Shape-Based Analysis of Image Ensembles

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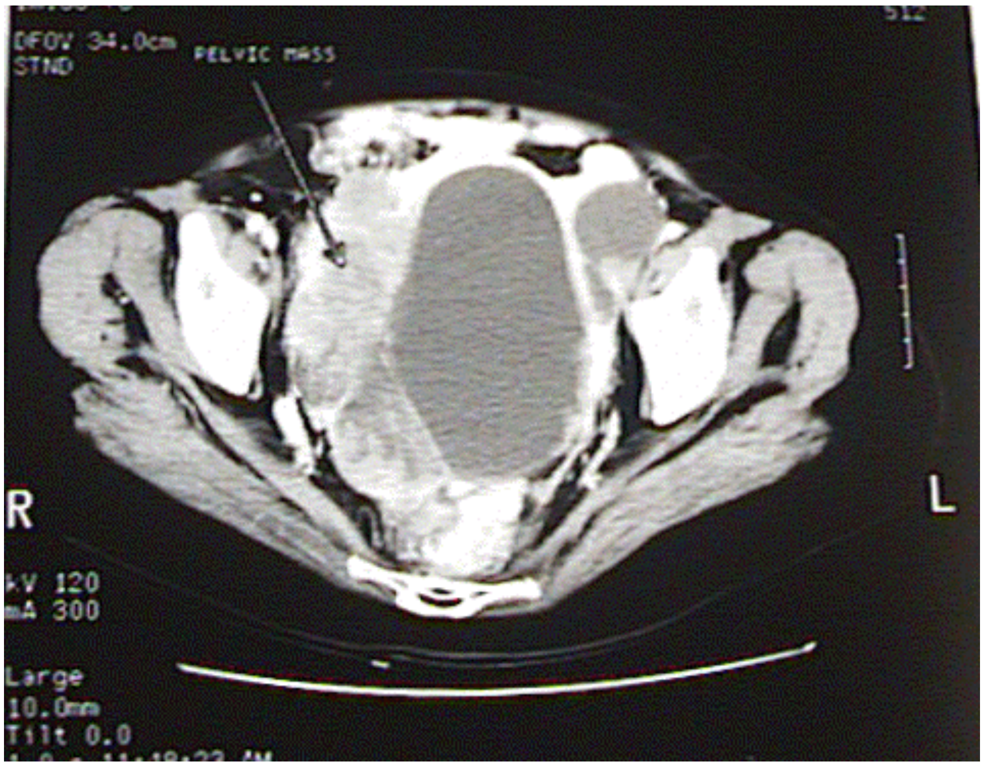
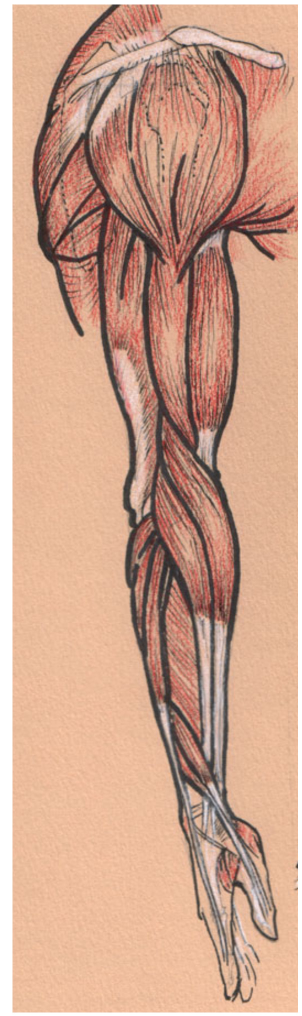
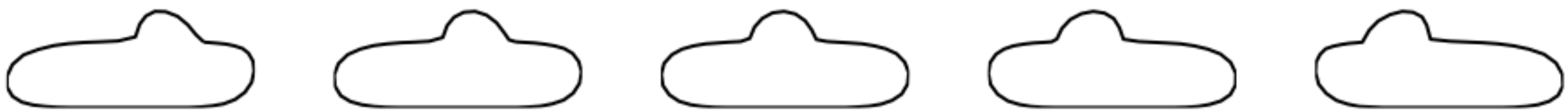
Shape and Pathology



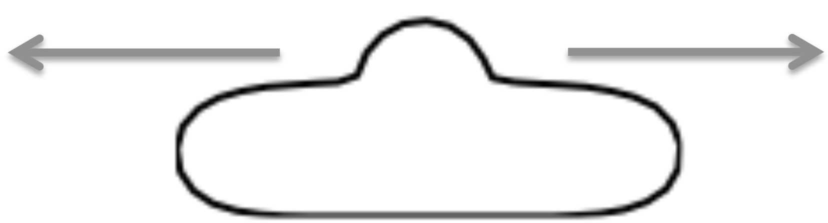


Quantitative Shape Analysis

- What is the mean of these shapes?



- Quantify variability



Historical Perspective

- D'Arcy Thompson, <u>On Shape and Form</u>, 1917

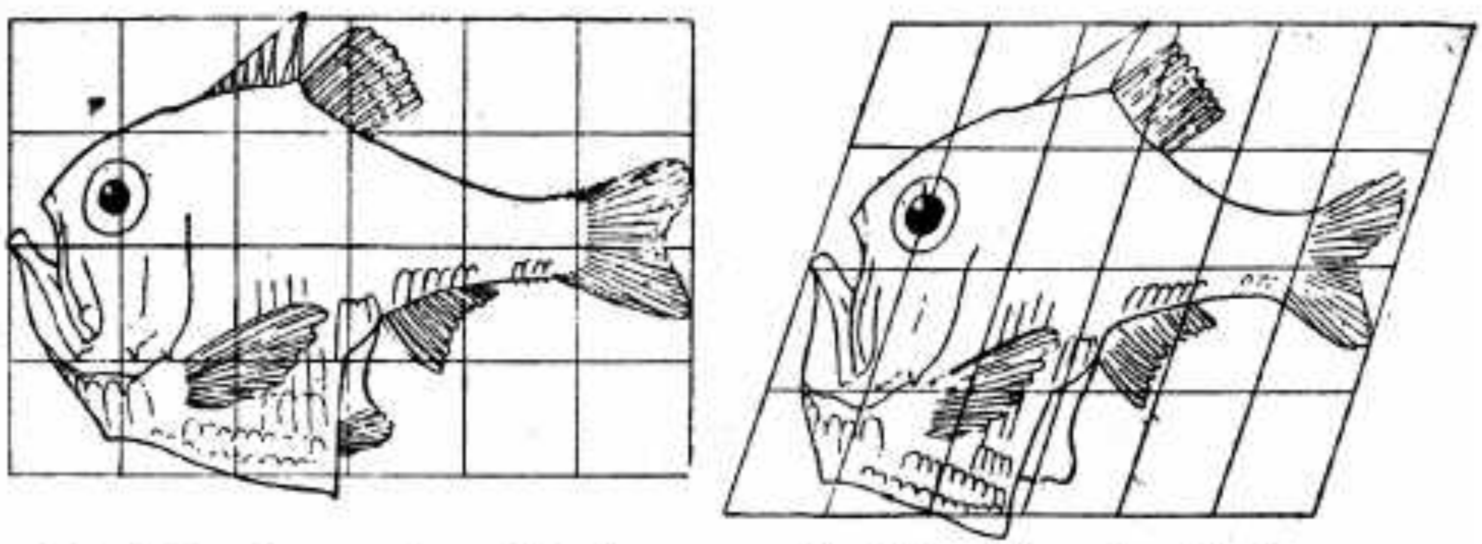
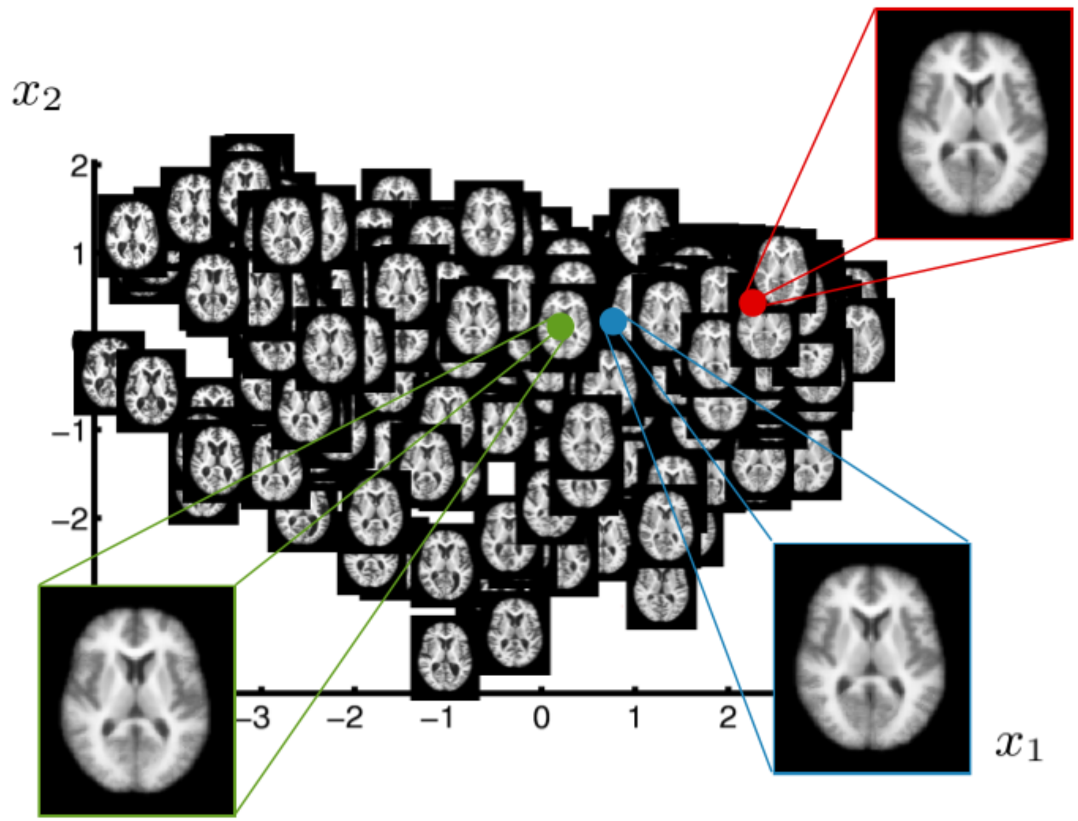


Fig. 517. *Argyropelecus Olfersi.* Fig. 518. *Sternoptyx diaphana.*

What do we do with shape statistics?

Big Data, Images, Shapes

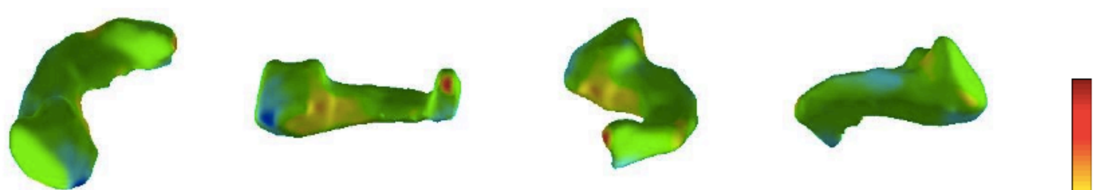
- Build tools for statistical analysis of shape and operate on large databases of images
- E.g. ADNI – Alzheimer's Disease Neuroimaging Initiative

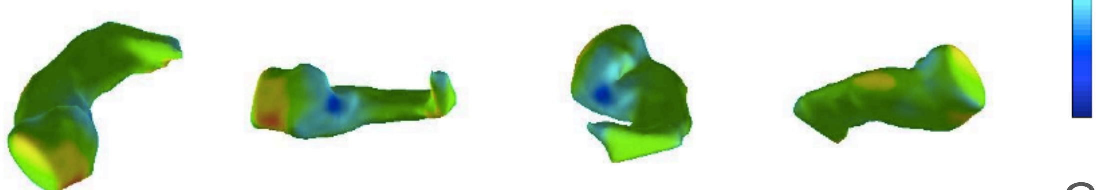


Greber et al., 2010

Shape Analysis – Statistical Comparisons

- Hypothesis testing on ensembles of shapes
  - Does on group demonstrate a different morphology?
  - What does that mean?

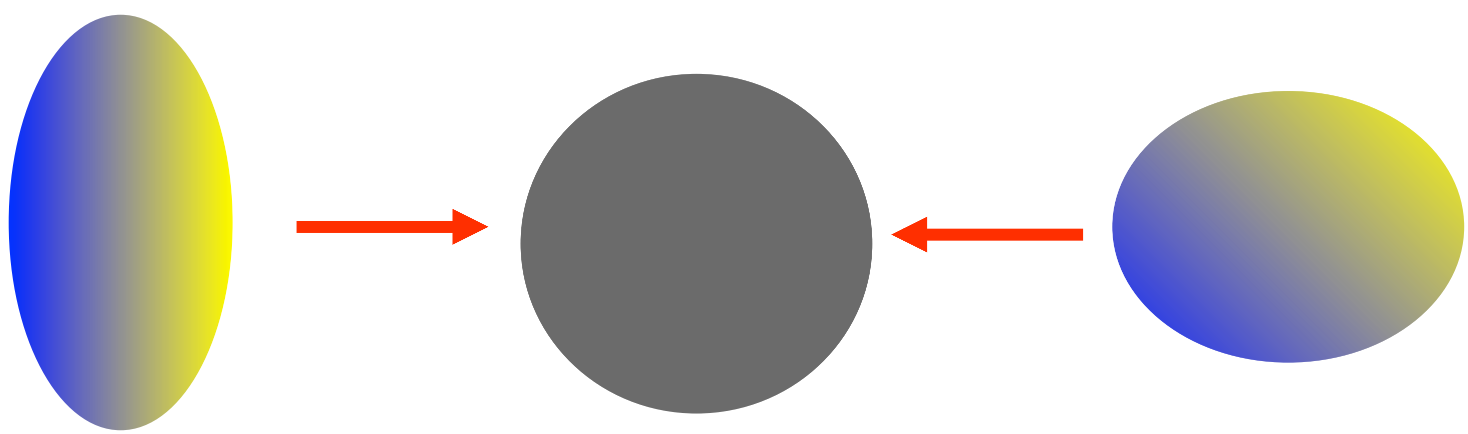

(a) Schizophrenia patient


(b) Normal control

Golland, 2001

Shape Analysis – Common Coordinate System

- Alignment of different organisms to template
- Compare other values
  - E.g. mechanical stresses or field strengths



Template (Statistical)

Shape Analysis – Segmentation/ Detection

- Shape leads to "appearance"
- Bayesian formulation

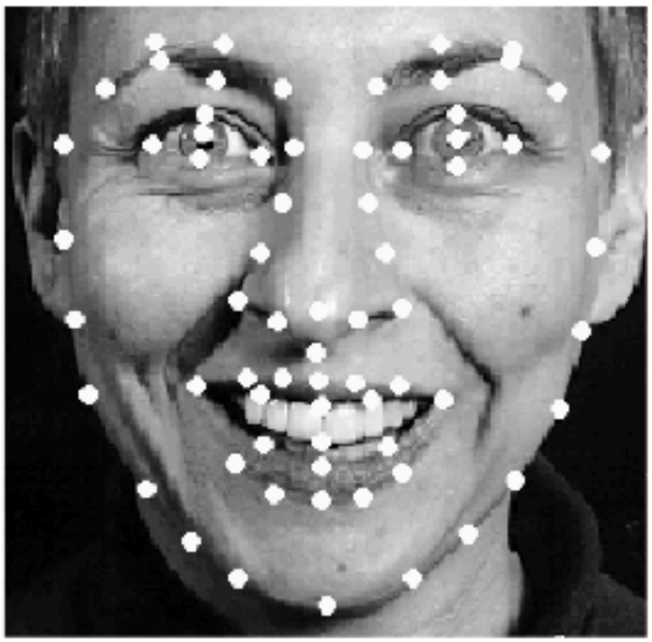
$$P(S|I) \propto P(I|S)P(S)$$

Posterior Likelihood Prior

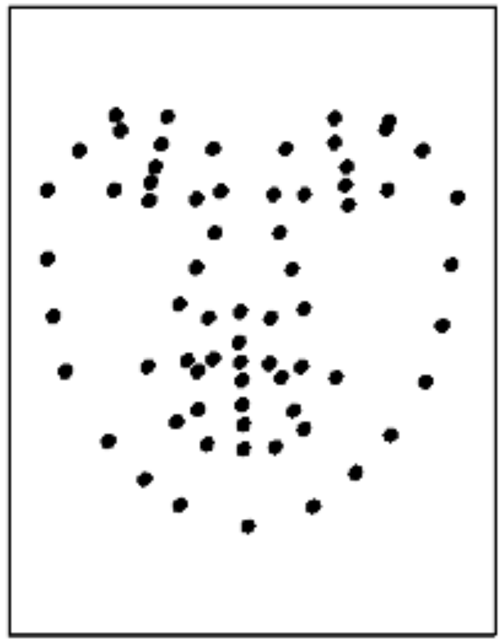
$$\log P(S|I) = \log P(I|S) + \log P(S)$$

For Gaussian distributions, these logs lead to quadratics

Active Appearance Models



Landmarks on training data



Shape Model (Incl. Variability)

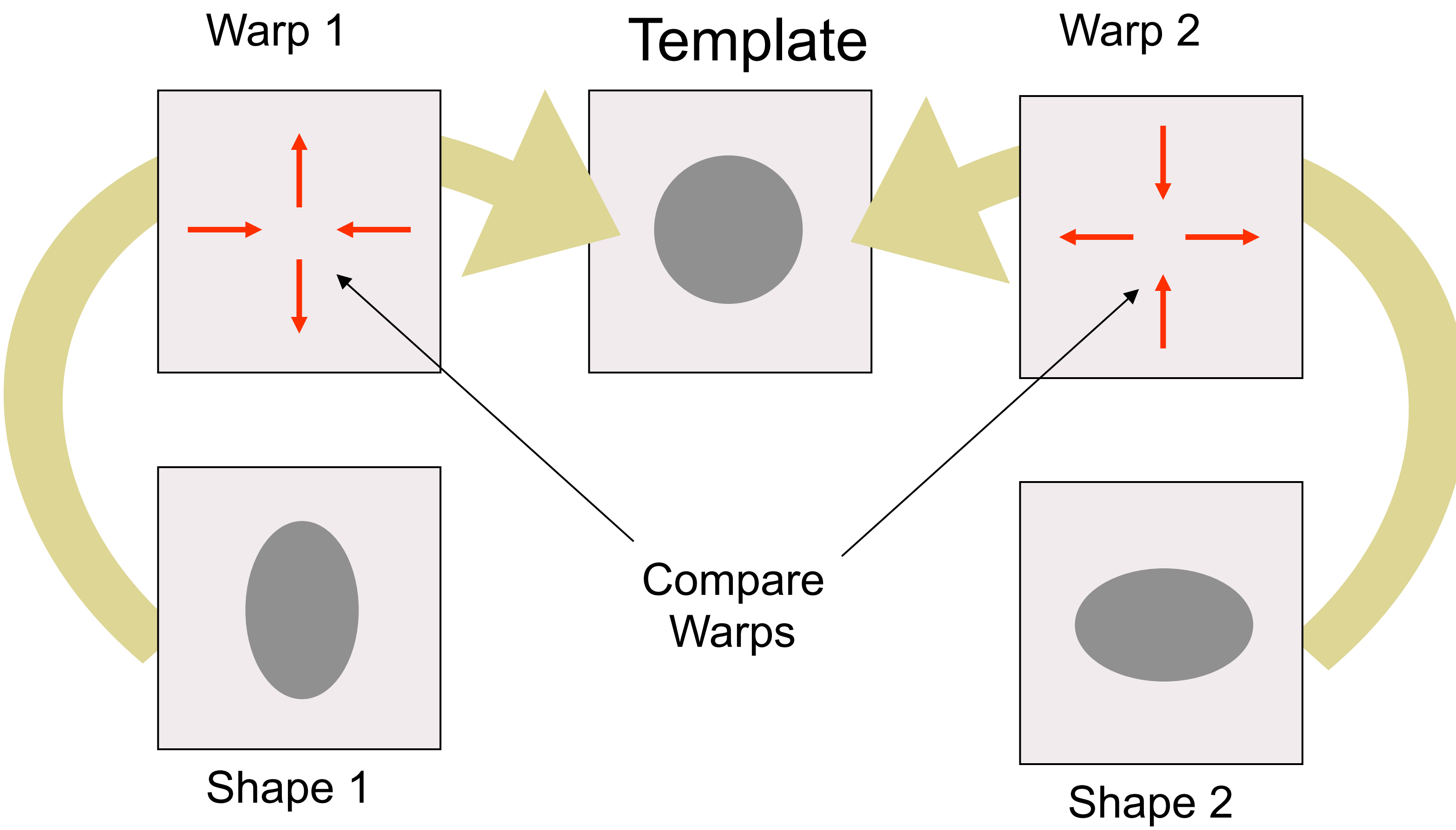
Appearance Model (Incl. Variability)

Cootes et al., 2001

Other Applications of Shape Analysis

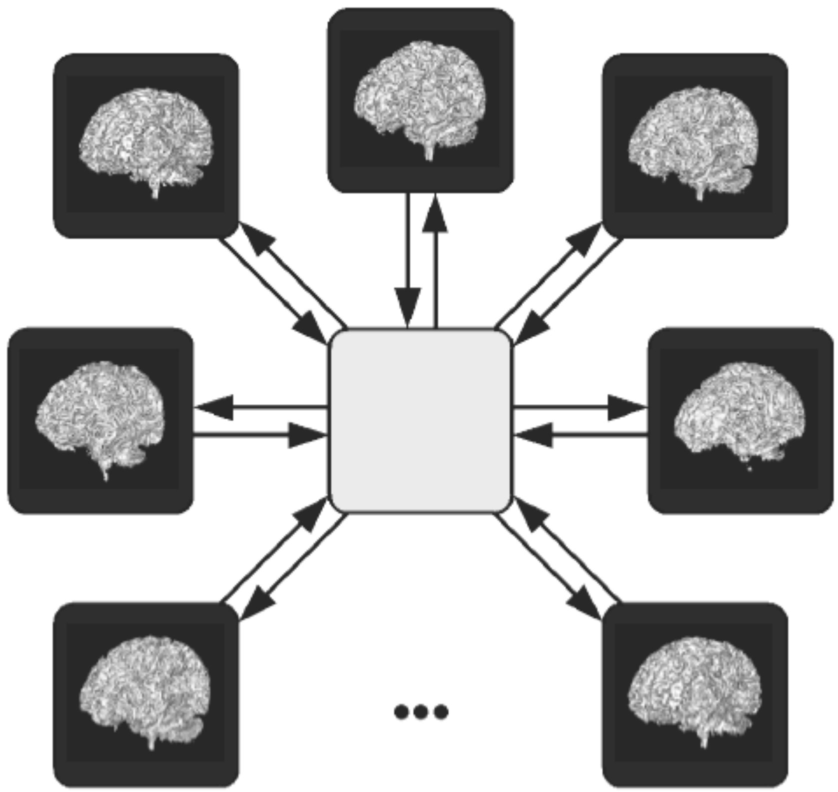
- E.g. sizes/shapes of prosthetics or implants
- Evaluating how a patient differs from population (z-score)
- Morphology and genetics
  - E.g. developmental, phenotypes
- Shape and function
  - How does shape impact physiology?

Image Deformation Approach to Shape



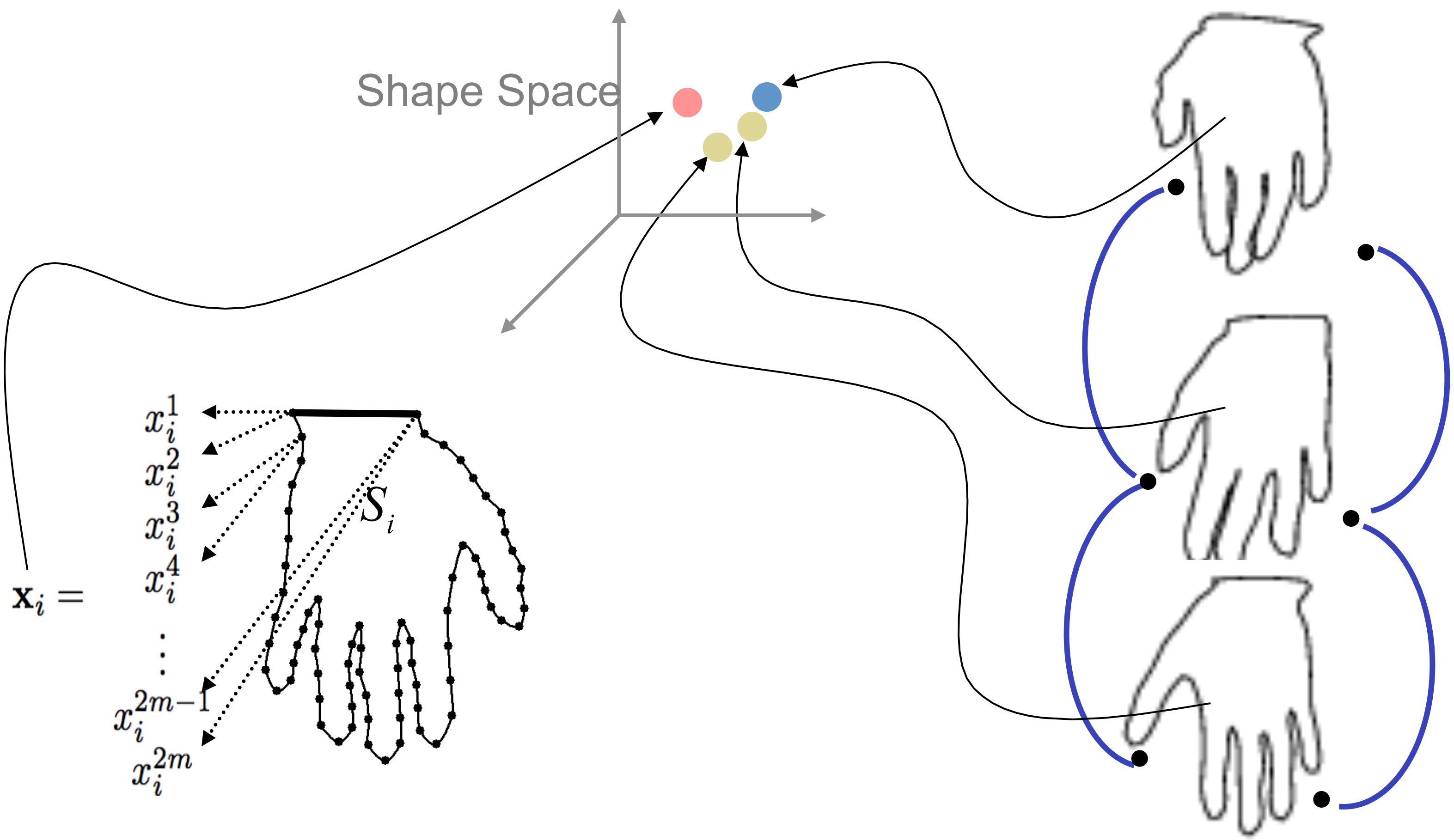
Unbiased Diffeomorphic Atlases

- Find a template that minimizes sum of distances to ensemble



Joshi et. al, 2004

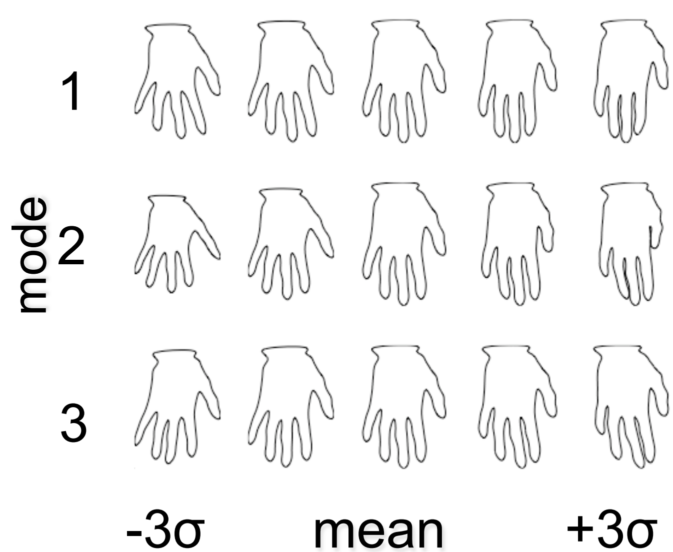
Shape from Correspondences/ Landmarks



Point Distribution Models (PDMs)

Hands: A Pattern Theoretic Study of Biological Shapes

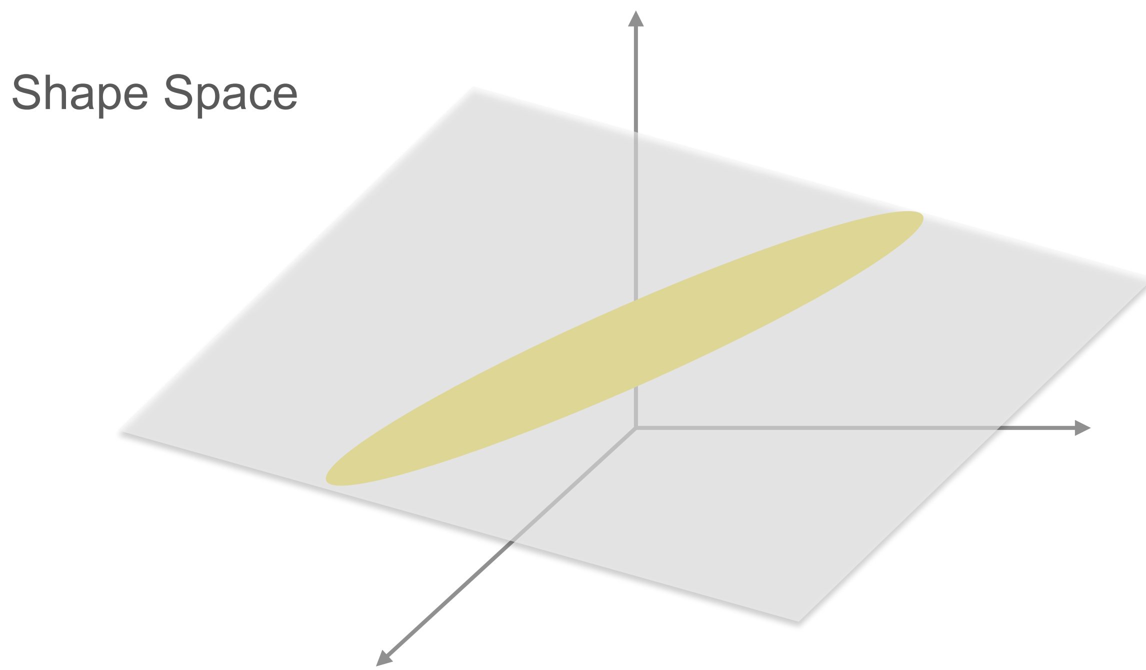
- Ulf Grenander, 1990
- Pick landmarks on sets of hands
- A few PCA modes capture variability



PCA modes visualization

Statistics in Shape Space

- PCA for dimensionality in shape space
- Gaussian models on linear subspace

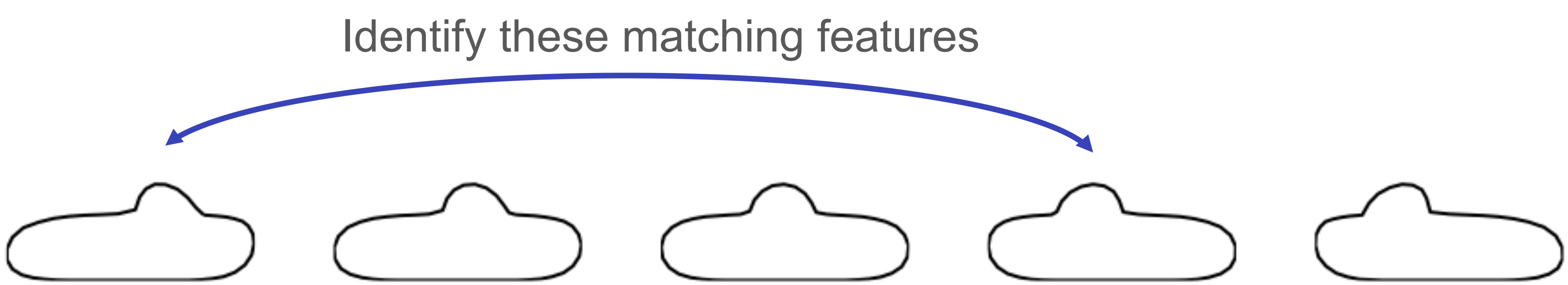


Correspondences and Shape

- The choice matters
  - Defines the shape space
- Manual landmarks
  - Not practical
  - 3D, not clear
  - User error
- Need: automatic 3D correspondence placement

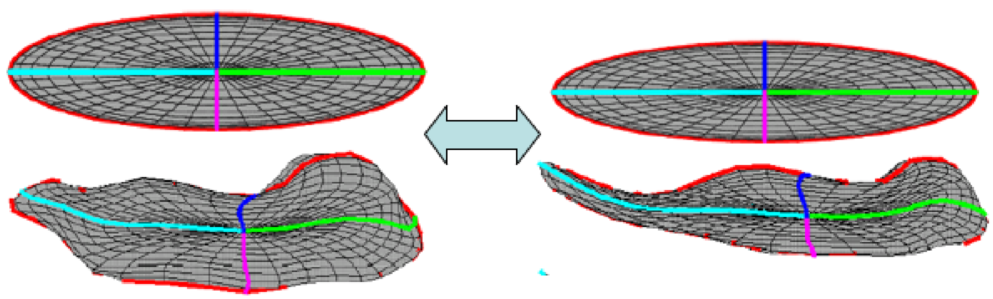
Shape Correspondence

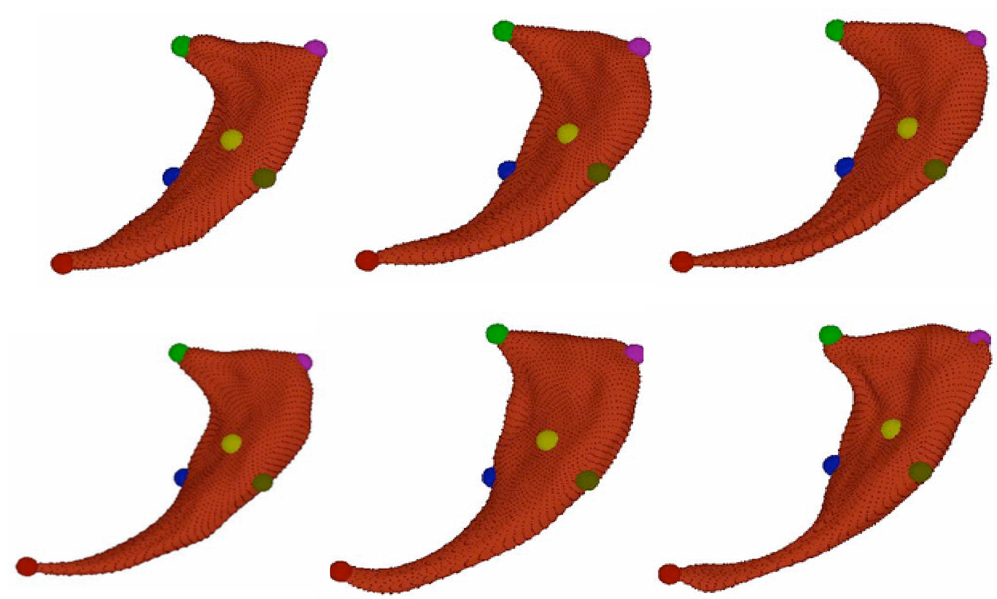
- Feature matching
  - E.g. Guibas et al.



Smooth Mappings to Primitives

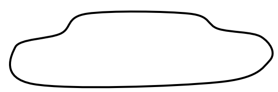
- E.g. SPHARM-PDM, Steiner et al., 2006



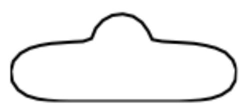


Correspondence Depends on the Population

- Optimize local/nearest differences



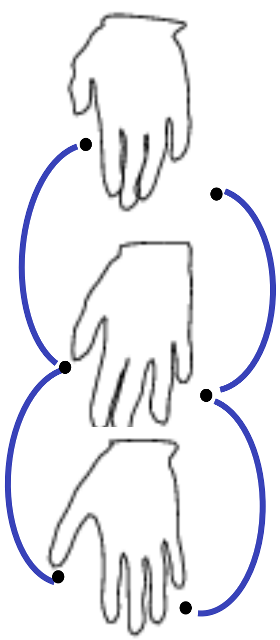
- Account for the trends in the ensemble

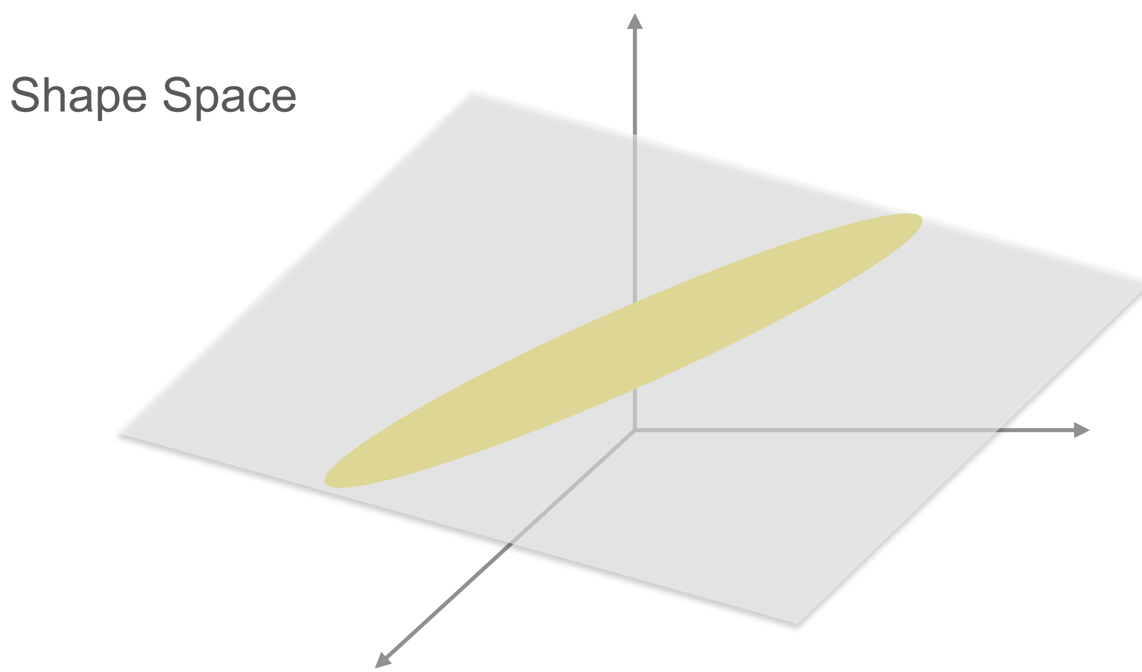


  - Davies et al. 2000 (MDL)
    - Parameterization should be such to minimize *description length* of ensemble

Basic Idea

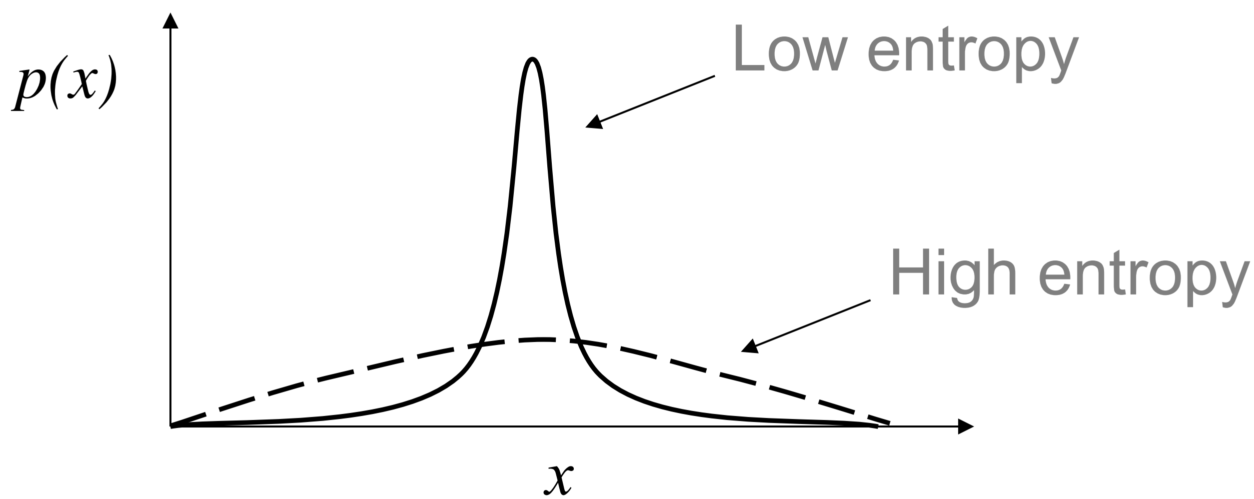
- Landmark (LM) positions are not unique
- LMs control behavior of shape space
- Strategy: position LMs to optimize the statistics in shape space





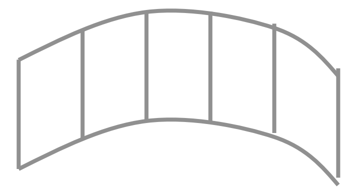
Occam's Razor

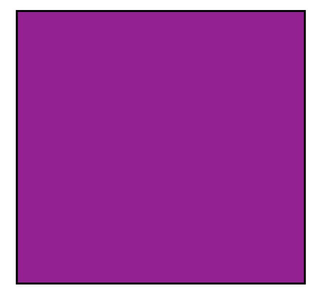
- Minimize entropy of distribution
  - Measure of uncertainty – information content of a sample



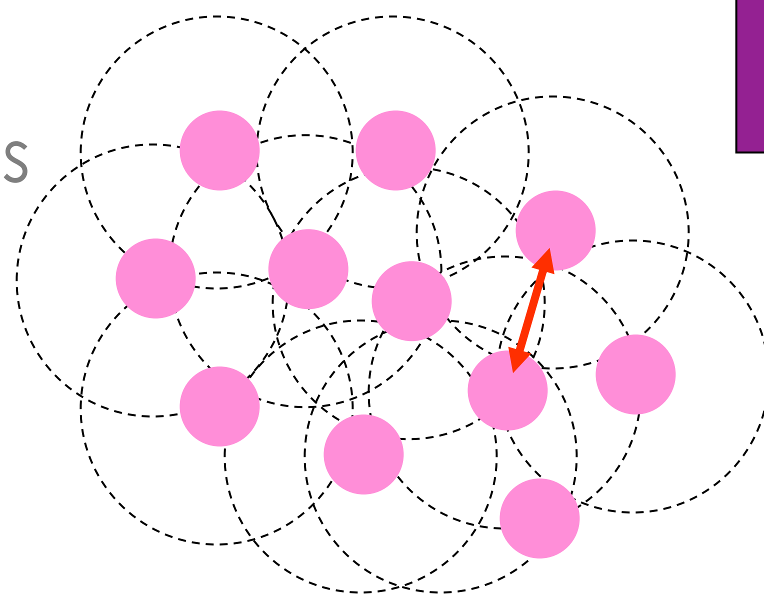
Particle Systems

- Particles distributed to minimize potential
  - Particle-particle interactions
  - Minimize through incremental updates (dynamic)





- Satisfy constraints
  - E.g. isosurfaces



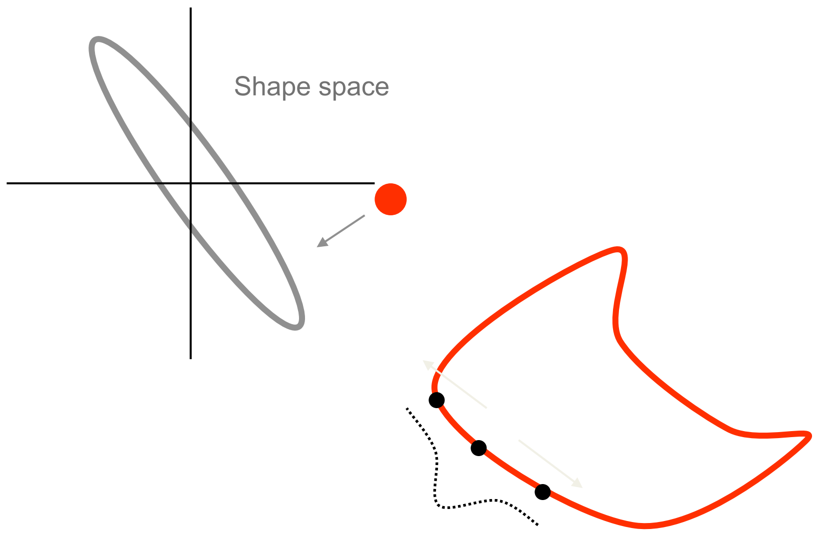
Particle-Based Shape Correspondences

- Shapes as a set of interacting particle systems
- Compact models, but balanced against geometric accuracy (good, adaptive samplings)
- Optimize particle positions by minimizing an entropy cost function

$$Q = H(Z) - \sum_k H(P^k)$$

Entropy of the shape ensemble

Potential energies for particle-particle interactions

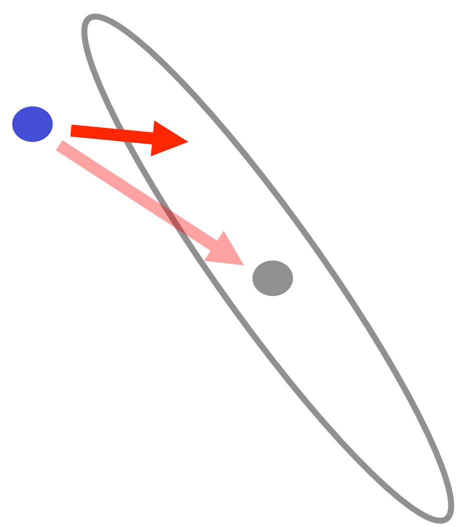


Minimizing Ensemble Entropy

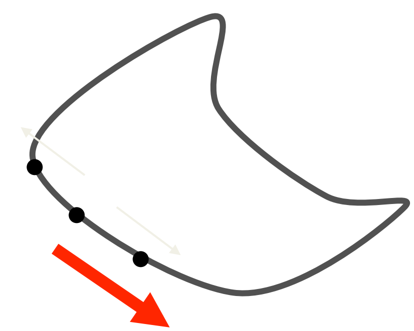
- Weighted movement toward mean

$$\frac{dX_i(t)}{dt} = \Delta t \, \Sigma^{-1}(\mu - X_i(t))$$

(+ forces between particles)



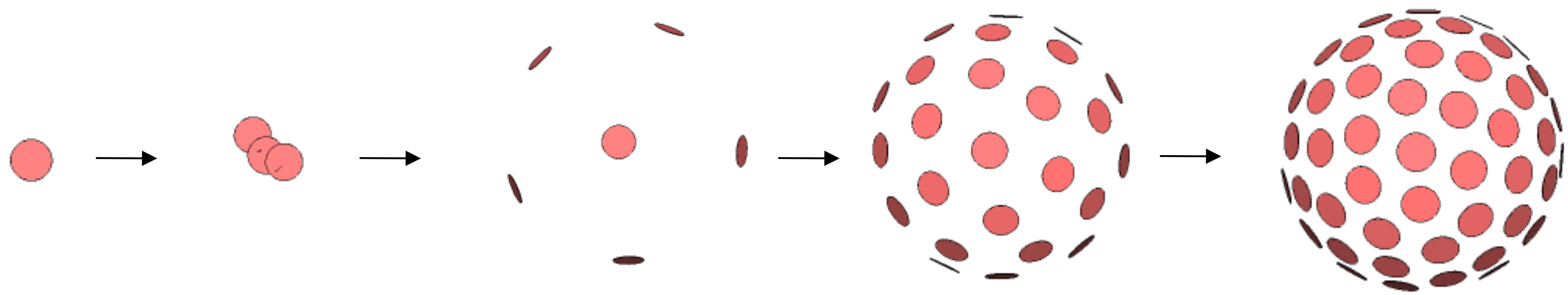
Shape Space



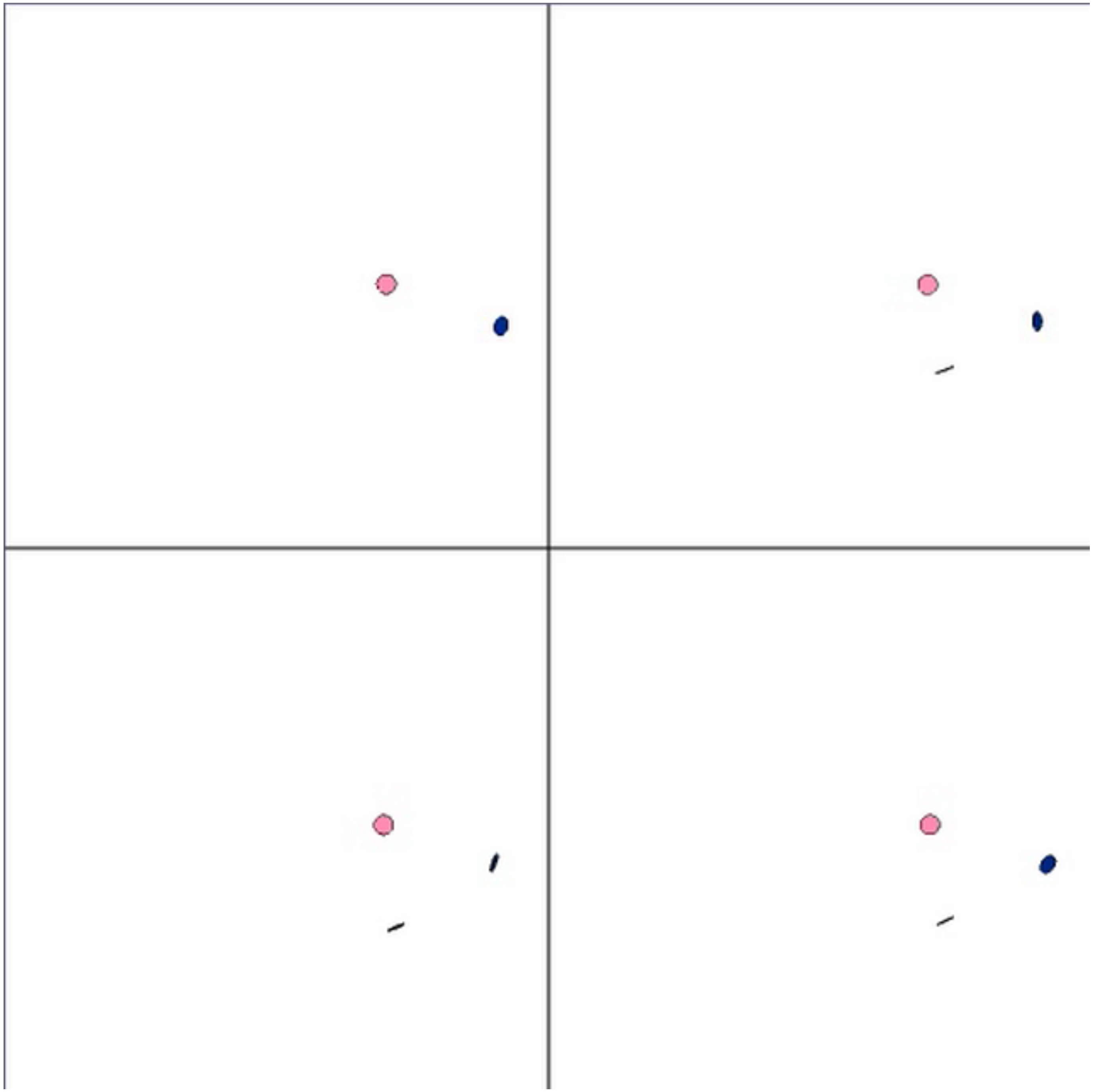
Object Space

Entropy-Based Surface Sampling

- Big issue: local minima and how to initialize
  - Lots of *tricks*



Surface sampling with a max entropy particle system.
Particles split under optimization until entire surface is sampled.

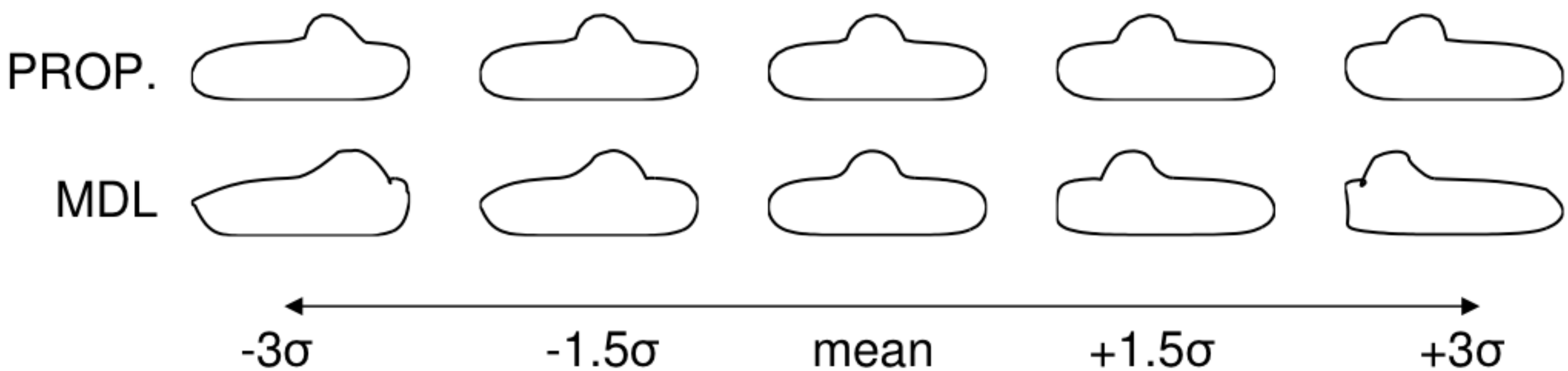


Shape Analysis Pipeline

1. Segmentation process -> binary volumes
2. Align segmentations
3. Distance transform from binary interface w/ smoothing
4. Initialize models (splitting under optimization)
5. Optimize Correspondences (w/ Procrustes)
6. Statistical Analysis

Box-Bump

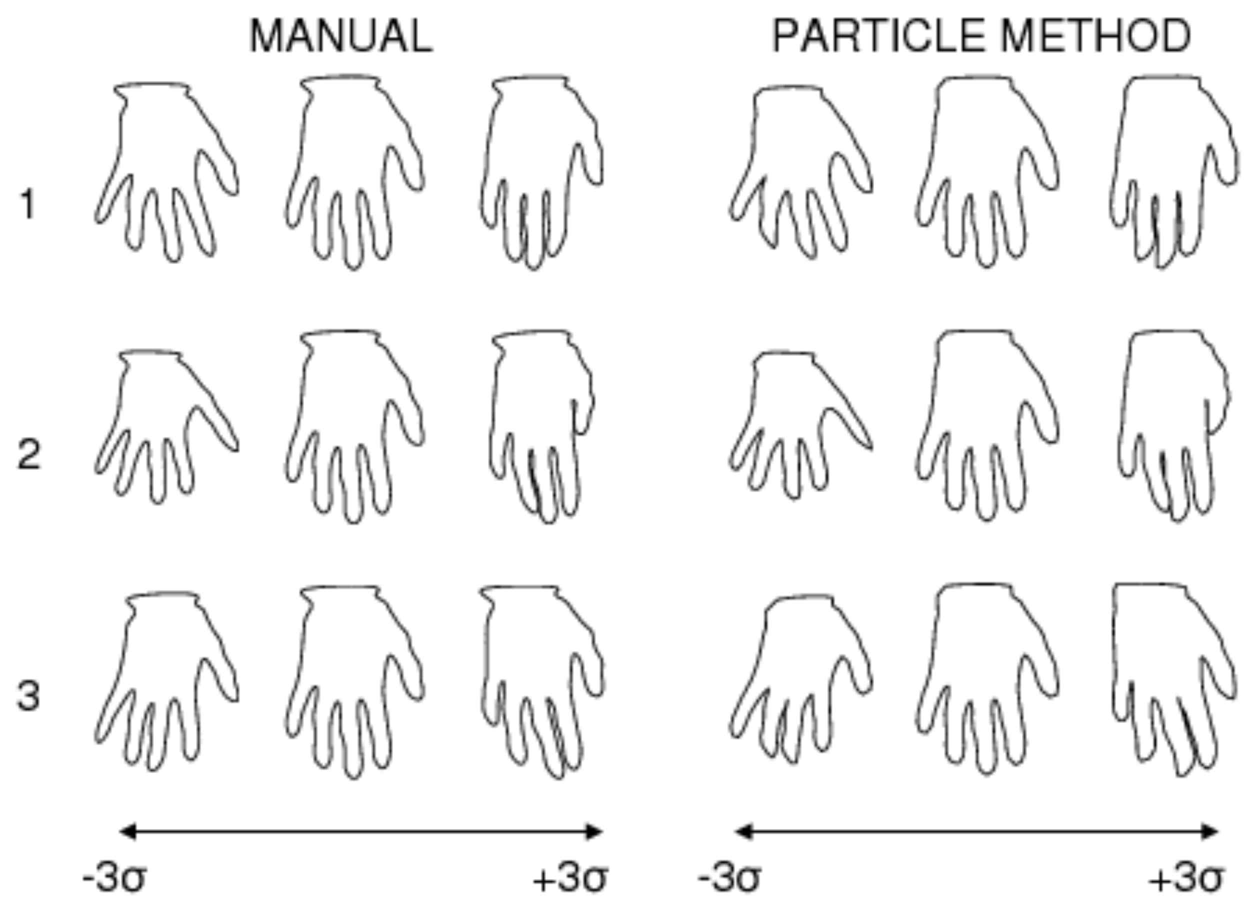
- Results
  - Single major mode of variation
  - Particle system: 0.0015% leakage



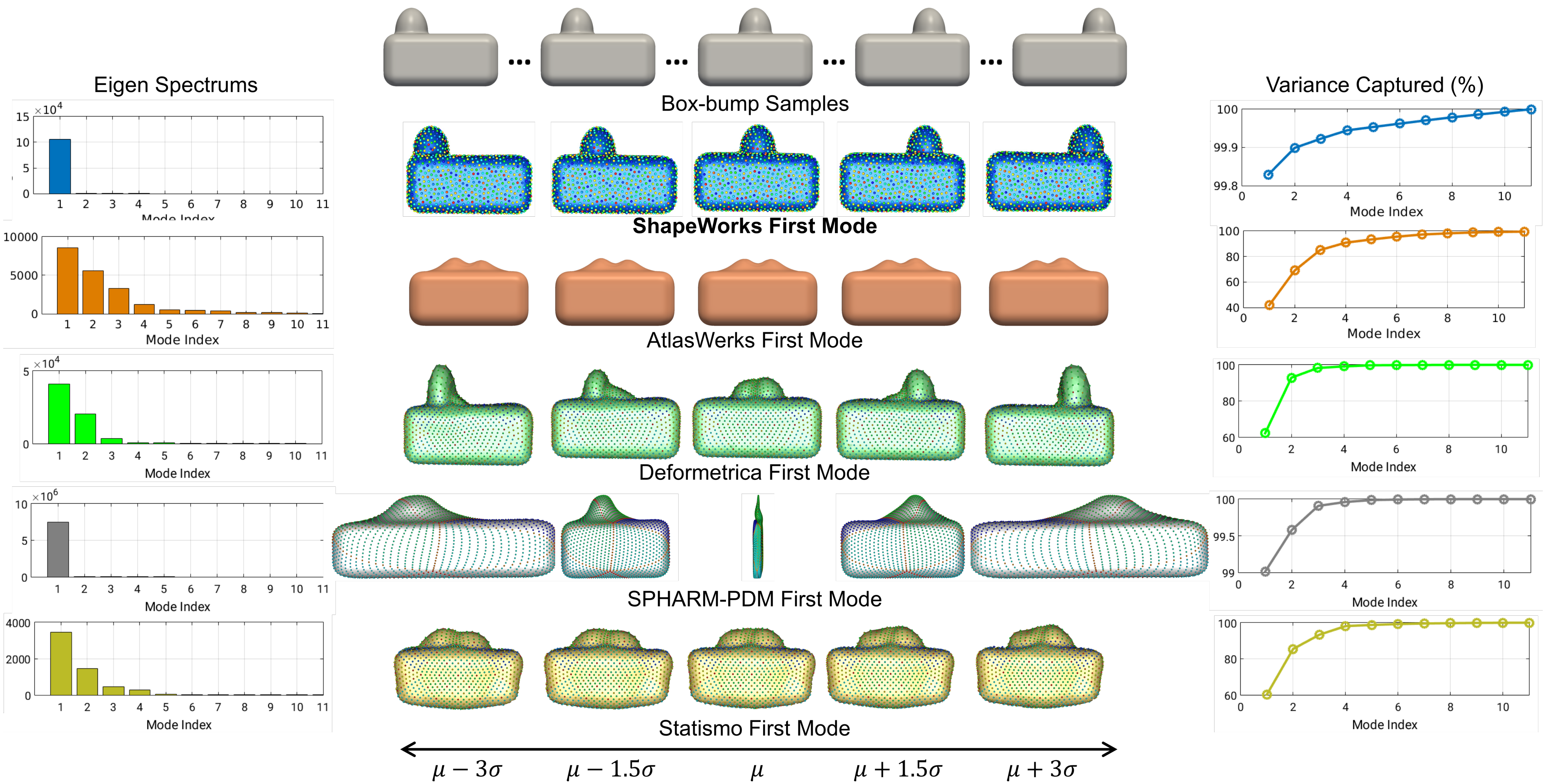
* See Thodberg, IPMI 2003 for details

Hand Contours

- Particle method similar to manual method

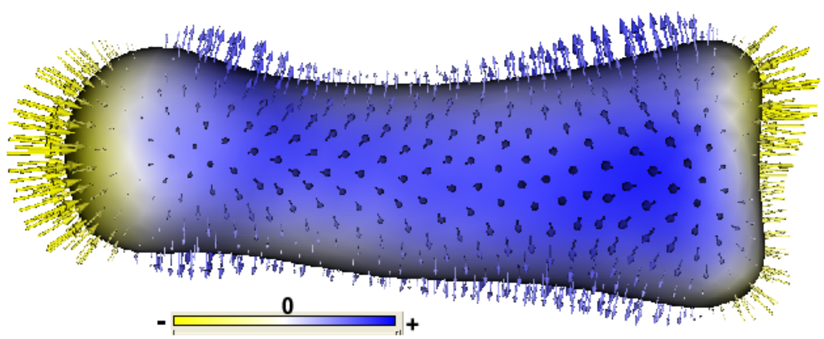


The Importance of Ensembles in Determining the *Metric*



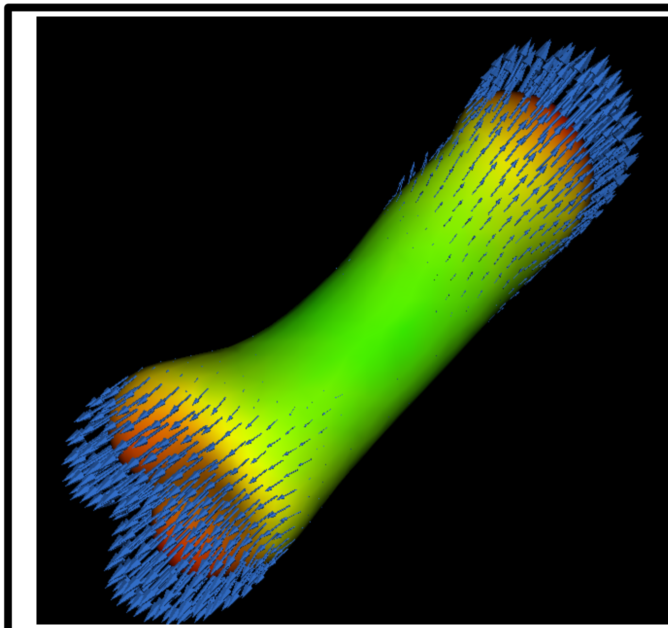
What can we do with this technology?

Genetic Phenotyping Results
Hoxd11 Phenotyping

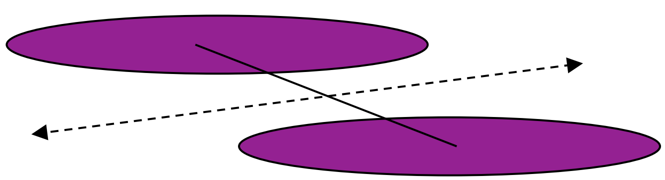


PA: 2 modes, ***p*** << 0.01

Proposed hypothesis test and LD visualization for Hoxd11 phalange.

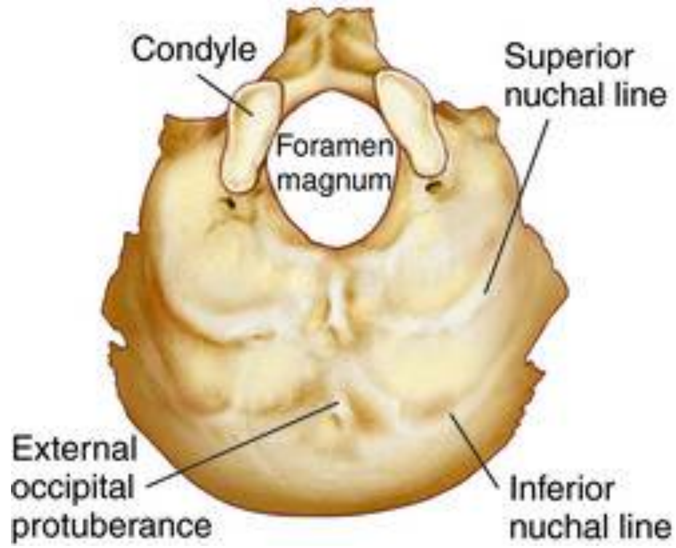


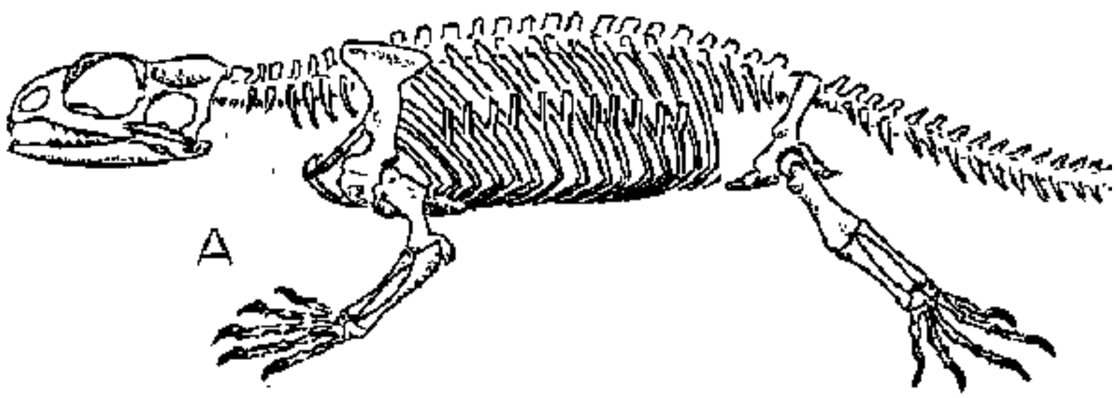
Comparison with a group-wise mean difference analysis.



Work with J. Cates, M. Cappechi

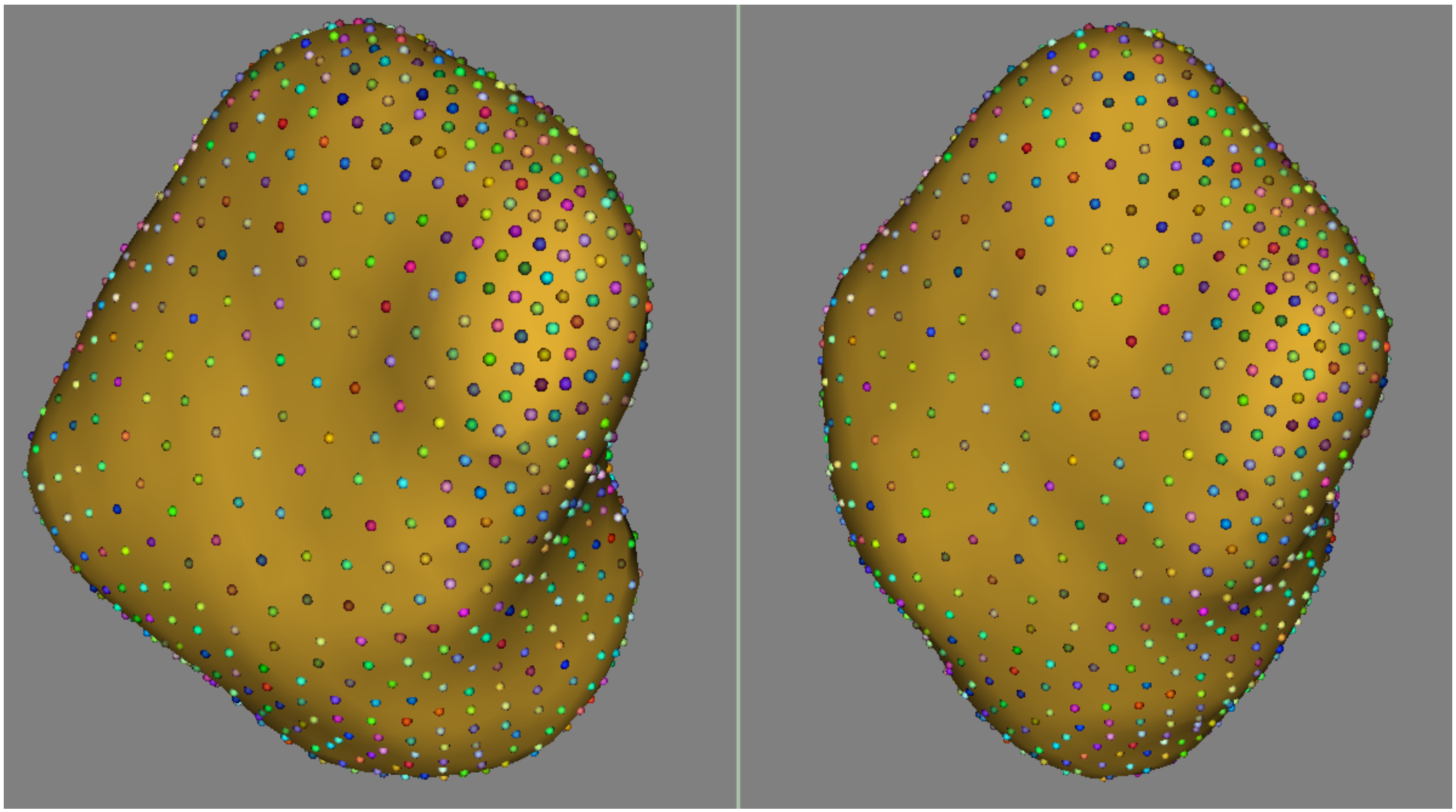
Baso-Occipital Bone and the Foramen Magnum



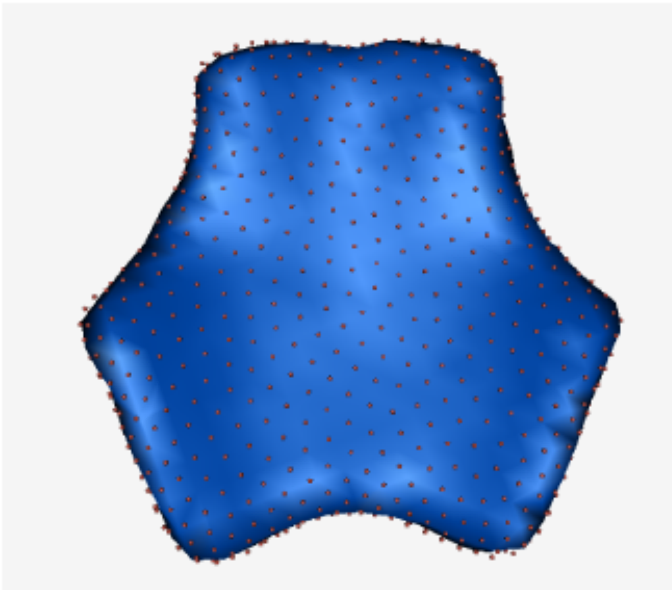


Can we understand the phenotypes associated with known genotypes for BO?

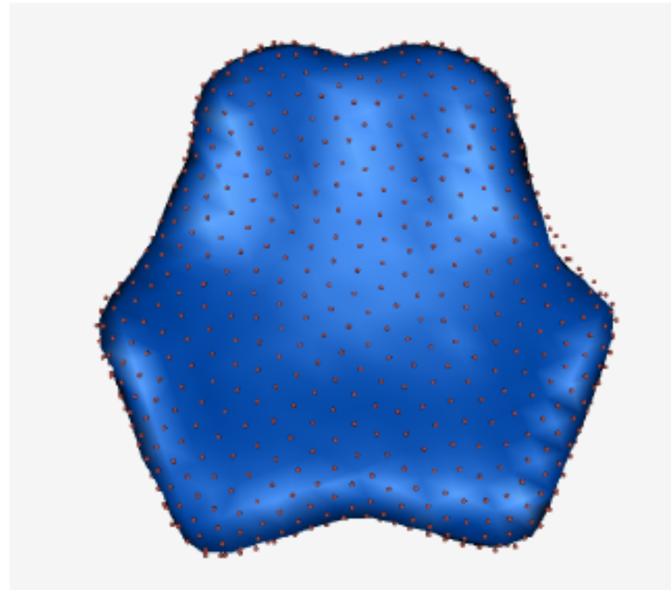
Baso-Occipital Shape Correspondence



Pax7 KO Mouse



Mean shape: LacZ -/-

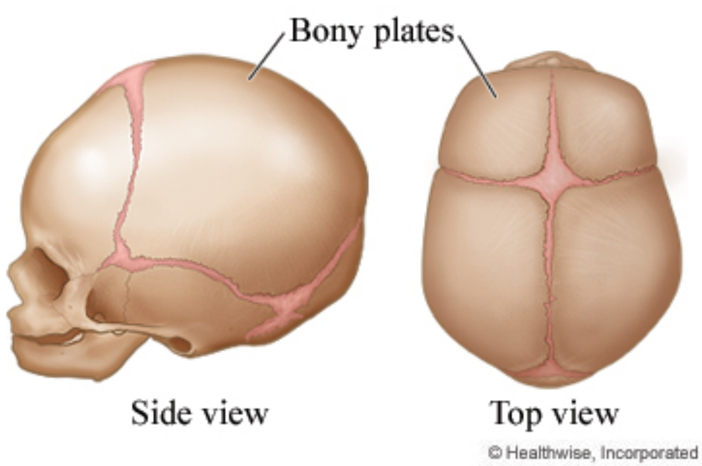


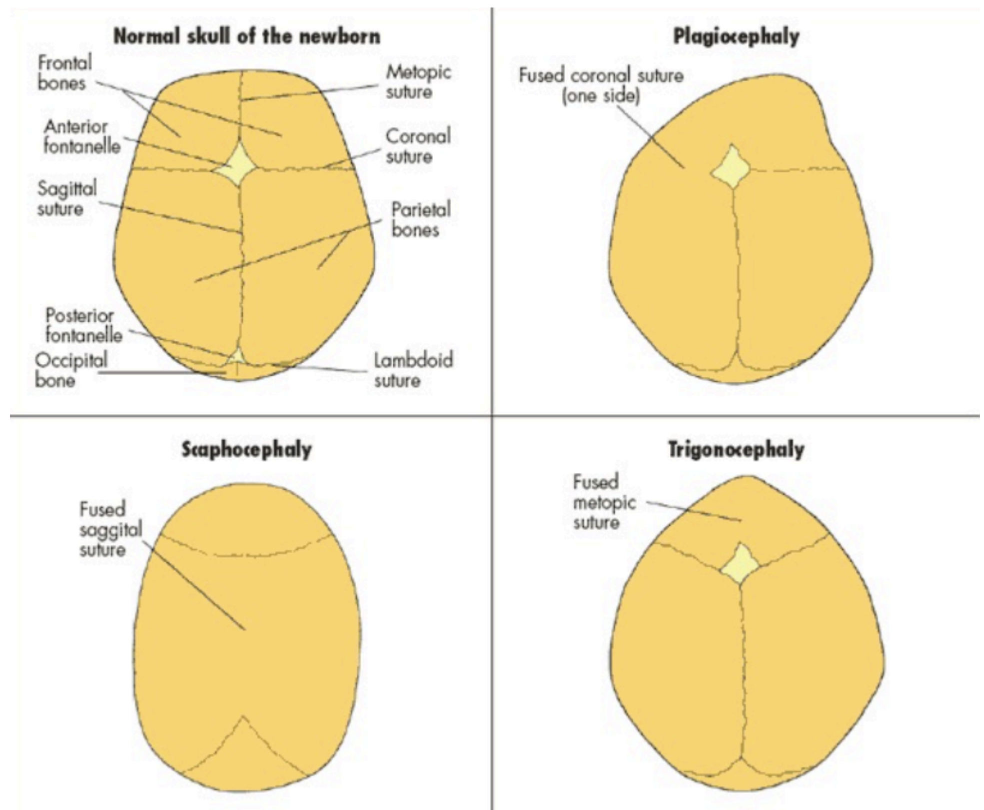
Wild Type

Work with C. Keller, J. Cates, L. Nevel

Pediatric Head Shape

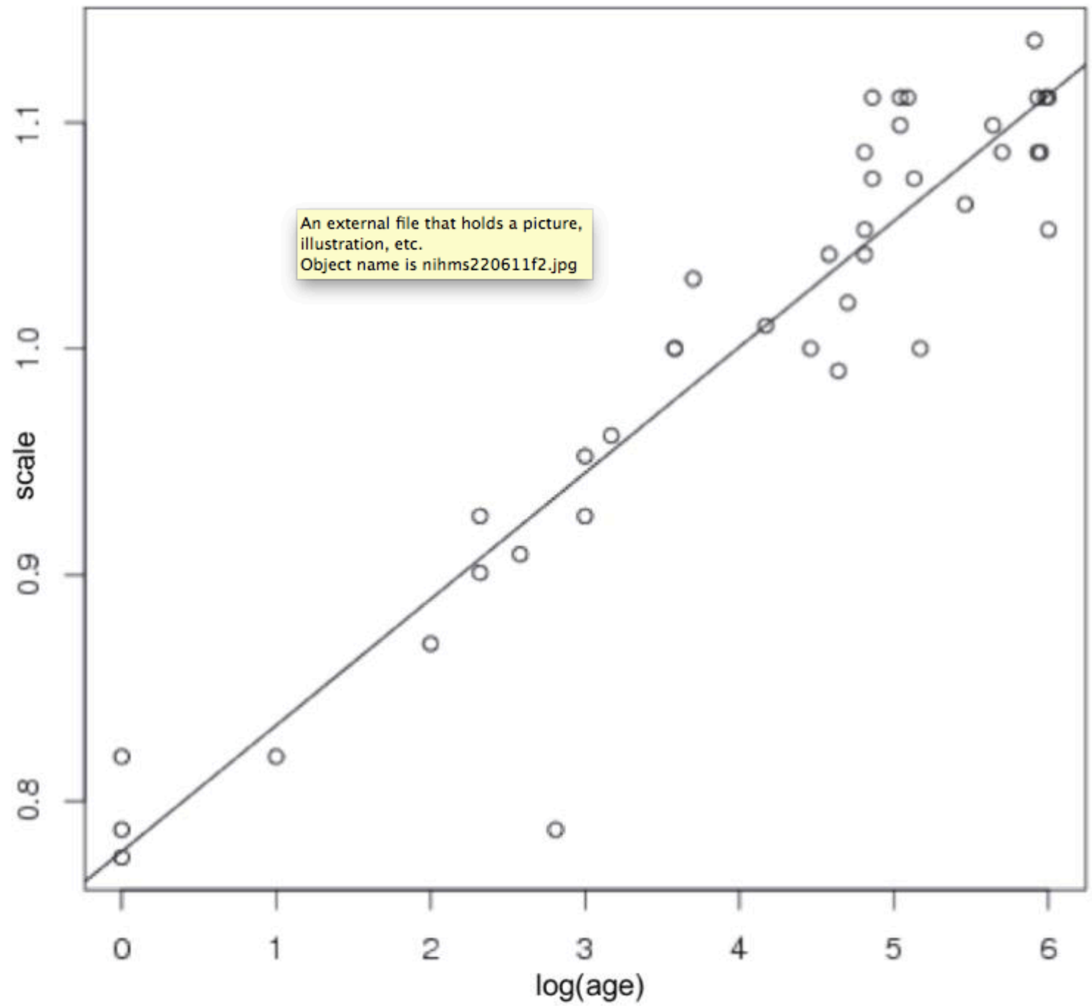
- Insight into normal and abnormal development





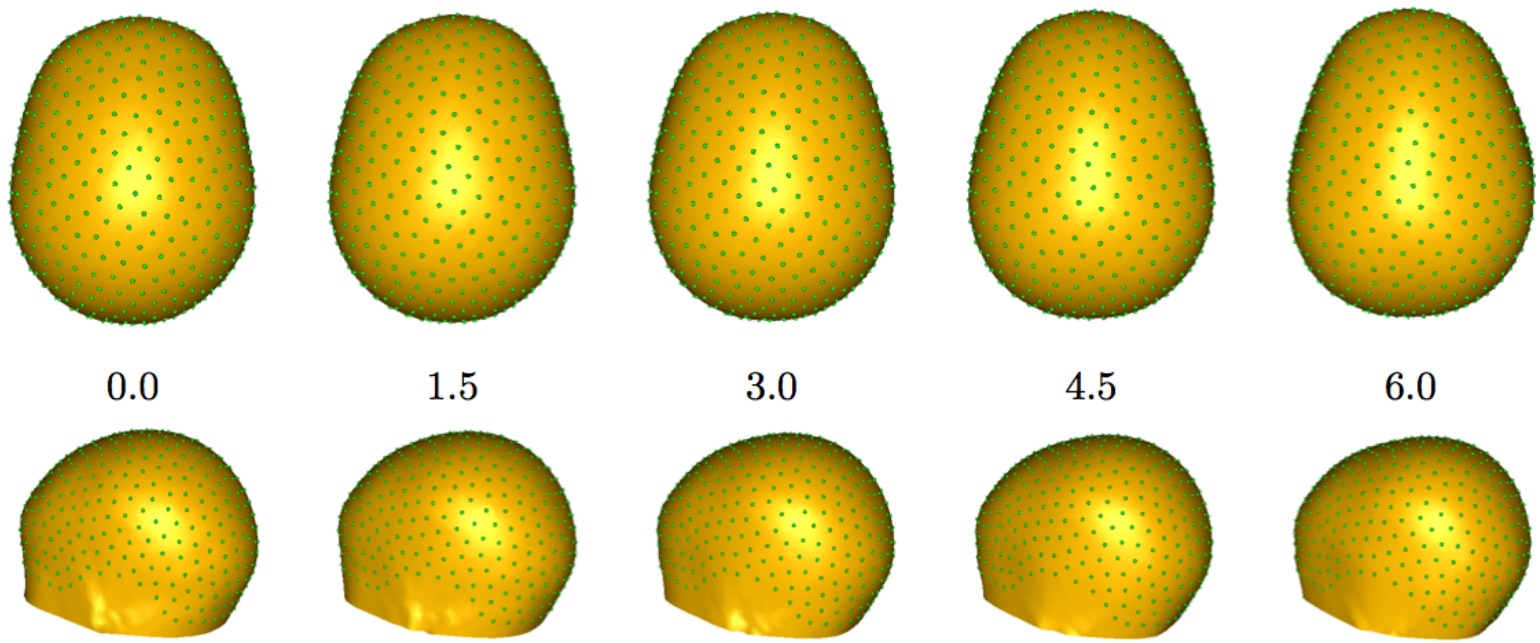
Nield and Kamat, 2011

Kids Heads – Size



Pediatric Head Shape
Size Normalized

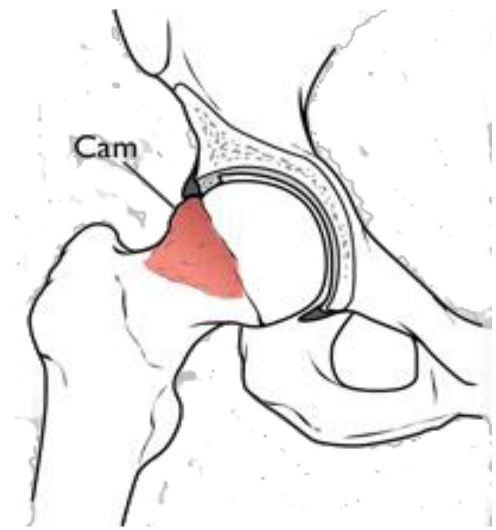
Datar et al., 2009



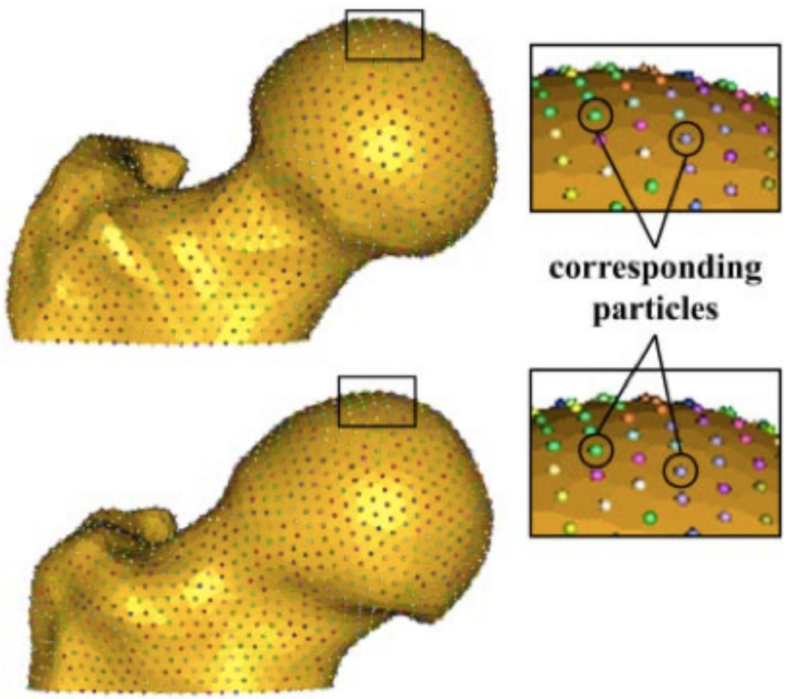
$$\arg\min_{\mathbf{a},\mathbf{b}} E(\mathbf{a},\mathbf{b}) = \frac{1}{2}\sum_{k} \left[(\mathbf{a}+\mathbf{b}t_k) - \mathbf{z}_k\right]^T \Sigma^{-1} \left[(\mathbf{a}+\mathbf{b}t_k) - \mathbf{z}_k\right]$$

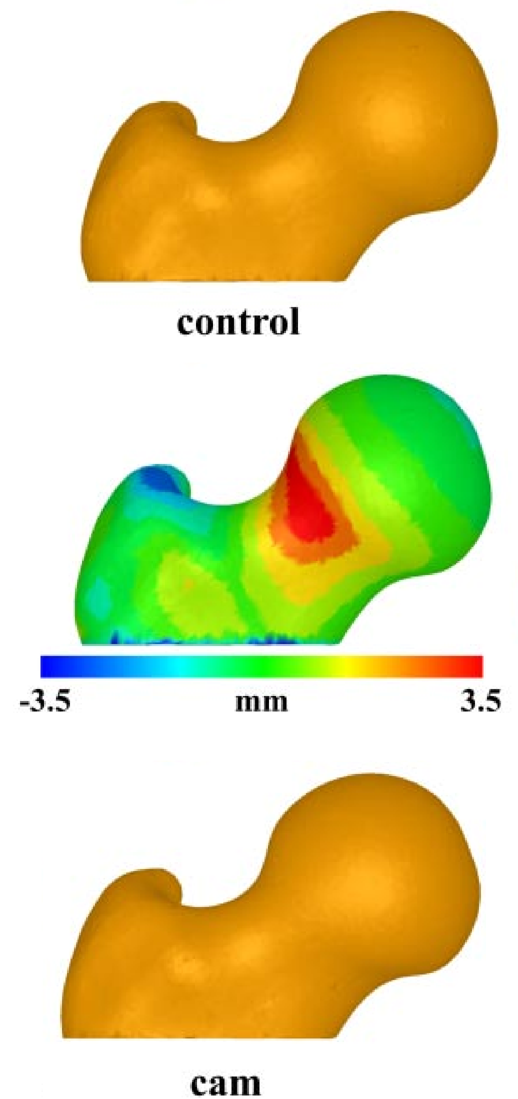
Orthopedics

- Can we characterize normal and pathological shape for joints?
- E.g. femoral-acetabular impingement
  - Segmented CT volumes
    - Normals, controls – approx. 30 of each
  - Build models -> hypothesis testing on point sets



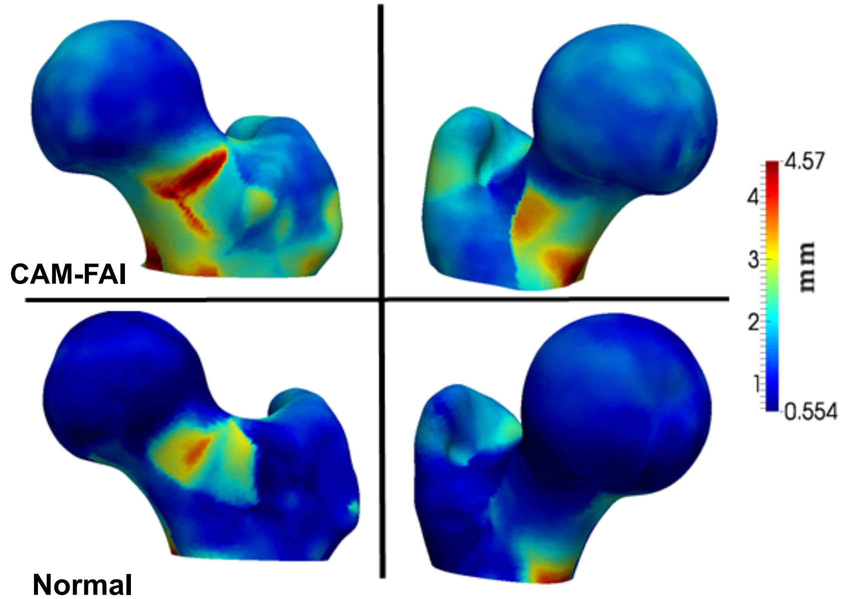
Hip Pathoanatomy
Harris et. al, 2013



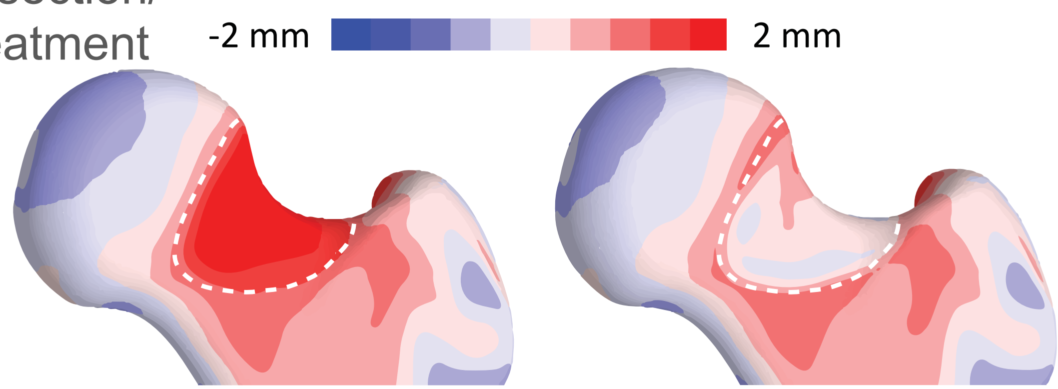


Cortical Thickness, Resection, Biomechanics

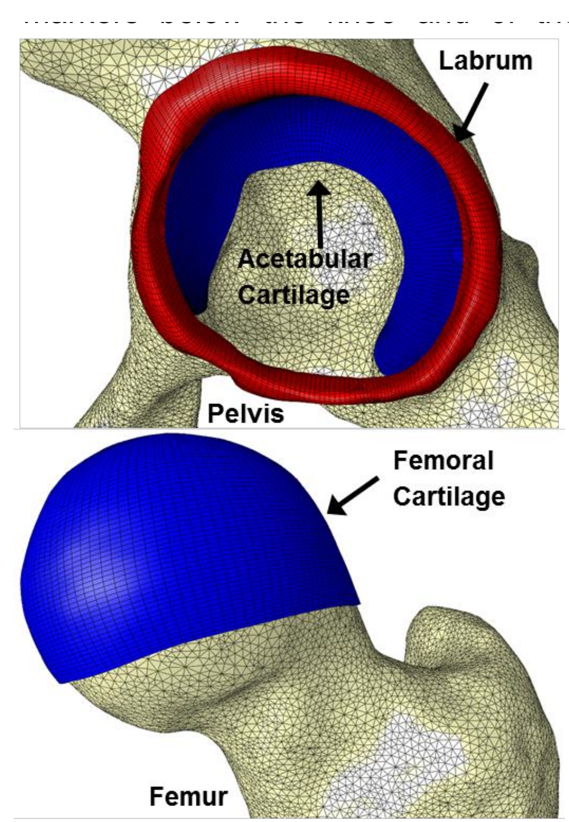
Cortical Thickness



Resection/ treatment

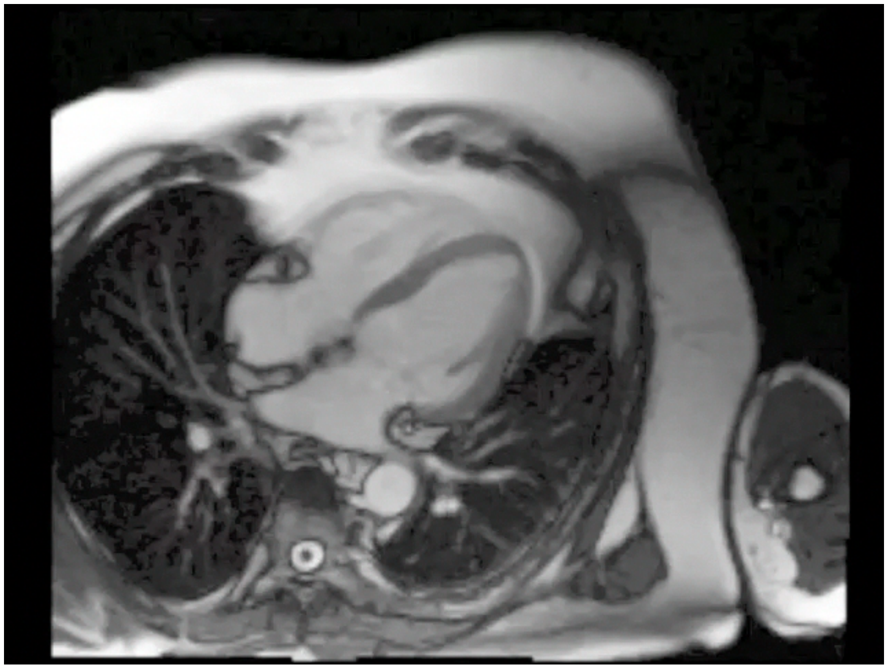


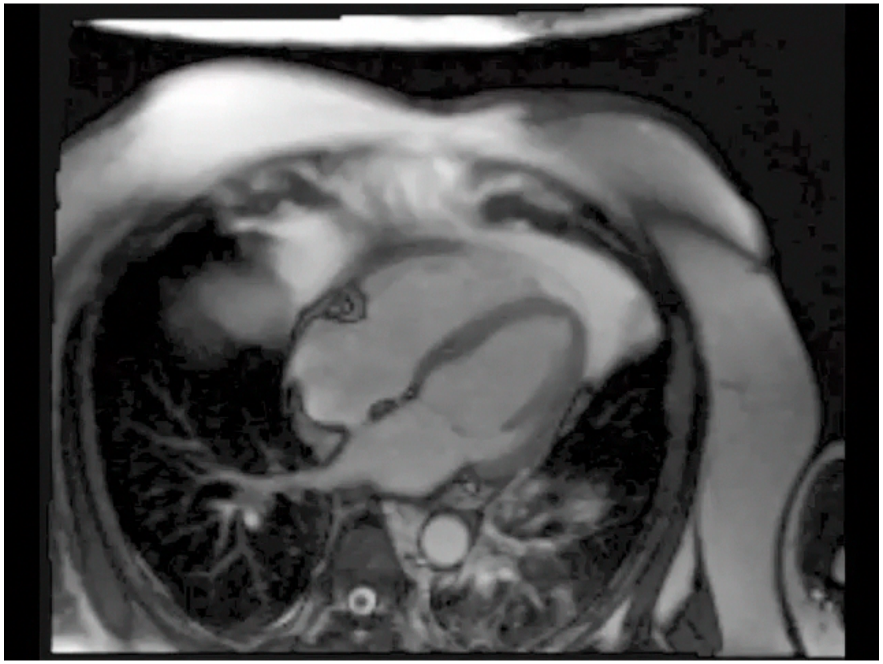
Biomechanics



Work with P. Atkins, A. Anderson, J. Weiss, P. Agarwal, S. Elhabian

Cardiac Imaging and Atrial Fibrillation

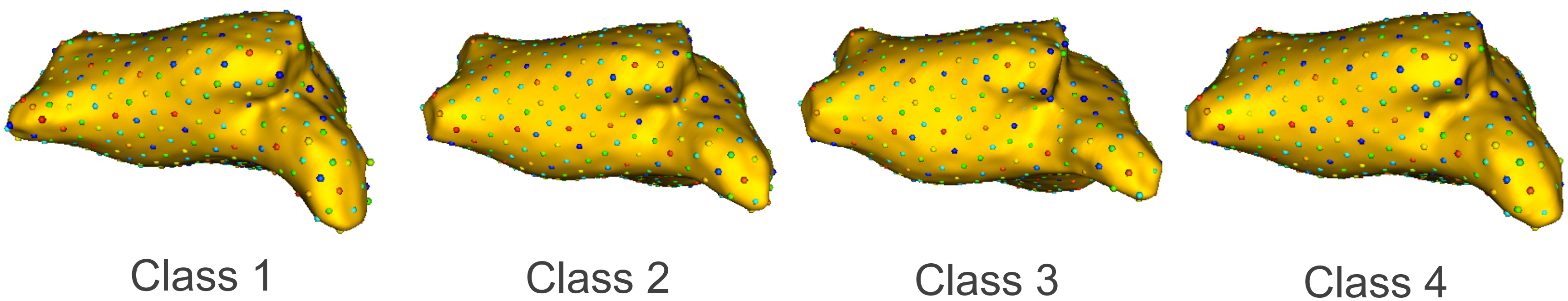




N. Marrouche, R. MacLeod

Shape and Clinical Outcomes
Statistical Shape Analysis

- Left atrium shape in Afib
- Does shape help predict treatment outcomes?



Cates et al., 2015

Shape Analysis Software

- Shapeworks (Cates, Whitaker – Utah)
- SHARM PDMs (Styner – UNC)
- Deformetrica (Durleman – ICM, Paris)
  - http://www.deformetrica.org
- Given sets of landmarks
  - The shapes package : statistical shape analysis in R

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  - Josh Cates, Andy Anderson, Jeff Weiss, Nassir Marrouche, Shireen Elhabian, Penny Atkins, Chris Peters, Steve Aoki, Manasi Datar, Rob MacLeod, …
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