Creation of an Unlimited Database of Virtual Bone Population using Mesh Morphing: Validation and Exploitation for Orthopedic Devices

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Outline

- VPHOP
- Mesh Morphing
- Mode Extraction
- Shape Indexation: Validation
- Applications
- Conclusions and Future Work

Introduction and Motivation

- Human variability and proximity
- Growing interest for virtual prototyping
  - *in silico* testing requires a large number of geometries
  - Workflow automation necessary to handle a large number of situations
- Cost effective prototyping
  - Time consuming *in vivo* / clinical testing
  - Expensive *in vivo* data (e.g. bone geometries from cadavers) to acquire
  - Labor intensive *in silico* workflow (meshing, modeling, interpreting results)

ANSYS Role in VPHOP project

Aim : numerical evaluation of risk of rupture for osteoporotic bones

✓ Step 1 : Mesh Morphing
  – Surface and volume mesh morphing of bones

✓ Step 2 : Indexation
  – Shape parameter indexation
  – Bone mineral density parameter (BMD) indexation

✓ Step 3 : Population Based Modeling
  – Virtual "*in-vivo*" models
  – Database of simulation results
  ❑ Parametric computation of risk of rupture for osteoporotic bones

❑ Step 4 : From DXA to Patient Specific Diagnosis
  – From 2D image (DXA) to personalized risk of rupture through morphological parameters (Shape + BMD)
  – Clinical tool (robustness, automation, ease of use, quasi real time)

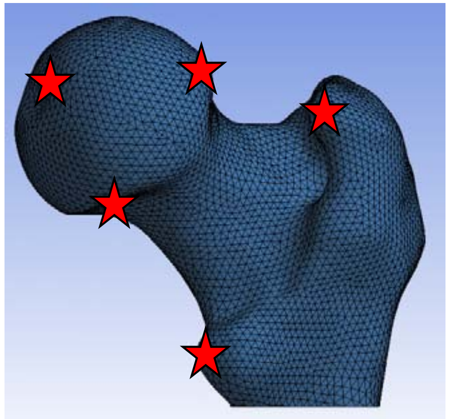
VPHOP
Osteoporotic
Virtual
Physiological
Human

Mesh Morphing

Method Overview

Input:

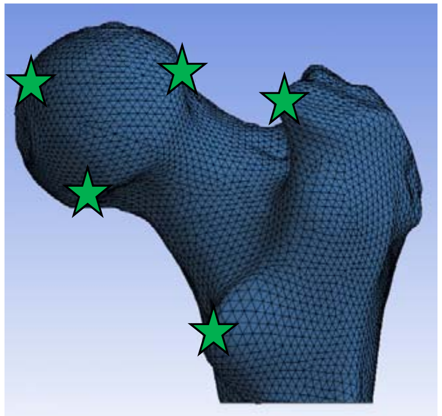
- 3D FE generic mesh
- Patient's geometry
- User-defined anatomical landmark points



Generic Mesh

Patient's Geometry(STL)

Method



Patient's Mesh

Output:

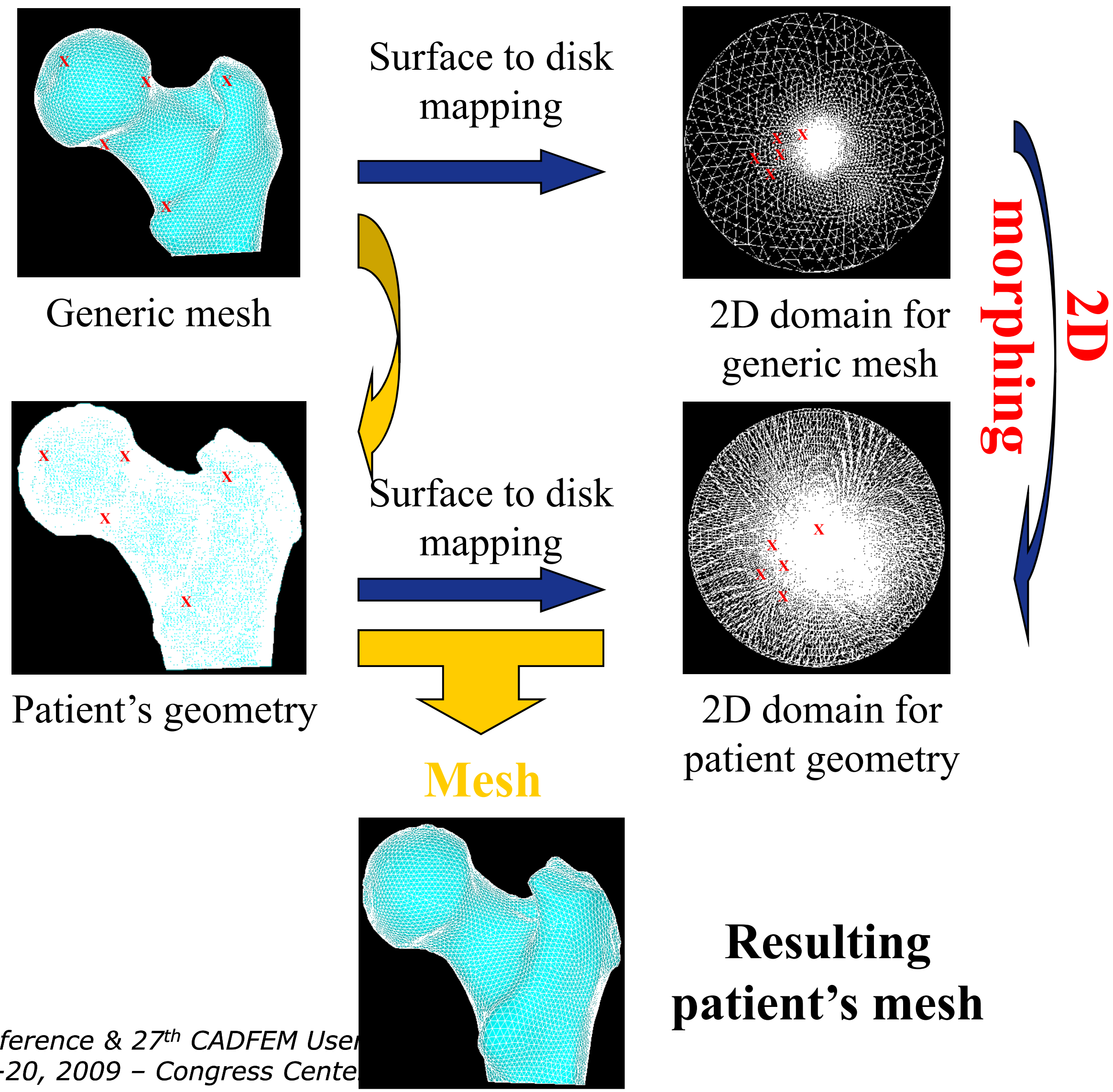
- Patient FE 3D mesh obtained by morphing

Method: Femur Morphing Via Planar Parameterization

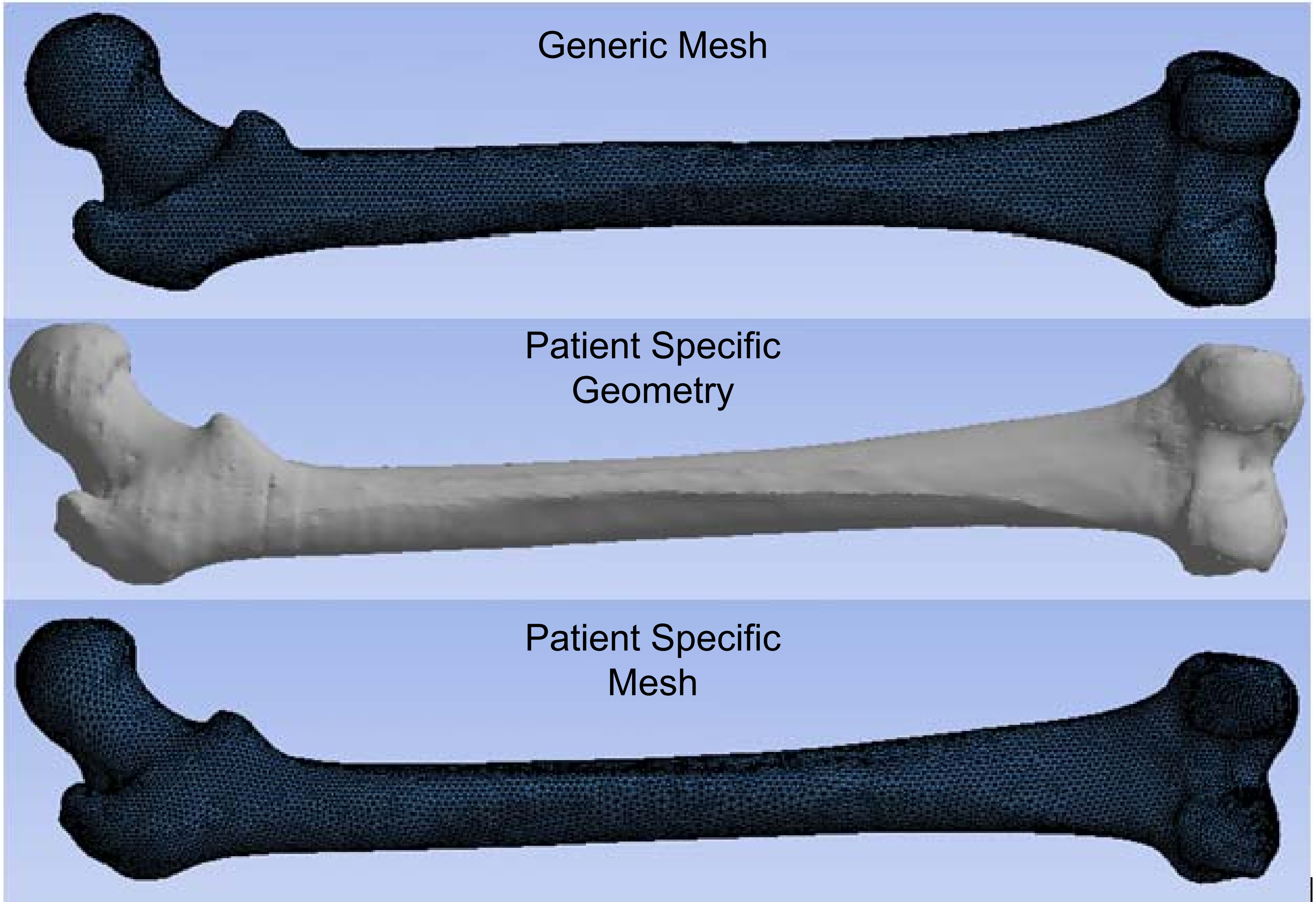
- *Planar parameterization technique is an exact 2D representation of an open 3D shape*

- Simplification of a 3D morphing problem on complex surfaces to a 2D morphing between 2 disks

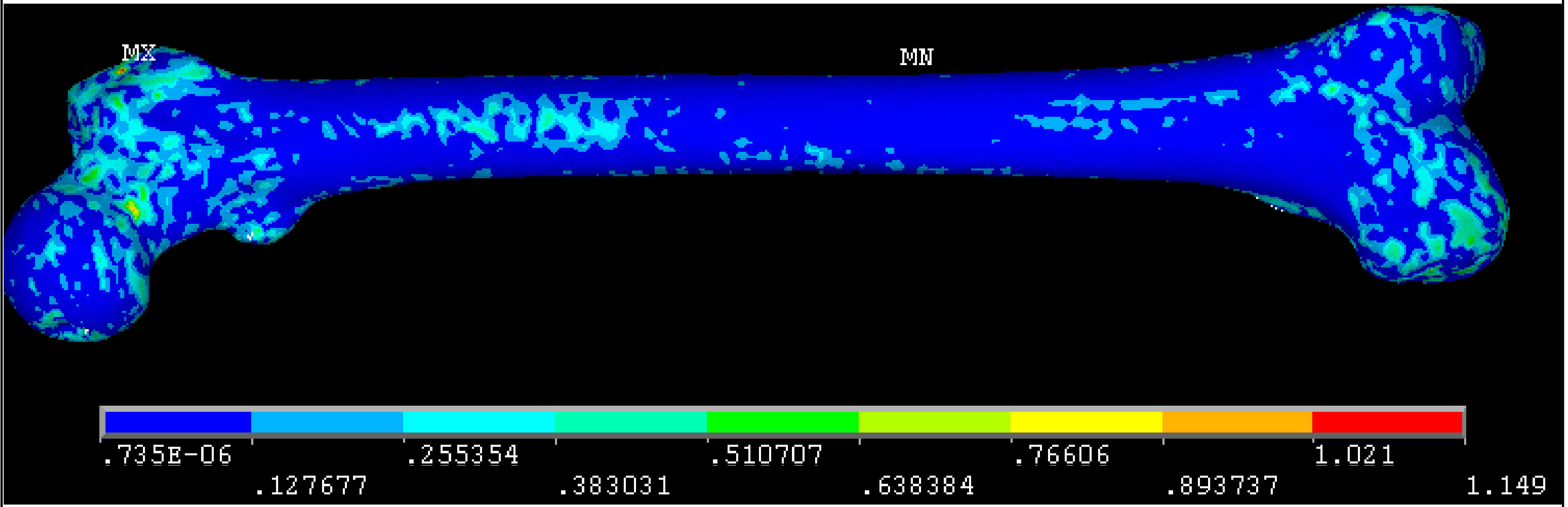
- Morphed mesh is perfectly projected onto the 3D patient geometry



Results


Generic Mesh
Patient Specific
Geometry
Patient Specific
Mesh

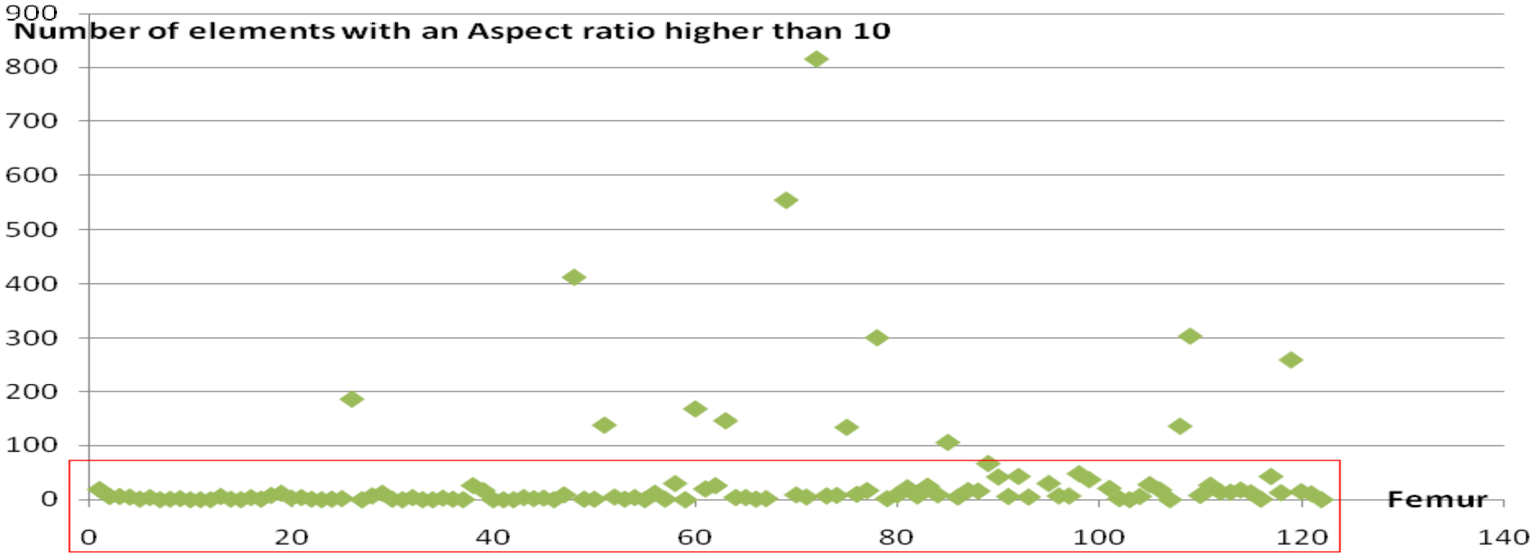
Geometrical Accuracy



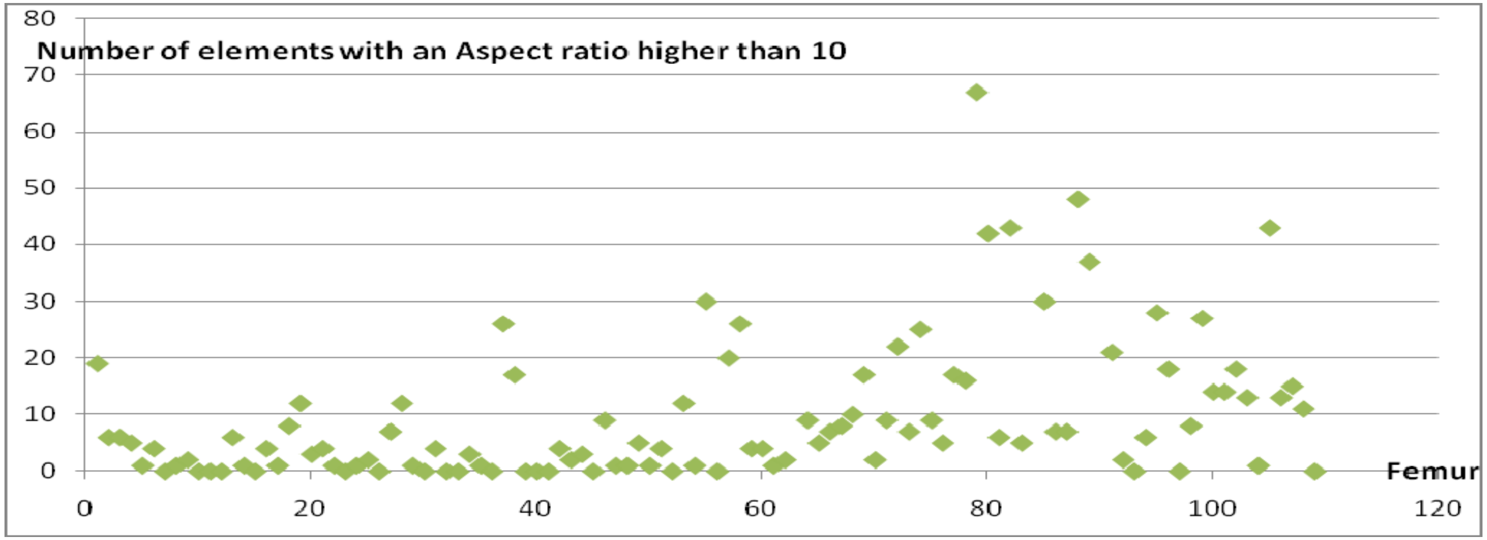
Distance between the morphed mesh and the STL geometry

Mean distance = 0.04 mm, Max distance = 1.15 mm

Validation on 120+ Femurs



Out of 300,000 volume elements, only a tiny fraction showed poor aspect ratio for very unusual femur bone geometries.



Mode Extraction

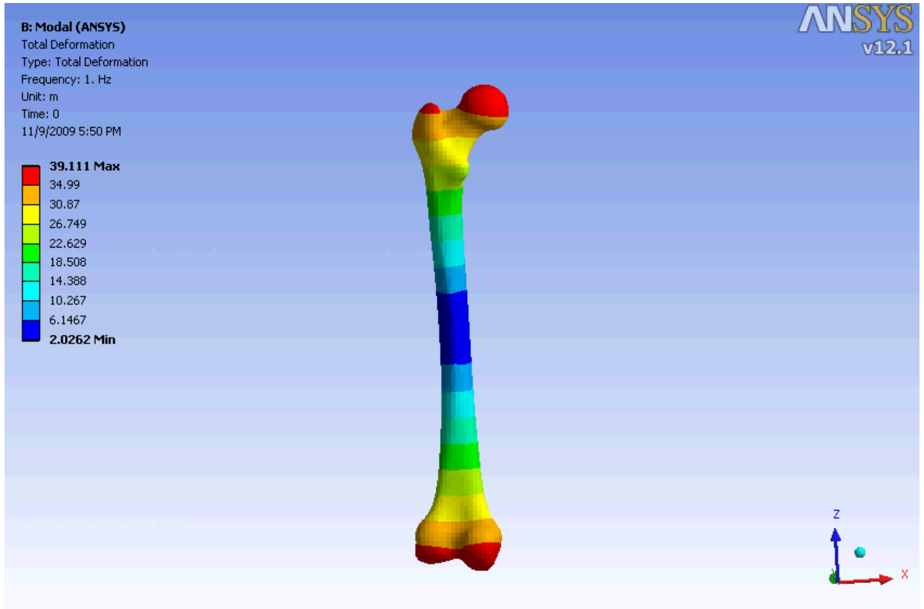
Shape Indexation
Method

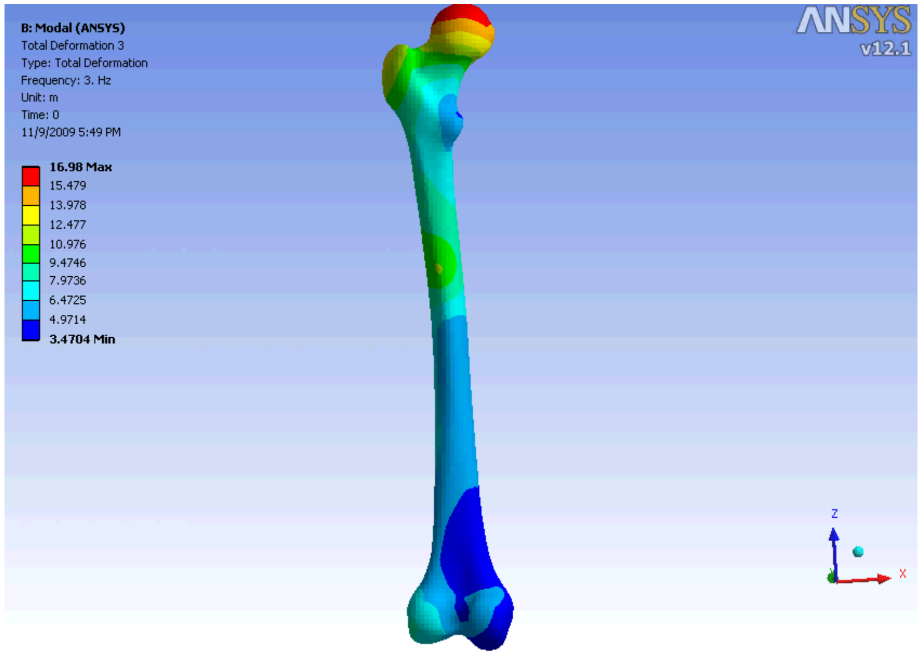
- Our goal: To represent human variability of bones
- Our starting point : A population of *in vivo* models
- The process
  - All bones of the population are morphed to have the same mesh topology
  - The population is a matrix with n (number of bones) columns and C (nodes coordinates) lines
  - Singular Value Decomposition (SVD) with a given accuracy => population representation with m modes (m<<n): $Q_1,\ldots,Q_m$

$$X_i \approx \sum_{j=1}^{m} \widetilde{x}_{ij} Q_j$$

Femur Modes

Out of the dozen of extracted modes, some suggest clear morphological interpretation





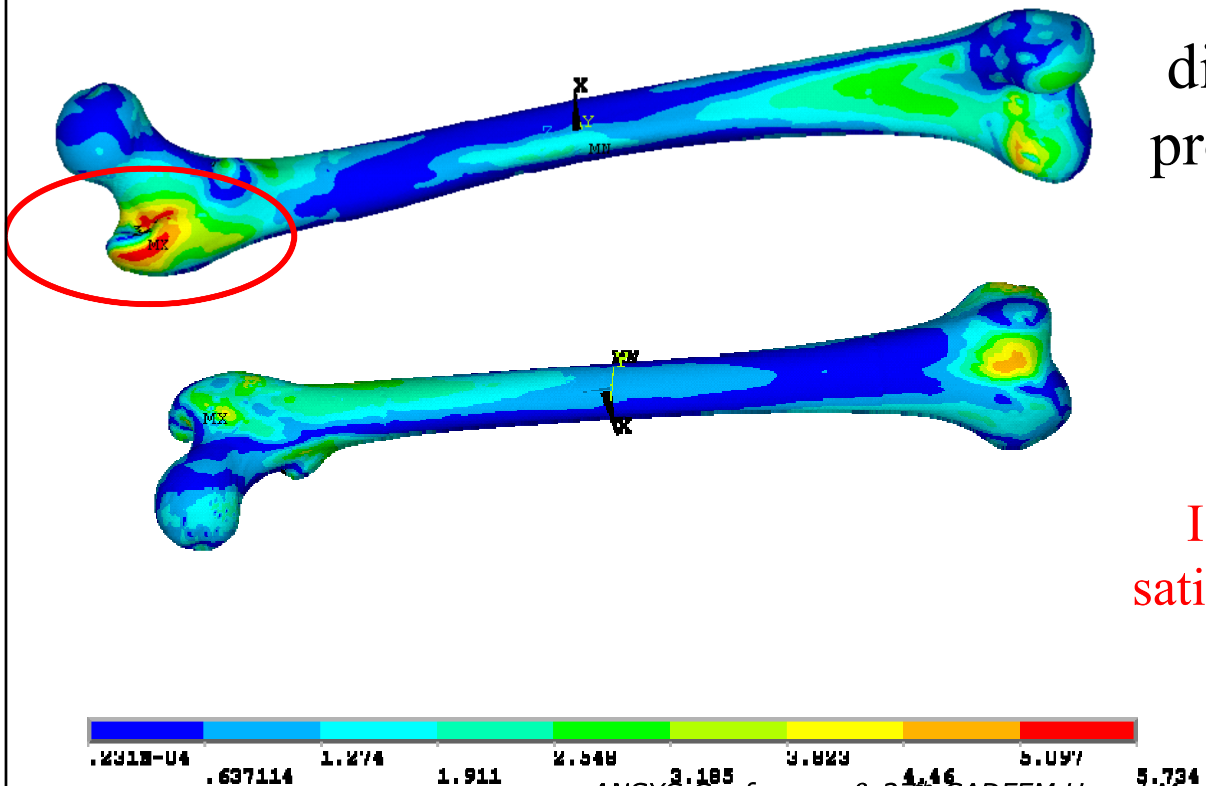
Homothetic mode

3D deformation mode

Shape Indexation

Distance between a real bone and its projection

- For a given in-vivo femur, visualization of the distance with its projection in the base :



Using 7 modes, the distance between real and projected bone is less than 1.2 mm for most of the bone (blue regions)

Max distance is 5.7 mm (red regions)

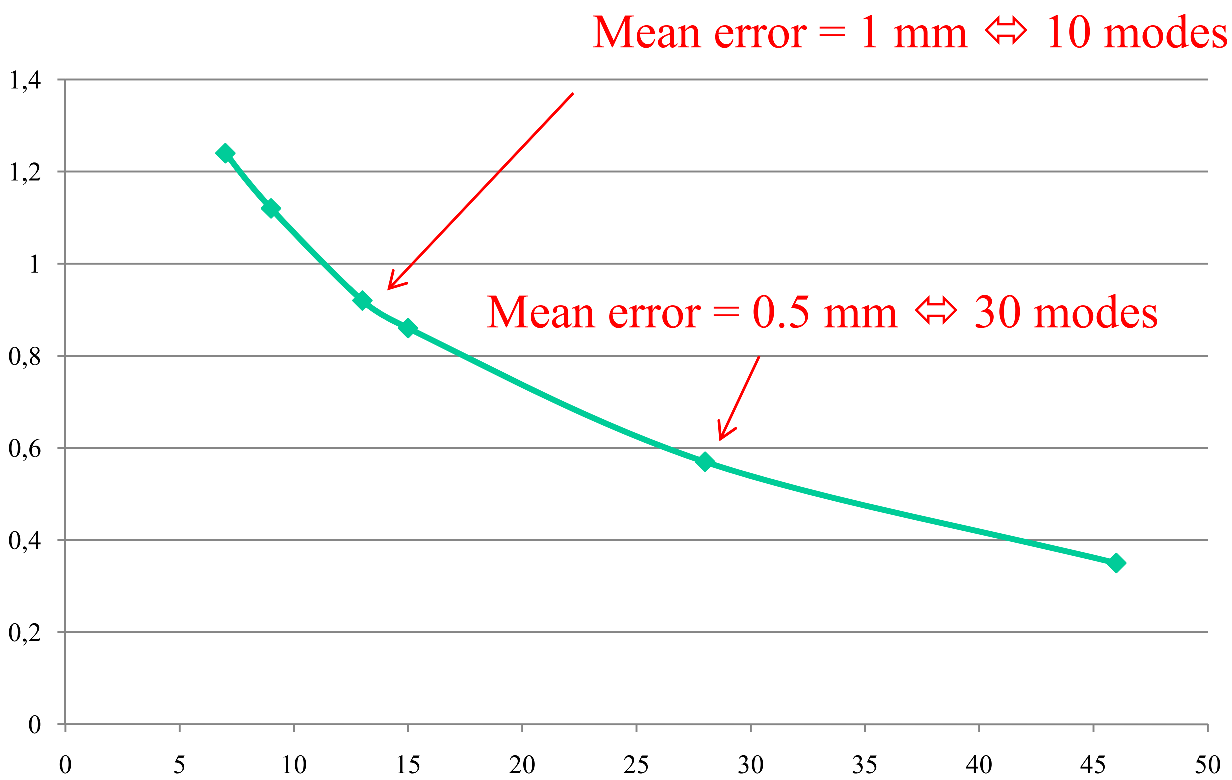
If the average bone accuracy is satisfying, the maximum distance can be too large especially for regions of great interest

Validation

Shape Indexation

Results : convergence

- Evolution of mean distance (in mm) between the real bones and their projections as a function of the number of modes considered (86 real bones):



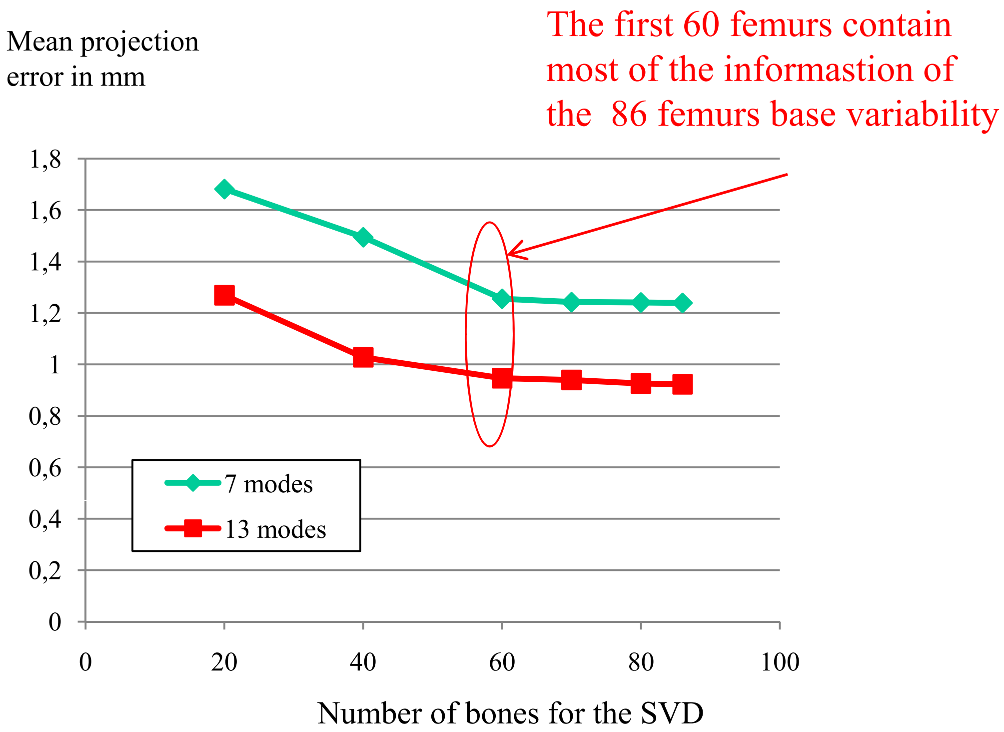
As expected, increasing the number of extracted modes globally improves the accuracy of bones representation.

Too many modes would however introduce segmentation noise in modes

Shape Indexation

Minimum Number of Bones for Mode Extraction

- Process :
  - the SVD is done with a small population of 20,40,etc.. bones
  - 7 or 13 modes are considered
  - We project the 86 real femurs in this base and calculate a mean projection error

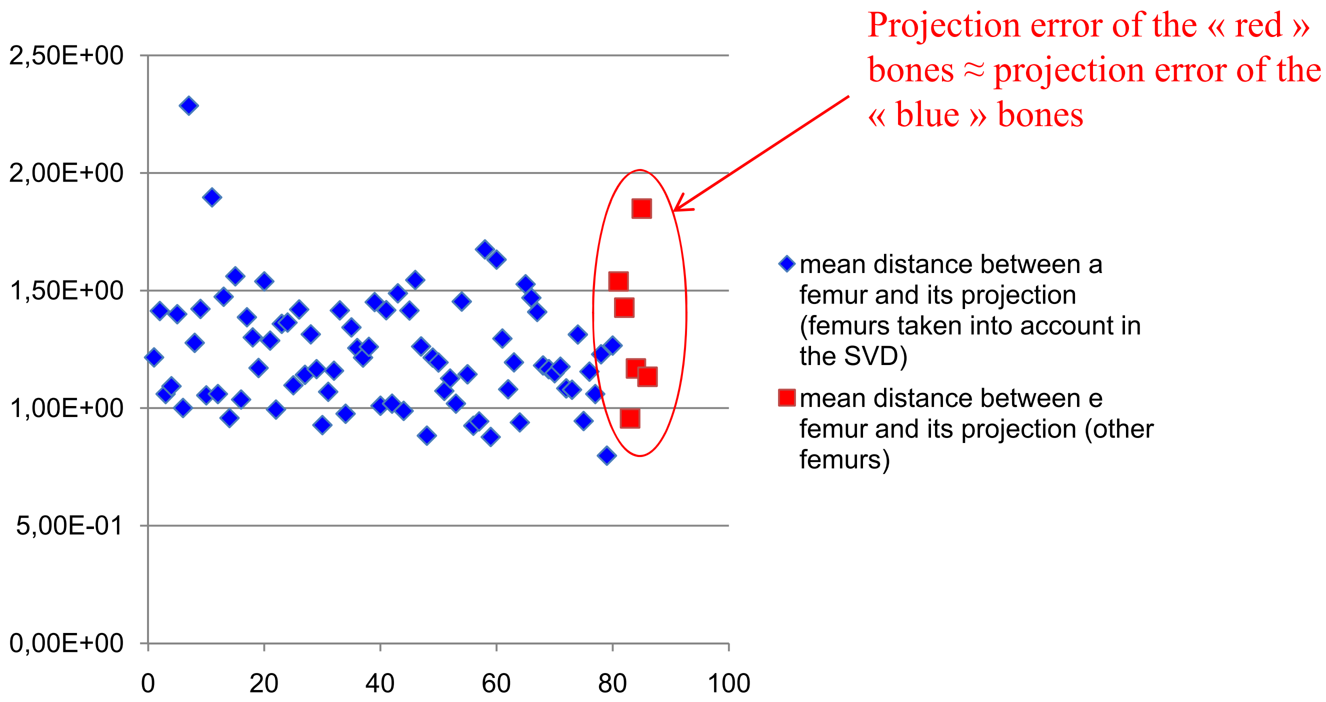


Whether we are extracting 7 or 13 modes, we observe that the accuracy of the projection increase with the number of bones in the database up to 60 bones. Beyond this threshold, the accuracy is stable.

60 bones is the ideal number of bone for mode extraction for this application

Shape Indexation
Validation with External Bones

- Are external bones well represented?
- Process :
  - SVD with 80 real bones : 7 modes considered
  - Computation of distance between real bones and their projections for these 80 bones and 6 other bones



The 6 external bones, not used in the mode extraction process, are as well represented as the 80 bones used for the mode extraction process.

80 bones are sufficient to extract representative modes.

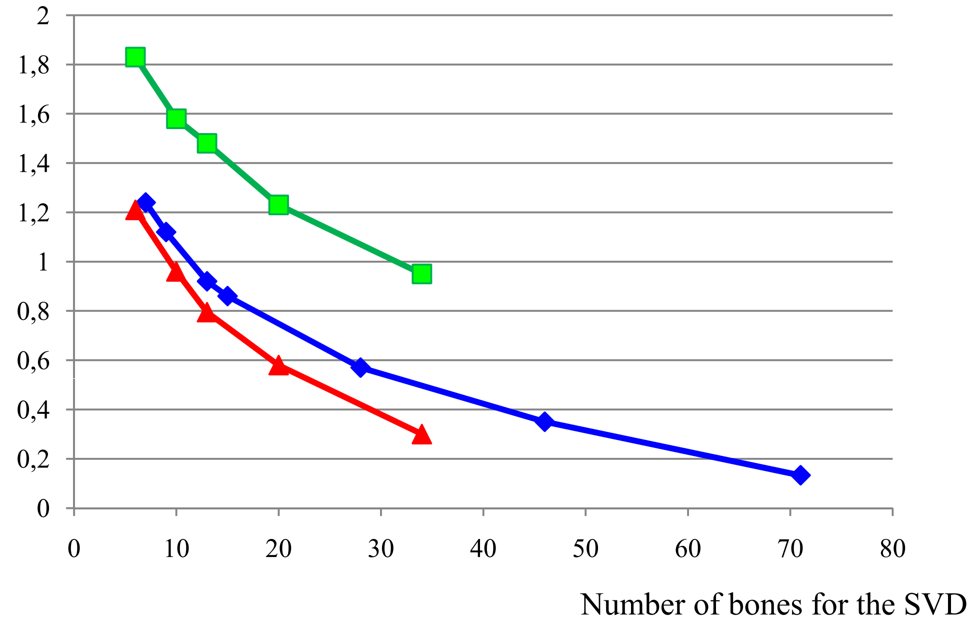
Shape Indexation

Focus on Specific Region

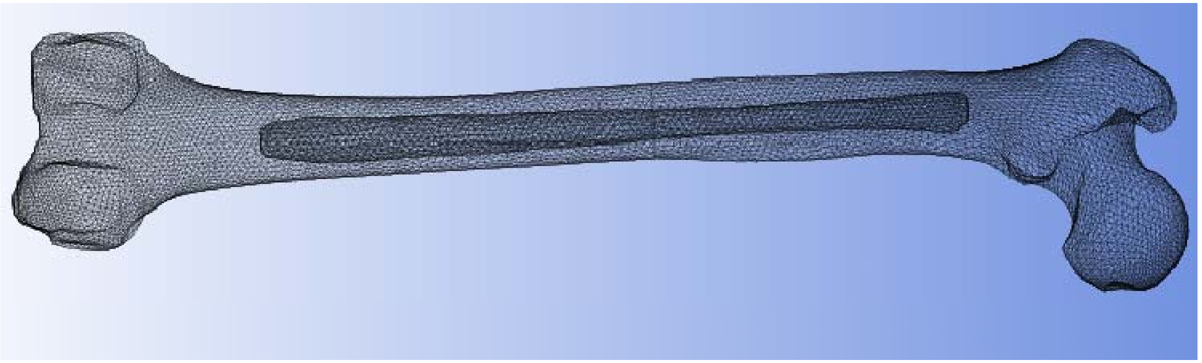
- By weighting some regions before computing the indexation we are able to have a better precision in specific regions of interest
- Illustration: Evolution of mean distance (in mm) as a function of the number of modes considered :

  Results comparison of the following cases :

  - Homogeneous weight on the whole femur
  - By weighting the superior part of the bone :
    - Mean distance for the whole femur
    - Mean distance for the superior part



Exploitation



Virtual *in vivo* Models

- From the population and the modes

$$X_i \approx \sum_{j=1}^{m} \widetilde{x}_{ij} Q_j$$

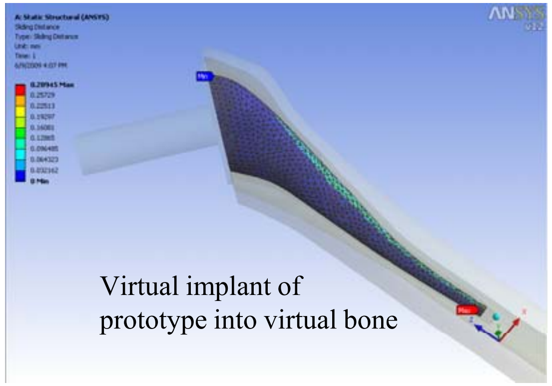
- Any new combination is a realistic virtual bone
- Using these modes we define a full parametric model representing human variability defined by the population
- It is possible to quickly generate a data base of realistic virtual bones as large as necessary

Virtual Prototyping for Prostheses

- Design performances evaluation

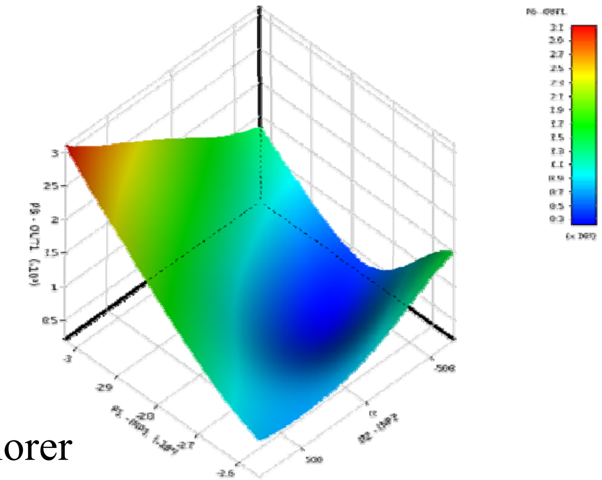
  For a given prosthesis design

  1. Computation of performance criteria on the atlas
  2. Design of Experiments (DOE) on the population using the shape modes
  3. Computation of performance criteria on each new bone (virtual *in-vivo* model)
  4. Surface response of performance criteria
  5. What is the fraction of the population for which this prosthesis design is relevant?



Virtual implant of prototype into virtual bone

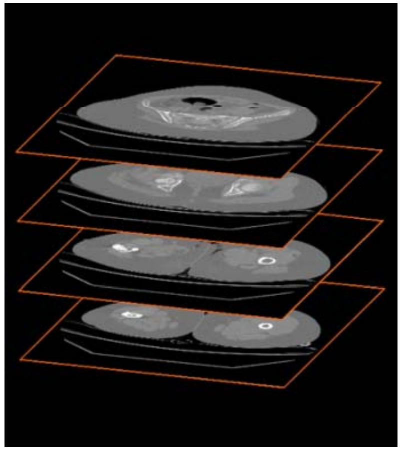
- Design Optimization
  - n_1 prosthesis design parameters
  - n_2 bone shape parameters (Q_j)
  - n_3 performance criteria
  - Design of Experiments, Interpolation of results using Design Xplorer
  - Review of performances:



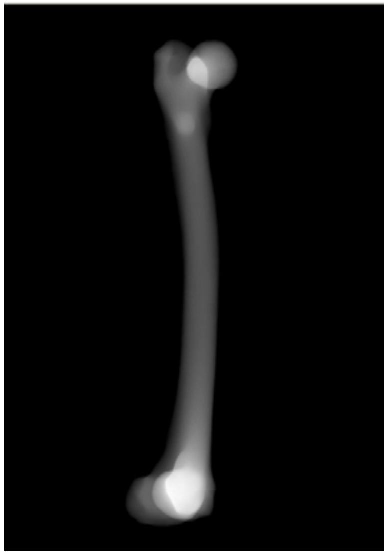
What is the optimal set of n_1 prosthesis parameters which maximizes the performances for the fraction of population represented by the n_2 bone shape parameters?

Future Work: From Patient to CAD

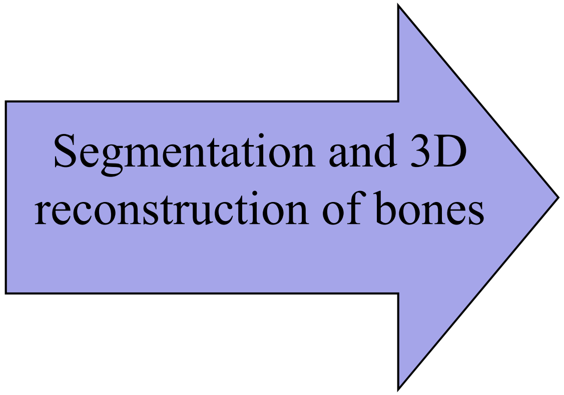
Imaging data are filtered out using modes extracted from a large data base of real femur bones. The output is a clean geometry of the bone under an STL or Parasolid format

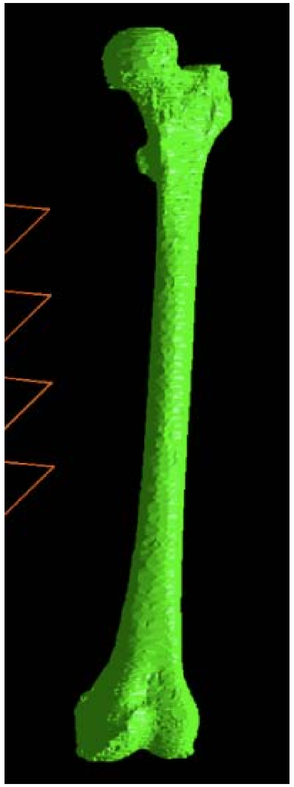


Either CT Scan



Or 2D X-Ray





CAD geometries can be used for Surgery planning or engineering simulation

Conclusions

- Mesh morphing: a straightforward tool to quickly generate good mesh on patient specific geometries
- Mode representation:
  - An efficient way to represent human variability
  - A valuable data base to reconstruct 3D geometries
- Contemplated applications:
  - Development of unlimited data bases of virtual bones
  - Large *in silico* virtual prototyping
  - Reconstruction of 3D bone geometry out of a 2D X-Ray