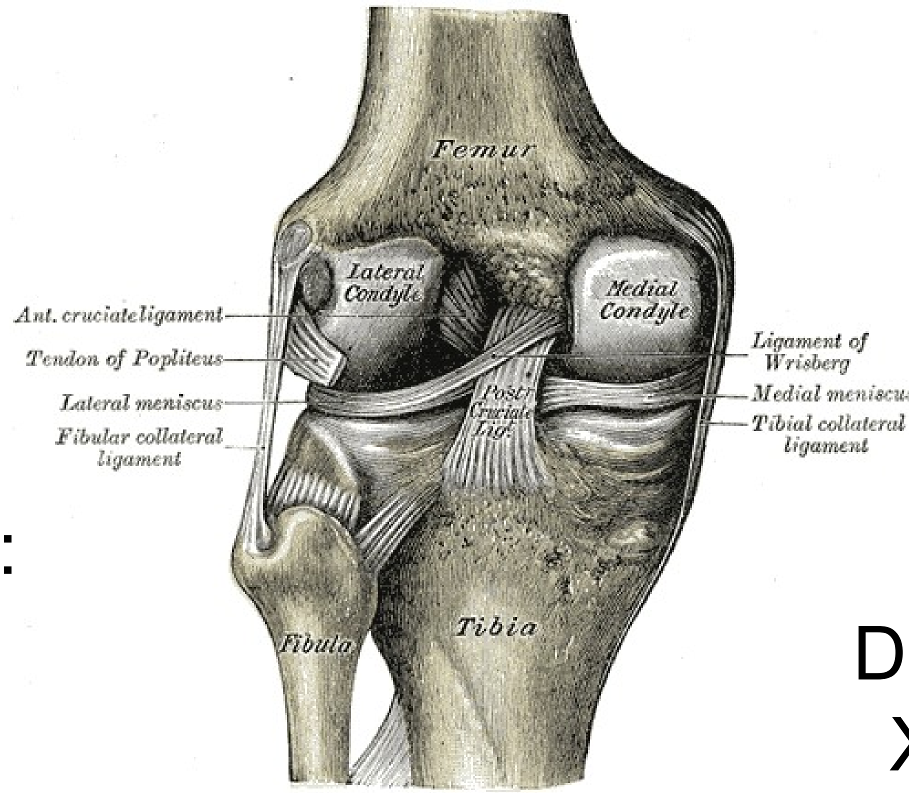
Statistical Atlas of the Knee

Paper Presentation *by Murat Bilgel*



Henry Gray, Anatomy of the Human Body, 1918
http://www.bartleby.com/107/93.html

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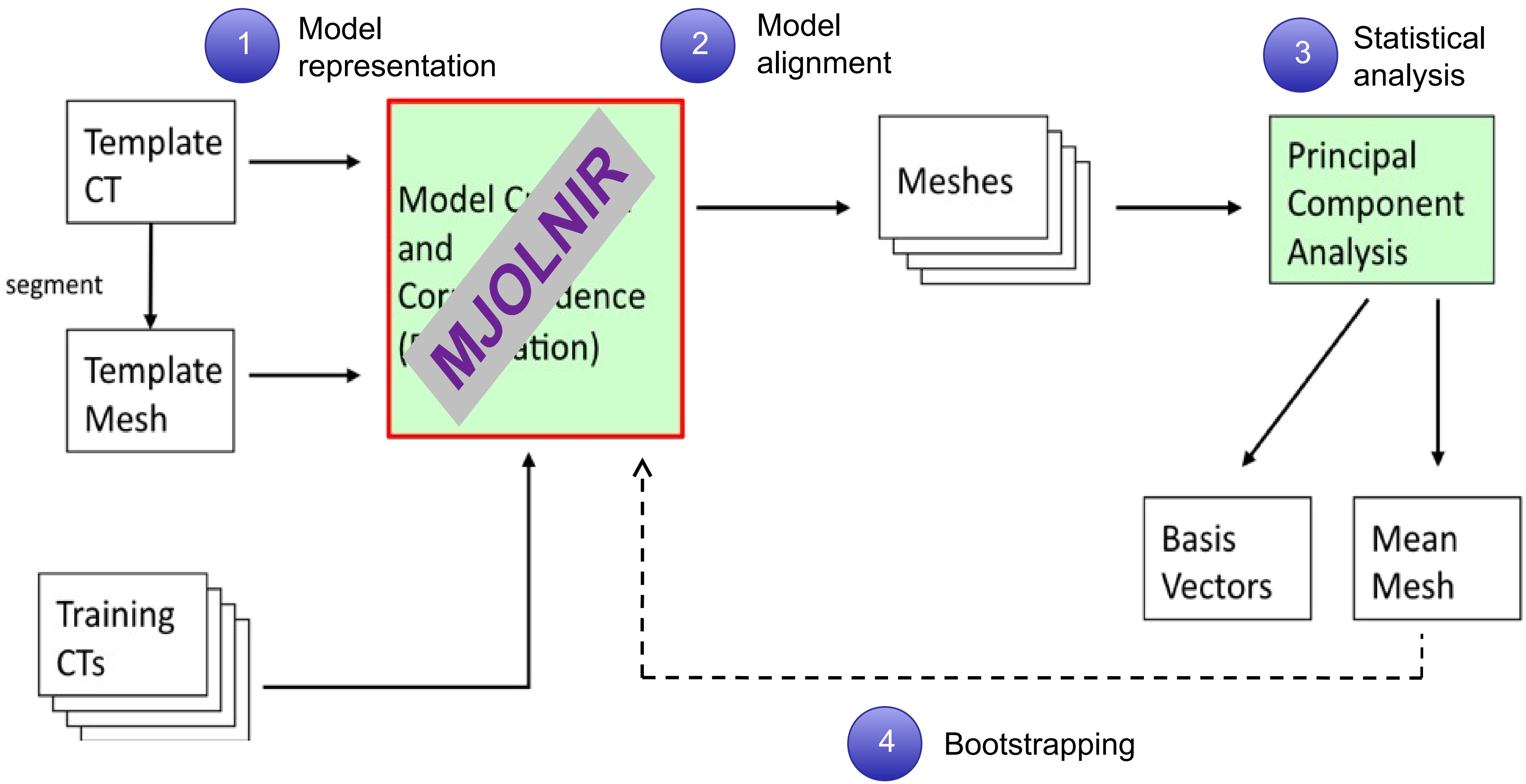
Project Overview

- Improve and automate the statistical atlas building pipeline developed by Dr. Gouthami Chintalapani at the Johns Hopkins University
- Build a statistical atlas of the knee using CT images

Basic Atlas Construction Process



from Dr. G. Chintalapani's PhD dissertation

Project Update

- Fixed the problem with MJOLNIR
- Had to downsample each CT image to avoid "out of memory" error
- Finished preprocessing of all CT images and created mesh of left and right femur
- Currently running MJOLNIR
- Expect to have the atlases by the planned date of 4/30

Paper Selection

G. Chintalapani, L. M. Ellingsen, O. Sadowsky, J. L. Prince, R. H. Taylor. **Statistical Atlases of Bone Anatomy: Construction, Iterative Improvement and Validation.** Medical Image Computing and Computer Assisted Intervention (MICCAI), 2007; 10 (Pt 1): 499-506.

Background

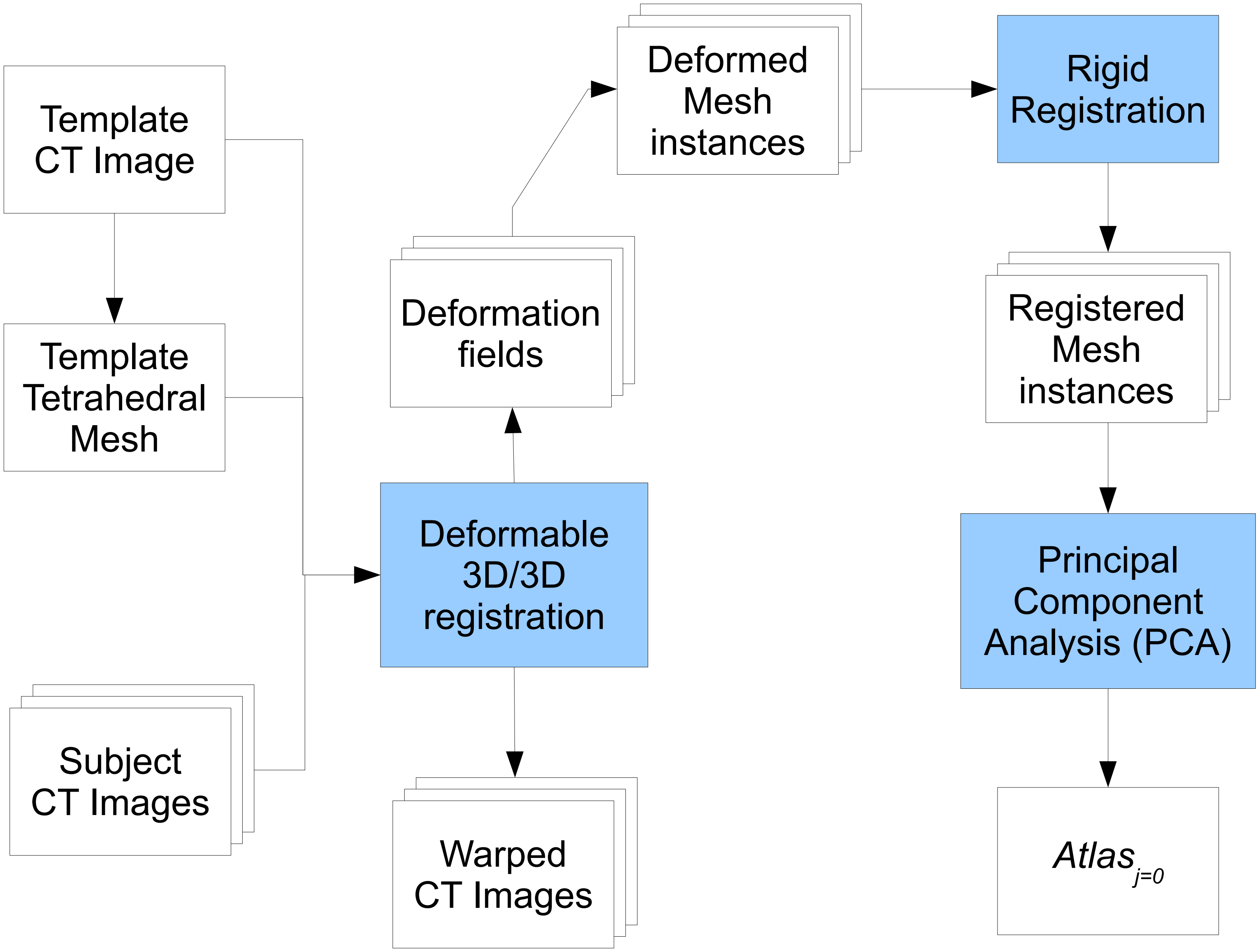
- Basic statistical atlas construction method involves identifying landmark points, establishing point to point correspondences between subjects, and performing statistical analysis
- Existing methods require all patient images to be segmented separately or pose difficulties when applied to volumetric data

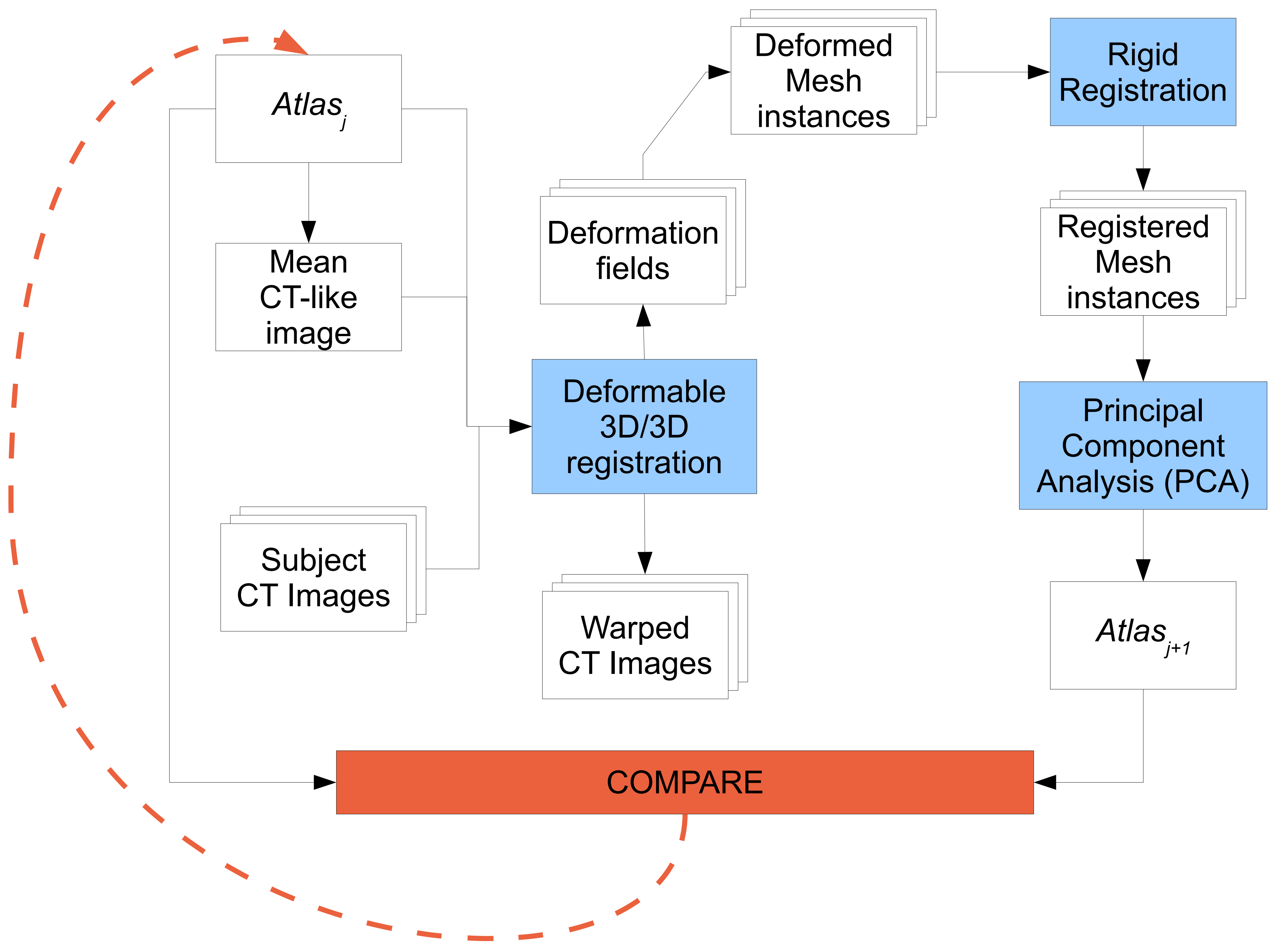
Paper Summary

- Iterative framework to create statistical atlases of human bone anatomy from CT images
- Initial atlas is created using deformable registration onto a template volumetric mesh
- Atlas is refined using bootstrapping to improve stability and consistency
- Validation results are presented using 110 male pelvis CT images

Significance

- Iterative approach eliminates the dependency on the choice of the initial template
- Method to analyze the effect of training sample size on atlas variations
- Atlases constructed using this approach can be used in applications such as image segmentation and hybrid reconstruction


Template CT Image
Template Tetrahedral Mesh
Subject CT Images
Deformable 3D/3D registration
Deformation fields
Warped CT Images
Deformed Mesh instances
Rigid Registration
Registered Mesh instances
Principal Component Analysis (PCA)
$Atlas_{j=0}$



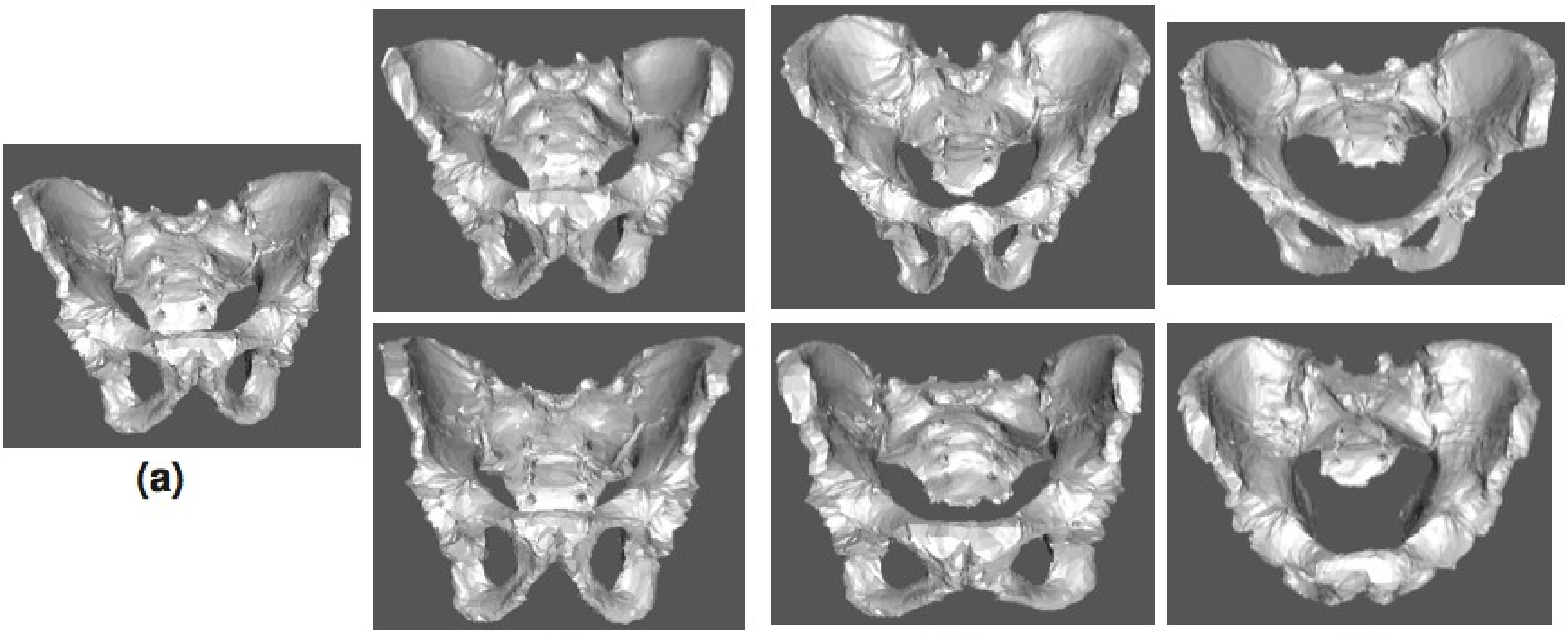
$Atlas_j$
Mean CT-like image
Subject CT Images
Deformable 3D/3D registration
Deformation fields
Warped CT Images
Deformed Mesh instances
Rigid Registration
Registered Mesh instances
Principal Component Analysis (PCA)
$Atlas_{j+1}$
COMPARE

Statistical Atlas

- The statistical atlas consists of:
  - M_0, a tetrahedral mesh representing the mean shape
  - Bernstein polynomials representing the CT intensities
  - D_k, the variational modes representing shape variations
- Any shape instance *S* can be expressed as a linear combination of the anatomical modes of variation using mode weights λ_k :

$$S = \bar{M} + \sum_k \lambda_k D_k$$

Mean Shape and First 3 Principal Modes



(a) (b) (c) (d)

Figure taken from G. Chintalapani, L. M. Ellingsen, O. Sadowsky, J. L. Prince, R. H. Taylor. Statistical Atlases of Bone Anatomy: Construction, Iterative Improvement and Validation. MICCAI, 2007.

Validation

$$S = \bar{M} + \sum_k \lambda_k D_k$$

- This equation can be rewritten as $S = \bar{M} + D\lambda$, where $\lambda \in \mathbb{R}^N$ and $D = [\, D_1 \;\; D_2 \;\; \cdots \;\; D_N \,]$.
- Using this equation, we can calculate the weights of the modes for a given shape instance S^{true} by $\lambda^{est} = D^{-1}\left(S^{true} - \bar{M}\right)$, and then use the first *n* dominant eigenvalues to estimate the shape:

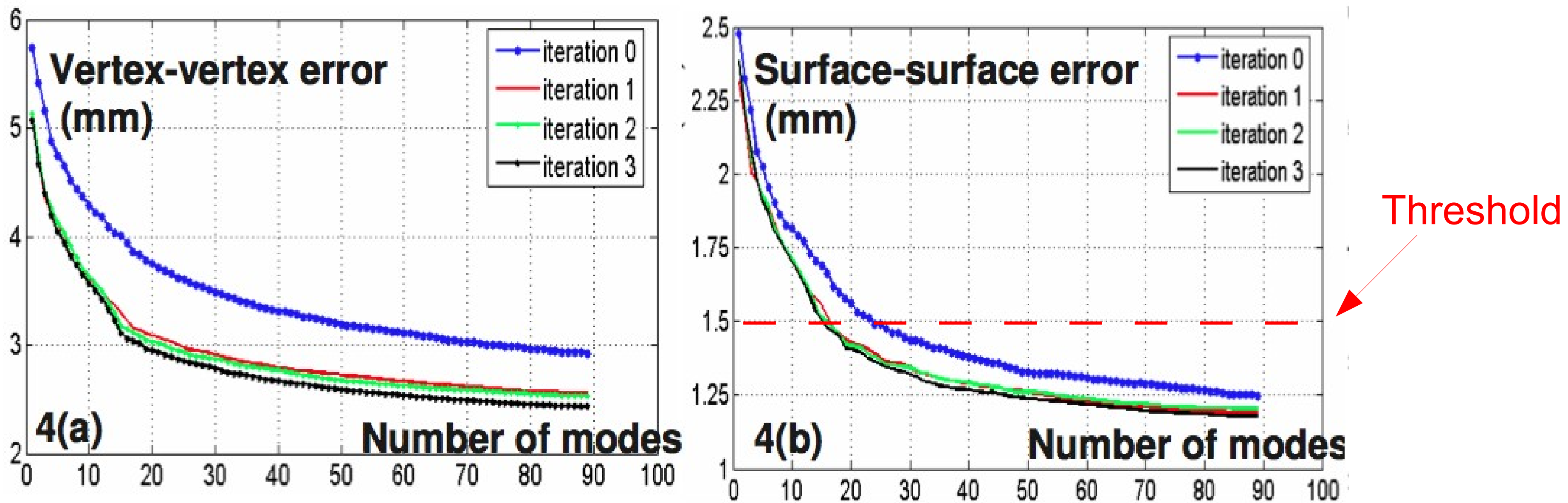
$$S^{est} = \bar{M} + \sum_{k=1}^{n} \lambda_k^{est} D_k$$

Validation Metrics

- Vertex to vertex correspondence error
  - Assumes that the meshes are similar
- Surface to surface distance
  - Computed by measuring the distances from the vertices of the model instance to the closest points on the surface

Validation

- Leave-out validation
  - Atlas was created using 90 data sets
  - Remaining 20 data sets were estimated using the mean shape and modes obtained



Figures taken from G. Chintalapani, L. M. Ellingsen, O. Sadowsky, J. L. Prince, R. H. Taylor. Statistical Atlases of Bone Anatomy: Construction, Iterative Improvement and Validation. MICCAI, 2007.

Population Size Analysis

- *n* meshes were selected randomly, where *n* = 20, 30, …, 90 to build the statistical atlas
- This process was repeated 20 times for each *n*
- Leave-out validation was used to calculate vertex-vertex error
- Results of the first iteration are shown

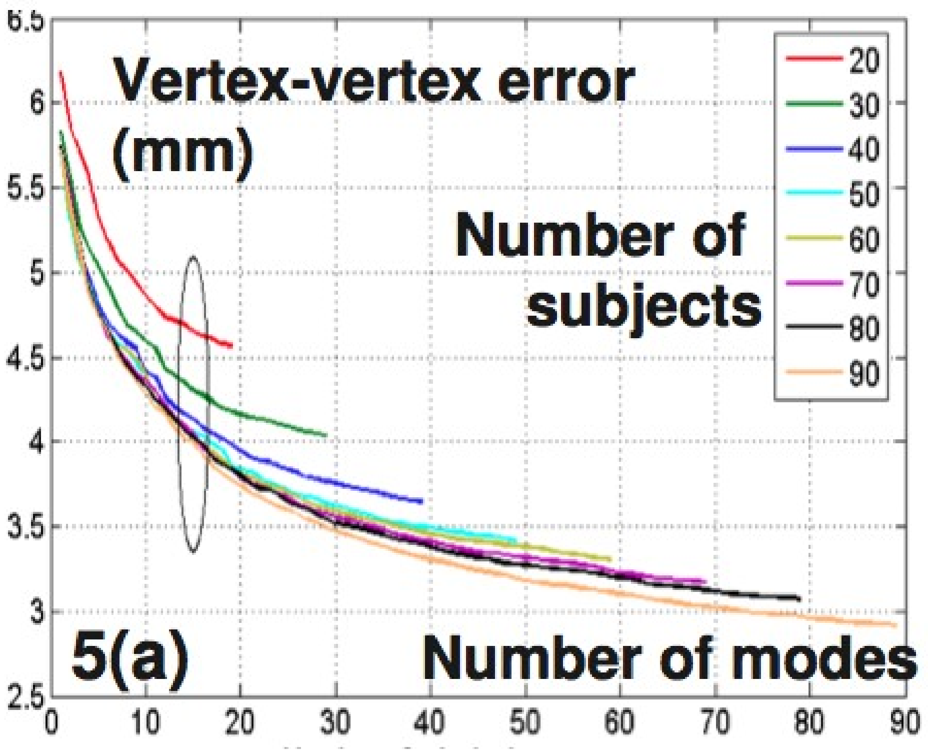


Figure taken from G. Chintalapani, L. M. Ellingsen, O. Sadowsky, J. L. Prince, R. H. Taylor. Statistical Atlases of Bone Anatomy: Construction, Iterative Improvement and Validation. MICCAI, 2007.

Conclusions

- 15 shape modes are sufficient to construct and shape instance
- ~40-50 data sets are enough to construct an accurate atlas that incorporates 15 shape modes.
  - Including additional data sets reduces residual errors by less than 0.1 mm
- Convergence by the end of iteration 2
- Accuracy of 1.5036 mm using 15 modes of the 90 data set atlas

Future Work

- Theoretically, the modular nature of the pipeline can be easily modified to incorporate any registration method, but this must be demonstrated in actual experiments
- The bootstrapping process must be validated with a consensus of multiple independent segmentations
- Pipeline is used to build an atlas of the male pelvis; need to apply the pipeline to other anatomical structures to show range of use

Unanswered Questions

- Which validation metric is more appropriate for quantifying the accuracy of a statistical atlas?
- How does template selection affect convergence? Does the initial template have to be an “average” CT image?
- Is there a theoretical guarantee that the algorithm will converge to a global optimum?

Relevance to Project

- We are following this atlas building pipeline
- Methods and metrics presented in the paper to evaluate atlas accuracy will be necessary for our project
- Expected number of iterations and required number of training images for our project can be estimated using the results presented

Next Steps

- Register all images onto the template mesh using MJOLNIR
- Visualize the deformation fields
- Align the deformed meshes and perform principal component analysis (PCA) on the vertices to obtain the mean image and the modes
- Perform atlas validation
- Estimate bone tunnel locations after ACL surgery by registering X-ray images onto the statistical knee atlas

Thank you!

Questions?