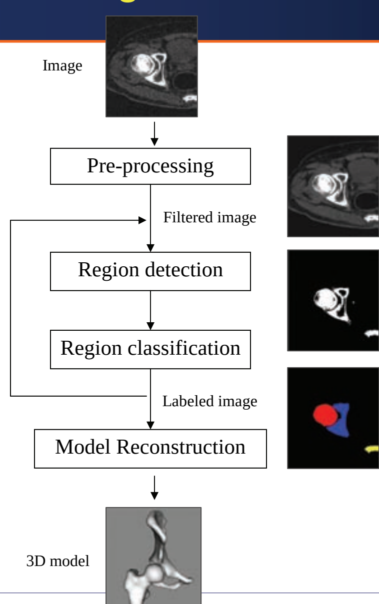
- Due to Partial volume effects (PVE) (Multiple tissues contribute to a single voxel)
- Due to Patient movement, incorrect calibration (e.g., wave-speed in US)

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:

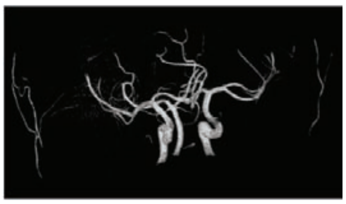
- region growing
- region splitting
- fuzzy connectedness, Watershed

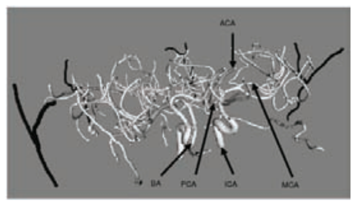
Model Reconstruction:

- 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]

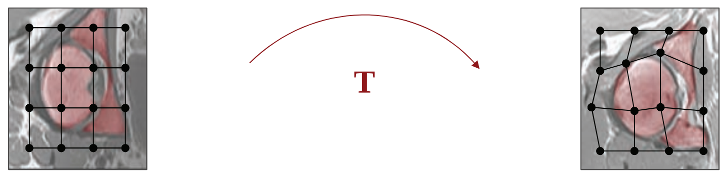




Direct segmentation

- Usually direct segmentation is sensible to noise and not robust
- Prior knowledge can significantly improve it
  - 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

Registration



Source Image J **Target Image I**

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], [maintz98],[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

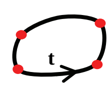
Two approaches:

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

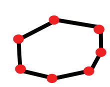
Registration features (2/3)

Three types of deformable models:

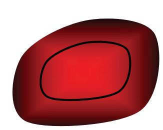
- Continuous models [kass88], [terzopoulos88], [cootes01]



  - Mapping between material parameters and spatial coordinates
    - For example, in 3D: $\mathbf{u} \in [0,1]^p \rightarrow [x(\mathbf{u}),y(\mathbf{u}),z(\mathbf{u})]^T \in \Re^3$
    - 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: $\{ \mathbf{p} \in \Re^3 \mid F(\mathbf{p})=0 \}$

Reviews: [McInerney96], [Jain98], [montagnat01], [nealen06]

Registration features (3/3)

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

Registration outline

What is registered: **Registration features**

[redacted] **Similarity measure**

How to constrain the problem: **Regularisation**

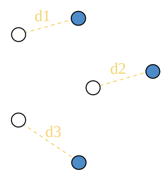
How the registration is performed: **Evolution**

Similarity measure (1/4)

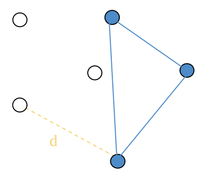
Geometric registration:

→ Minimise the distance btw geometric features

- Two points:
  - Euclidian distance: $d = [\Sigma_3(x_j\text{-}y_j)^2]^{1/2}$
  - p-order Minkowski distance: $d = [\Sigma_3(x_j\text{-}y_j)^p]^{1/p}$



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



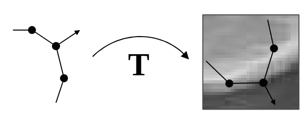
Similarity measure (2/4)

Iconic registration:

→ Align the source model to contours in the target image

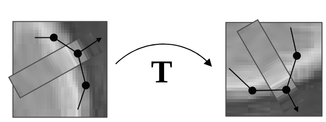
- Maximise gradient magnitude : $d = -\,||\nabla I||$
- Align model and image gradient : $d = \pm\, \nabla \mathbf{I}.\mathbf{n}$

[kass88] [xu98]



→ Maximise the similarity btw icons

- Region of Interest (vertex neighbourhood) :
  - Blocks → template matching [ding01]
  - Direction of expected changes
    - Intensity profile matching [montagnat00]
    - (normalised) gradient profile matching [cootes93]

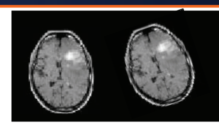


Similarity measure (3/4)

Intensity differences [horn81]

→ Assume intensity conservation: $I \approx T(J)$

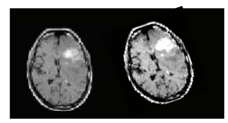
- Sum of absolute differences
- Sum of squared differences



Intensity correlation [holden00]

→ Assume affine correlation btw intensities: $I \approx \alpha T(J)+\beta$

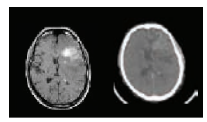
- Normalised cross-correlation



Histogram correlation [viola95], [wells96], [maes97], [roche00], [woods92]

→ Assume functional relation btw intensities: $I \approx \Phi(T(J))$

- Normalised mutual information
- (bi-variate) Correlation ratio
- Woods criterion

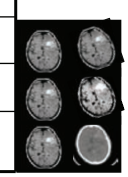


Use of

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

Similarity measure (4/4)

	Different modalities	Different protocols	Large displacements
Geometric *[audette00]*	Depends on the feature extraction algorithm		
Gradient *[kass88] [xu98]*	+	+	
Intensity differences *[horn81], [thirion95]*			+
Intensity correlation *[holden00]*		+	+
Histogram correlation *[viola95], [woods92]*	+	+	+



Registration outline

What is registered: **Registration features**

Registration criterion: **Similarity measure**

[redacted] **Regularisation**

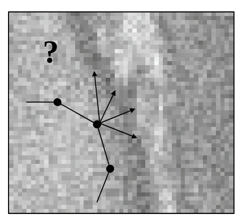
How the registration is performed: **Evolution**

Regularisation (1/5)

Noise

+ Local solutions

+ Aperture problem

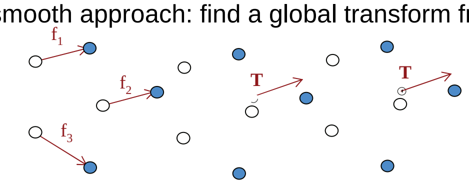


→ The problem needs to be constrained through parameterisation and internal forces

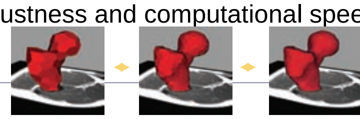
Regularisation (2/5)

Parameterisation

- Hypothesis about the form of the solution **T**
  → 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 [shen00] [szeliski96] [rueckert99] [ho04]
  → Improve robustness and computational speed



Regularisation (3/5)

global ↔ local

Transform	DOF	General form	
Centred rigid	3	$\delta \mathbf{p} = \begin{bmatrix} \mathbf{R}-\mathbf{I} & \mathbf{0} \\ \mathbf{0}^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix}$	
Rigid	6	$\delta \mathbf{p} = \begin{bmatrix} \mathbf{R}-\mathbf{I} & \mathbf{t} \\ \mathbf{0}^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix}$	
Similarity	7	$\delta \mathbf{p} = \begin{bmatrix} s\mathbf{R}-\mathbf{I} & \mathbf{t} \\ \mathbf{0}^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix}$	
Affine	12	$\delta \mathbf{p} = \begin{bmatrix} \mathbf{A}-\mathbf{I} & \mathbf{t} \\ \mathbf{0}^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix}$	
Projective	15	$\delta \mathbf{p} = \begin{bmatrix} \mathbf{A}-\mathbf{I} & \mathbf{t} \\ \mathbf{x}^T & v-1 \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix}$	
FFD (e.g cubic splines)	$3.N_x.N_y.N_z$	$\delta \mathbf{p} = \sum_{i,j,k}^{Nx,Ny,Nz} f_{i,j,k}(\mathbf{p}) \delta \mathbf{p_{i,j,k}}$	[sederberg86], [rueckert99]
Unstructured (e.g. RBF)	3.N	$\delta \mathbf{p} = \sum_i^N \mathbf{w_i}(\delta \mathbf{p_i}) \phi(\Vert \mathbf{p} - \mathbf{p_i} \Vert) + \mathbf{f}(\mathbf{p})$	[rohr96], [rohde03]
Constrained pairing	User-defined	Normals, image gradients (optical flow)…	[montagnat00], [thirion95]
Example-based	Sample size N	$\delta \mathbf{p} = \sum_i^N \delta w_i \mathbf{p}_i$	[szekely95], [cootes01]

Regularisation (4/5)

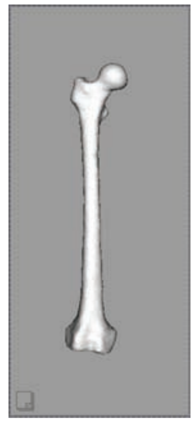
Internal constraints

→ Enforce shape continuity via energy minimisation

- Smoothing → Tikhonov differential stabilisers [terzopoulos87], [mcinerney95]
  - 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 [montagnat05] [pizer03]
- Shape constraints:
  - Shape variations modelling (e.g. ASM [cootes93])

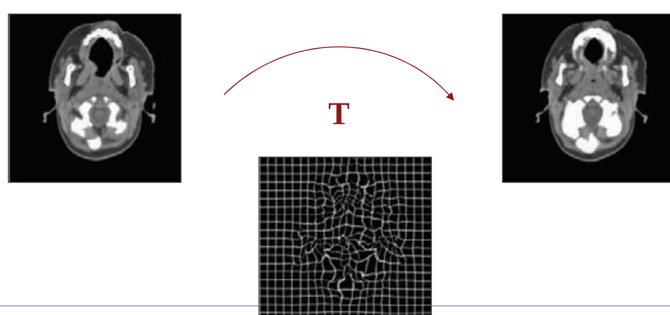
$$x \approx T(\overline{x} + \Phi.b)$$

- Volume preservation



Regularisation (5/5)

- Physically-based
  - Minimisation of the strain energy [christensen96], [bro-nielsen96], [wang00], [veress06]
    - Space discretisation with FDM, FEM or FVM
    - Linear elasticity (small displacements), hyperelastic, fluid
  - Collision handling [park01]
  - Topological constraints [yang04]



Regularisation (5/5)

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  - 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**

[redacted] **Evolution**

Evolution (1/4)

Explicit resolution [arun87] [pennec96]

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

$$A^* = \Sigma_i (X_i - \mu_X)(Y_i - \mu_Y)^T [\Sigma_i (X_i - \mu_X)(Y_i - \mu_Y)^T]^{-1}$$

$$t^* = \mu_Y - A^* \mu_X$$

- Pair & smooth approach [cachier02]
- Iterative closest point [besl92]

Evolution (2/4)

Energy minimisation = relaxation

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

→ The global minimum is reached at the price of computational cost

Evolution (3/4)

- Local methods = Oriented research
  - Bracketing: simplex (amoeba) method [nelder65]
  - Gradient descent → $\delta P = -\nabla E(P).dt$ [thirion95]
  - Powell's method → conjugate directions [Press92]
  - Newton (2nd order development) → $\delta P = -\nabla^2 E(P)^{-1}.\ \nabla E(P)$ [vemuri97]
  - Levenberg-Marquardt = Newton+ Gradient descent [Marquardt63]
  - Newton-Raphson (1st order development) → $\delta P = -\|\nabla E(P)\|^{-2}.E(P).\nabla E(P)$ [müller06]

- 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):

  $\delta P = V.dt$

  $\delta V = M^{-1}F(P,V).dt$

- Explicit schemes (Euler, RK) → Unstable for large time-step !!
- Semi-Implicit schemes (Euler, Verlet) → Unstable for large time-step !!
- Implicit schemes (Euler, BDF) → 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**

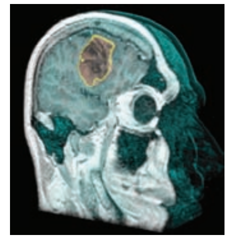
→Interactivity

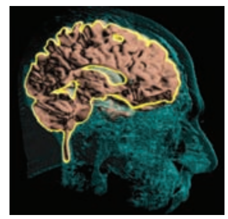
→Control and tuning

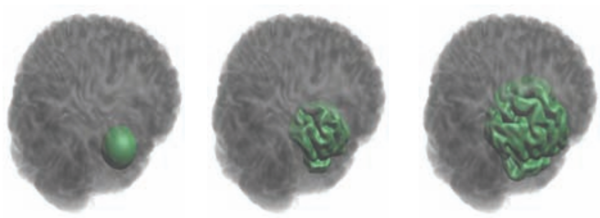
Level-set most popular [Lefohn03, hadwiger03, [klar07]

But also MI-based approach [Shams07, Tessmann08]

watershed [Stoev00] ...







[Lefhon03]

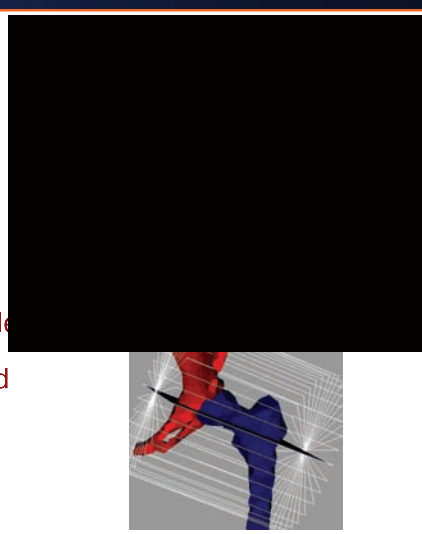
[Klar08]

Review: [Hadwiger2004]

Examples (1/4)

Bones modelling [gilles06, schmid08]

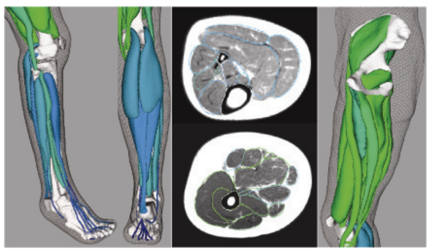
- Dynamic evolution
  - Implicit integration
  - CG resolution
- Multi-resolution approach
- External forces: intensity profil[redacted]
- Internal forces: Smoothing and PCA-based regularization

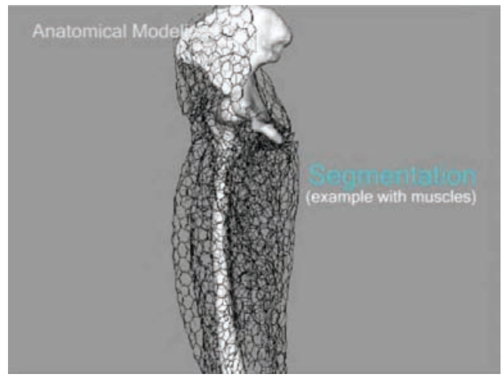


Examples (2/4)

Muscles modelling [gilles06, schmid08]

+ topological constraints (attachments)
+ radial forces
+ collision handling

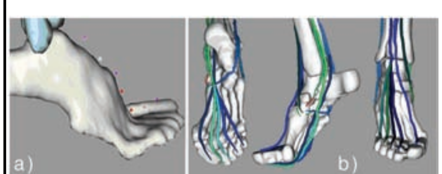


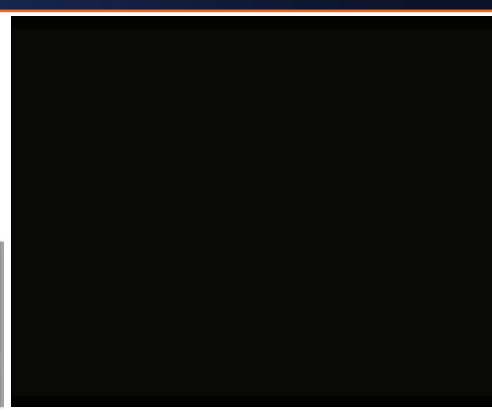


Examples (3/4)

Tendons modelling [schmid08]

+ tubular structures
+ semi-automatic tracing

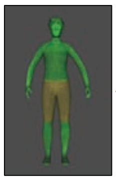




Examples (4/4)

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

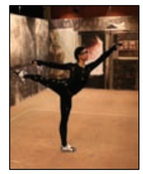
MoCap system: Vicon MX, 120 Hz



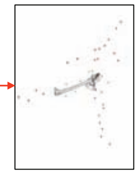
Body scanner data

registered data

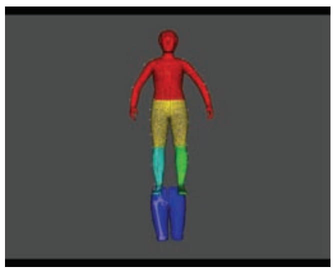
MRI segmented data



MoCap data



Simulation



Conclusion

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