Combined statistical model of bone shape and mechanical properties for bone modeling

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How can we model bone variability?

> State of the art of bone mechanical studies:
  - Based on patient-specific models
  - Limited number of bones
  - Variability included in boundary conditions, or mechanical properties

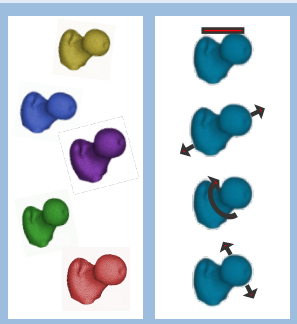
Objective

- To model bone shape variability
- To evaluate bone mechanical behavior
- Population-based study:
  - Gender
  - Ethnicity
  - Age
- Initial application about femurs
  - Stiffness comparison between genders

Method overview

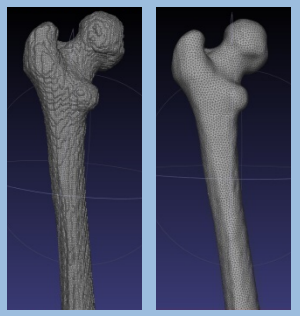
Segmented CT images

Rigid and non-rigid registration

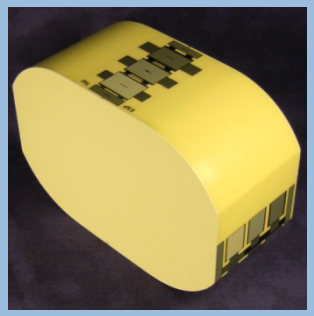


Shape Model

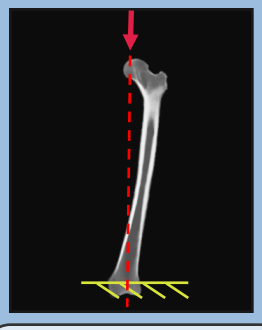
New instances



Volume mesh

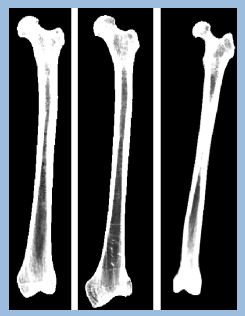


Material properties



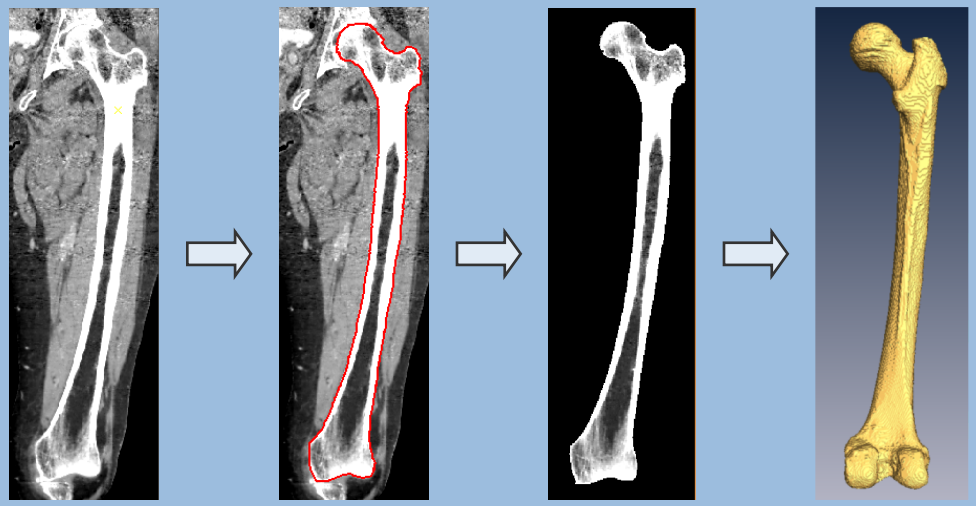
BC propagation

1. Segmentation



Segmented CT images

> Identification and delineation of structures in images:

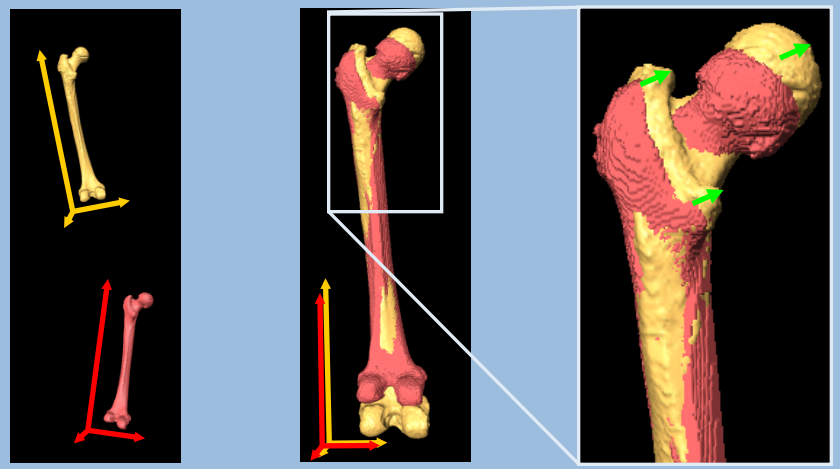


— Semi-automatic method: thresholding + region growing

2. Registration

Rigid and non-rigid registration

> Process of aligning images so that corresponding features can be extracted
  - *Correspondences*: establishment of which point on one image corresponds to the same anatomical point in the other



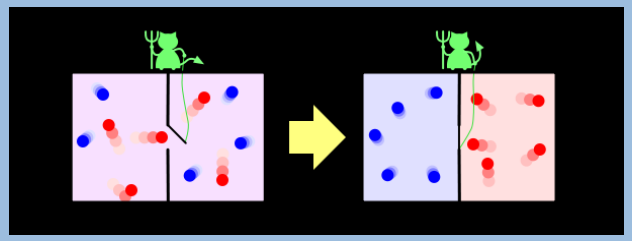
Rigid registration **Non-Rigid registration**

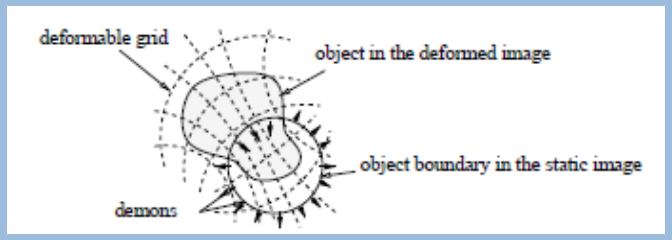
Hajnal J.V. et al. *Medical Image Registration*. Biomedical Engineering Series. 2001.

2.1 Non-rigid registration

Rigid and non-rigid registration

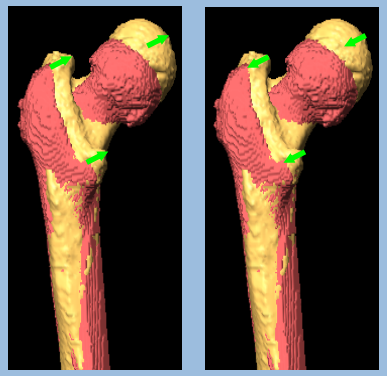
> Demons





> Correspondences stored as “deformation vector fields” (DVFs)

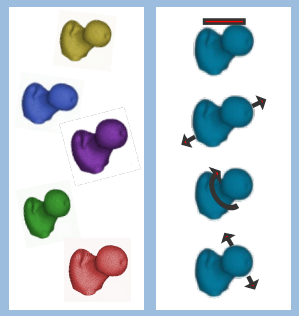
— Diffeomorphic
  – invertible
  – smooth in both ways



Thirion J.-P. *Image matching as a diffusion process: an analogy whit Maxwell’s demons.* Medical Image analysis, 2(3), 243-260, 1996.

Vercauteren T. et al. *Symmetric log-domain diffeomorphic registration: a demons-based approach*. MICCAI 2008.

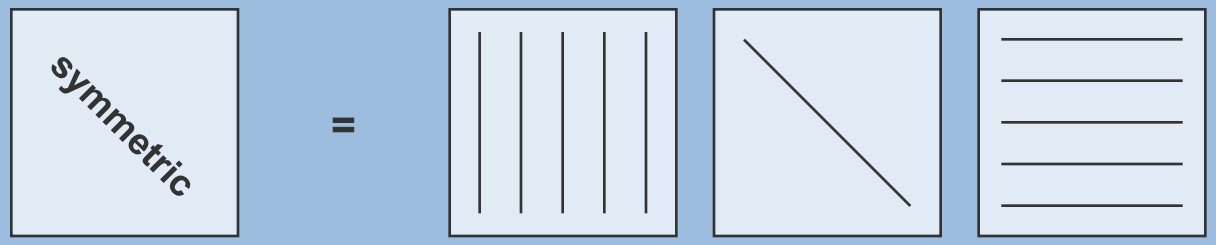
3. Shape model
Principal Component Analysis (PCA)



Shape Model

> Correspondences allow us to calculate images covariance matrix

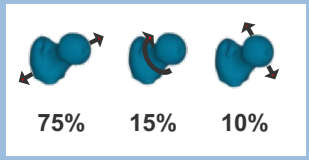
> Eigenvector problem:



Covariance matrix | **Γ (eigenvector matrix)** | **Λ (eigenvalues matrix)** | **Γ^T (eigenvector matrix)^T**

— Eigenvectors: direction of variation

— Eigenvalues: amount of variation along the correspondent direction



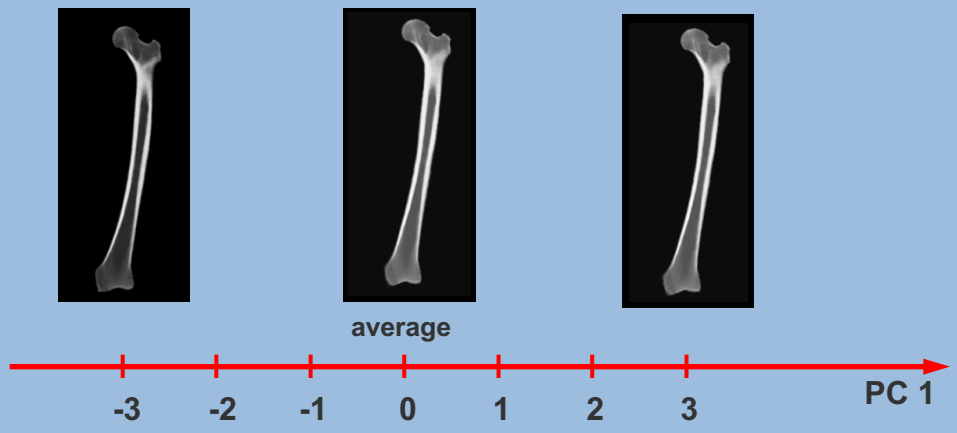
Cootes T.F. et al. *Active shape models – their training and application*. Computer vision and image understanding, 61(1), 38-59, 1995.

4. Virtual instances

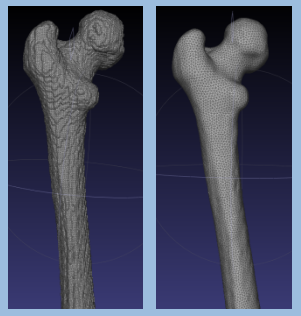
New instances

> They are created along eigenvector directions and for variations defined by the eigenvalues:

$$x = \bar{x} + \phi b, \quad -3\sqrt{\lambda} \le b \le +3\sqrt{\lambda}$$



5. Volume mesh



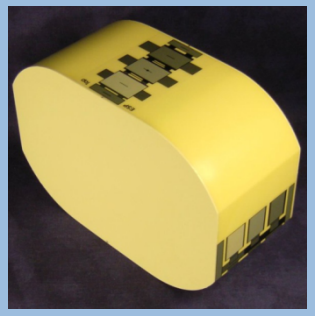
Volume mesh

- Surface mesh creation
  - marching cubes
- Mesh decimation and smoothing
- Recreation of mesh topology (MRFSurface)
- Tetrahedral mesh creation (NetGen)

Paulsen R.R. et al. *Markov Random Field Surface Reconstruction*. IEEE Transactions on Visualization and Computer Graphics. 99, 2009.

Schöberl J. at al. http://www.hpfem.jku.at/netgen/

6. Material properties assignment



Material properties

Bone Mineral Component | **Complete Bone**

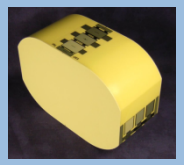
CT intensities → ρ_{QCT} → ρ_{ash} → ρ_{app} → E

Image calibration: ESP - EFP

$\rho_{Ash} = (\rho_{QCT}+0.09)/1.14$

$\rho_{ash}/\rho_{app}=0.60$

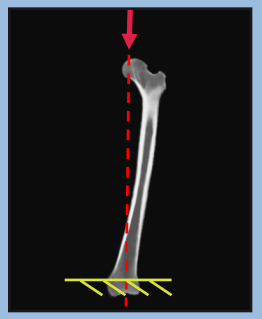
$E(GPa)=6.850\,\rho_{app}^{1.49}(g/cm^3)$



Schileo E. et al. *An accurate estimation of bone density improves the accuracy of subject-specific finite element methods.* Journal of Biomechanics, 2008, 41, 2483-2491.

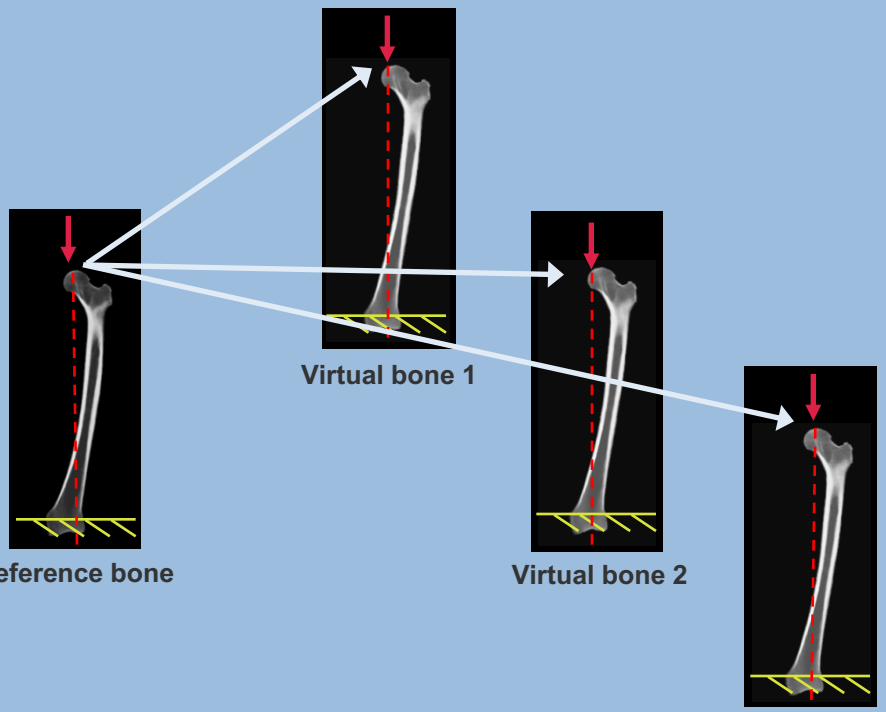
Helgason B. et al. *Mathematical relationship between bone density and mechanical properties: a literature review.* Clinical Biomechanics, 2008, 23, 135-146

7. Boundary condition propagation



BC propagation

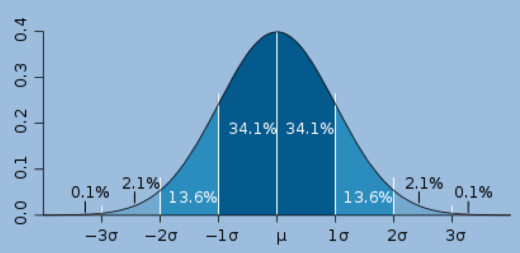
> Load application points and boundary conditions can be propagated using calculated DVFs

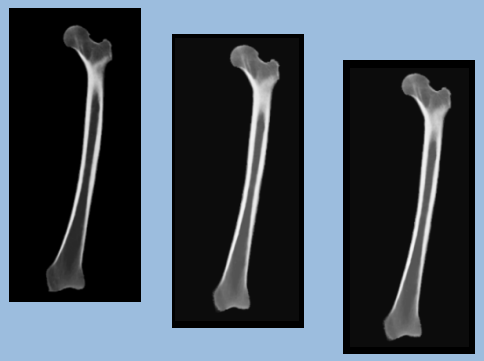


Application on the femur
Statistical model

- CT images
  - 80 for females
  - 57 for males

- Statistical Shape Model:
  - Use of the first 4 modes
    (77% of variation for females, 83% for males)
  - Generation of 40 instances for each gender



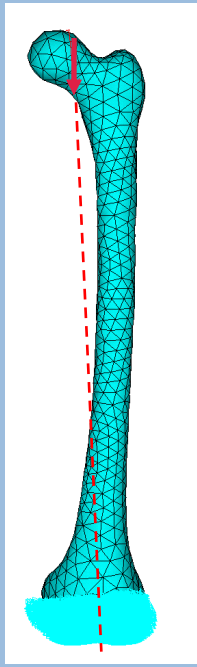


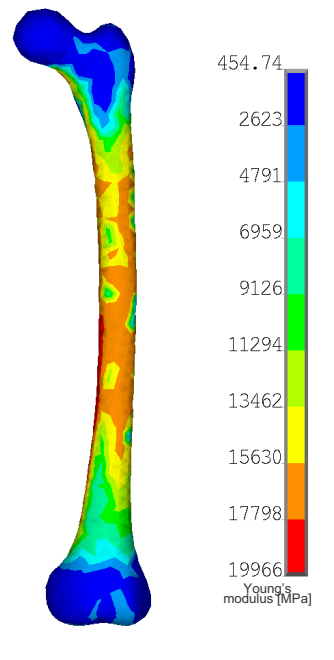
Application on the femur
Mechanical simulation

- 10-node tetrahedral mesh
- L = 800N, head-intercondyle direction
- Distal part encastred

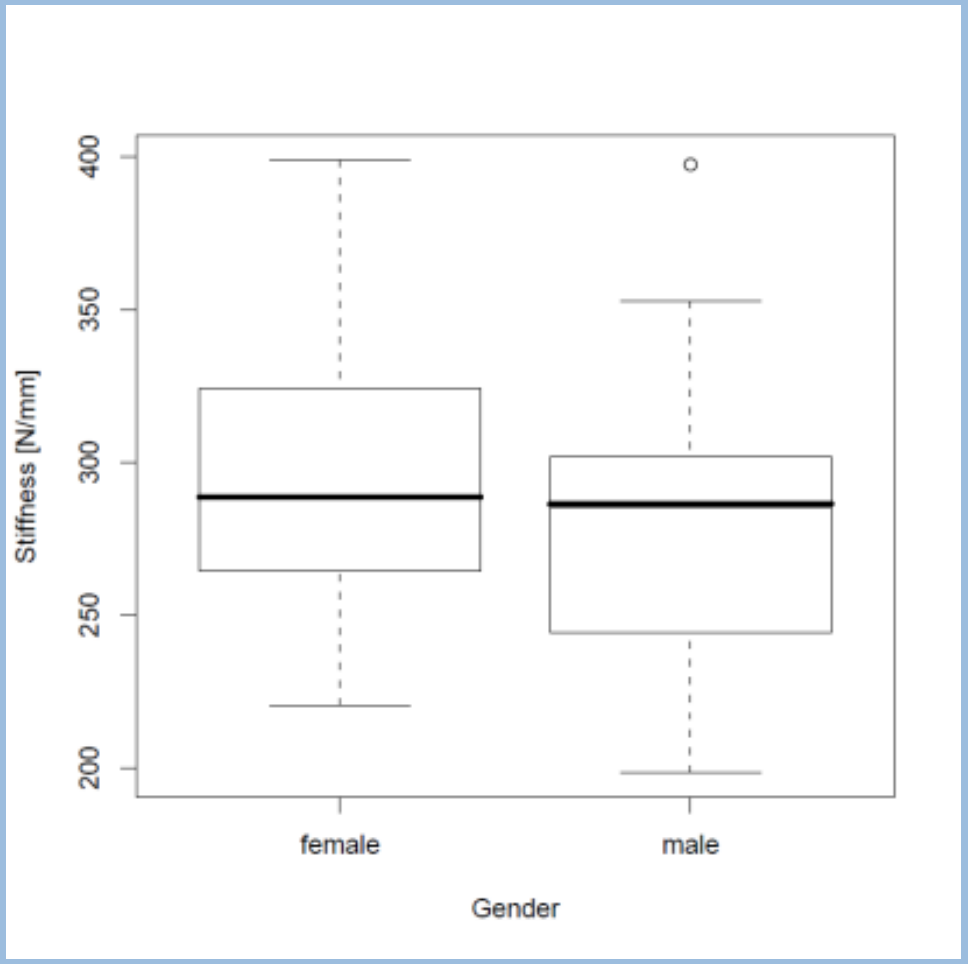
- Inhomogeneous mechanical properties

E(GPa)=6.850 $\rho_{app}^{1.49}$ **(g/cm³)**





Application on the femur
Results



- Bone length not modeled
- Same mineral content in all instances

Conclusion and future work

- Conclusion
  - We proposed a method to model bone variability
  - Finite element are used to evaluate bone mechanical behavior
  - Semi-automatic pipeline

- Future work
  - Shape model validation
  - Statistical model that includes both shape and intensities
  - Mechanical simulation of physiological situations

Thank you