Human 3D Anatomical

methods of segmentation and modeling of the hip

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Pula, Italy 21/05/2008

MIRALab
Where research means creativity

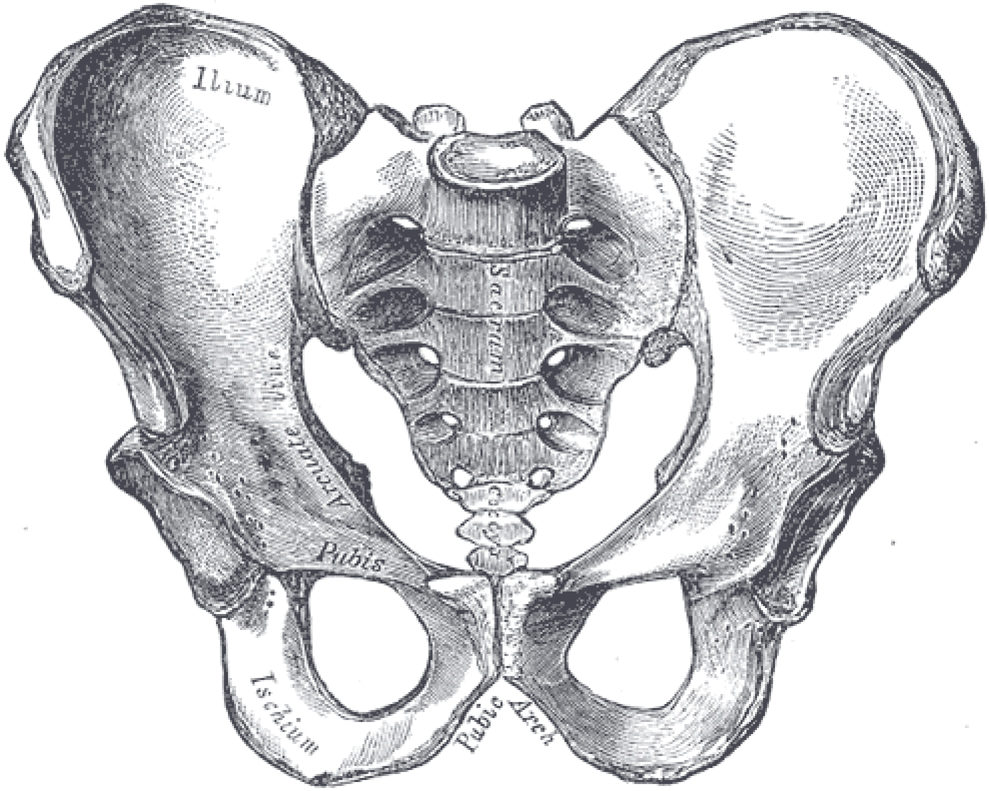
UNIVERSITÉ
DE GENÈVE

Outline

- Hip anatomy and clinical context
- Musculoskeletal modeling and problematic
- Acquisition
- Segmentation
- Results and applications

Hip Anatomy (1/5)

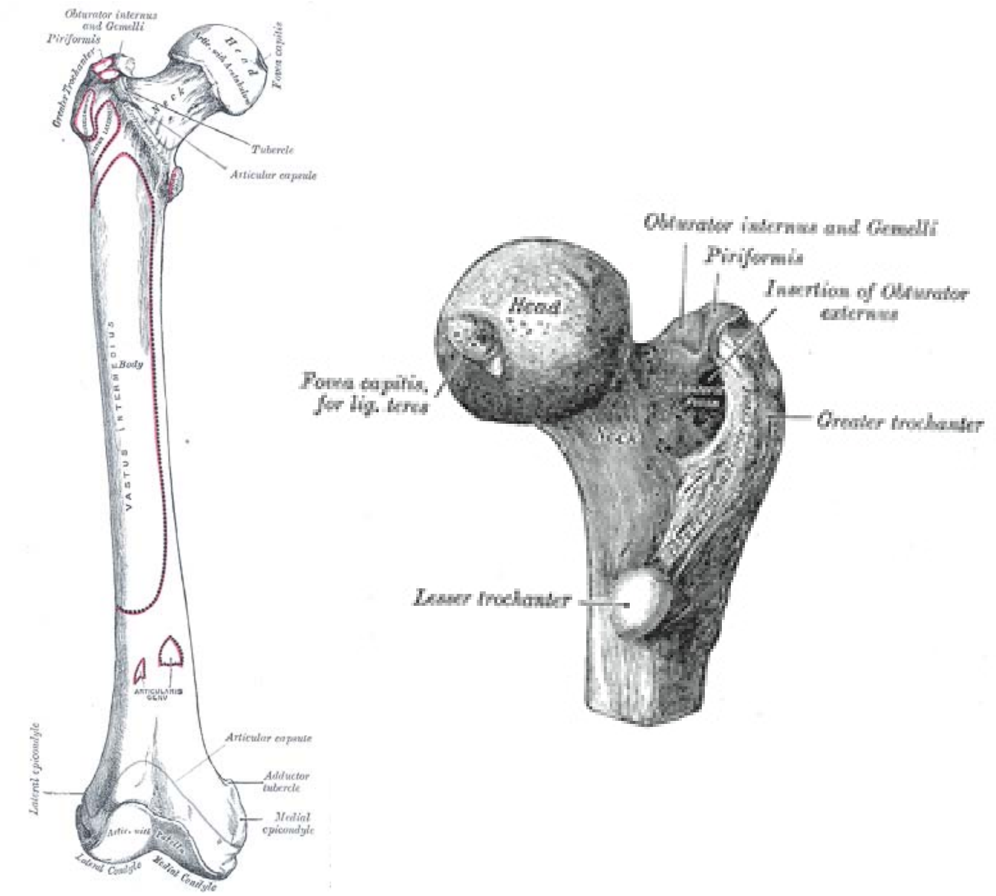
- Bones
  - Pelvis
    - Hip bone (ilium, ischium and pubis)
    - Coccyx
    - Sacrum



Henry Gray, 1918, Anatomy of the human Body

Hip Anatomy (1/5)

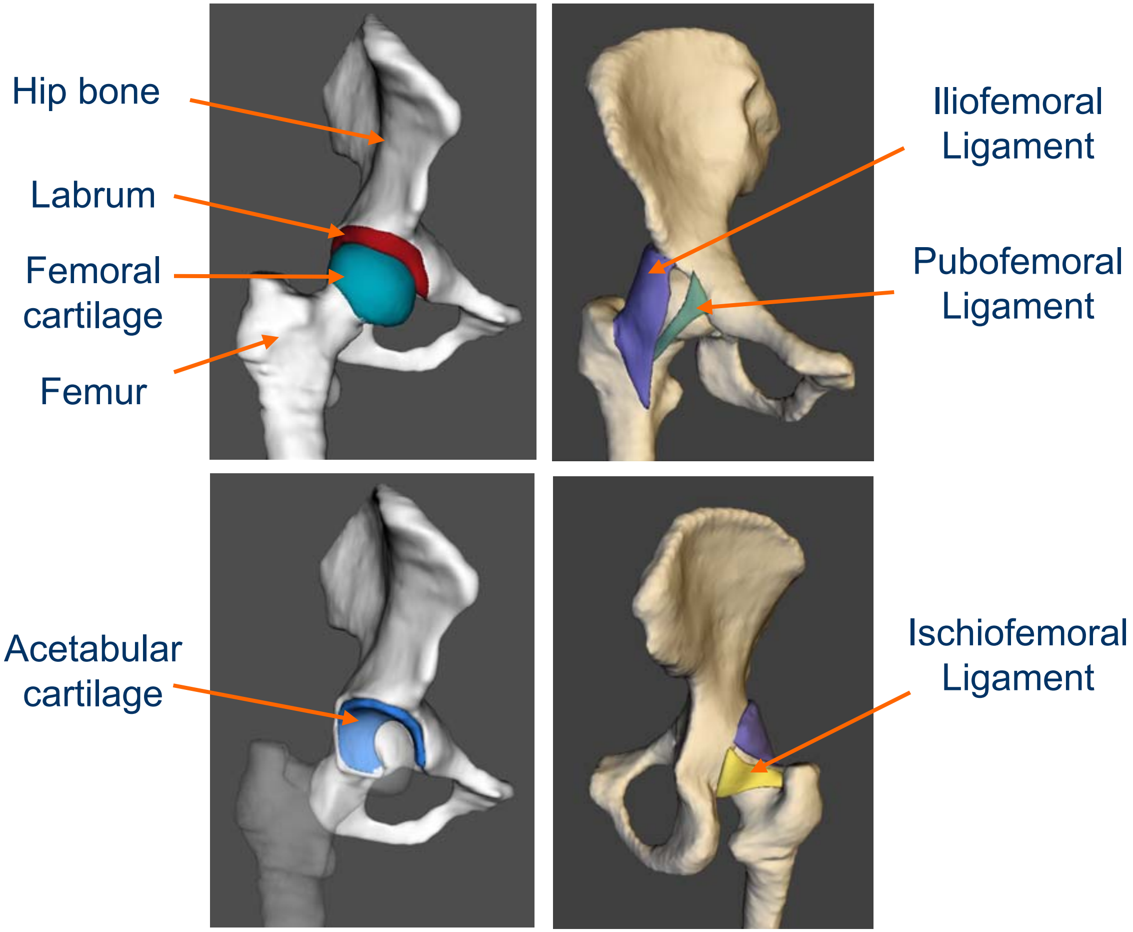
- Bones
  - Pelvis
    - Hip bone (ilium, ischium and pubis)
    - Coccyx
    - Sacrum
  - Femur



Henry Gray, 1918, Anatomy of the human Body

Hip Anatomy (2/5)

- Cartilages
  - Labrum
  - Femoral
  - Acetabular
- Ligaments
  - Iliofemoral
  - Pubofemoral
  - Ischiofemoral



Hip bone

Labrum

Femoral cartilage

Femur

Acetabular cartilage

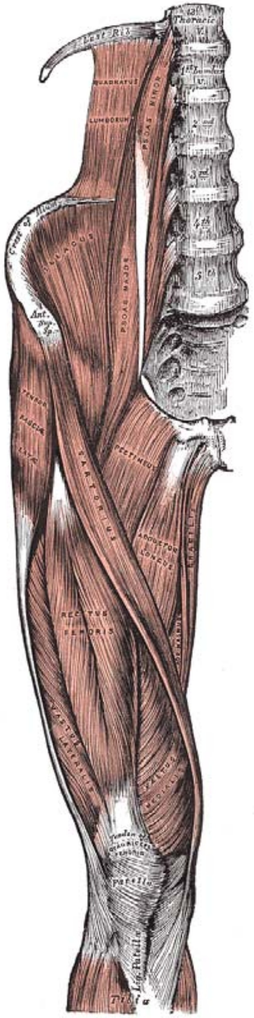
Iliofemoral Ligament

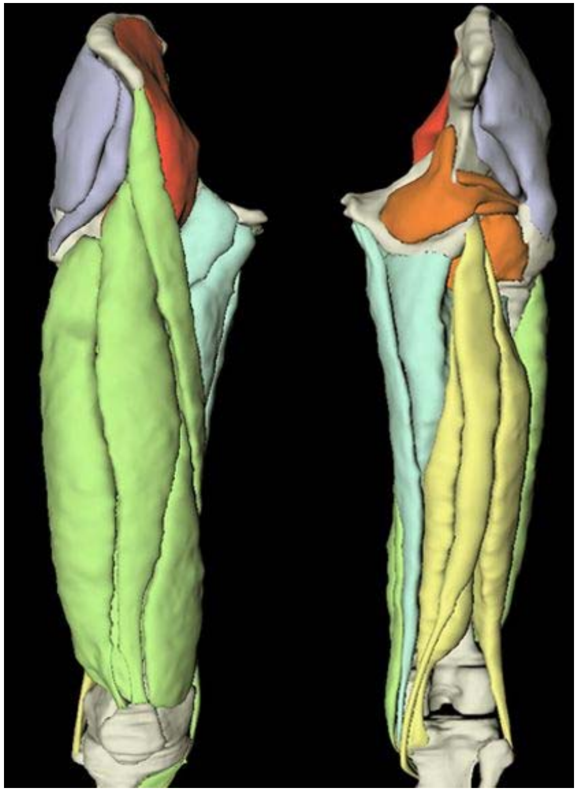
Pubofemoral Ligament

Ischiofemoral Ligament

Hip Anatomy (3/5)

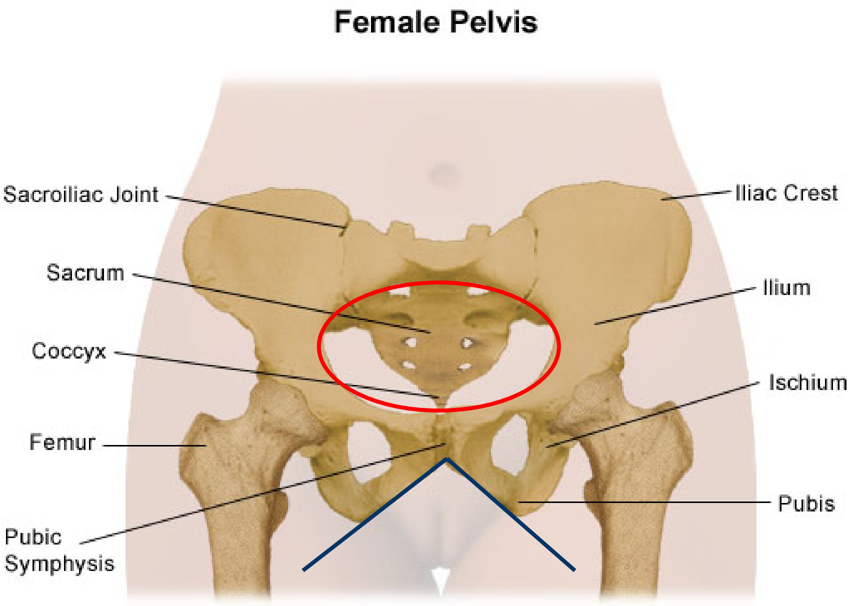
- Muscles of hip are those that cause movement in the hip
  - Muscles of iliac region
  - Muscles of thigh

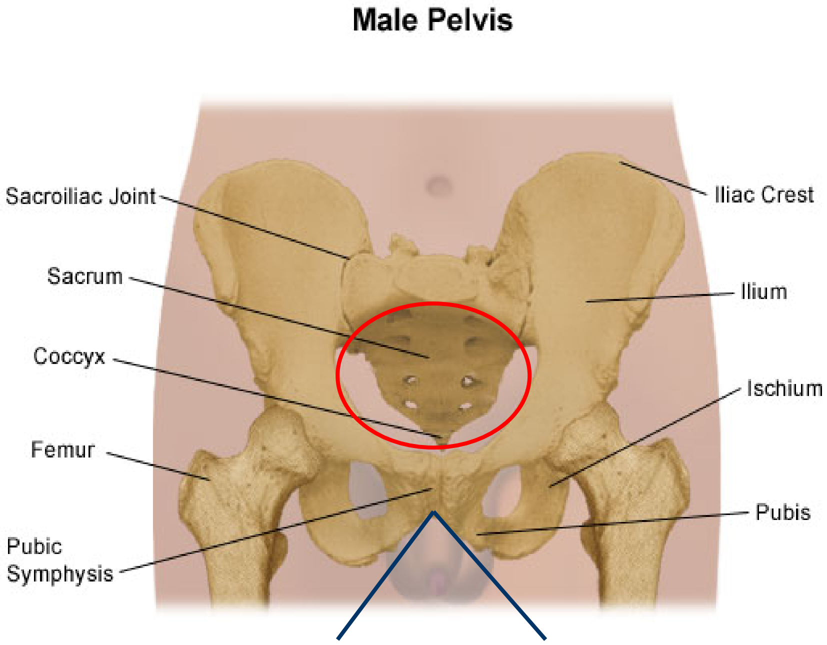




Hip Anatomy (4/5)

- Female/ Male differences



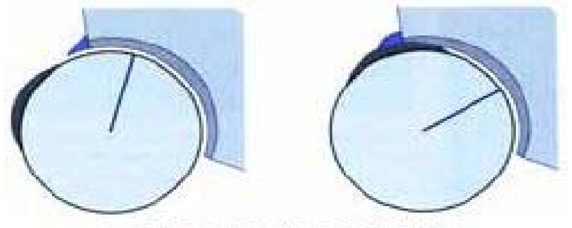


Hip Anatomy: Joint (5/5)

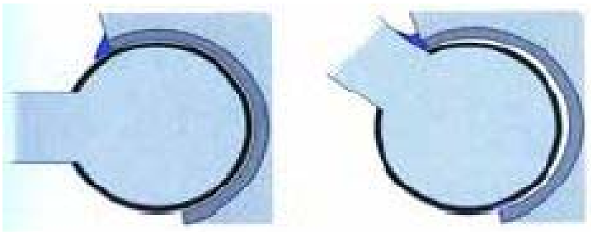
- Synovial joint
  - Wide range of movement (abduction/ adduction, flexion/ extension, int./ ext. rotation)
  - Capsule with lubricating fluid
- Modeled as a ball and socket joint
  - True for low amplitude movements
  - Not always valid with extreme movements (slight translations of rotation center)

Clinical Context

- Osteoarthritis (OA): hip joint degeneration
- Symptoms: impairment, stiffness, pain, inflammation and loss of mobility [1]
- Attack major joints and affect the majority of individuals over 50
- Origin hypothesis: repetitive and abnormal collisions (impingements)



CAM IMPINGEMENT



PINCER IMPINGEMENT

[1] D.T. Felson. *Clinical practice*. Osteoarthritis of the knee. N Engl J Med 354: 841-848, 2006

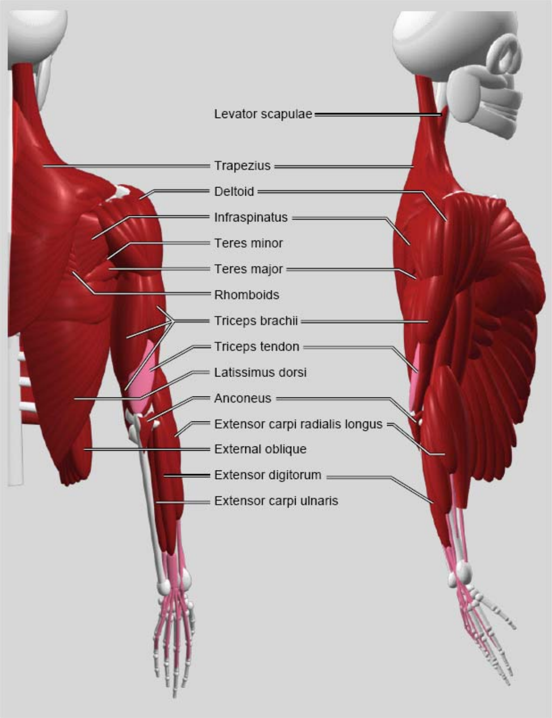
Musculoskeletal Modeling (1/4)

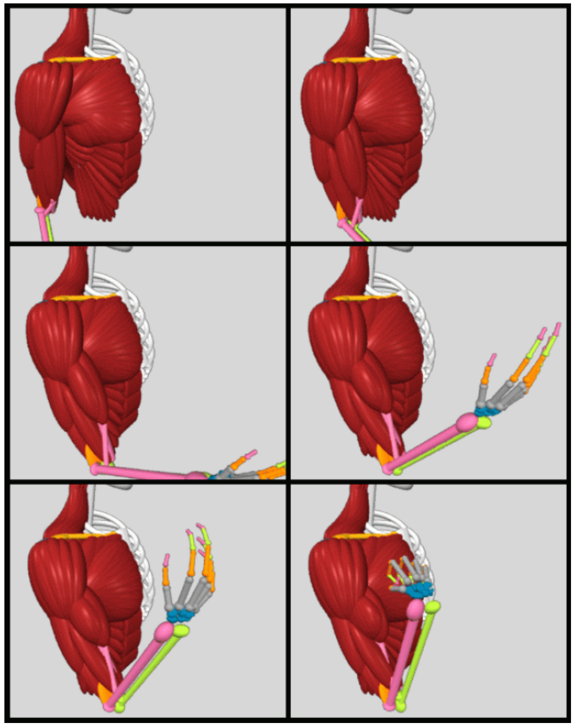
Scheepers et al. 97

- **Anatomical concepts**
- **Anatomical constraints**

BUT

- **Not patient-specific**
- **Unrealistic simplifications**





Scheepers, F.; Parent, R. E.; Carlson, W. E. & May, S. F. *Anatomy-based modeling of the human musculature*. SIGGRAPH '97, 1997, 163-172

Musculoskeletal Modeling (2/4)

Aubel and Thalmann 2001

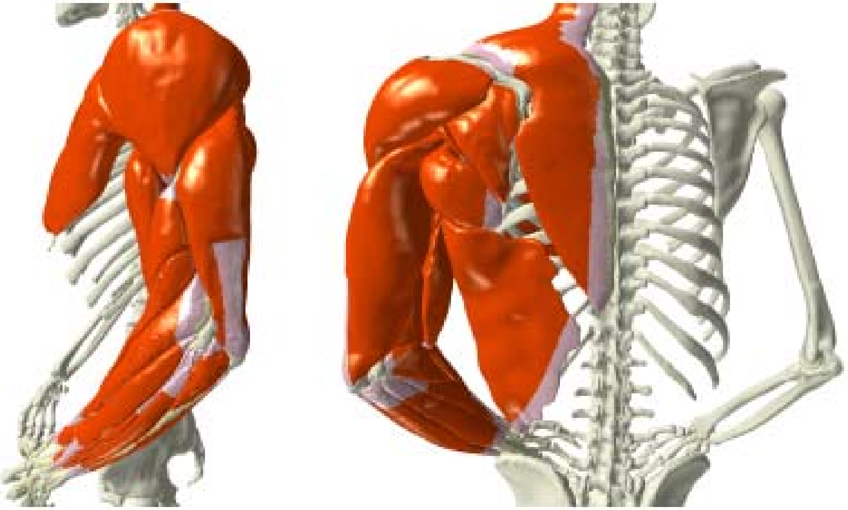
- **Anatomical Concepts (muscles, fat, bones)**
- **Anatomical constraints (e.g., attachements)**

BUT

- **Not patient-specific**
- **Interactive**
- **simplifications**

A. Aubel and D. Thalmann. *Interactive Modeling of the human musculature*. Computer Animation, 2001

Musculoskeletal Modeling (3/4)



Teran et al. 2005

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

BUT

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

J. Teran, E. Sifakis, S.S Blemker, V. Ng-Thow-Hing, C. Lau and R. Fedkiw. C*reating and Simulating Skeletal Muscle from the Visible Human Data Set*. I*EEE Trans. Visual. Comput. Graph.*, 2005, 11, 317-328

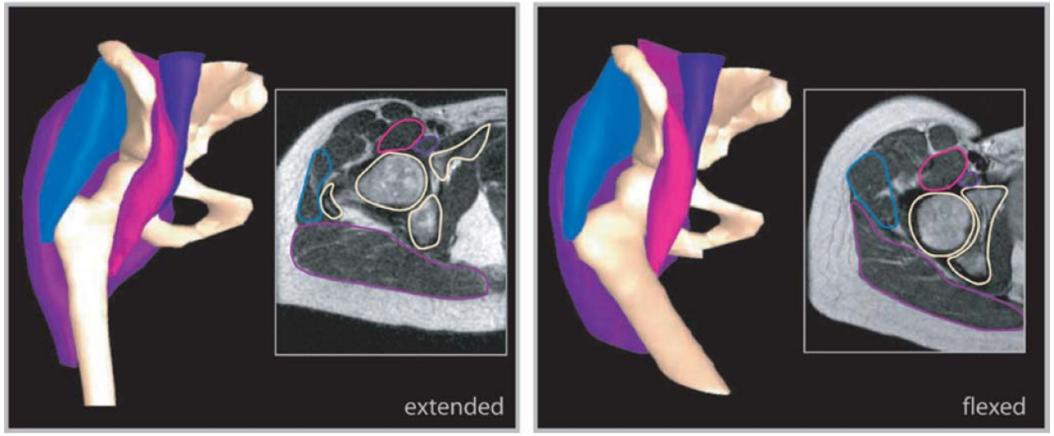
Musculoskeletal Modeling (4/4)

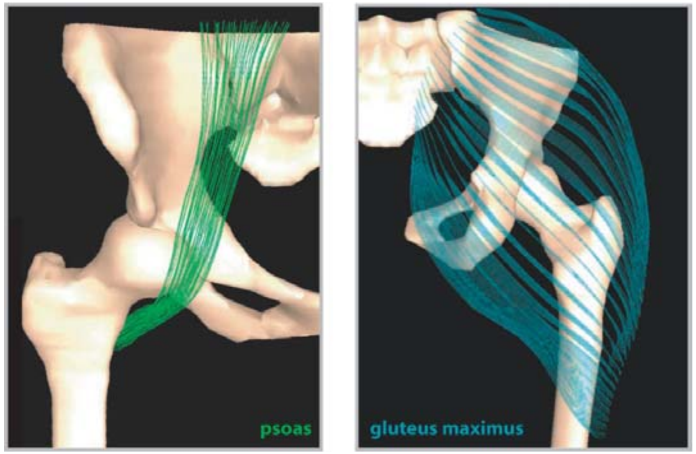
Blemker and Delp 2005

- **Complex Anatomical Model (e.g., fiber direction, FEM)**
- **Patient-specific (MRI segmentation)**
- **Medical validation**

BUT

- **Interactive (e.g., manual segmentation and attachments definition)**





S. Blemker and S. Delp.*Three-Dimensional Representation of Complex Muscle Architectures and Geometries*. Annals of Biomedical Engineering, 2005, 33, 661-673

Hip Modeling (1/2)

- For what?
  - Improve understanding
    - Cause OA: repetitive femoro-acetabular impingement?
  - Improve detection
    - Support early diagnosis
    - Provide more automatic and objective assessment
  - Improve treatment
    - Support corrective surgery planning: bone and labrum resection
    - Support arthroscopy
- How?
  - Acquire
    - Choose an adequate modality and define a protocol
  - Segment
    - Devise an efficient segmentation approach that considers anatomical constraints
  - Analyze
    - Provide tools for data examination and diagnosis

Hip Modeling (2/2)

- Requirements
  - High accuracy
  - Reasonable time
    - Acquisition + transfer time
    - Modeling time
  - Integration in clinical sites if possible
    - Direct clinical benefits
    - Provide valuable feedback
  - **Patient specific**

Modeling Problematic

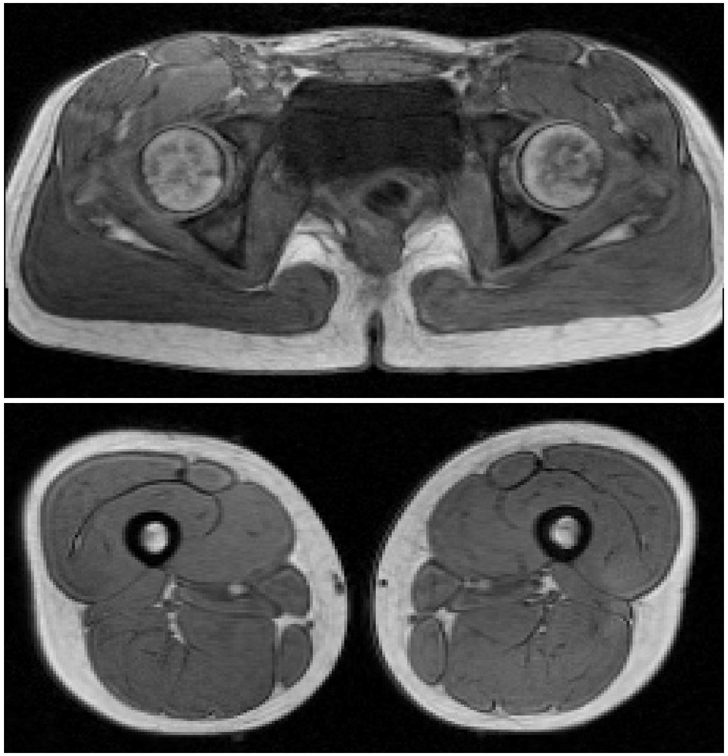
Goal: Extract from (multimodal) data patient anatomical structures

Context:

- MRI
  - Noise
  - A lot of textural information
  - Low resolution, partial volumes
- Musculoskeletal system
  - Many interconnected components in contact
  - Large displacements

Acquisition (1/9)

- Requirements
  - Volumetric data
  - Non invasive
  - Routinely used
  - Soft and bony tissue
  - Versatile



>> Magnetic Resonance Imaging (MRI)

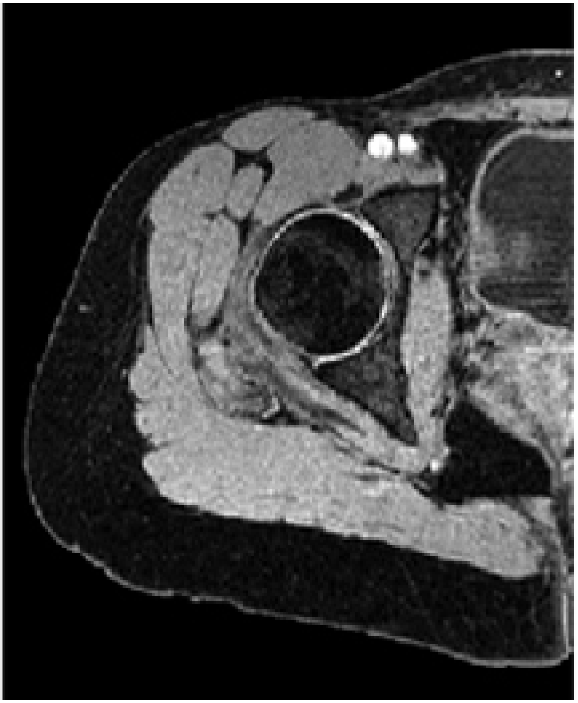
Acquisition: MRI (2/9)

- MRI aims at measuring the signal from the resonance of hydrogen atoms, contained in all tissues (water)
- In particular, MRI considers
  - T1 (longitudinal) and T2 (transversal) relaxation times
  - Proton density (tissue concentration in water)
  - Fluid flow

Acquisition: MRI (3/9)

Spin-echo T1,
TR=578ms, TE=18ms

Gradient-echo T2*,
TR=30ms, TE=14ms



Gradient-echo T1,
TR=20ms, TE=7ms

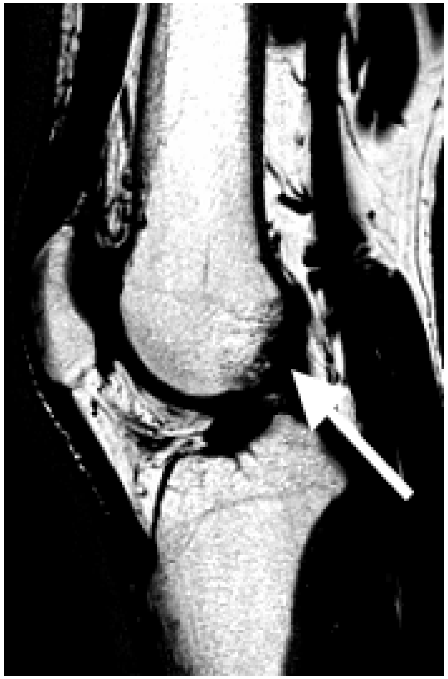
Acquisition: MRI (4/9)

T1-Weighted Short TR =
bone highlight

⊖

Fat suppressed scan

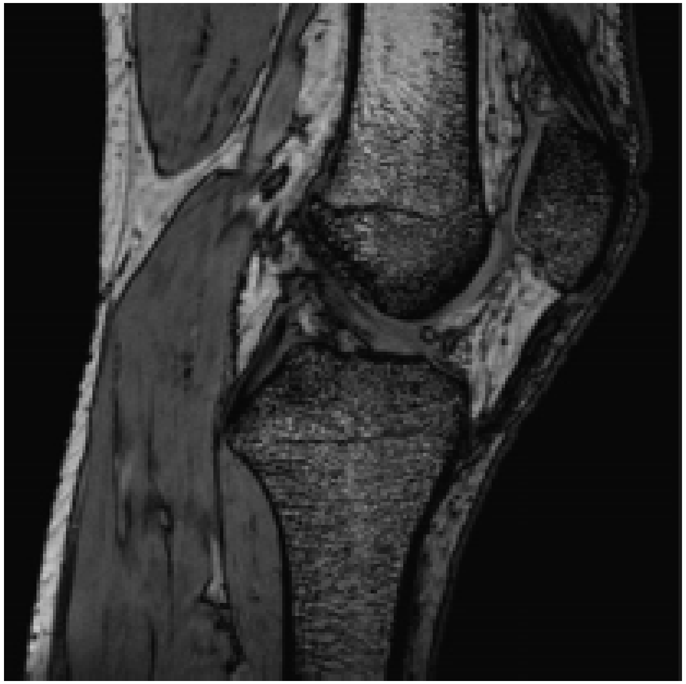
⊜



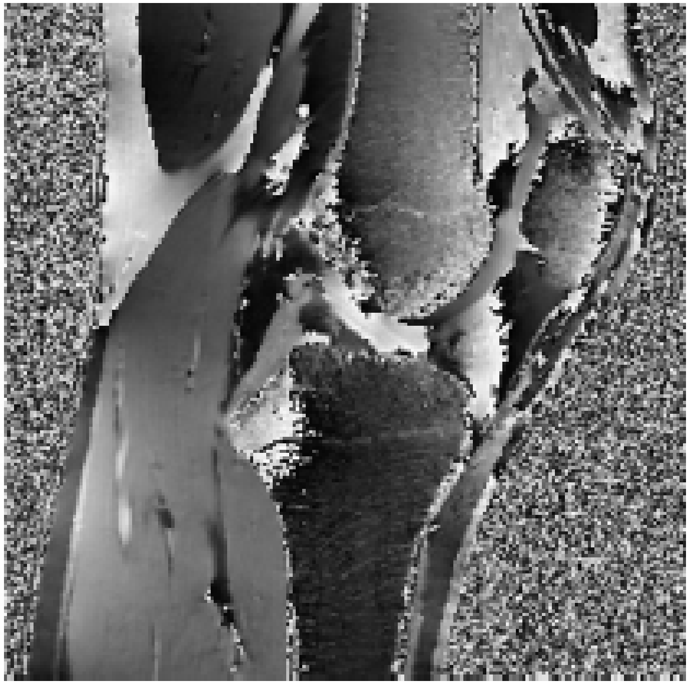
Difference image
(more adapted
for segmentation)

R. Dalvi, R. Abugharbieh, D. C. Wilson and D. R. Wilson. *Multi-Contrast MR for Enhanced Bone Imaging and Segmentation*. International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Lyon-France, 2007, 5620-5623

Acquisition: MRI (5/9)



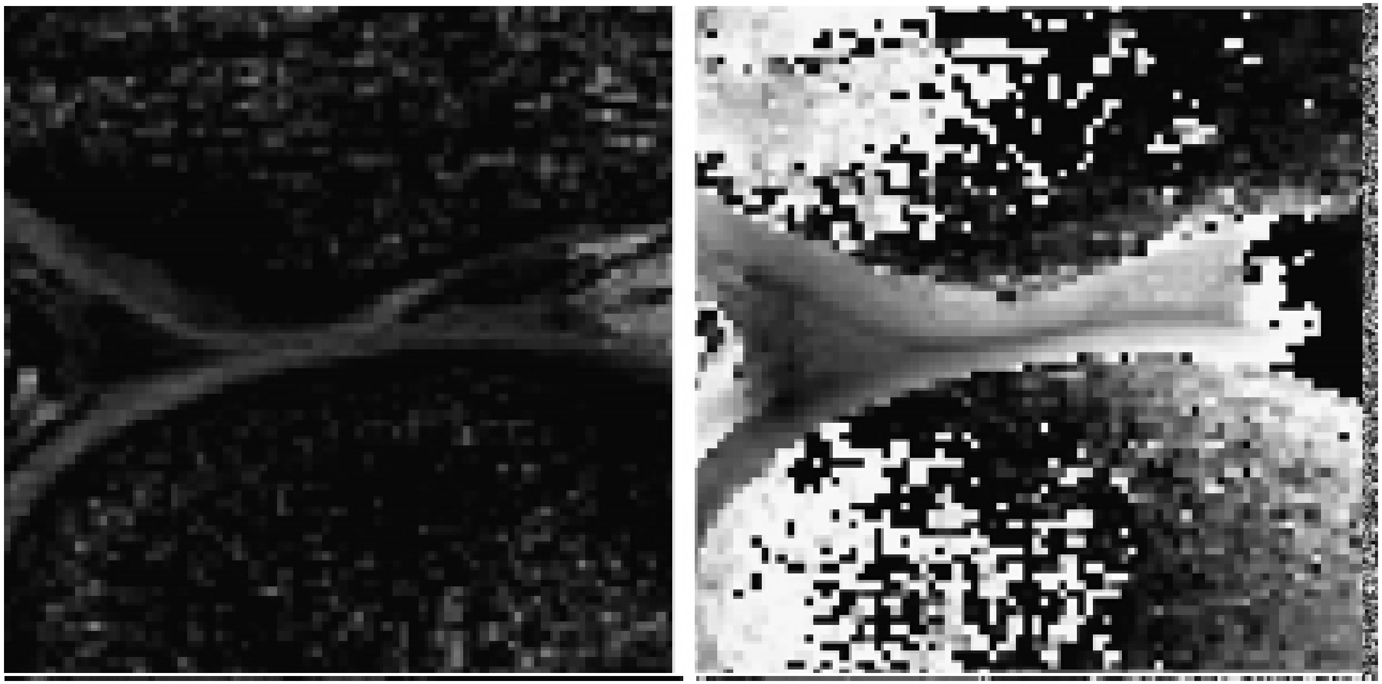
Magnitude of complex MRI signal



Phase of complex MRI signal

P. Bourgeat, J. Fripp, P. Stanwell, S. Ramadan and S. Ourselin. *MR image segmentation of the knee bone using phase information*. Medical Image Analysis, 2007, 11, 325-335

Acquisition: MRI (5/9)



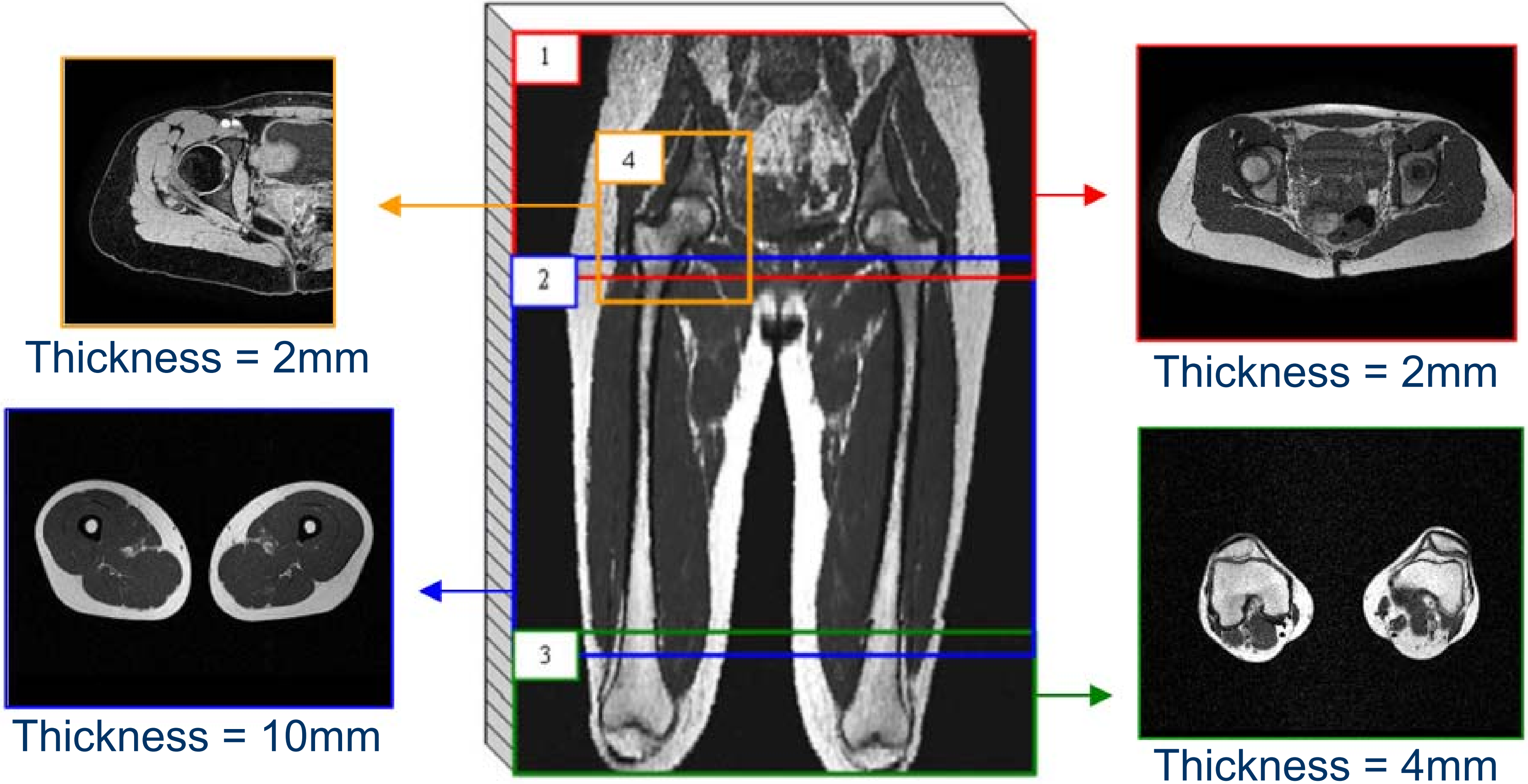
Detail: knee cartilage

Magnitude of complex MRI signal Phase of complex MRI signal

P. Bourgeat, J. Fripp, P. Stanwell, S. Ramadan and S. Ourselin. *MR image segmentation of the knee bone using phase information*. Medical Image Analysis, 2007, 11, 325-335

Acquisition: MRI (6/9)

MIRALab - HUG



Thickness = 2mm

Thickness = 2mm

Thickness = 10mm

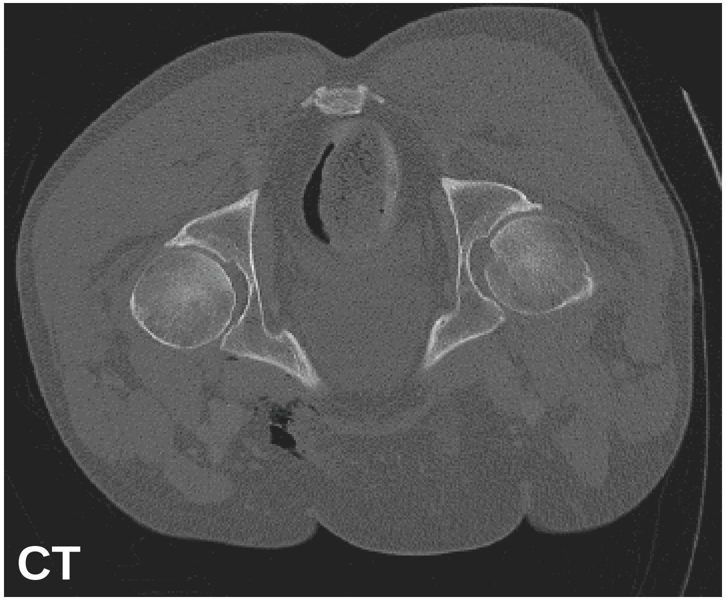
Thickness = 4mm

#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

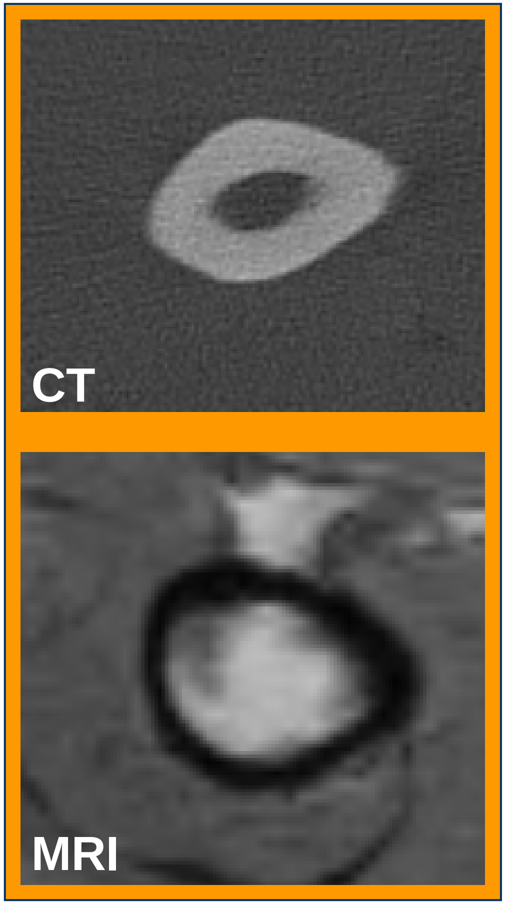
Acquisition: CT vs MRI (7/9)

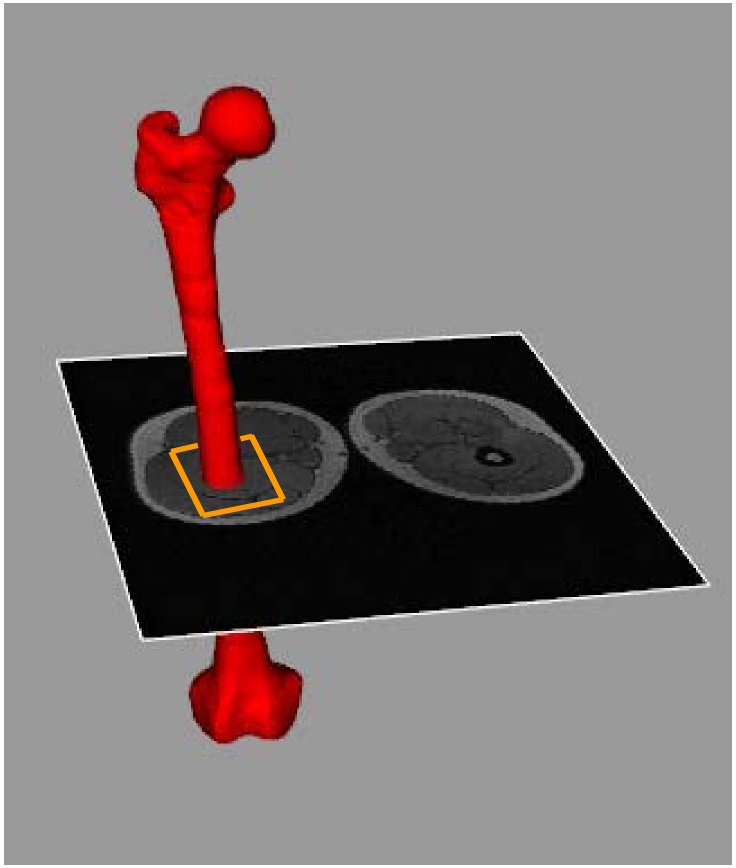
- Computed Tomography (CT)
  - Appropriate for bone imaging but some difficulties in presence of osteoporosis
  - Visualization of soft tissues is difficult
  - Invasive (exposure to X-ray radiation)

Acquisition: CT vs MRI (8/9)



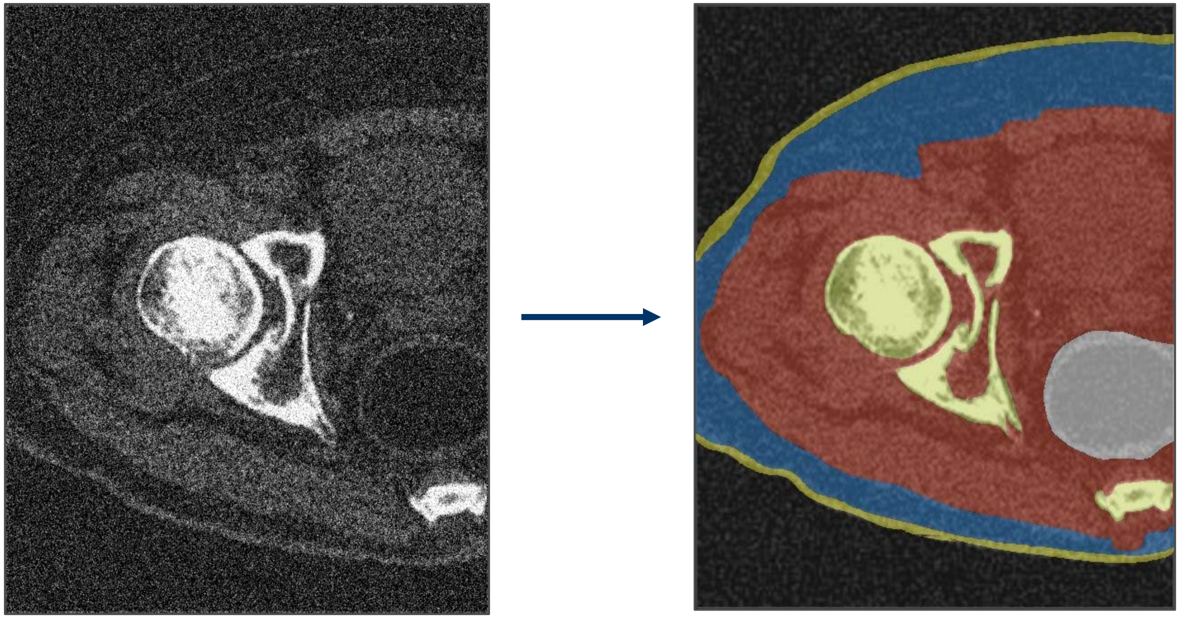
Acquisition: CT vs MRI (9/9)





Segmentation: definition

- Image partitioning
  - non overlapping regions
  - homogeneous regions



Segmentation: requirements

- Flexibility
  - Fit different type of organs (i.e., soft and bony organs)
- Control
  - Regularization
  - Constraints consideration
  - Possible interaction
- Efficiency
  - Robust to image noise and artefacts
  - Fast computation
  - Multi-resolution
- Accuracy

Segmentation: categories

- Direct segmentation methods
  - Thresholding
  - Region growing
  - Edge detection
  - Classification
- Registration methods
  - Image to image
  - Model to image
  - Model to model
- Hybrid methods

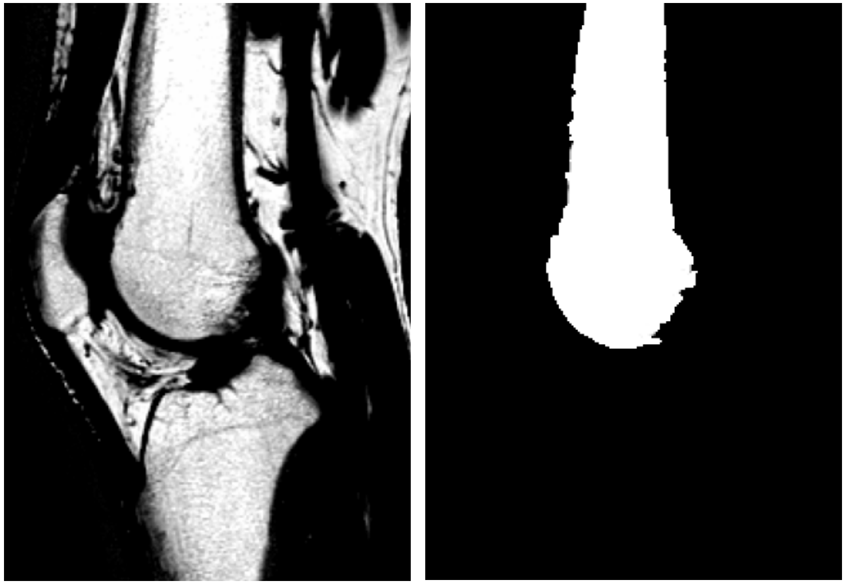
Direct Segmentation (1/2)

For complex problems, direct segmentation is:

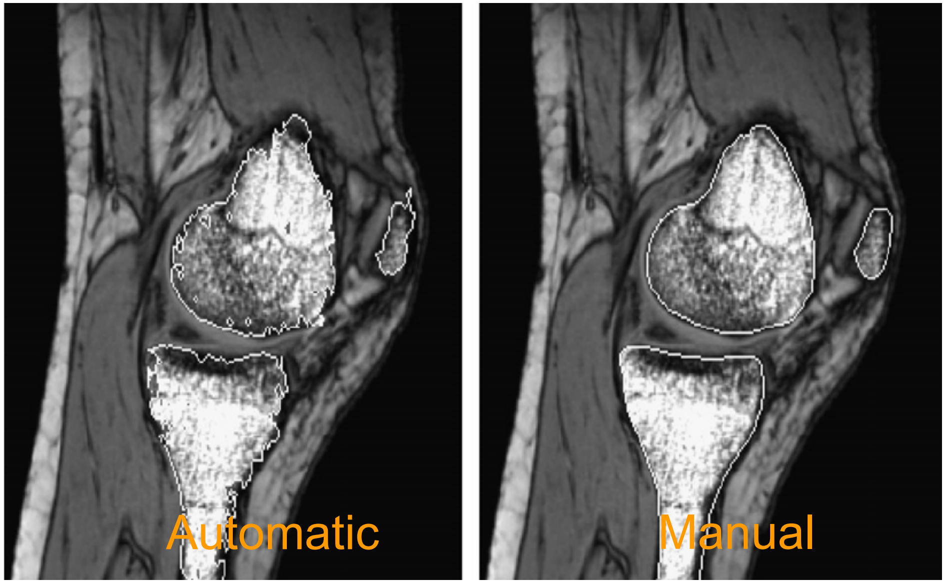
- Noise-sensitive
- Not robust
- Quite inaccurate

Direct Segmentation (2/2)

As a result, additional and more complex stages are used for a more efficient direct segmentation (e.g., training, pre-processing)



Dalvi et al.: MRI protocol + region growing

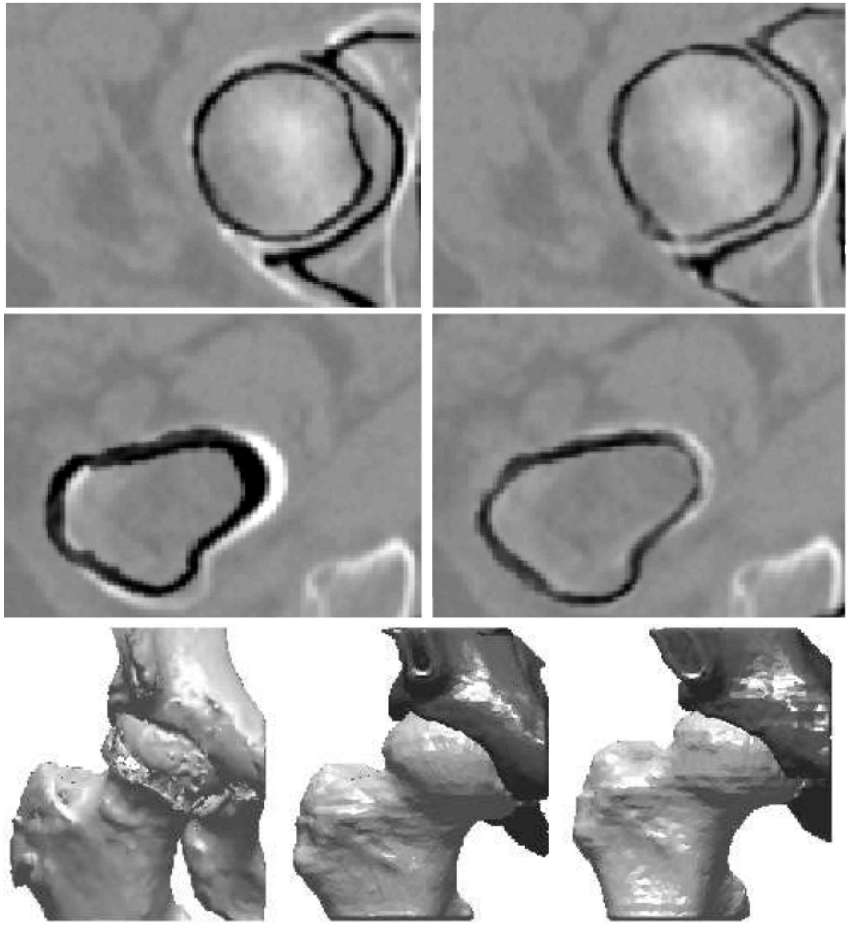


Bourgeat et al.: MRI protocol + classification (SVM)

Image to Image registration

Petterson et al. 2006

- Quadrature phase registration
- Multiscale and regularization
- Shape constraints not present
- Time?



J. Pettersson, H. Knutsson and M. Borga. *Automatic Hip Bone Segmentation Using Non-rigid Registration*. ICPR, 2006, 3, 946-949

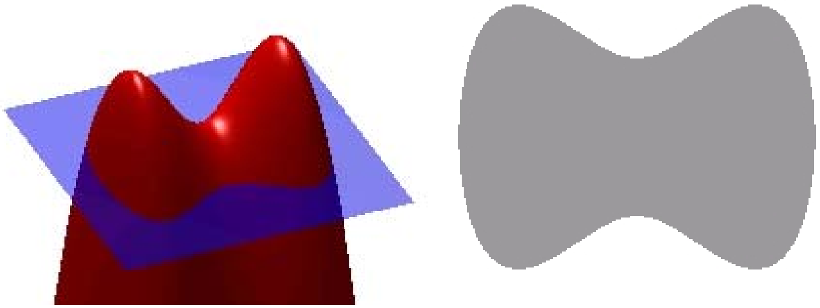
Model to Image registration

Lorigo et al. 1997

- Geodesic Active Contours
- Level set
- Exploit intensity and variance
- Cortical/ trabecular Intensity problem
- Possible leaking

$$E[(C)(p)] = \int_0^1 \underbrace{g(\ |\nabla I(C(p))|\ )}_{Boundary\ attraction} \underbrace{|\ \dot{C}(p)\ |}_{Regularity} dp$$

$$C_t = [g(|\nabla I|)\mathcal{K} - \nabla g(|\nabla I|) \cdot \mathcal{N}]\mathcal{N}$$



$$\phi_t = g(|\nabla I|)\mathcal{K}|\nabla\phi| \ + \ \nabla g(|\nabla I|) \cdot \nabla\phi$$

L. M. Lorigo, O.D. Faugeras, W.E.L. Grimson, R. Keriven and R. Kikinis. *Segmentation of Bone in Clinical Knee MRI Using Texture-Based Geodesic Active Contours*. MICCAI, 1998, 1195-1204

Model to Image registration

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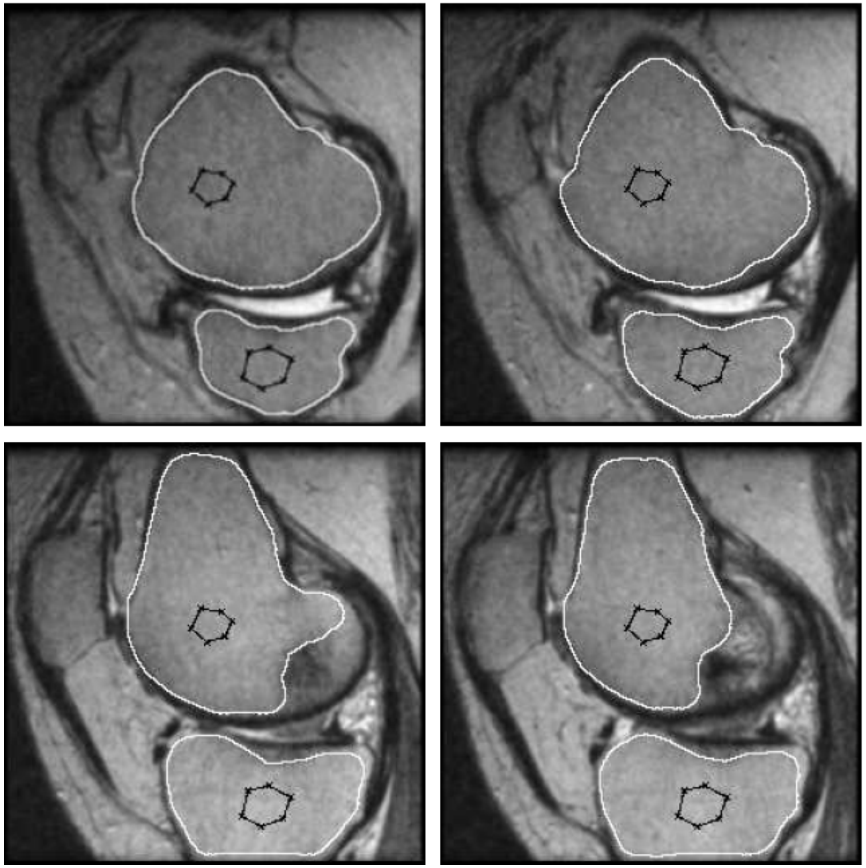
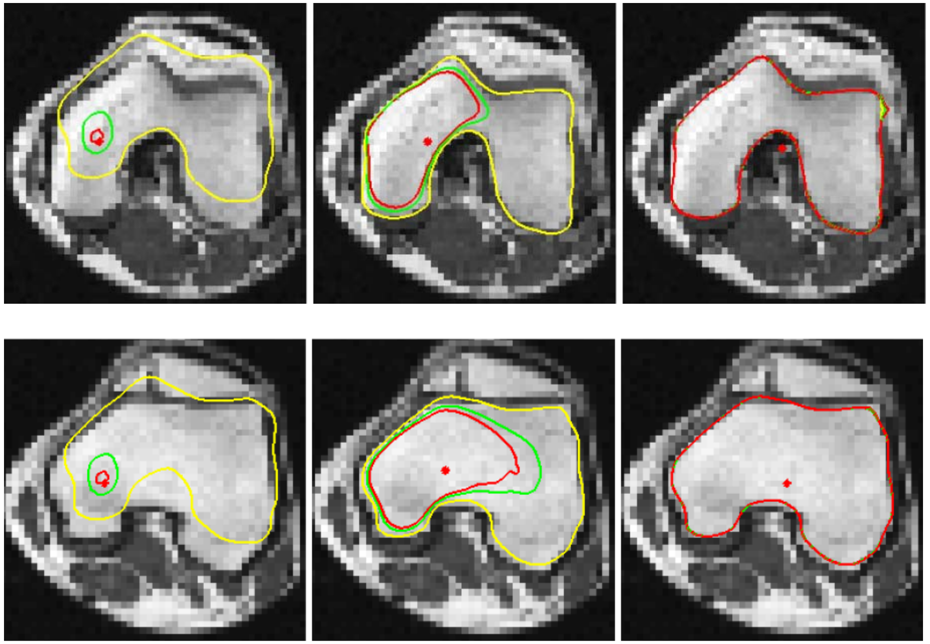


L. M. Lorigo, O.D. Faugeras, W.E.L. Grimson, R. Keriven and R. Kikinis. *Segmentation of Bone in Clinical Knee MRI Using Texture-Based Geodesic Active Contours*. MICCAI, 1998, 1195-1204

Model to Image registration

Leventon et al. 2000

- Levelset evolution
- PCA regularization
- MAP formulation
- Difficult to consider constraints
- Potential cortical/ trabecular Intensity problem

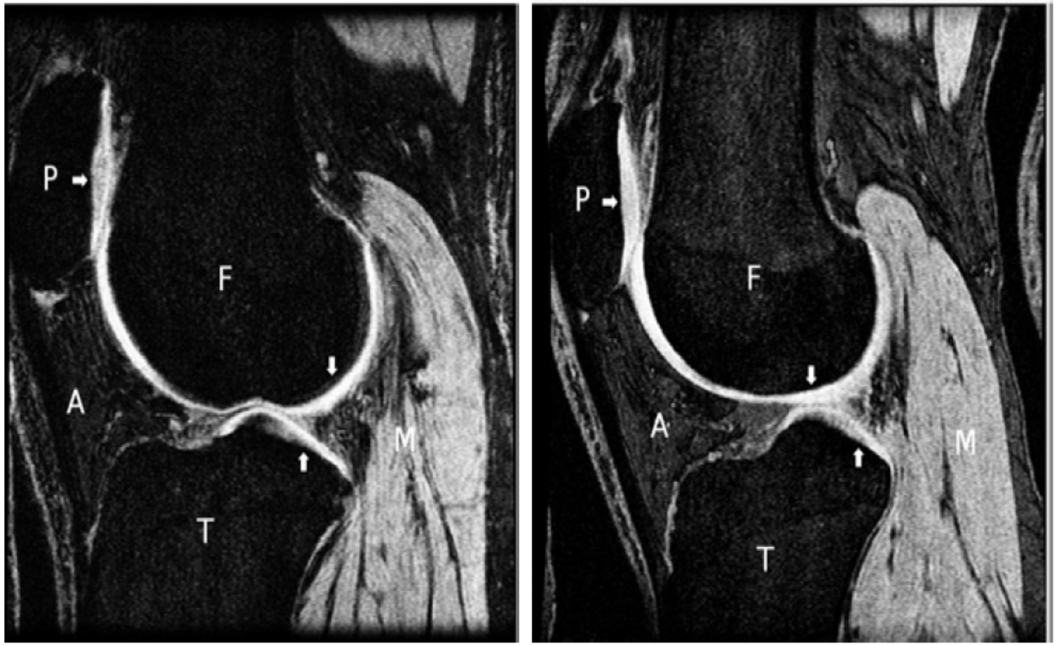


M.E. Leventon, W.E.L. Grimson and O. Faugeras. *Statistical shape influence in geodesic active contours*. CVPR, 2000, 1, 316-323

Model to Image registration

Fripp et al. 2004

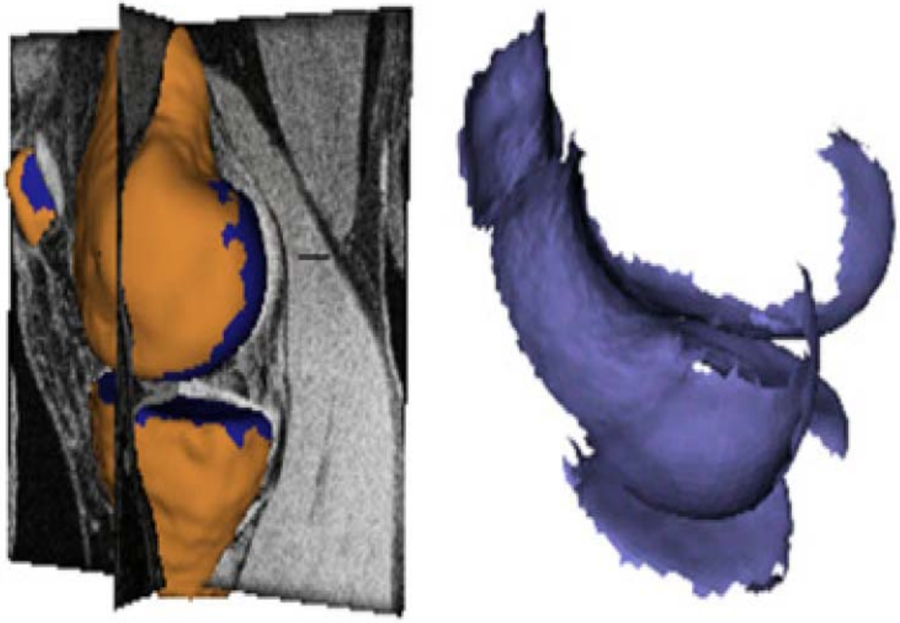
- SSM
- Fat suppressed MRI



Model to Image registration

Fripp et al. 2004

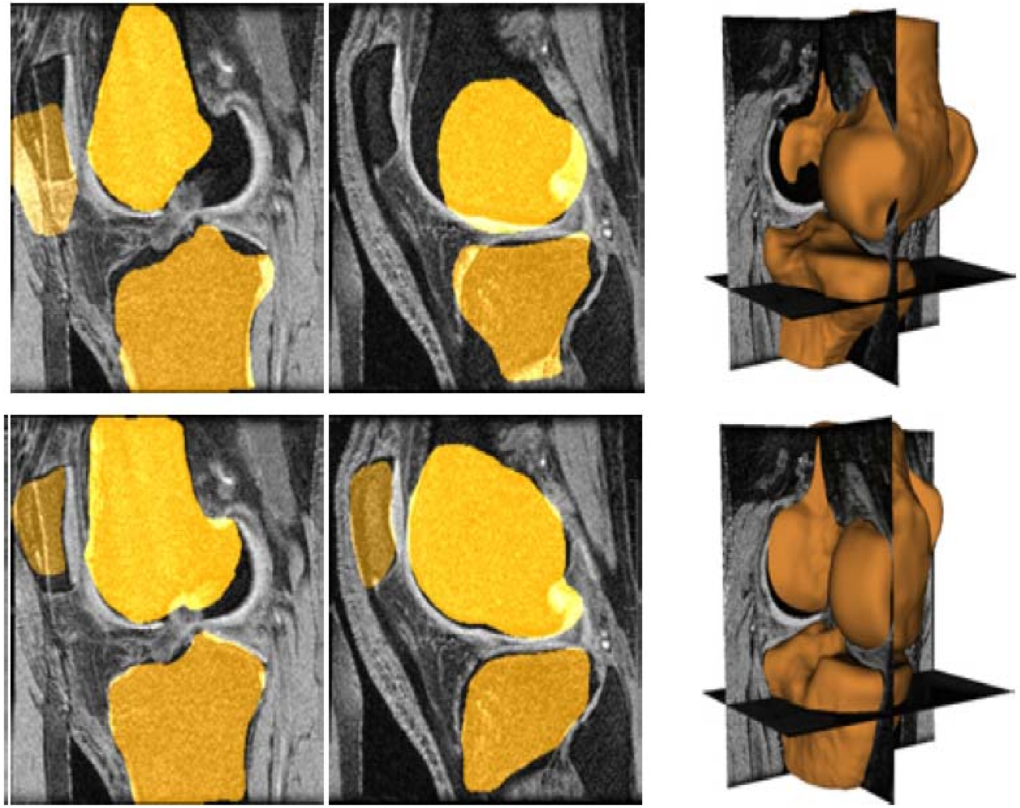
- SSM
- Fat suppressed MRI
- Gradient as clue
- Cartilage extraction



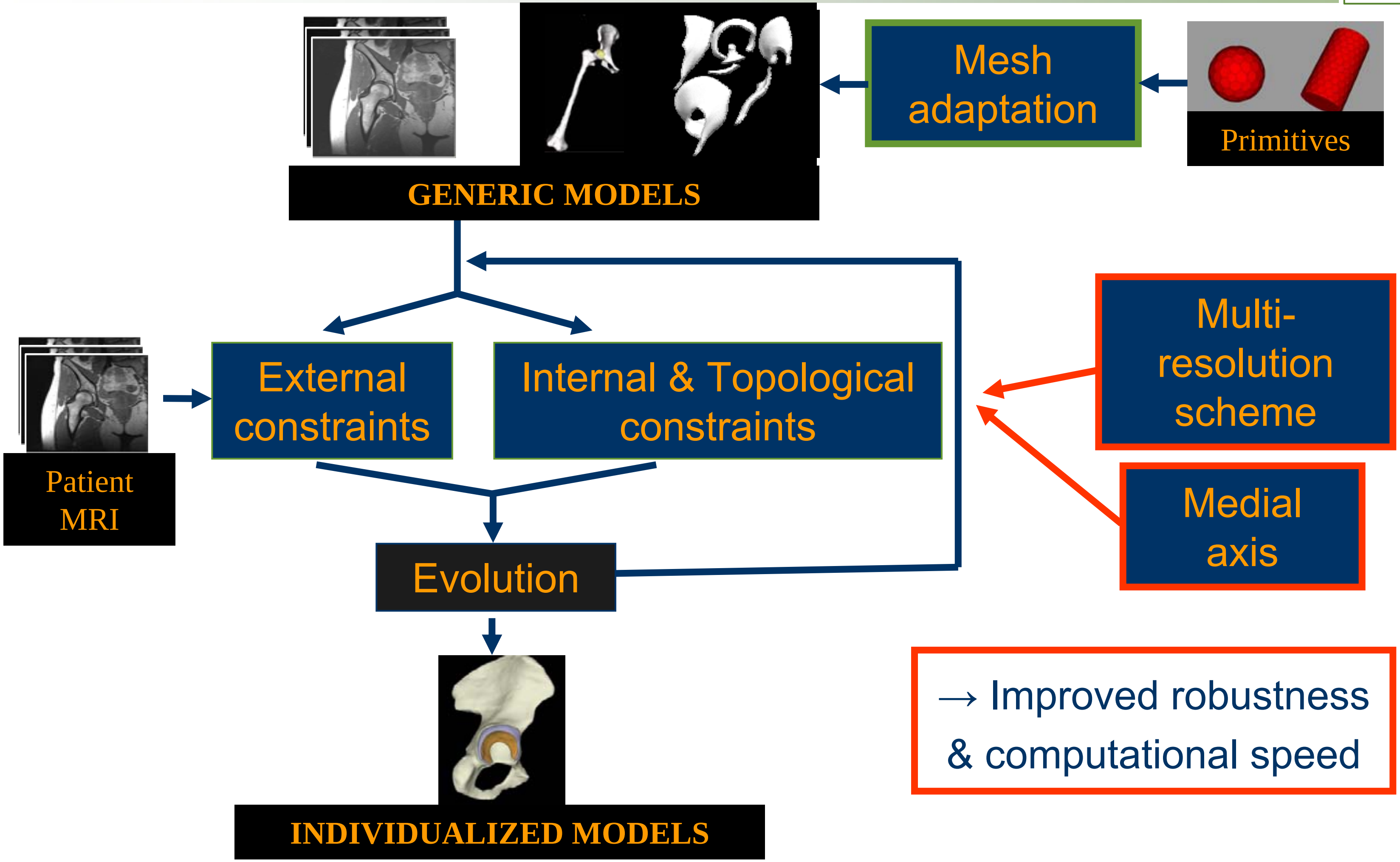
Model to Image registration

Fripp et al. 2004

- SSM
- Fat suppressed MRI
- Gradient as clue
- Cartilage extraction
- Errors



Proposed Segmentation



GENERIC MODELS

Mesh adaptation

Primitives

Patient MRI

External constraints

Internal & Topological constraints

Multi-resolution scheme

Medial axis

Evolution

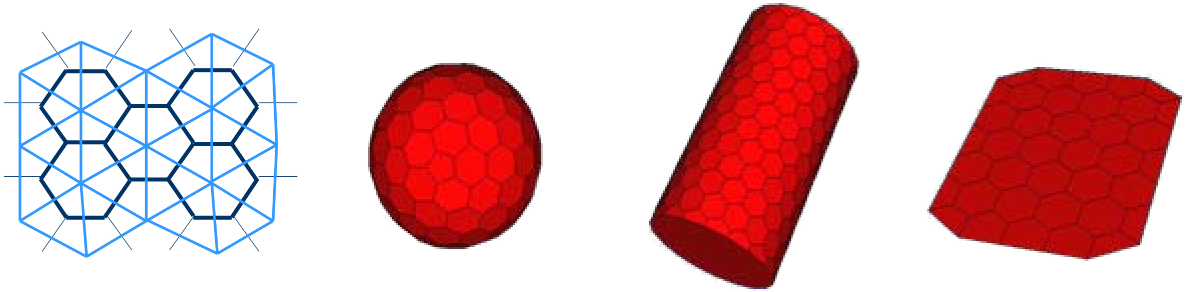
INDIVIDUALIZED MODELS

→ Improved robustness & computational speed

B. Gilles, *Anatomical and kinematical modelling of the musculoskeletal system from MRI*. Ph.D. dissertation, Université de Genève, 2007.

Generic Model Creation (1/3)

- 2-Simplex meshes [1][2]
  - Dual to triangle mesh
  - Each vertex has exactly 3 neighbors
  - Simple local geometric description (3 similitude-invariant “simplex parameters”)
  - Simple mesh topology description

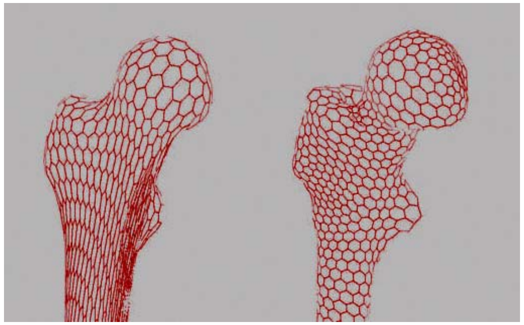


[1] Delingette, H. *General Object Reconstruction Based on Simplex Meshes*. Int. J. Comput. Vis., 1999, *32*, 111-146

[2] J. Montagnat and H. Delingette. *4D deformable models with temporal constraints: application to 4D cardiac image segmentation*. Medical Image Analysis, 9(1), 87-100, 2005

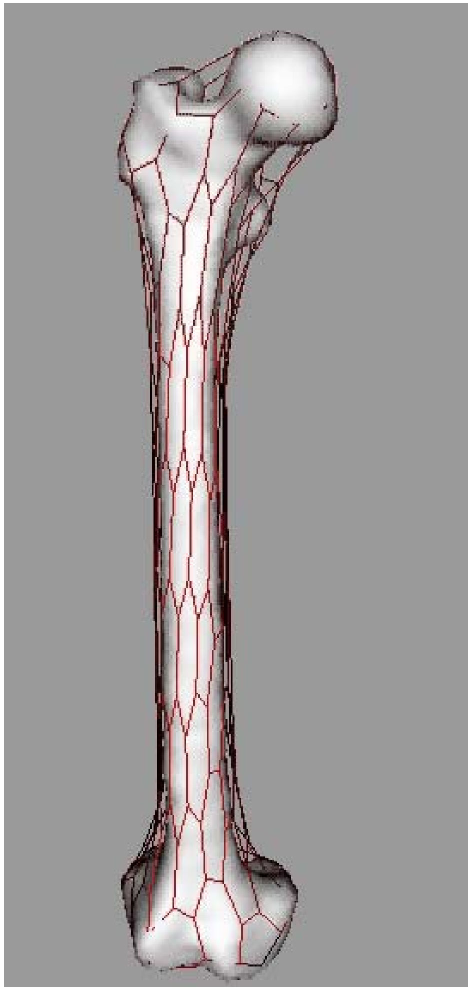
Generic Model Creation (2/3)

- Coarse construction
  - from a series of constraints (points manually defined in MRI) primitives are deformed to match the structures of interest
- Refinement:
  - Topological optimization to get a quasi regular triangulation



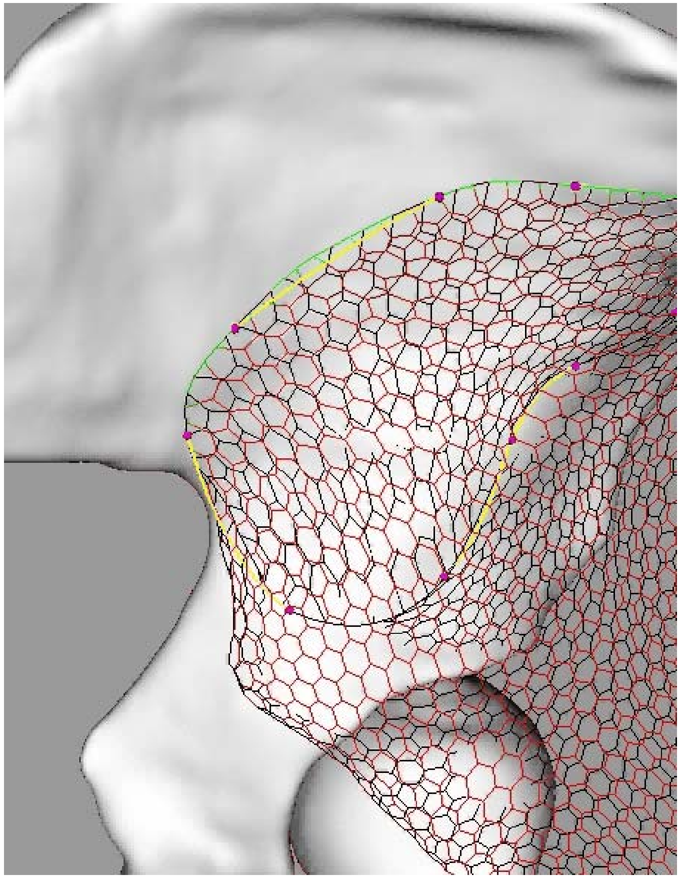
Without topology optimization

With topology optimization



Generic Model Creation (3/3)

- Bone/ Muscle attachment
  - Splines parameterization
  - 50 generic attachments
  - Rely on anatomical assumptions [1]
- Cartilage/ Bone attachment
- Muscle/ Muscle contact
  - Fascia modeling



[1] B.L. Kaptein and F.C,T Van Der Helm. *Estimating muscle attachment contours by transforming geometrical bone models*. J. Biomech, 37, 263-273, 2004.

Dynamic Evolution

- lumped mass particles submitted to forces
- Newtonian law of motion
  - Euler implicit

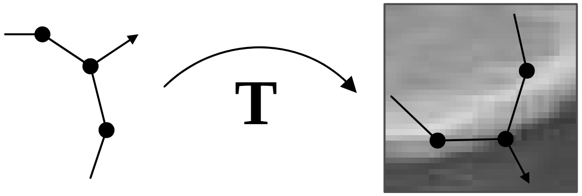
$$\begin{cases} \mathbf{P}_{\mathbf{t+dt}} - \mathbf{P}_{\mathbf{t}} & = \quad (\mathbf{V}_{\mathbf{t}} + \quad (\mathbf{V}_{\mathbf{t+dt}} - \mathbf{V}_{\mathbf{t}}))dt \\ \mathbf{V}_{\mathbf{t+dt}} - \mathbf{V}_{\mathbf{t}} & = \quad \mathbf{H}^{-1}\mathbf{Y} \end{cases}$$

where

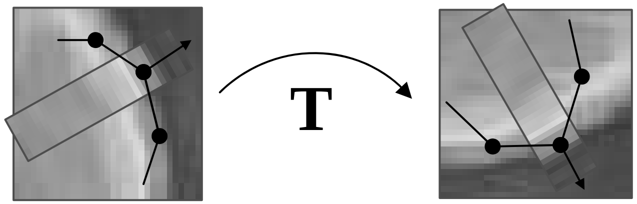
$$\begin{cases} \mathbf{H} & = \quad \mathbf{I} - \quad \mathbf{M}^{-1}\frac{\partial \mathbf{F}}{\partial \mathbf{V}}dt - \quad \mathbf{M}^{-1}\frac{\partial \mathbf{F}}{\partial \mathbf{P}}dt^2 \\ \mathbf{Y} & = \quad \mathbf{M}^{-1}\mathbf{F}(\mathbf{P}_{\mathbf{t}}, \mathbf{V}_{\mathbf{t}})dt + \quad \mathbf{M}^{-1}\frac{\partial \mathbf{F}}{\partial \mathbf{P}}\mathbf{V}_{\mathbf{t}}dt^2 \end{cases}$$

External Forces (1/2)

- Image forces
  - Align model with model contours in image
    - Maximize gradient magnitude
    - Align model and image gradient



  - Register reference with image features
    - Intensity profiles matching
    - Similarity measure

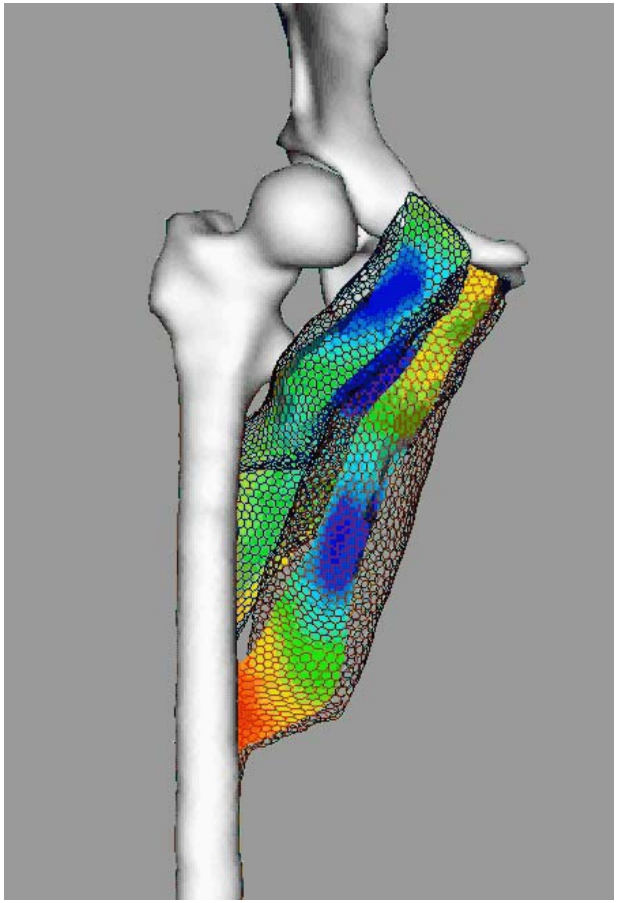


External Forces (2/2)

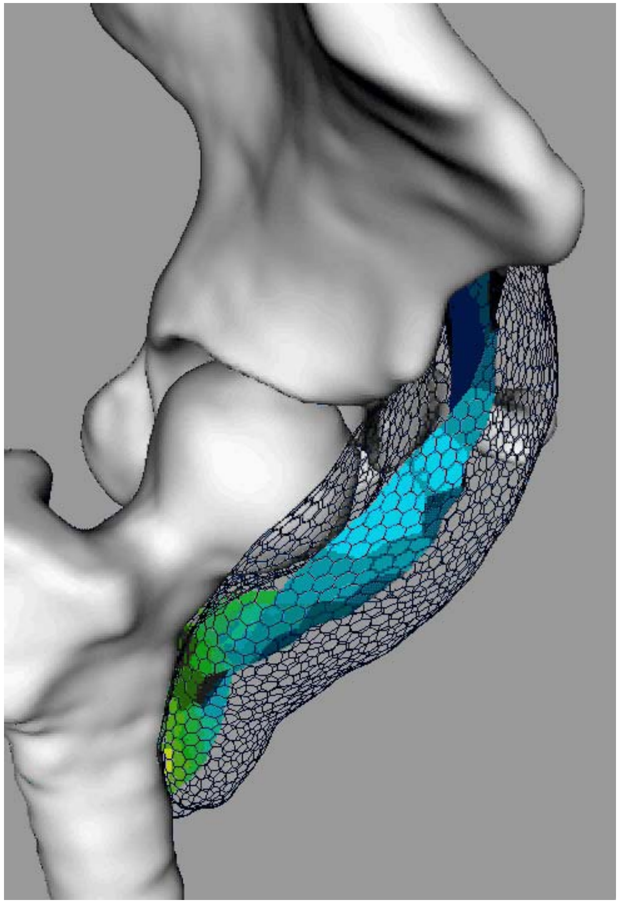
- Collision
  - Collision detection
    - Deformable/ deformable: bounding box hierarchy
    - Rigid/ Deformable: distance maps
  - Collision response [1]
    - Penalty forces
    - Velocity/ position alteration
- Constraints
  - Attachments
    - Mass modification [2]
  - Contact

[1] P. Volino and N. Magnenat-Thalmann. *Implementing fast Cloth Simulation with Collision Response*. Comput. Graph. Int., 257-266, 2000.
[2] D. Baraff and A. Witkin. *Large Steps in Cloth Simulation*. SIGGRAPH'98, 43—54, 1998

External Forces (2/2)



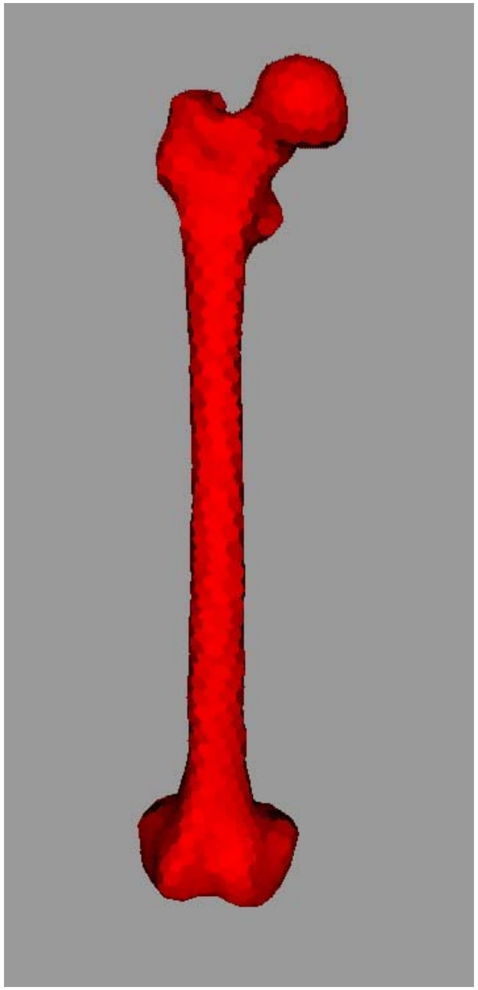
Deformable/ deformable



Rigid/ deformable

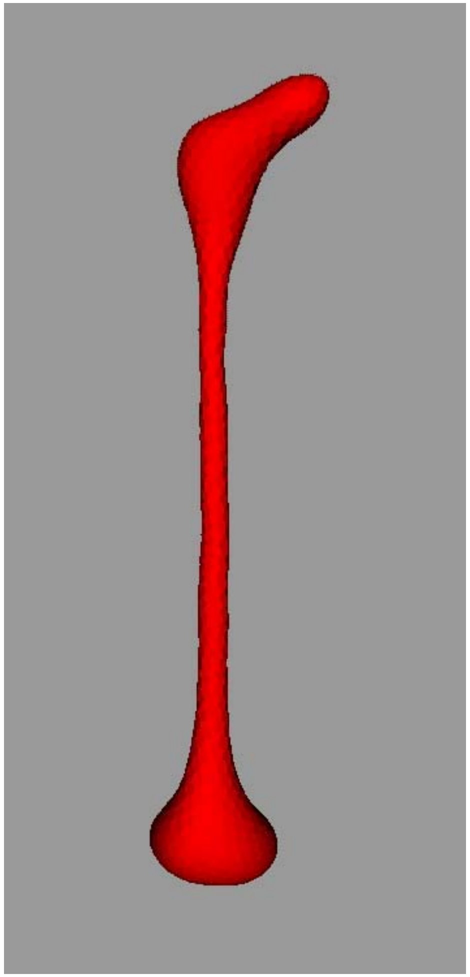
Internal Forces (1/3)

- Smoothing forces
  - Laplacian smoothing
    - Shrink effect
  - Bending force (curvature average)
    - Modify tangential term
    - Consider 2nd order neighbor



Internal Forces (2/3)

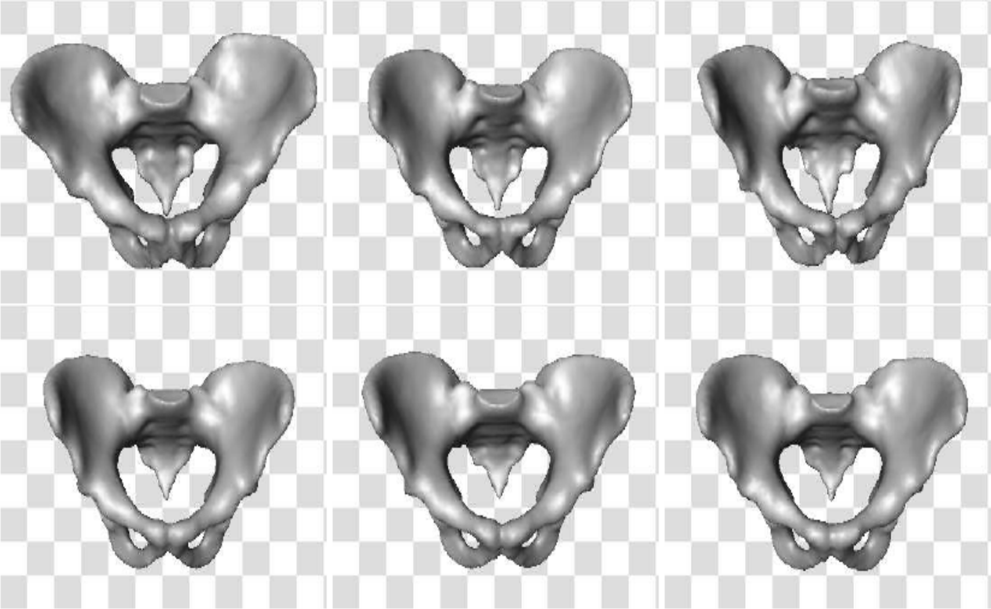
- Shape forces
  - Strain energy
    - Matching to a reference local geometry
    - Use of reference simplex parameters



Internal Forces (3/3)

- Shape forces
  - Principal Component Analysis (PCA)

$$x \approx \overset{\text{Pose transform}}{T}\left(\underbrace{\overline{x}}_{\text{Mean shape}} + \overset{\text{Principal vectors}}{\Phi}.\underbrace{b}_{\text{Shape parameters}}\right)$$



Reproduced from [1]

[1] H. Lamecker, M. Seebass, H-C Hege, P. Deuflhard. *A 3D statistical Shape Model Of The Pelvic Bone For Segmentation*. SPIE, 2004.

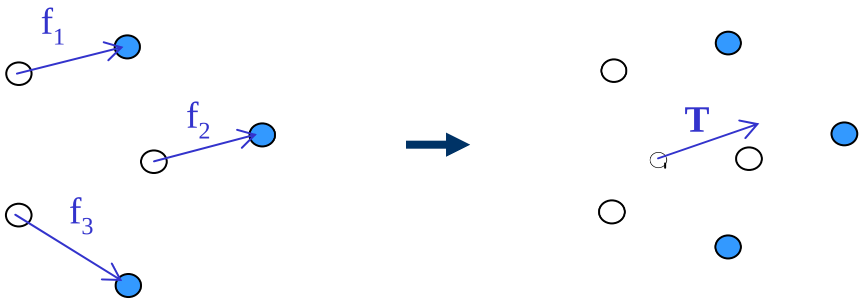
Internal Forces (3/3)

- Shape forces
  - PCA regularization
    - Discard “invalid” shapes
    - Exploit LODs and alignment transform type [1]
  - Correspondence problem
  - Training dataset
  - Linearity/ sufficient statistics

[1] J. Schmid and N. Magnenat-Thalmann. *MRI Bone Segmentation using Deformable Models and Shape Priors*. MICCAI 2008.

Forces regularization

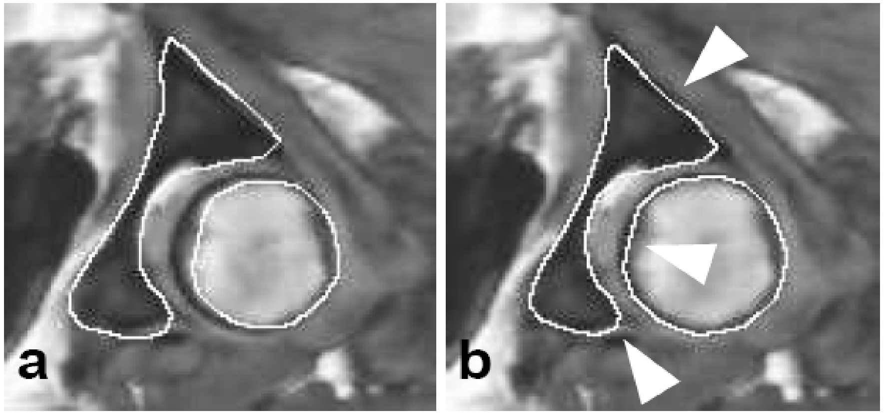
- Locally, noise and adjacent structures can affect the external forces computation
- Use “pair & smooth” approach to find a global transformation T from local displacements fi

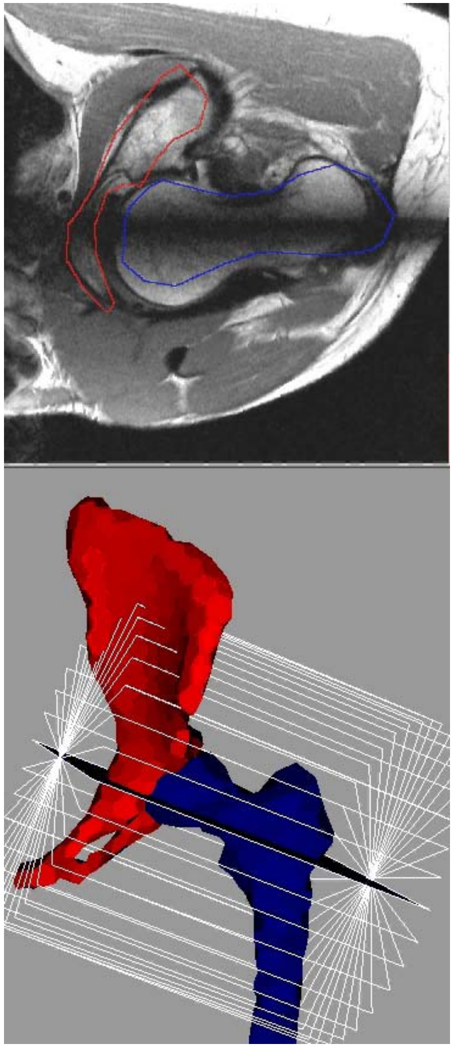


- Progressively decrease the regularization influence

Results (1/4)

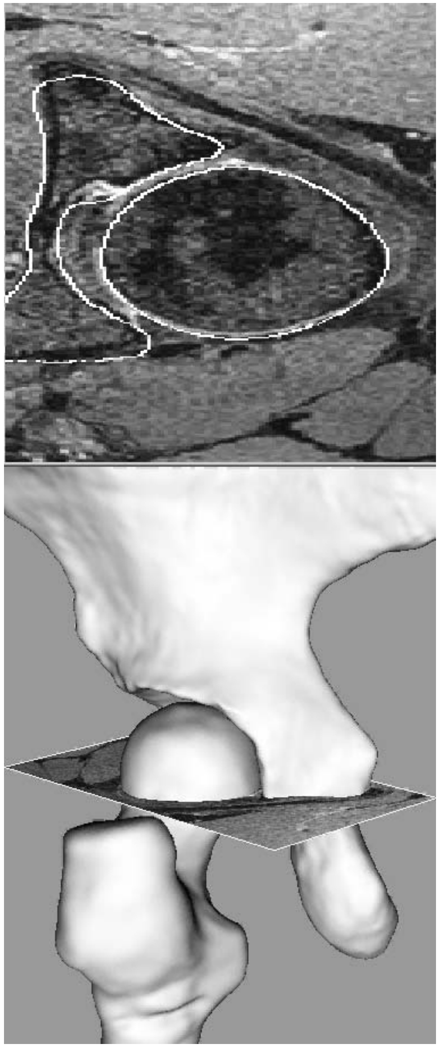
- Bone Modeling
  - Comp. time ~2min
  - accuracy ~1.5mm
  - Validated on low resolution images





Results (2/4)

- Periarticular tissue modeling
  - 3 cartilages and 3 ligaments
  - Automatic initialization from bones
  - Computation time ~3min
  - Mostly relies on geometric constraints
    - Shape and smoothness
    - Contacts
    - Thickness
  - Validation difficult

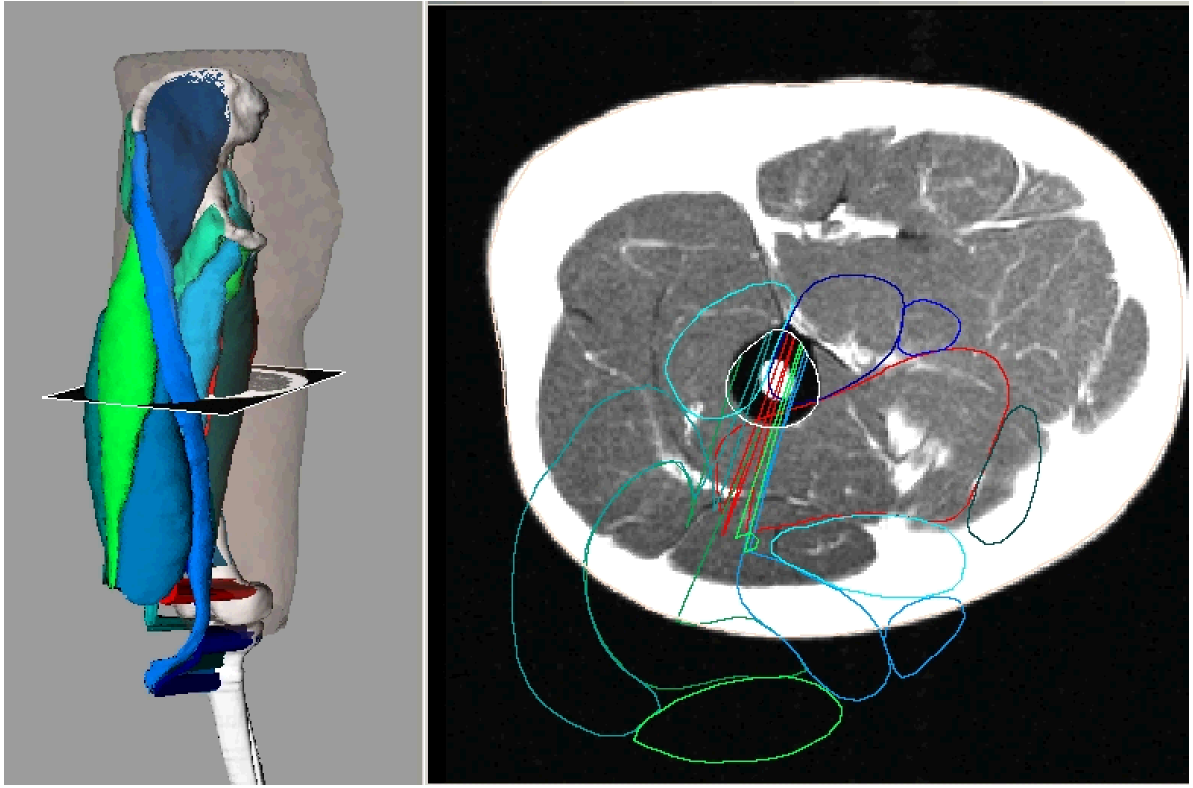


Results (3/4)

- Muscle Modeling
  - 21 muscles in contact
  - Automatic initialization from bones
  - Comp. time ~10min
  - accuracy ~1.5mm

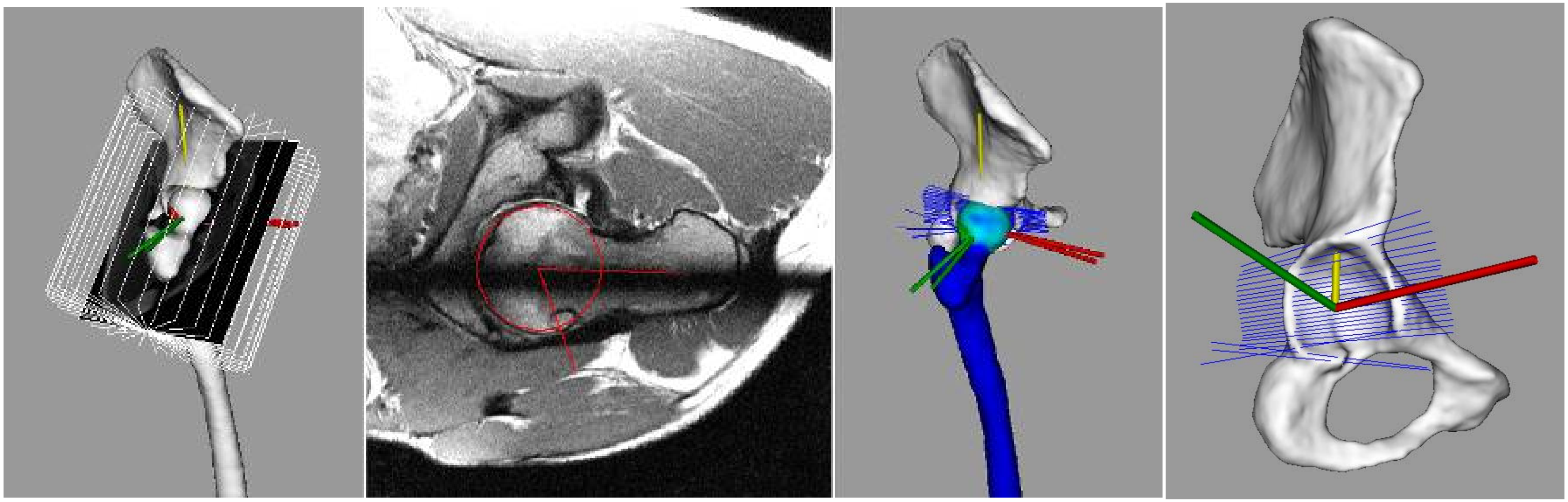
Results (3/4)

- Muscle Modeling



Results (4/4)

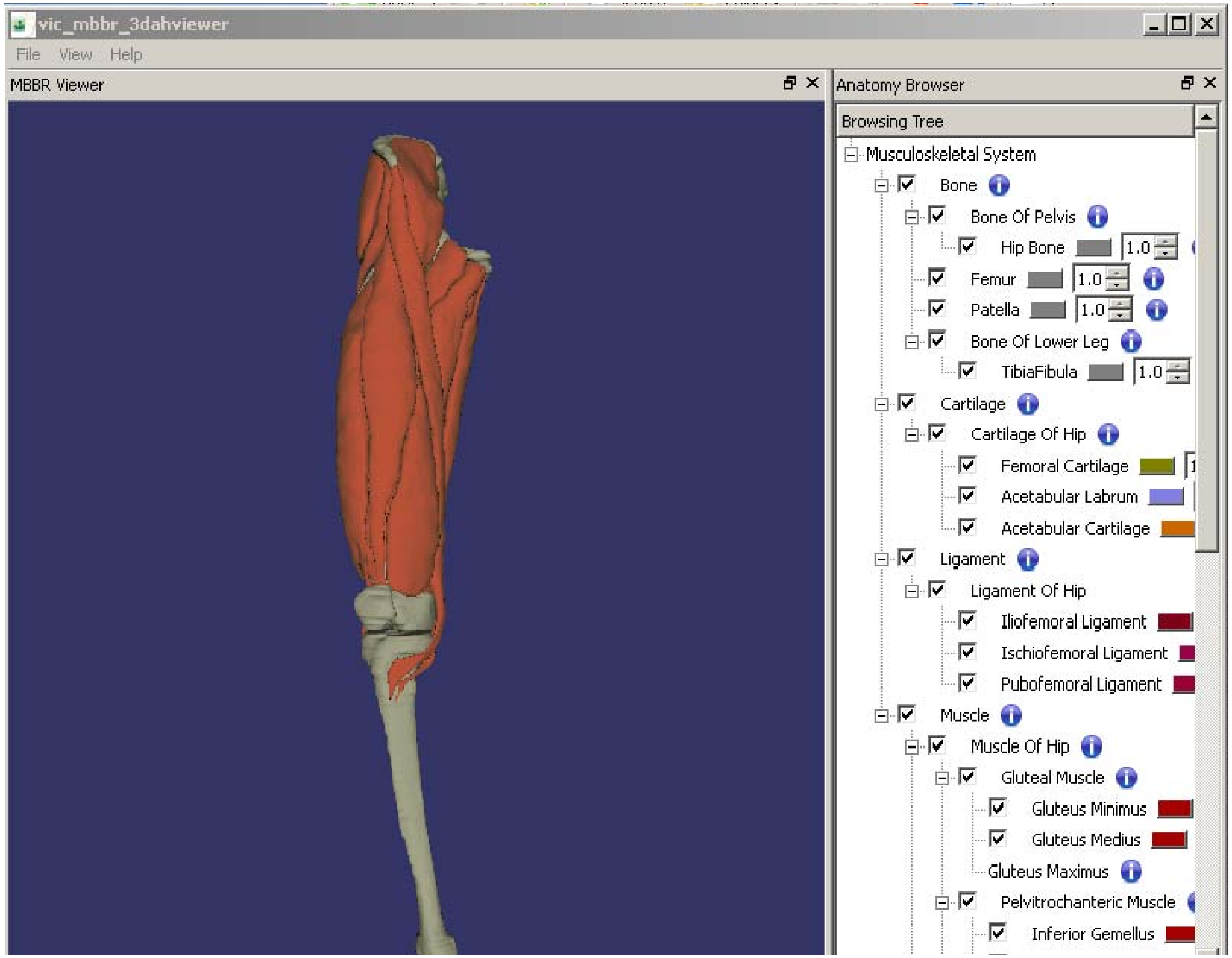
- Analysis



[1] C.W.A. Pfirrmann, B. Mengiardi, C. Dora, F. Kalberer, M. Zanetti and J. Hodler. *Cam and Pincer Femoroacetabular Impingement: Characteristic MR Arthrographic Findings in 50 Patients*. Radiology, 240(3), 778-785, 2006.

[2] D. Reynolds, J. Lucas and K. Klaue. *Retroversion of the acetabulum: A cause of hip pain*. J. Bone. Joint Surg., 81-B(2), 281-288, 1999.

Demo


vic_mbbr_3dahviewer
File View Help
MBBR Viewer
Anatomy Browser
Browsing Tree
Musculoskeletal System
☑ Bone
☑ Bone Of Pelvis
☑ Hip Bone 1.0
☑ Femur 1.0
☑ Patella 1.0
☑ Bone Of Lower Leg
☑ TibiaFibula 1.0
☑ Cartilage
☑ Cartilage Of Hip
☑ Femoral Cartilage
☑ Acetabular Labrum
☑ Acetabular Cartilage
☑ Ligament
☑ Ligament Of Hip
☑ Iliofemoral Ligament
☑ Ischiofemoral Ligament
☑ Pubofemoral Ligament
☑ Muscle
☑ Muscle Of Hip
☑ Gluteal Muscle
☑ Gluteus Minimus
☑ Gluteus Medius
Gluteus Maximus
☑ Pelvitrochanteric Muscle
☑ Inferior Gemellus

Thank you for your attention!