

# ShapeWorks

## Introductory Session

Scientific Computing and Imaging Institute  
Department of Orthopaedics, School of Medicine  
University of Utah

Wednesday, 19<sup>th</sup> March, 2025

[shapeworks-users@sci.utah.edu](mailto:shapeworks-users@sci.utah.edu)    [shapeworks.sci.utah.edu](http://shapeworks.sci.utah.edu)

[shapeworks.discourse.group](https://shapeworks.discourse.group)



Orthopaedic  
Research  
Laboratory

# Workshop Program

## Part 1: Introduction

- Introduction to Statistical Shape Modeling (SSM) and ShapeWorks



## Part 2: Demonstration

- ShapeWorks Software Demonstration
- Installation

# What is ShapeWorks?

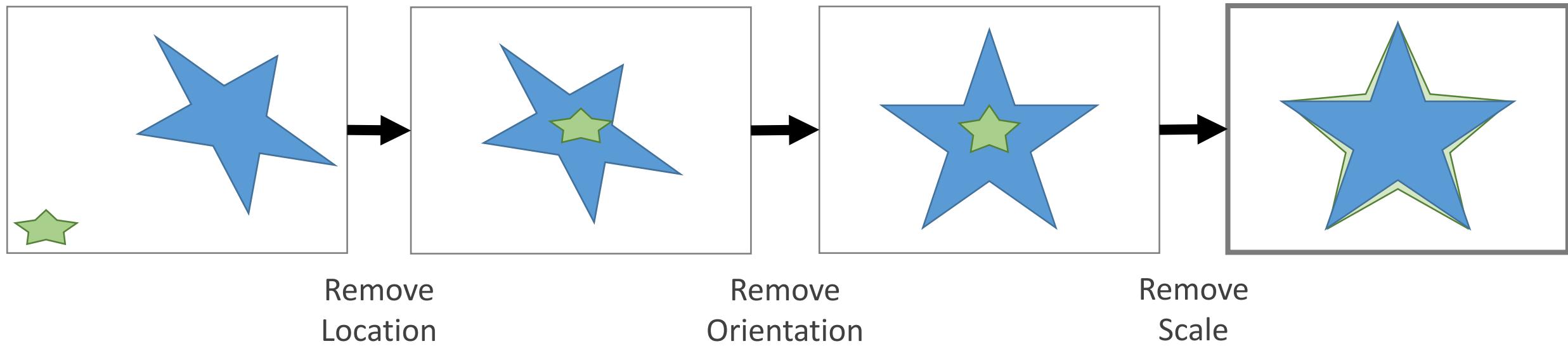
## ShapeWorks

- An integrated suite for interactive and automated anatomy modeling
- A population/data-driven approach that respects and captures natural variability directly from data
- A landmark-based approach for detailed and interpretable study of form and morphology
- General, flexible, and reproducible
- Free and open-source ([shapeworks.sci.utah.edu](http://shapeworks.sci.utah.edu))





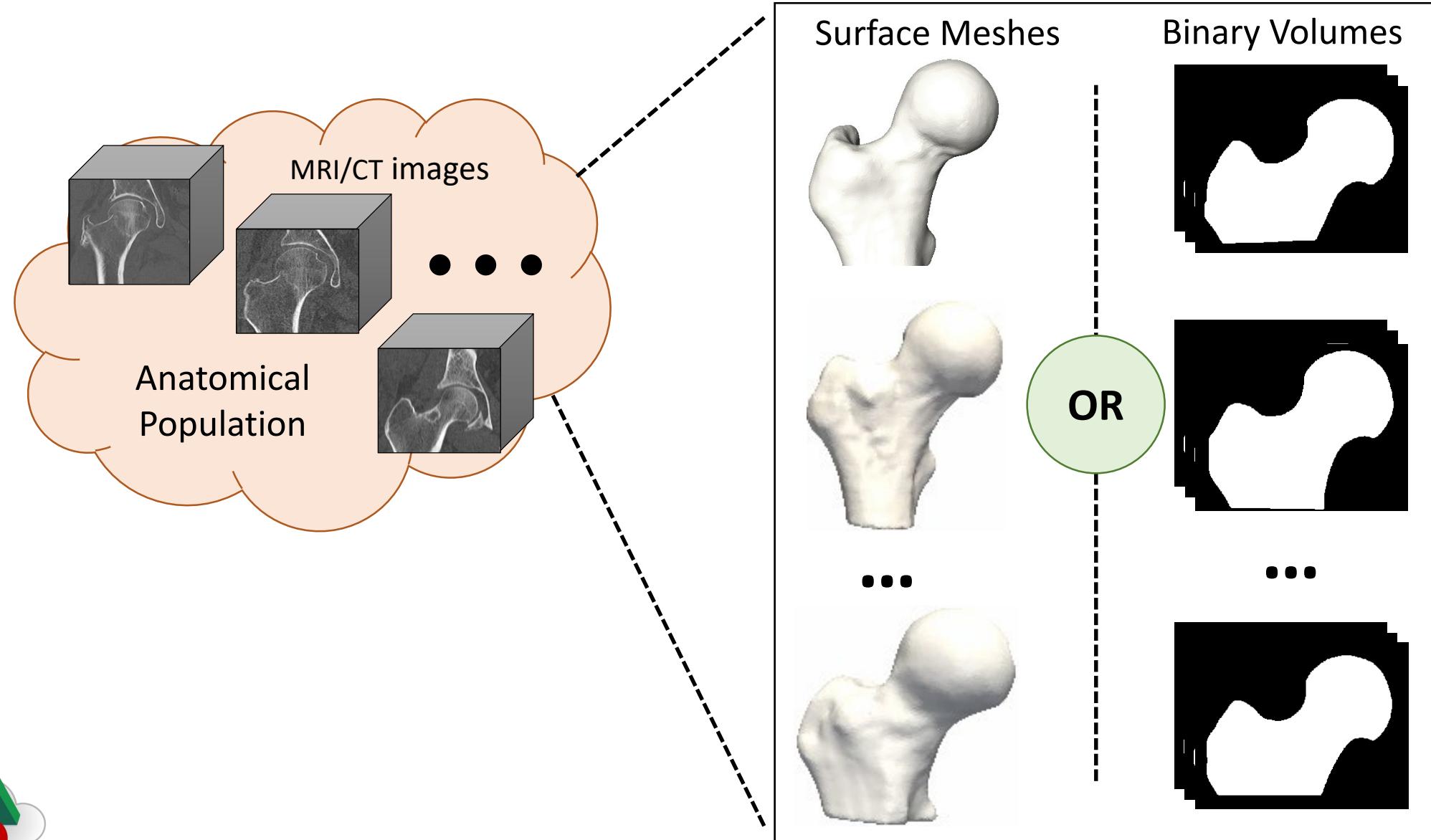
# What is shape?



Object – Location – Orientation – Size [optional] = **Shape**

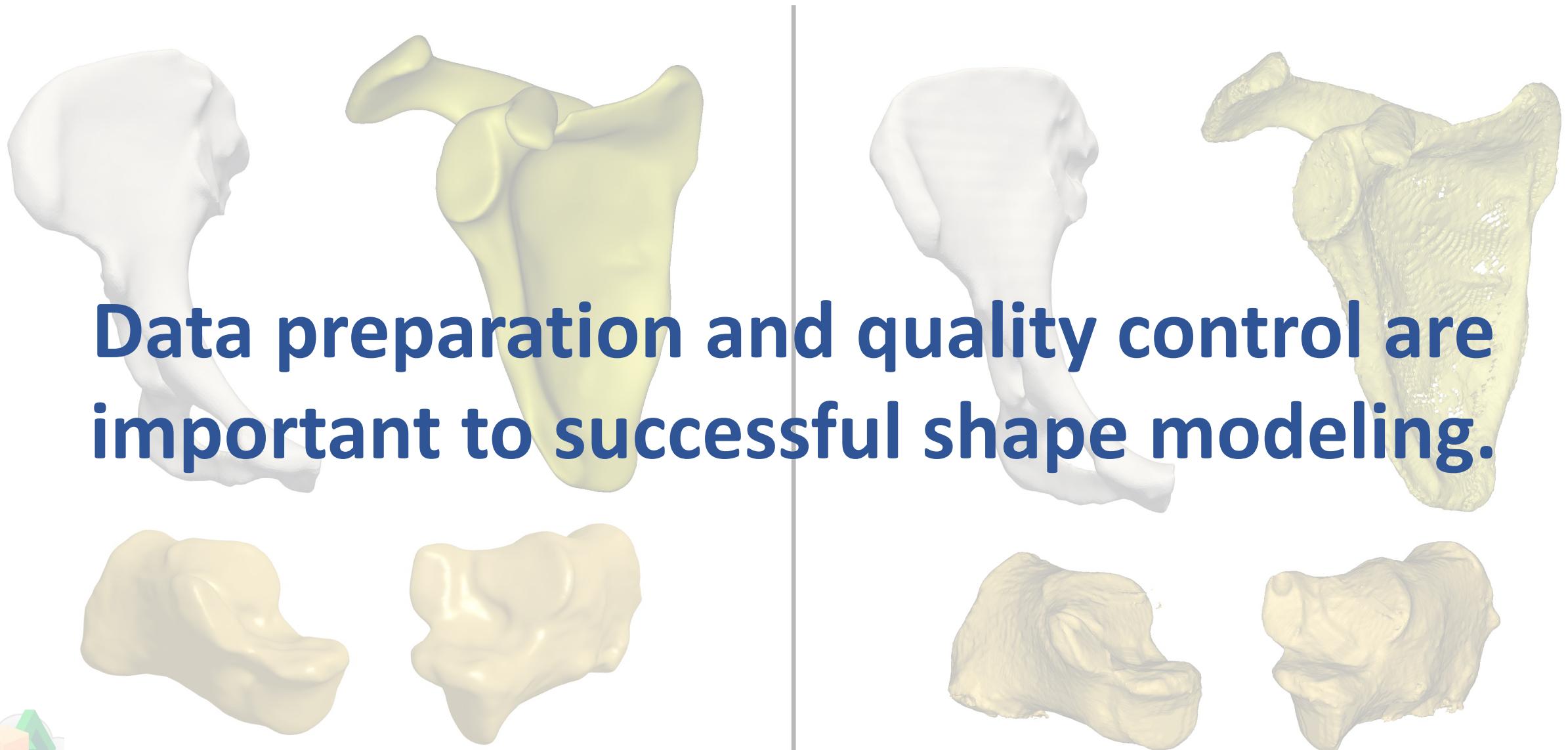


# Where does shape come from?





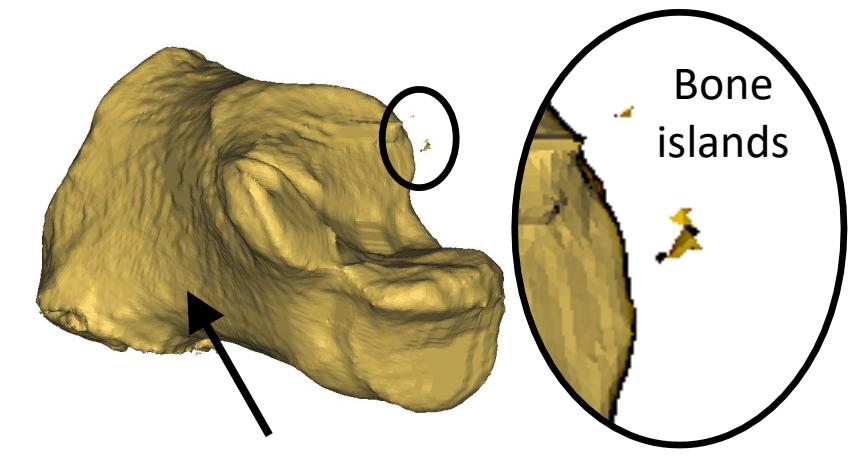
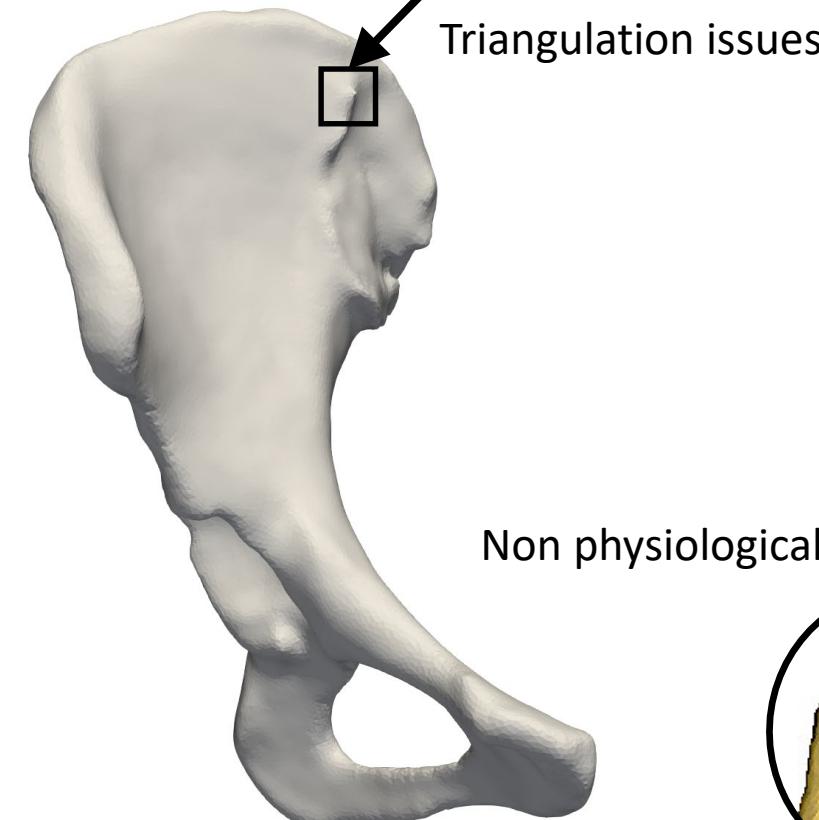
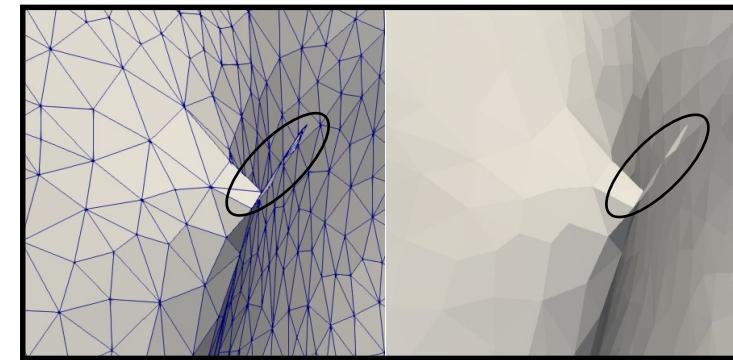
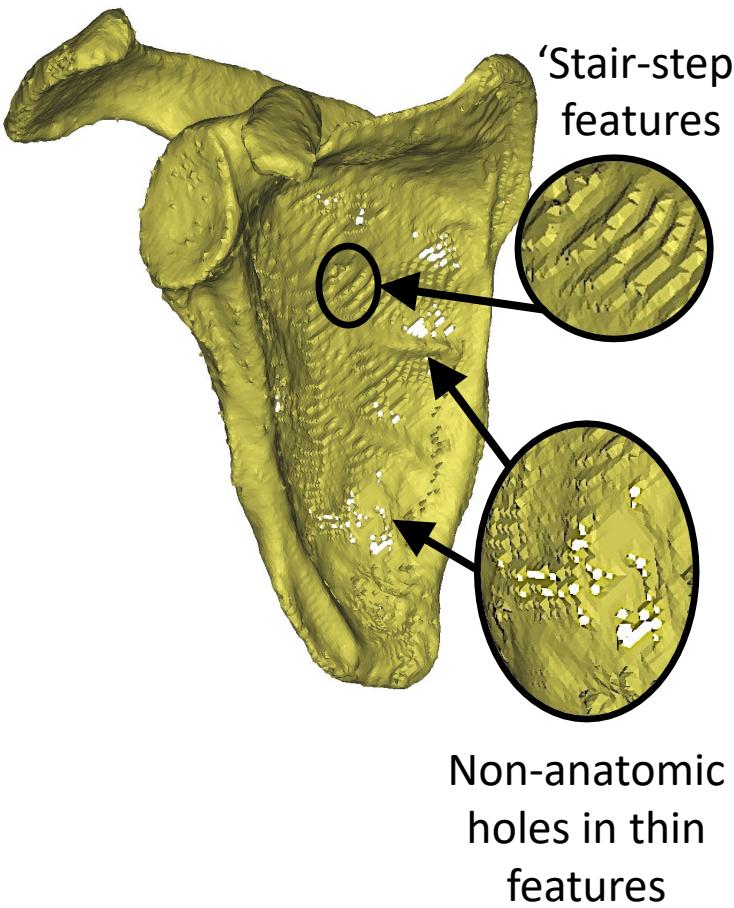
# What surfaces **can** and **cannot** be used?



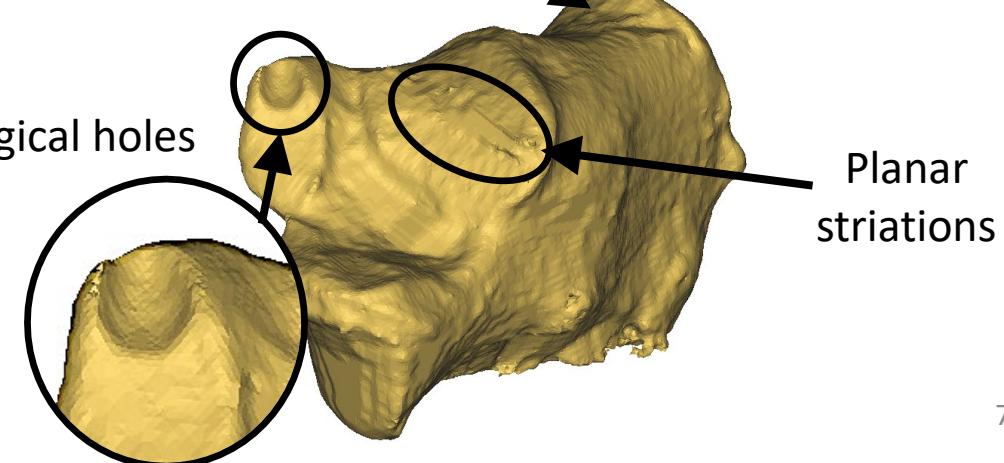
**Data preparation and quality control are important to successful shape modeling.**



# What surfaces can and cannot be used?

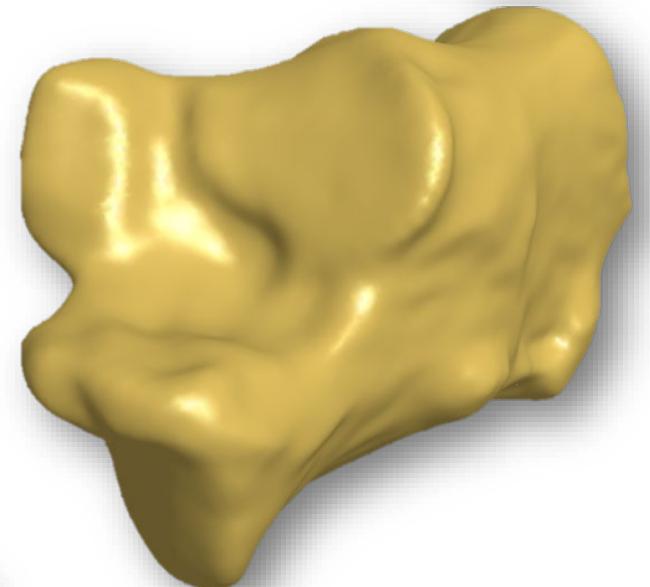
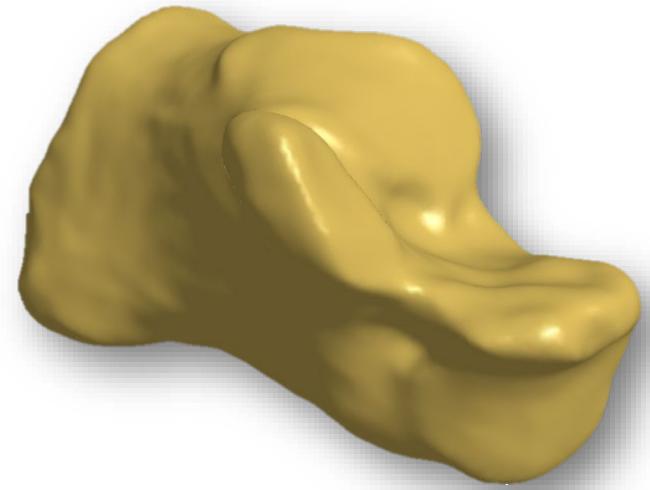
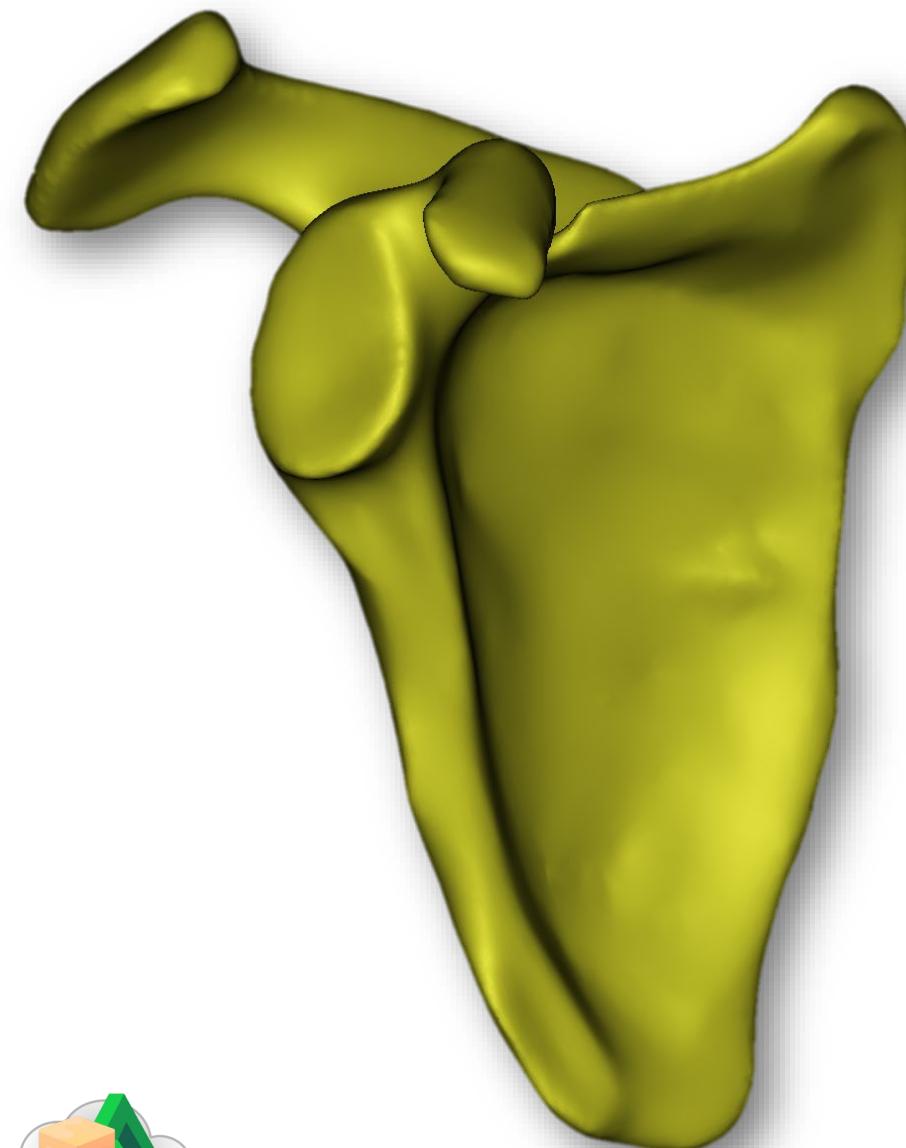


Lack of decimation  
and smoothing





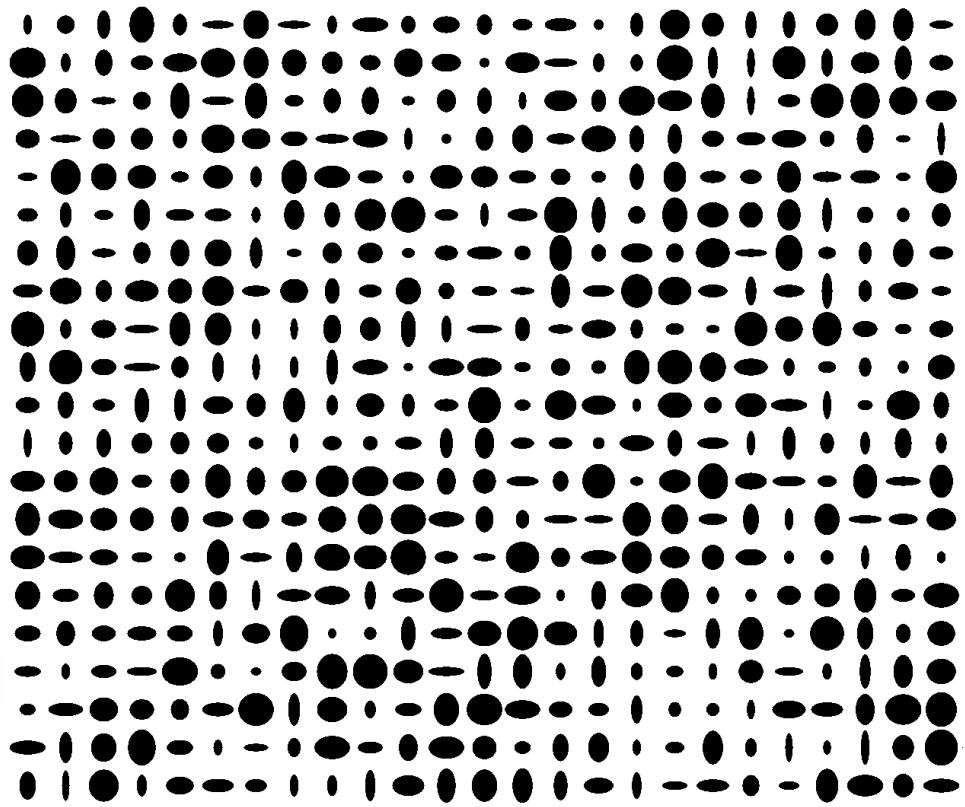
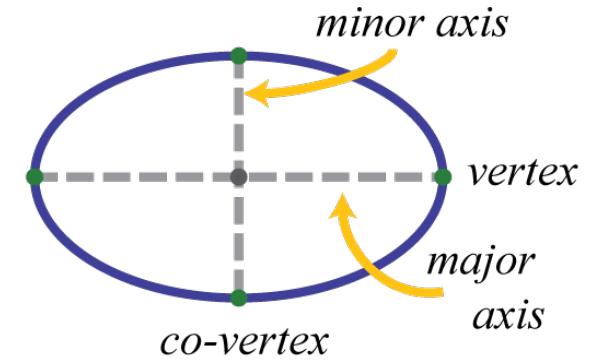
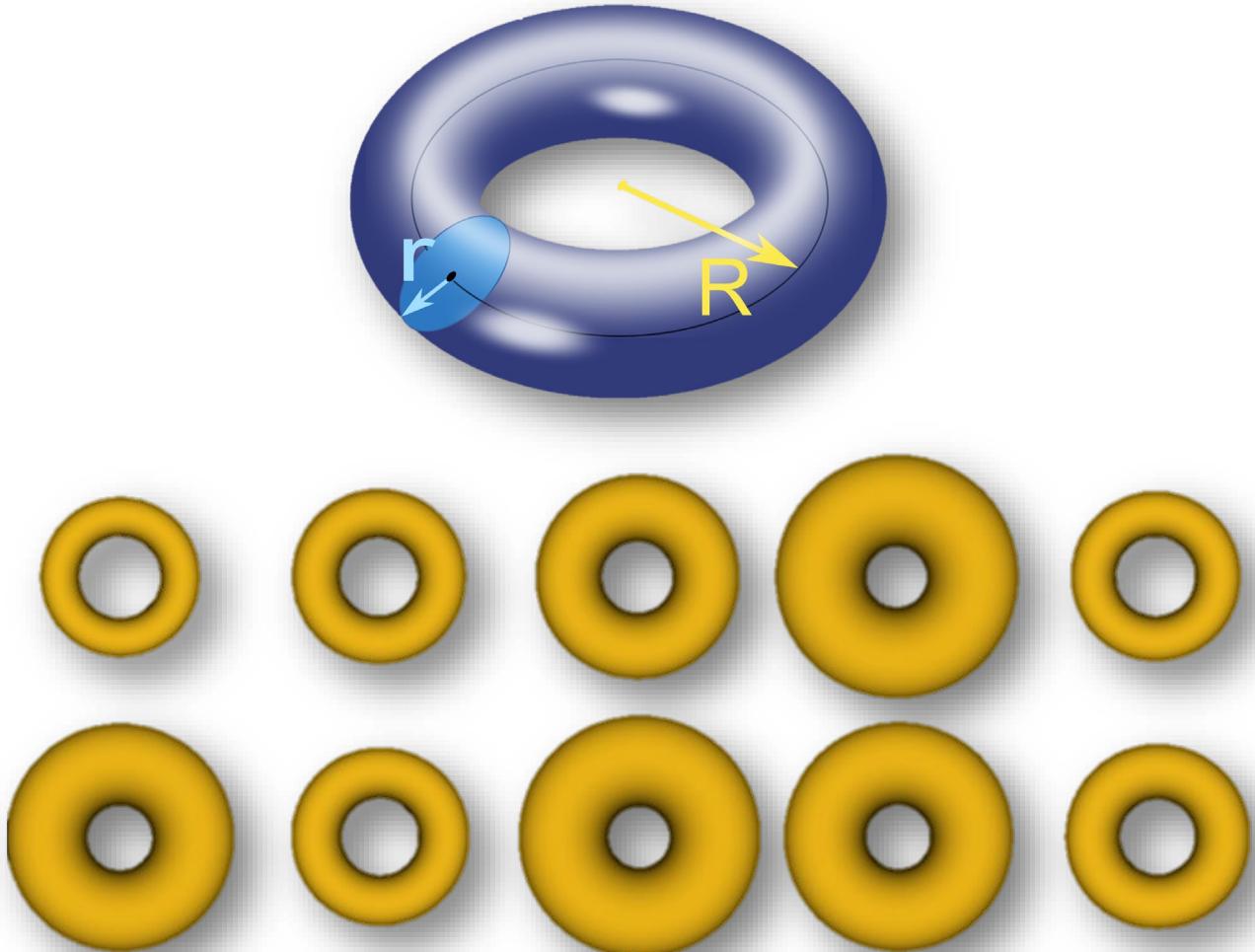
# What surfaces can and cannot be used?





# What is shape modeling?

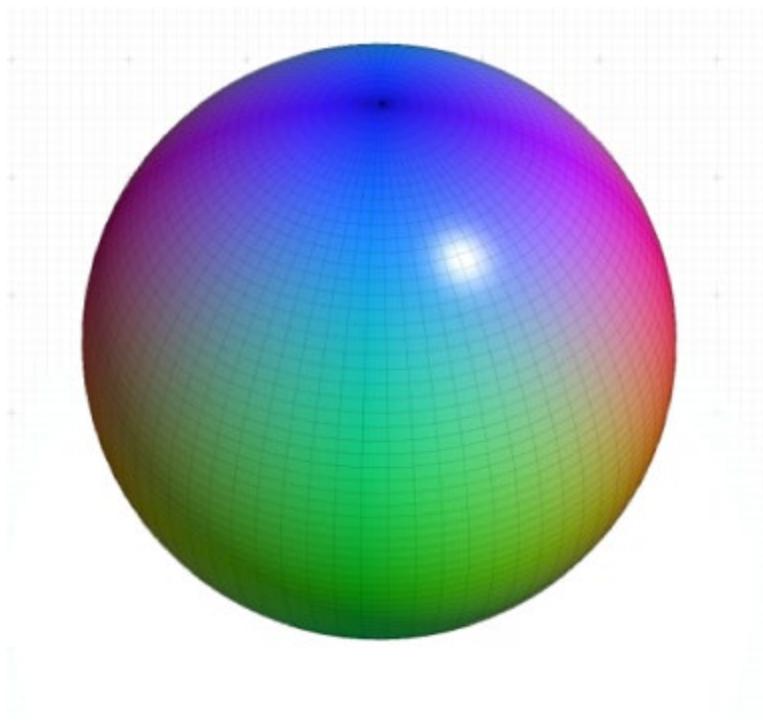
Shapes with known parameters...





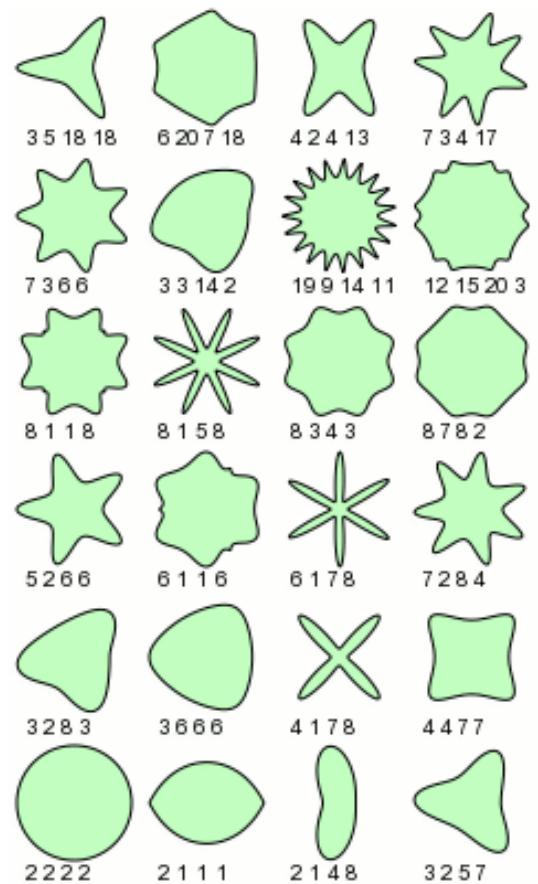
# What is shape modeling?

Shapes with known parameters...



## 2D Super Shapes

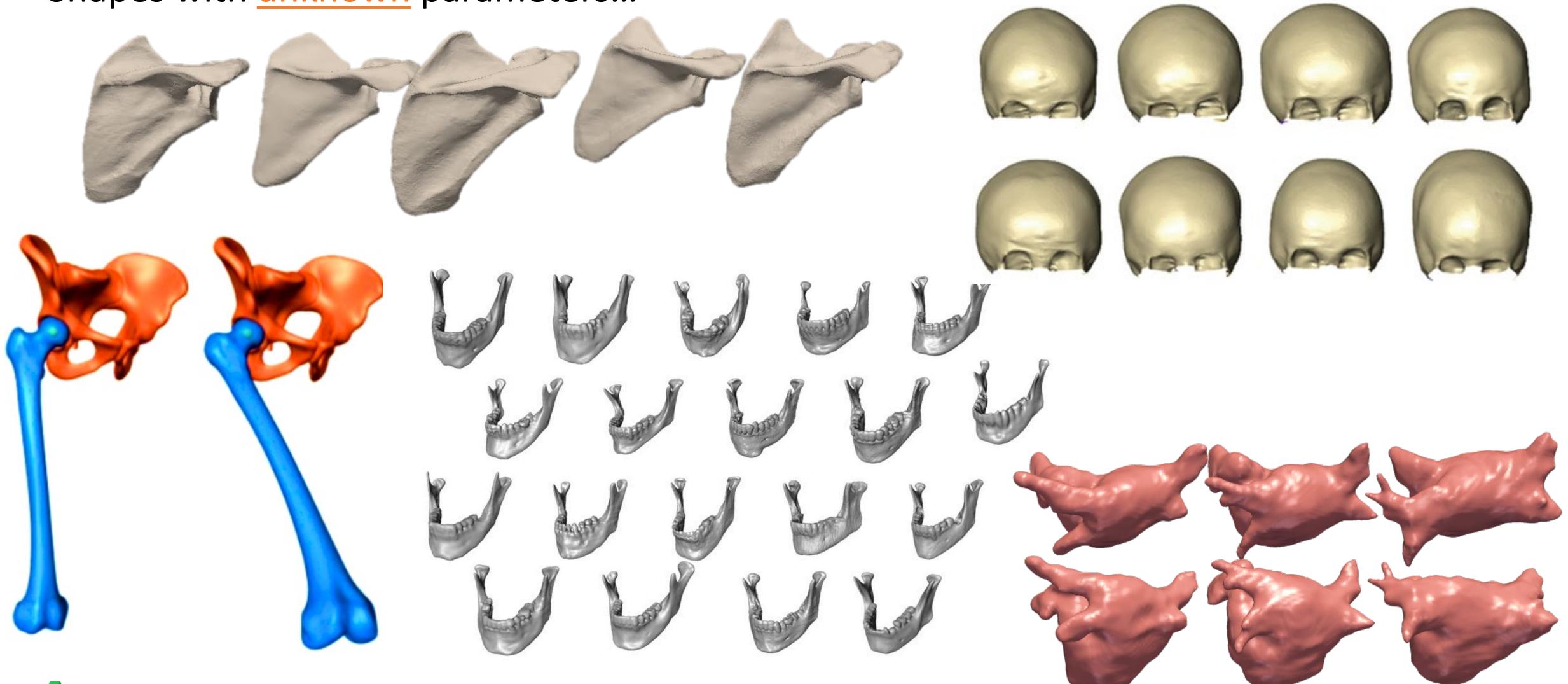
$$r(\theta) = \left[ \left| \frac{1}{a} \cos\left(\frac{m\theta}{4}\right) \right|^{n_2} + \left| \frac{1}{b} \sin\left(\frac{m\theta}{4}\right) \right|^{n_3} \right]^{-\frac{1}{n_1}}$$





# What is shape modeling?

Shapes with unknown parameters...



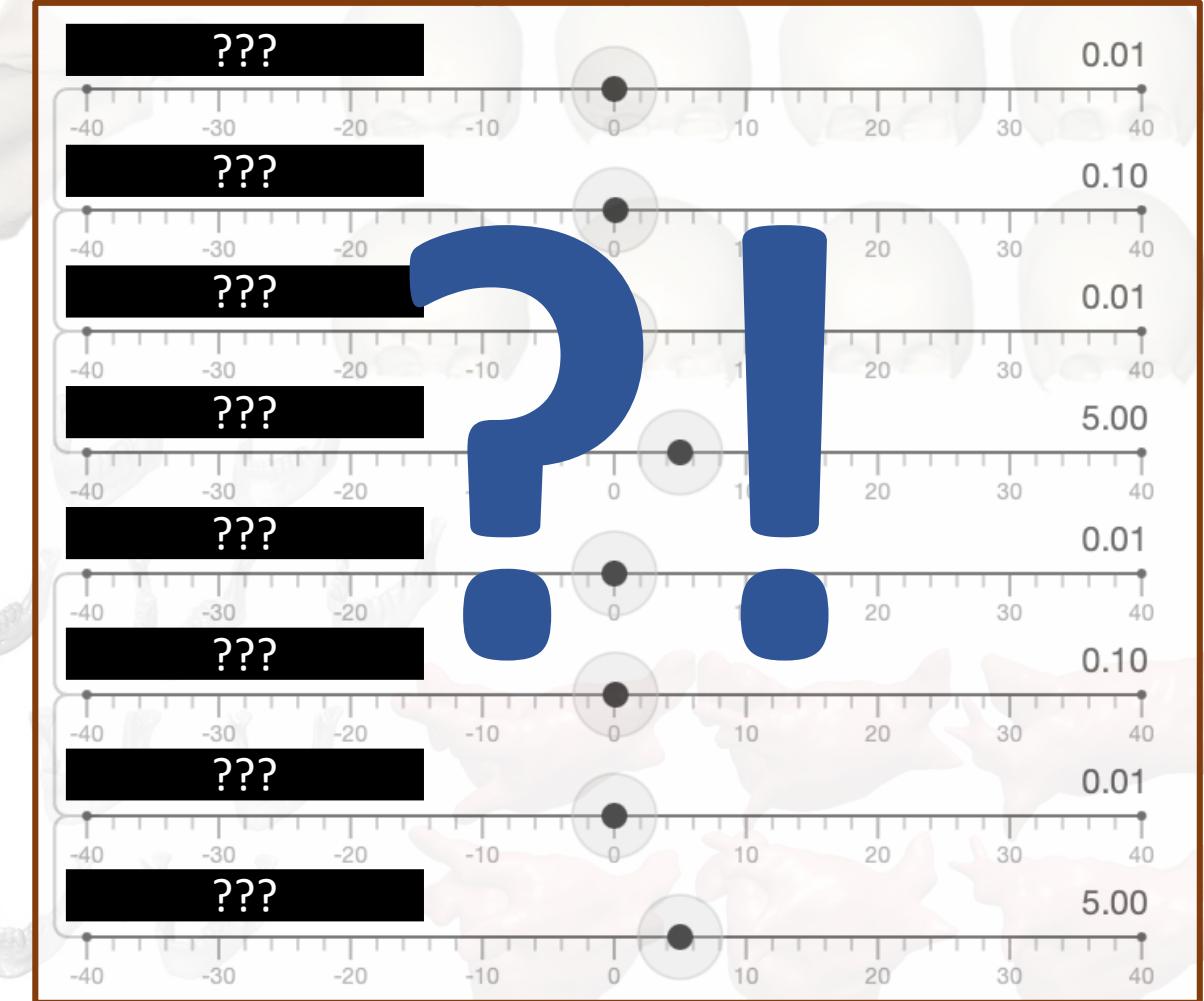
# What is shape modeling?

Shapes with unknown parameters...

What parameters?

How many?

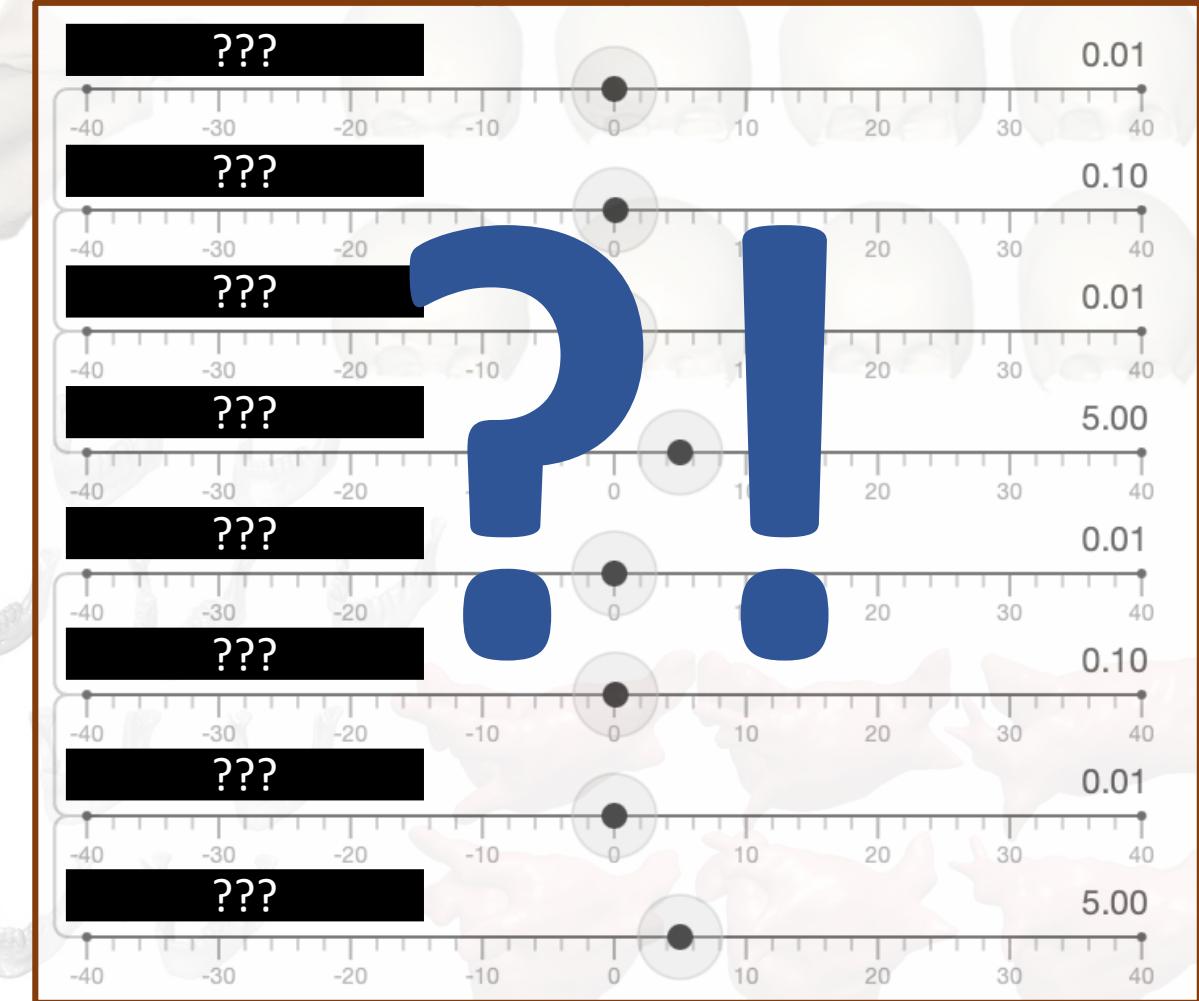
Relative importance?



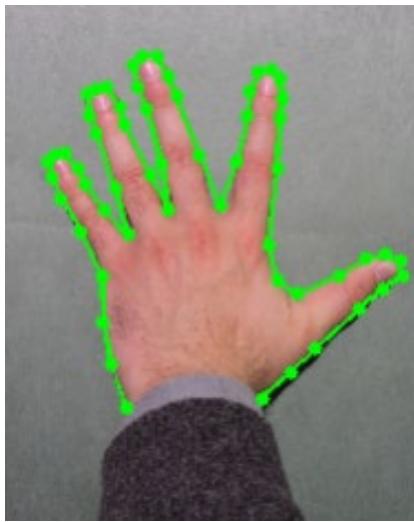
# What is shape modeling?

Shapes with unknown parameters...

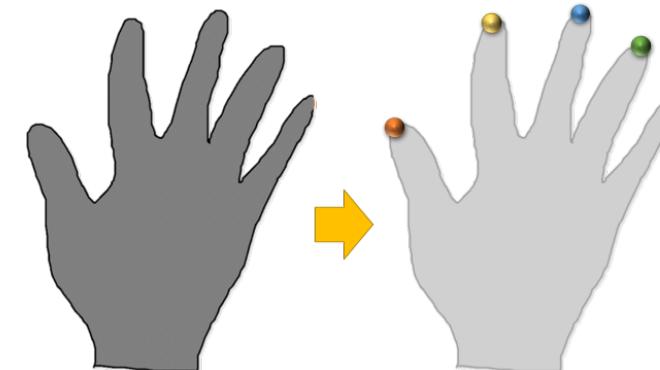
Shape modeling is  
about learning  
population-specific  
parameterization  
directly from data



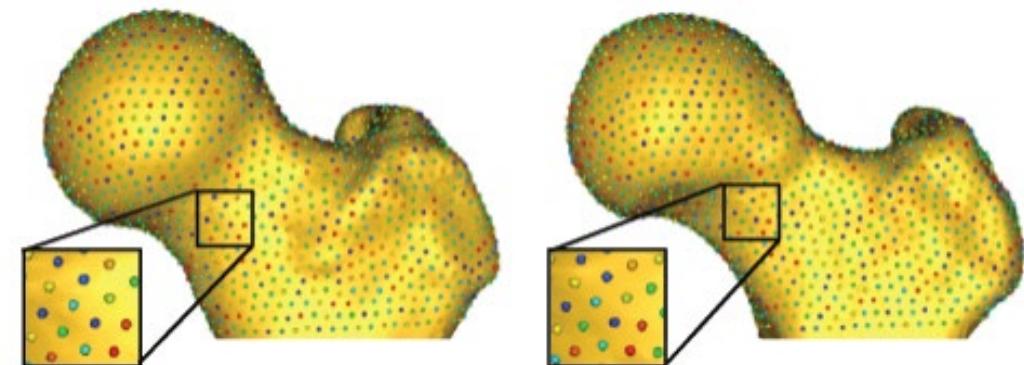
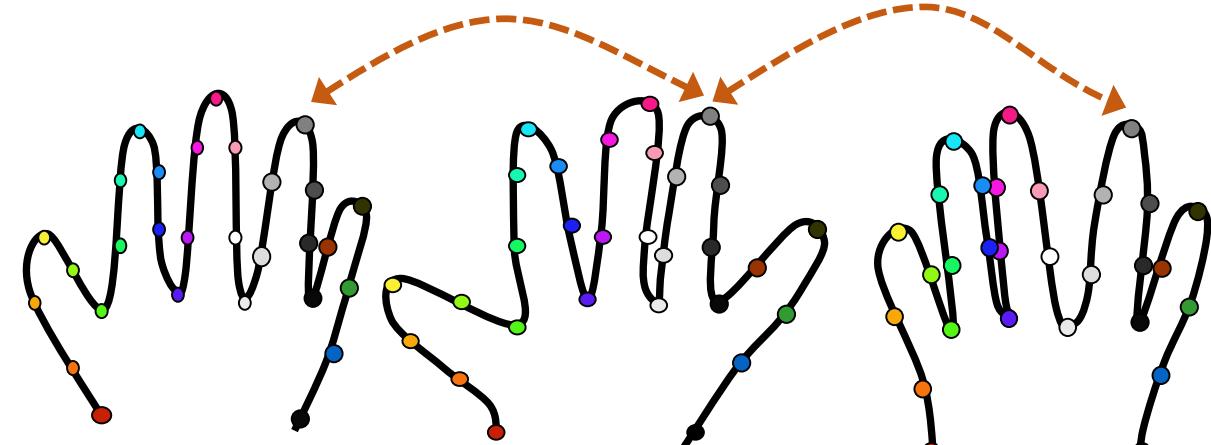
# Correspondence-based approach to shape



A statistically compact model but  
not detailed enough to capture  
geometrical details

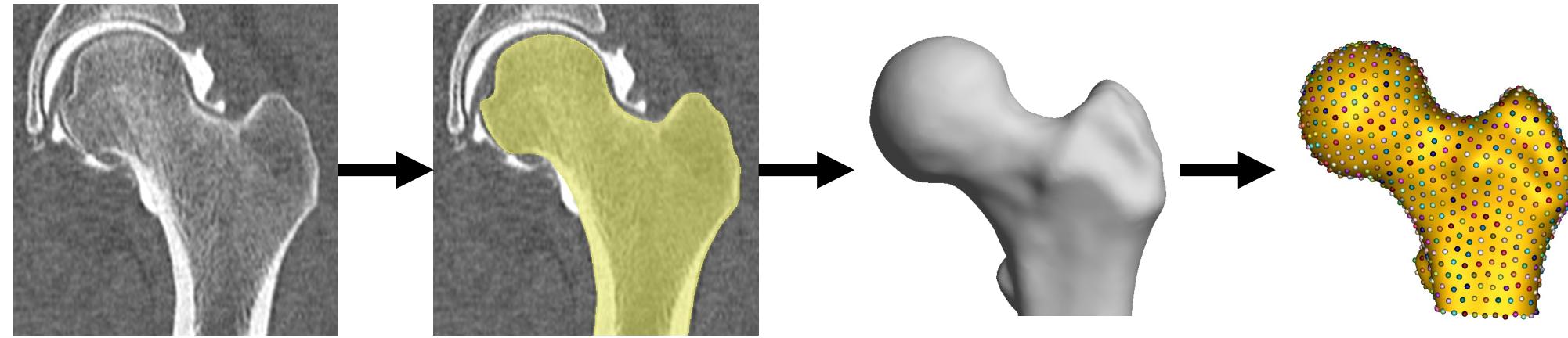


How do we choose the  
“same” points ??



Particle Distribution Models (PDMs)

# ShapeWorks – Workflow



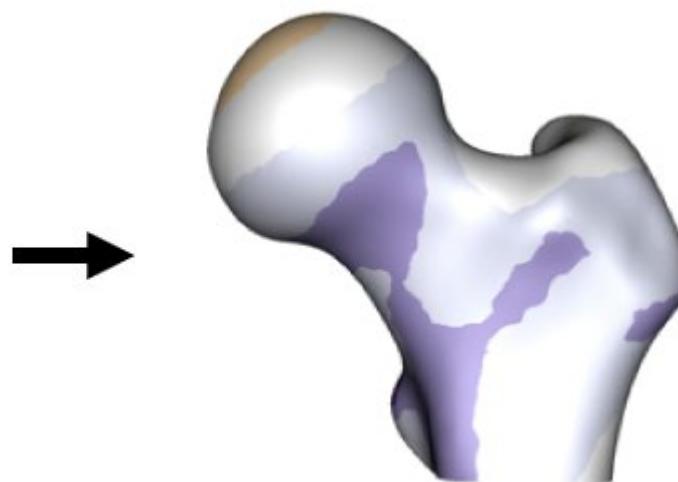
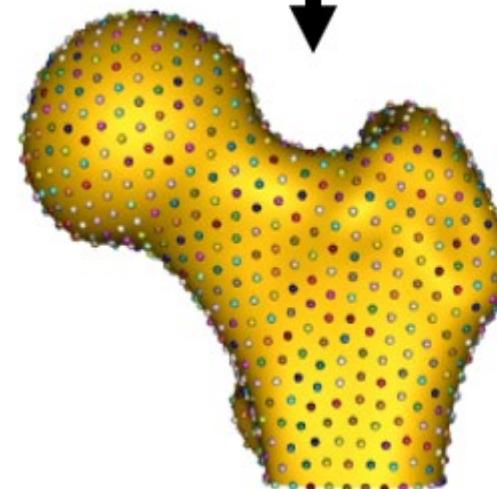
Medical Imaging

Segmentation

Surface Meshes

Correspondence Model

---

 $n_1, n_2, \dots, n_N$ 

Statistical Shape Model

Morphometric (Shape) Analyses



# ShapeWorks Studio

Supports typical and customized shape modeling workflows



Data input and preprocessing

Grooming and alignment of data

Optimization of particle correspondence

Analysis of shape variation

# ShapeWorks Studio – Data

## Data

### Upload Files

- Segmentations
- Meshes
- Constraints



Binary  
Segmentations



Surface Meshes

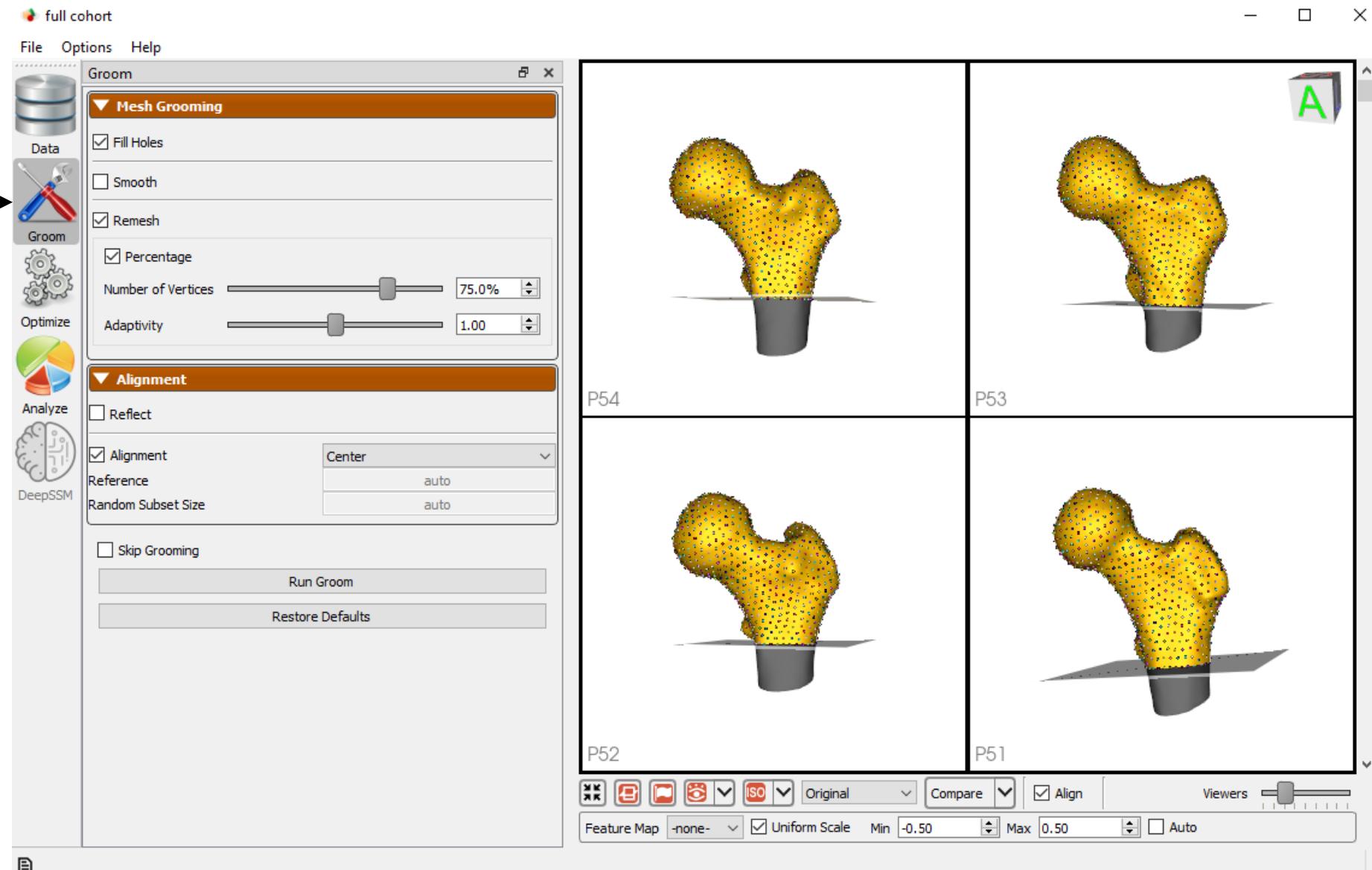
The interface shows the 'full cohort' data table with columns: name, notes, shape\_1, group\_sex, and group\_group. The table lists subjects P54 through P48, all identified as male and belonging to the athlete group. Below the table are buttons for Landmarks, Constraints, and Notes, each with a red minus sign and a blue plus sign. To the right, four 3D surface meshes of the sacrum are displayed in a grid, labeled P54, P53, P52, and P51, each with a yellow surface and colored landmarks. A legend at the bottom indicates 'A' for the current viewer. At the bottom, there are controls for Feature Map, Uniform Scale, Min (-0.50), Max (0.50), and Auto.

	name	notes	shape_1	group_sex	group_group
1	P54		P54.ply	male	athlete
2	P53		P53.ply	male	athlete
3	P52		P52.ply	male	athlete
4	P51		P51.ply	male	athlete
5	P50		P50.ply	male	athlete
6	P49		P49.ply	male	athlete
7	P48		P48.ply	male	athlete

# ShapeWorks Studio – Groom

## Groom

- Pre-processing
- Smooth
  - Reflect
  - Alignment

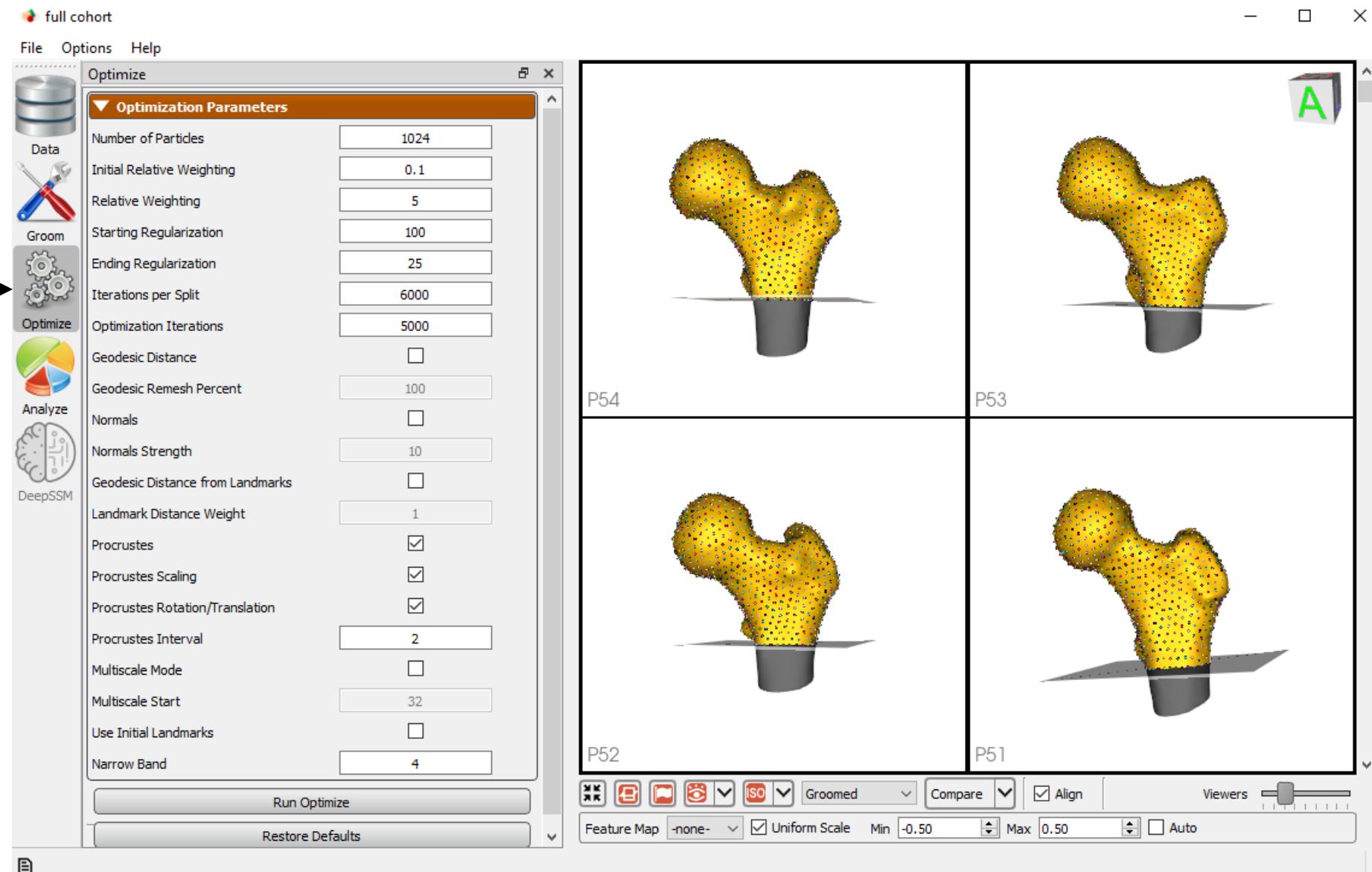


# ShapeWorks Studio – Optimize

## Optimize

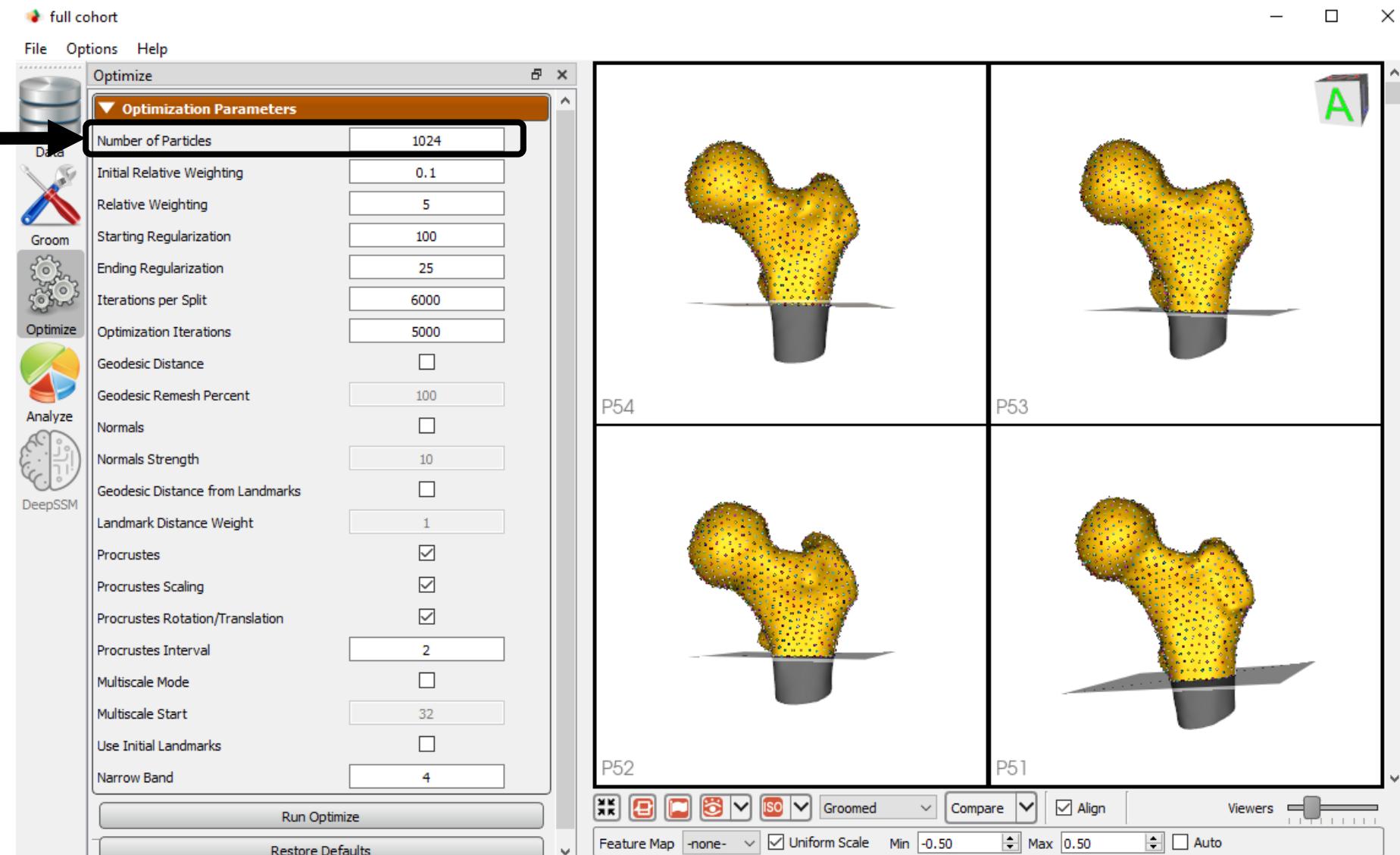
### Parameter Tuning

- Particle count ( $2^n$ )
- Normals
- Procrustes



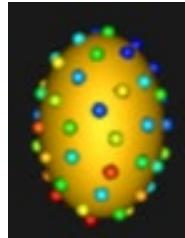
# ShapeWorks Studio – Optimize

Number of Particles  
 $(2^n)$

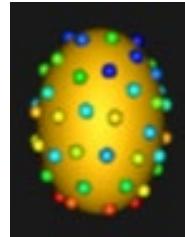


# ShapeWorks Studio – Optimize

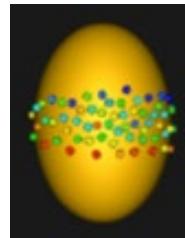
Relative Weighting



= 1



= 10



= 50

full cohort

File Options Help

**Optimize**

**Optimization Parameters**

Number of Particles	1024
Initial Relative Weighting	0.1
Relative Weighting	5
Starting Regularization	100
Ending Regularization	25
Iterations per Split	6000
Optimization Iterations	5000
Geodesic Distance	<input type="checkbox"/>
Geodesic Remesh Percent	100
Normals	<input type="checkbox"/>
Normals Strength	10
Geodesic Distance from Landmarks	<input type="checkbox"/>
Landmark Distance Weight	1
Procrustes	<input checked="" type="checkbox"/>
Procrustes Scaling	<input checked="" type="checkbox"/>
Procrustes Rotation/Translation	<input checked="" type="checkbox"/>
Procrustes Interval	2
Multiscale Mode	<input type="checkbox"/>
Multiscale Start	32
Use Initial Landmarks	<input type="checkbox"/>
Narrow Band	4

Run Optimize

Restore Defaults

P54

P53

P52

P51

A

Groomed

Compare

Align

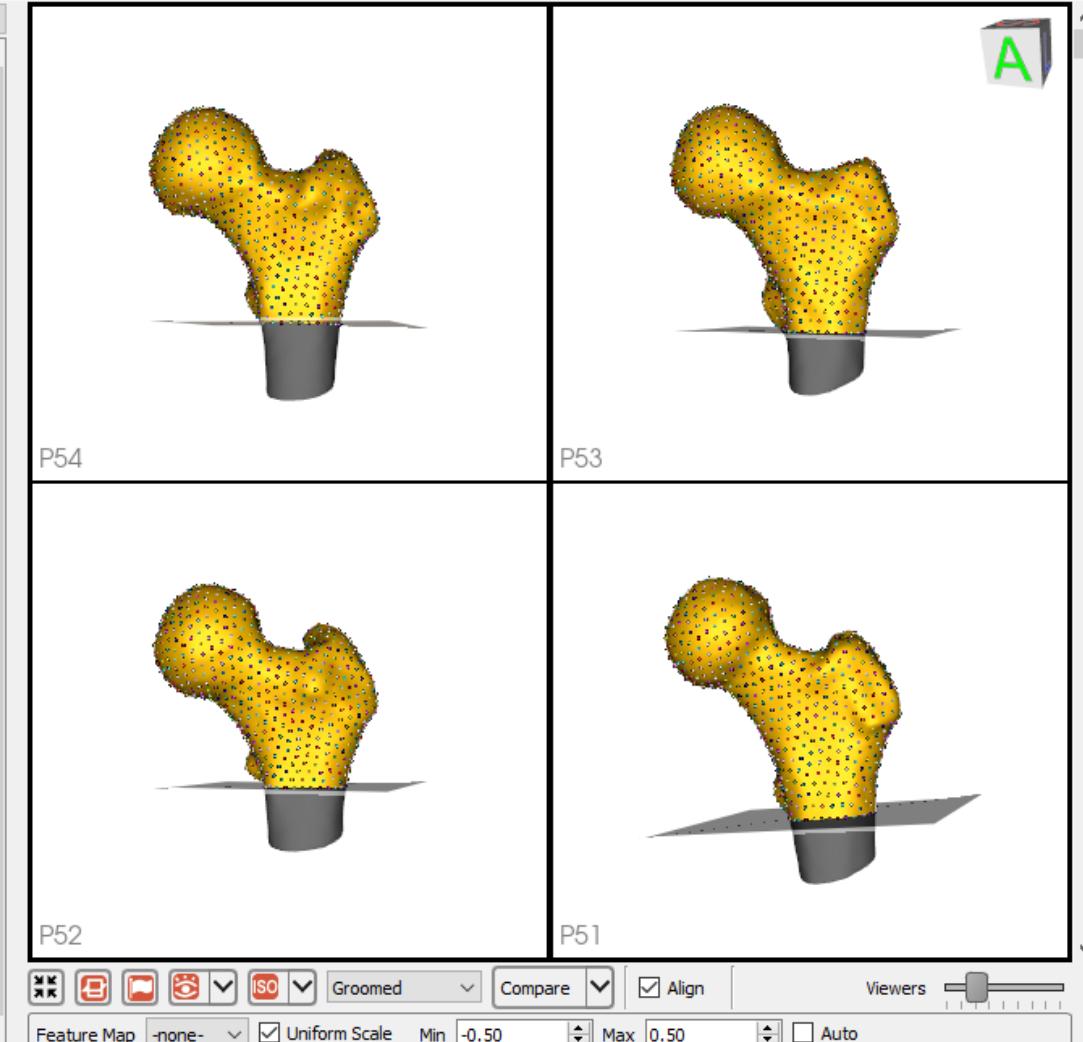
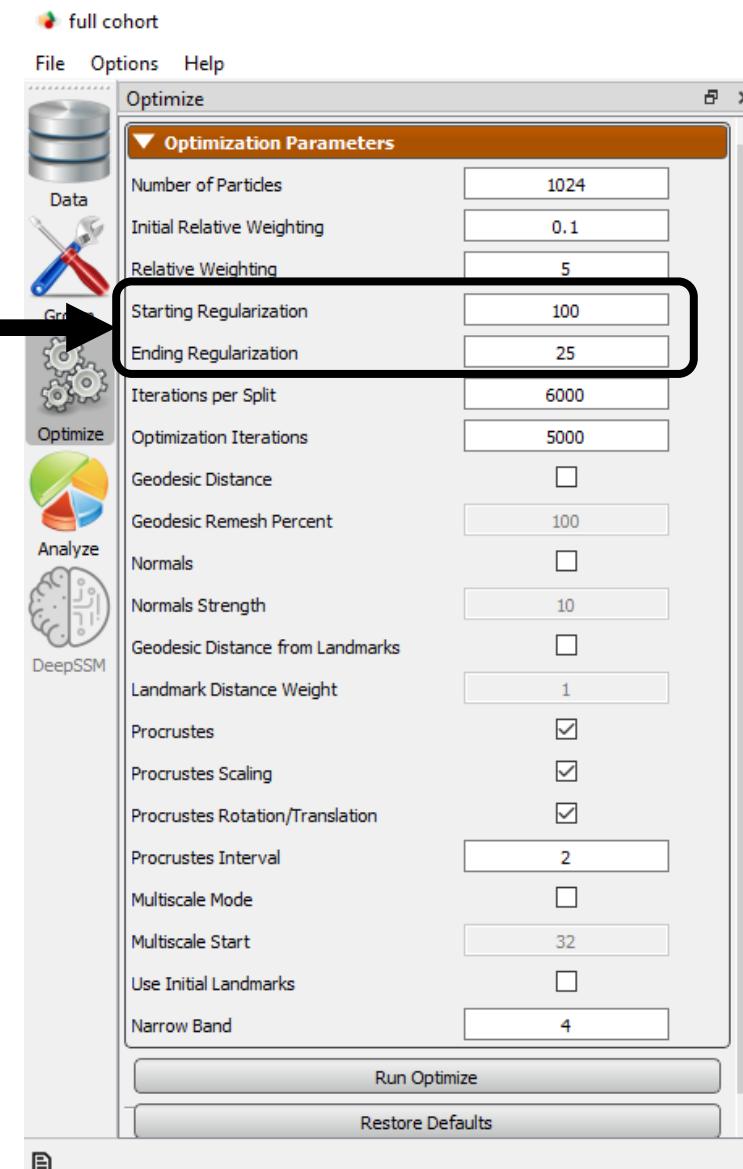
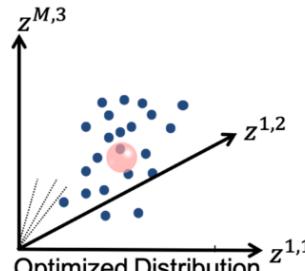
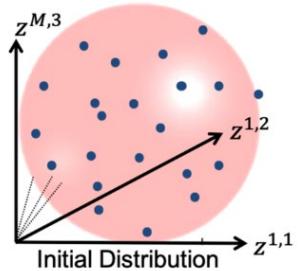
Viewers

Feature Map -none-

Uniform Scale Min -0.50 Max 0.50 Auto

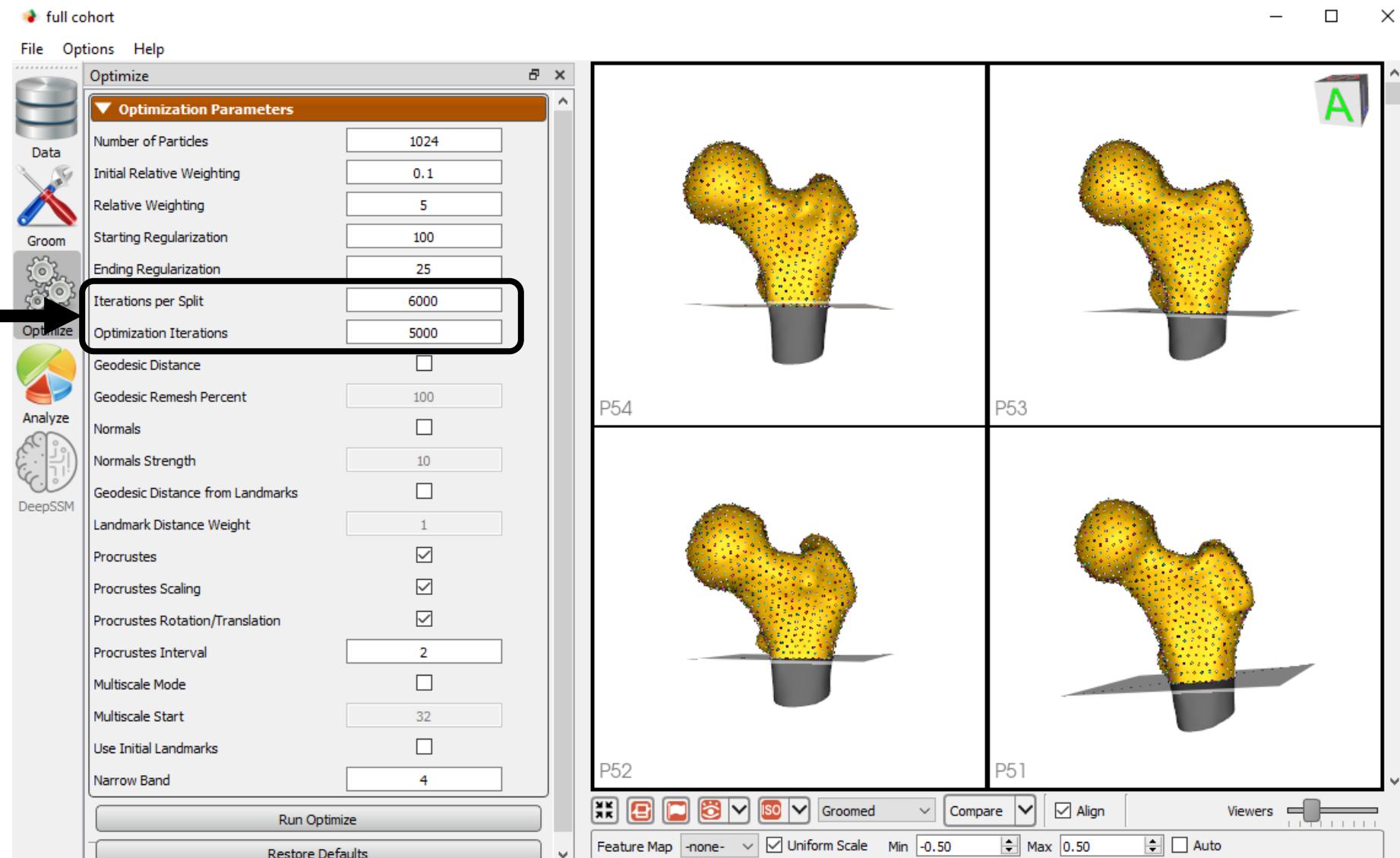
# ShapeWorks Studio – Optimize

Regularization  
Start: ~5% highest eigenvalue  
End: ~10x less than start



# ShapeWorks Studio – Optimize

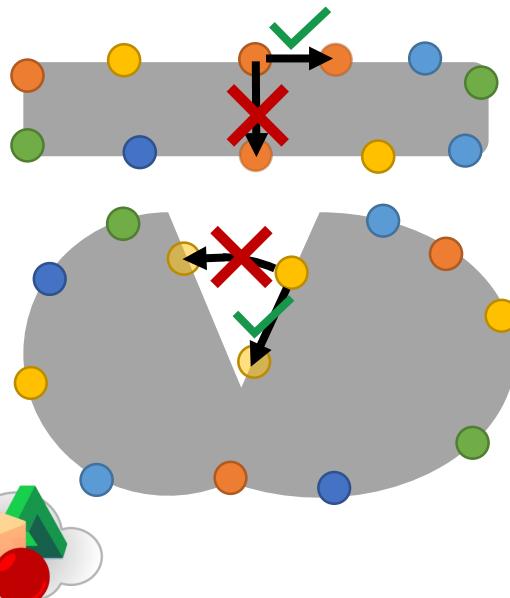
Iterations per Split  
Optimization Iterations



# ShapeWorks Studio – Optimize



## Particle Movement



full cohort

File Options Help

Optimize

▼ Optimization Parameters

Number of Particles	1024
Initial Relative Weighting	0.1
Relative Weighting	5
Starting Regularization	100
Ending Regularization	25
Iterations per Split	6000
Optimization Iterations	5000
Geodesic Distance	<input type="checkbox"/>
Geodesic Remesh Percent	100
Normals	<input type="checkbox"/>
Normals Strength	10
Geodesic Distance from Landmarks	<input type="checkbox"/>
Landmark Distance Weight	1
Procrustes	<input checked="" type="checkbox"/>
Procrustes Scaling	<input checked="" type="checkbox"/>
Procrustes Rotation/Translation	<input checked="" type="checkbox"/>
Procrustes Interval	2
Multiscale Mode	<input type="checkbox"/>
Multiscale Start	32
Use Initial Landmarks	<input type="checkbox"/>
Narrow Band	4

Run Optimize

Restore Defaults

P54

P53

P52

P51

A

ISO

Groomed

Compare

Align

Viewers

Feature Map -none-

Uniform Scale

Min -0.50

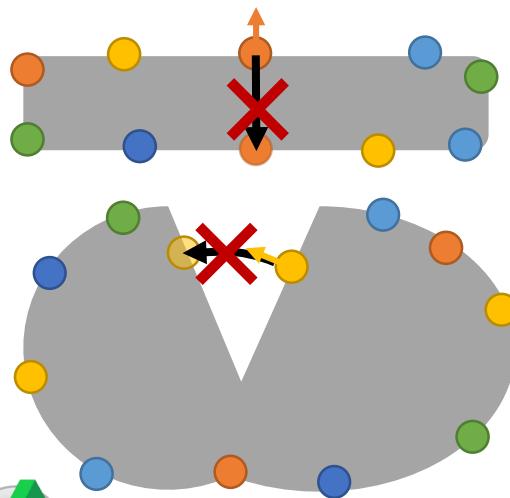
Max 0.50

Auto

# ShapeWorks Studio – Optimize



Particle Movement



full cohort

File Options Help

Optimize

▼ Optimization Parameters

Number of Particles: 1024  
Initial Relative Weighting: 0.1  
Relative Weighting: 5  
Starting Regularization: 100  
Ending Regularization: 25  
Iterations per Split: 6000  
Optimization Iterations: 5000  
Geodesic Distance:   
Geodesic Remesh Percent: 100  
Normals:   
Normals Strength: 10  
Geodesic Distance from Landmarks:   
Landmark Distance Weight: 1  
Procrustes:   
Procrustes Scaling:   
Procrustes Rotation/Translation:   
Procrustes Interval: 2  
Multiscale Mode:   
Multiscale Start: 32  
Use Initial Landmarks:   
Narrow Band: 4

Run Optimize

Restore Defaults

P54

P53

P52

P51

A

ISO

Groomed

Compare

Align

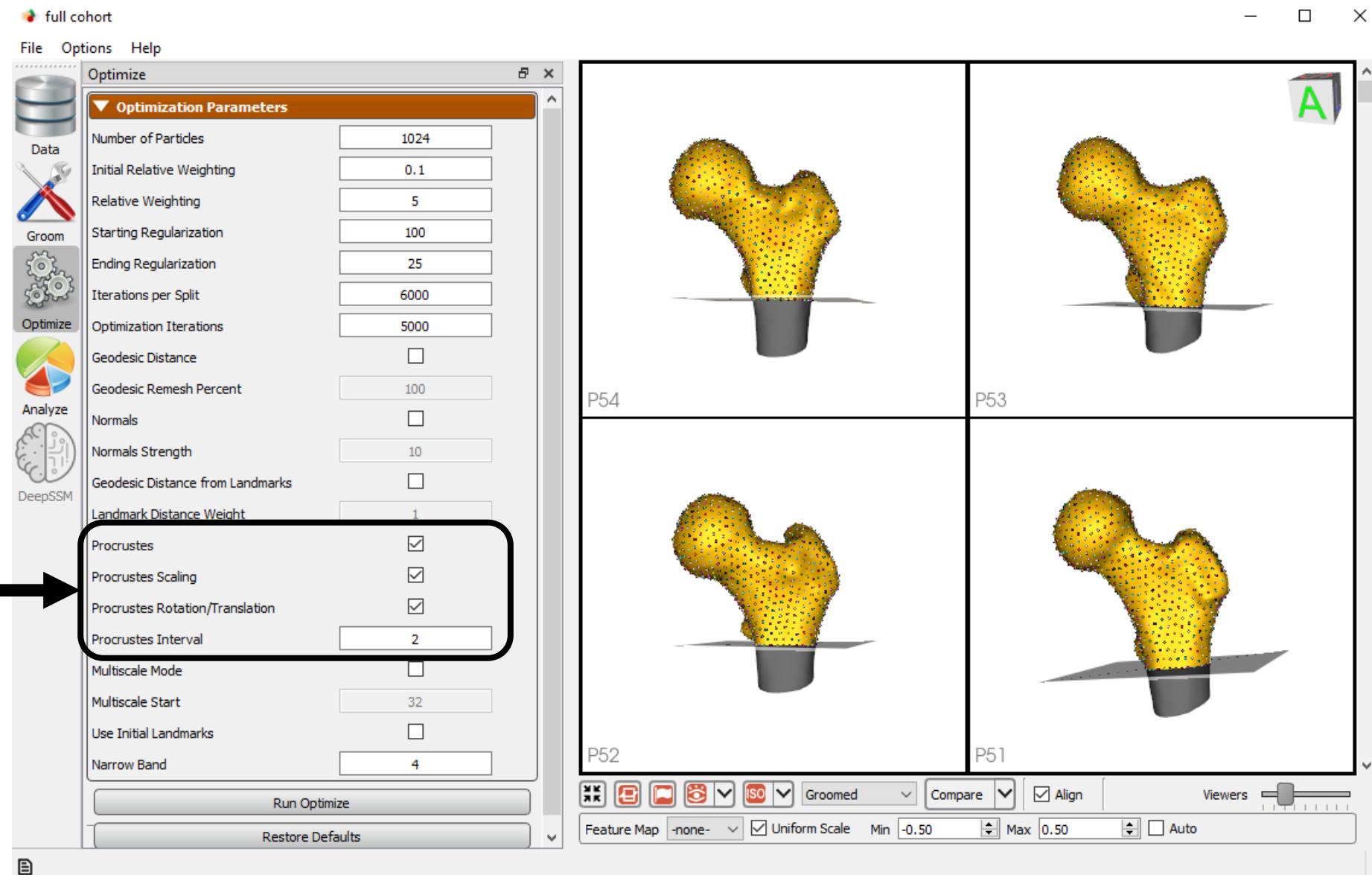
Viewers

Feature Map: -none-

Uniform Scale:  Min: -0.50 Max: 0.50 Auto

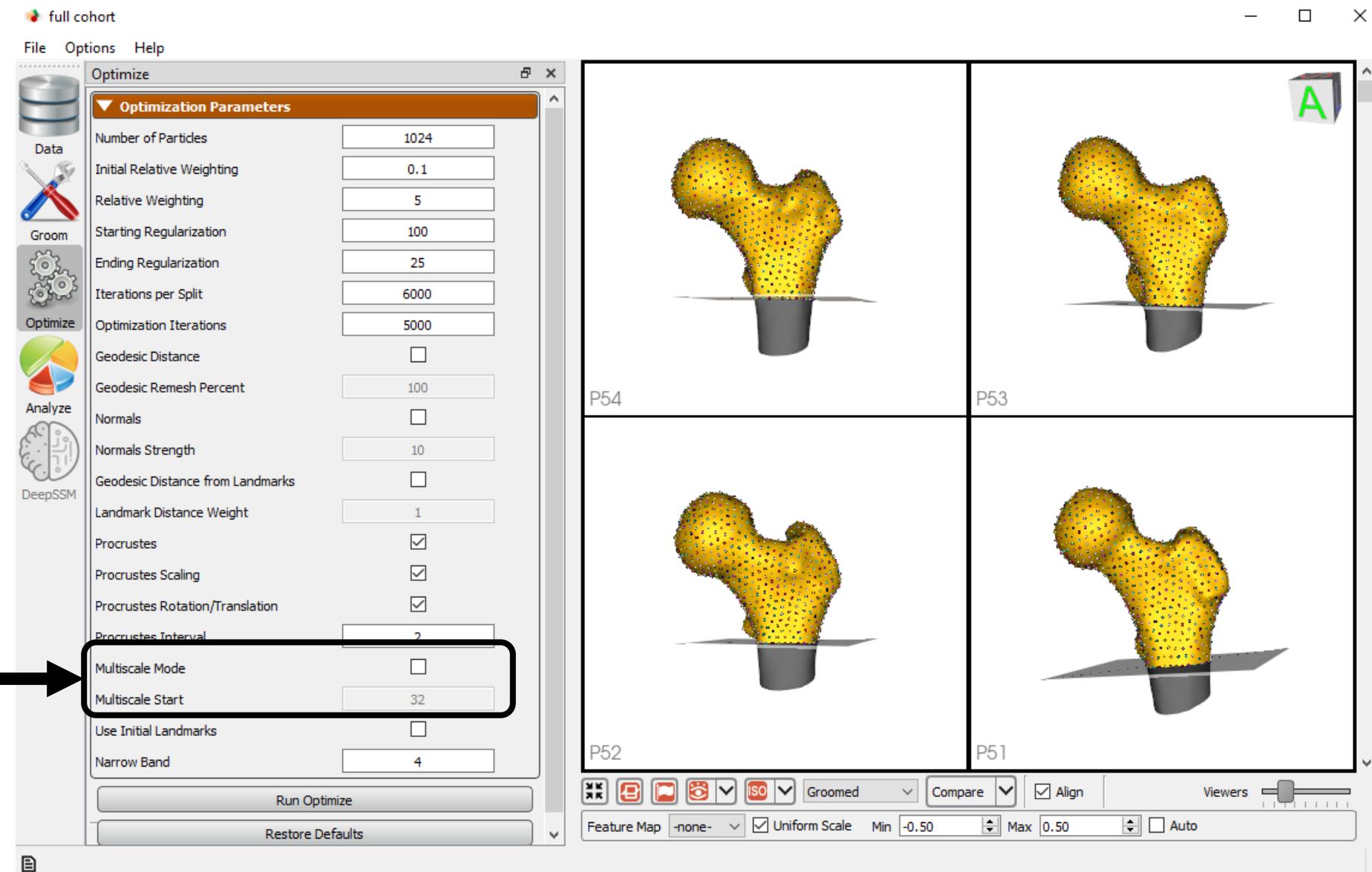
# ShapeWorks Studio – Optimize

Procrustes



# ShapeWorks Studio – Optimize

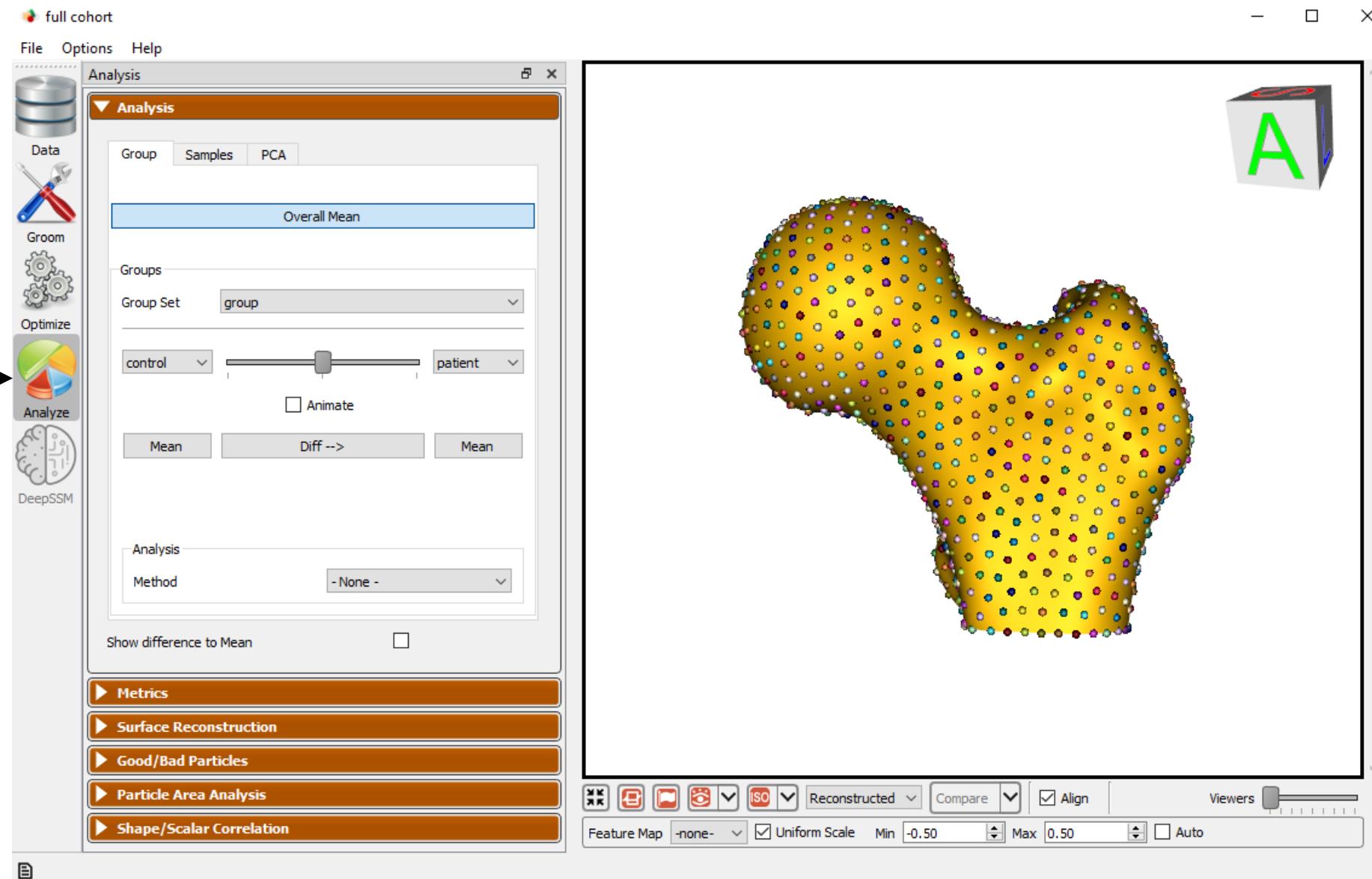
Multiscale Mode



# ShapeWorks Studio – Analyze

## Analyze

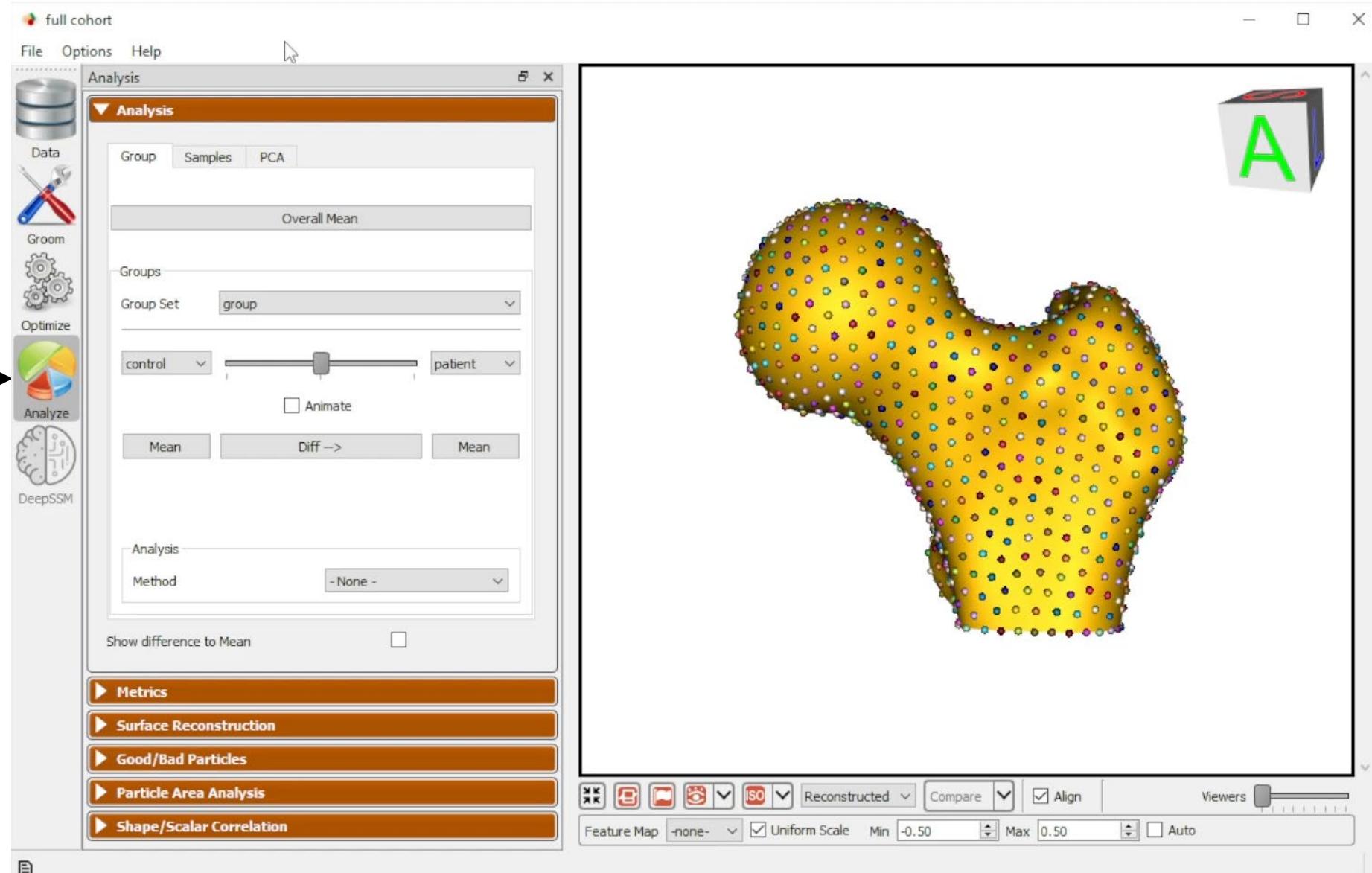
- Group Differences
- Hotelling's  $T^2$
- LDA
- PCA



# ShapeWorks Studio – Group Differences

## Analyze

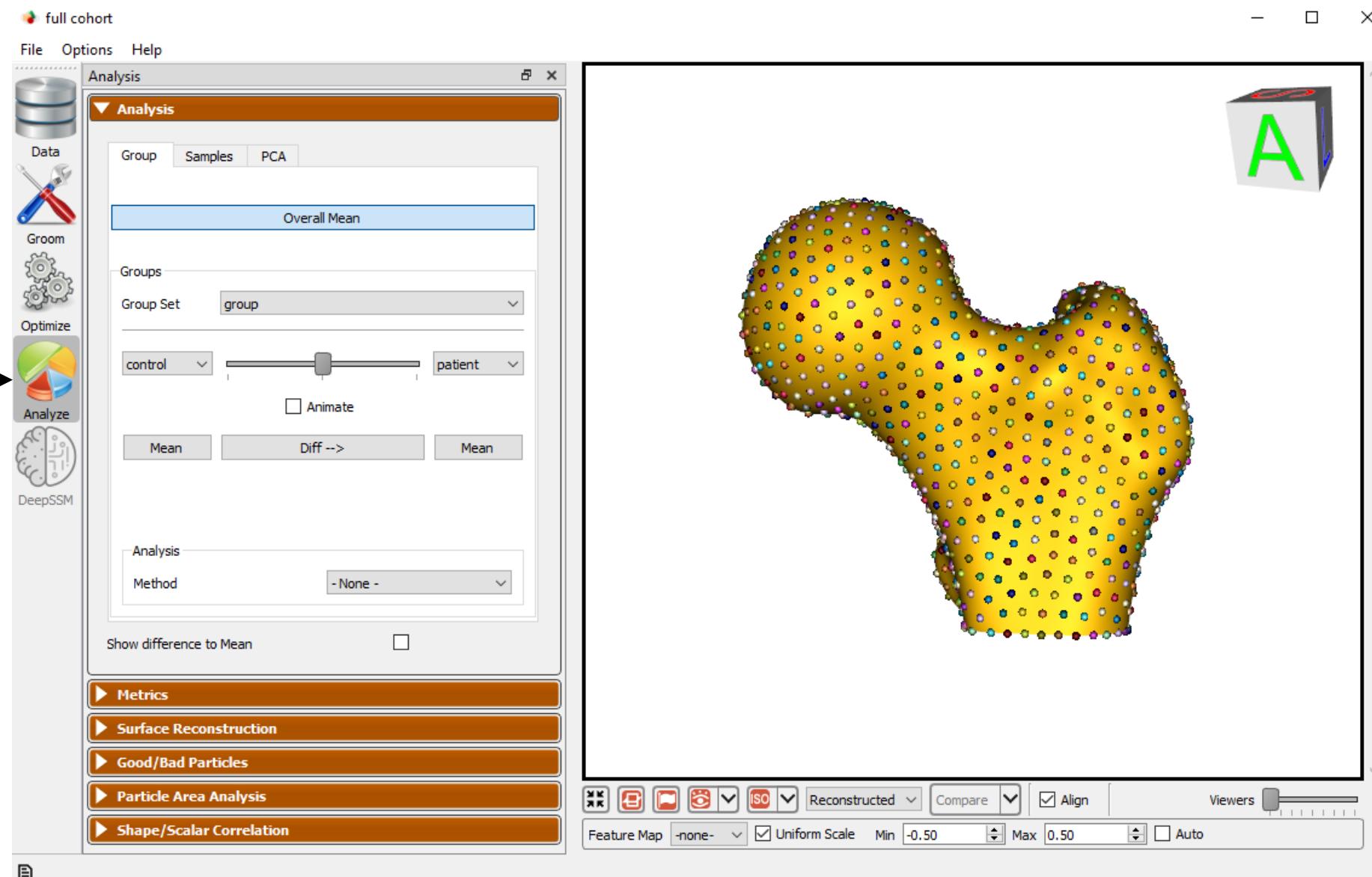
- Group Differences



# ShapeWorks Studio – Hotelling's T<sup>2</sup> Multivariate Test

## Analyze

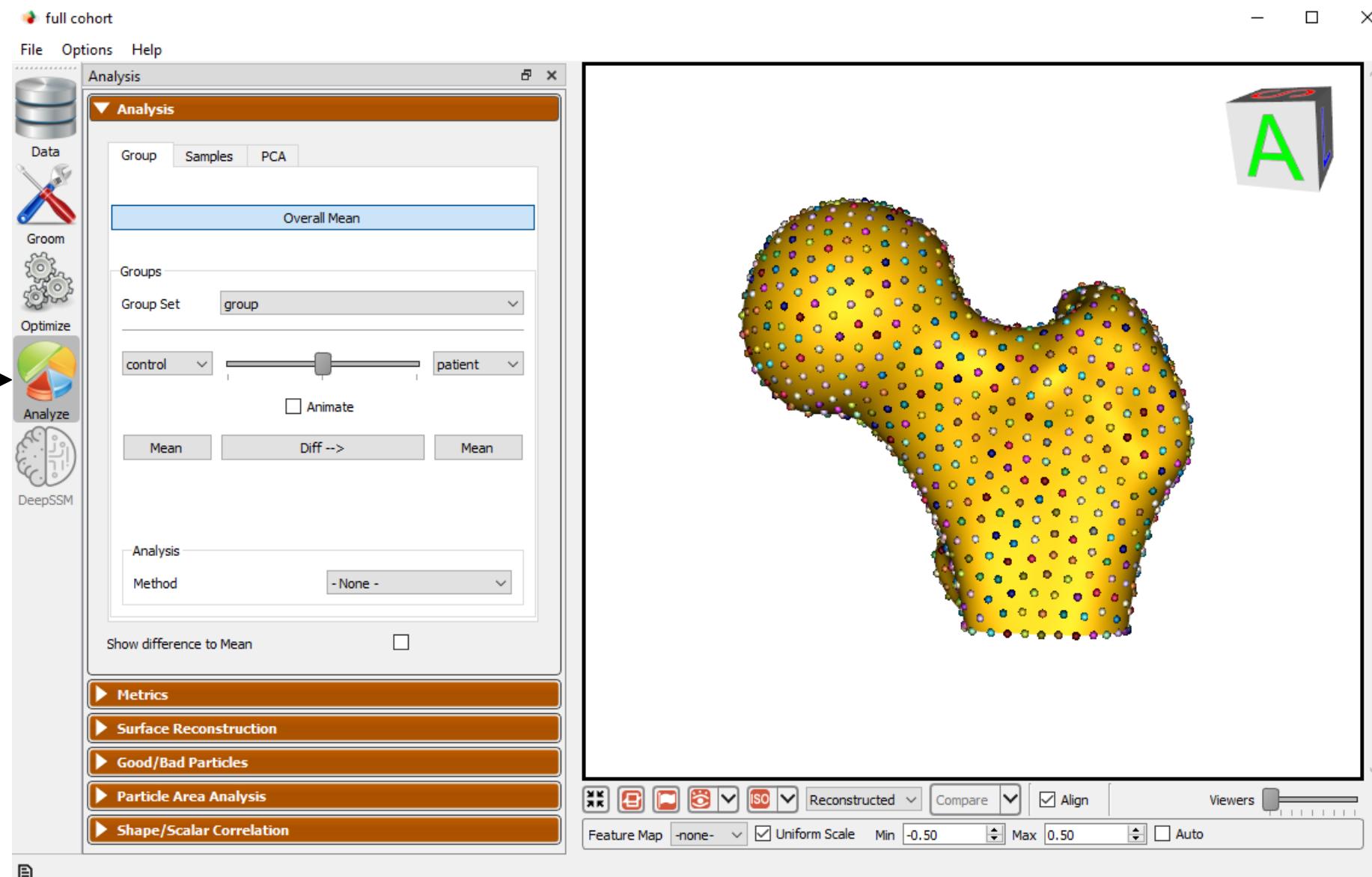
- Hotelling's T<sup>2</sup>



# ShapeWorks Studio – Linear Discriminant Analysis

Analyze

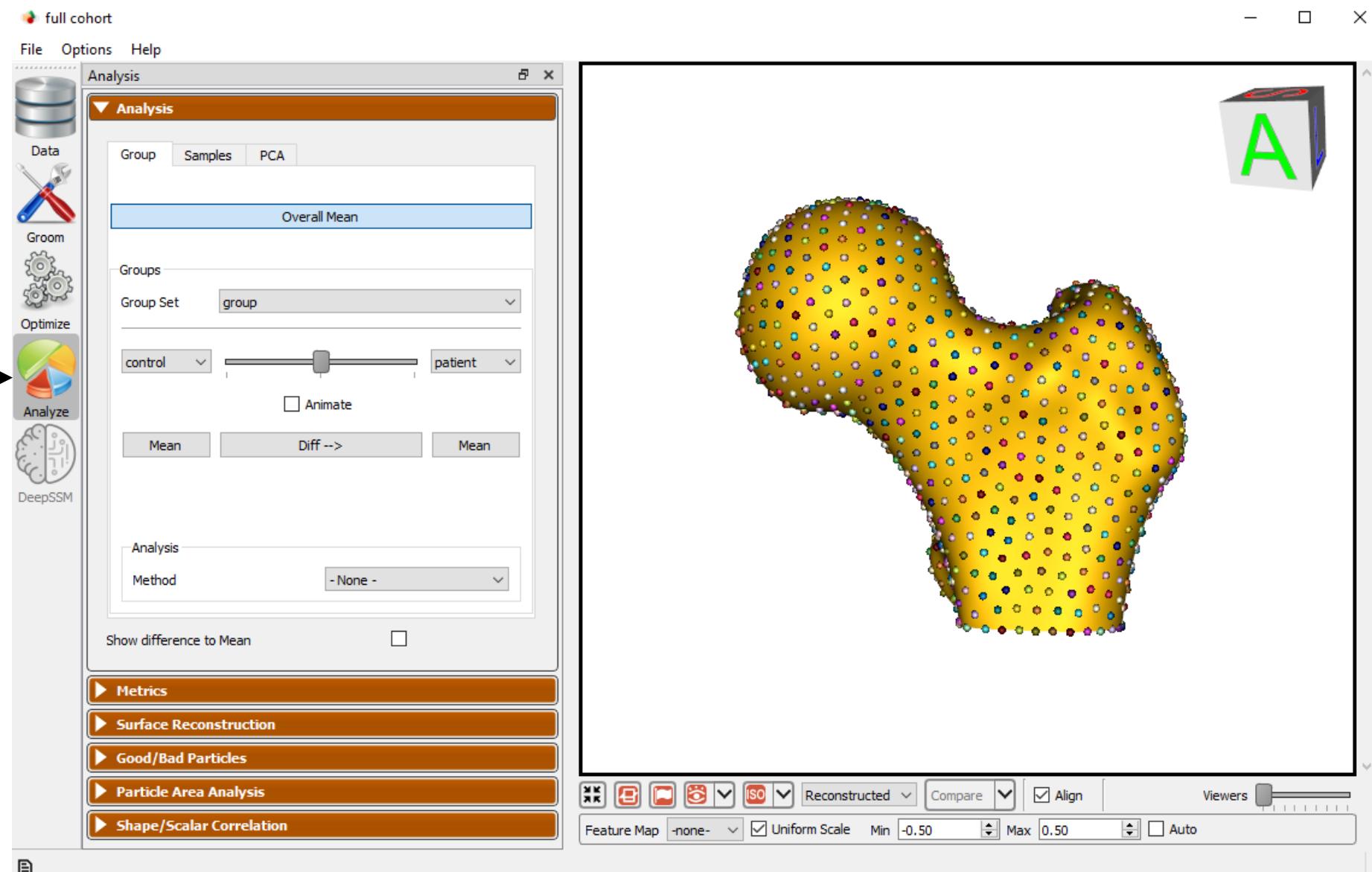
- LDA



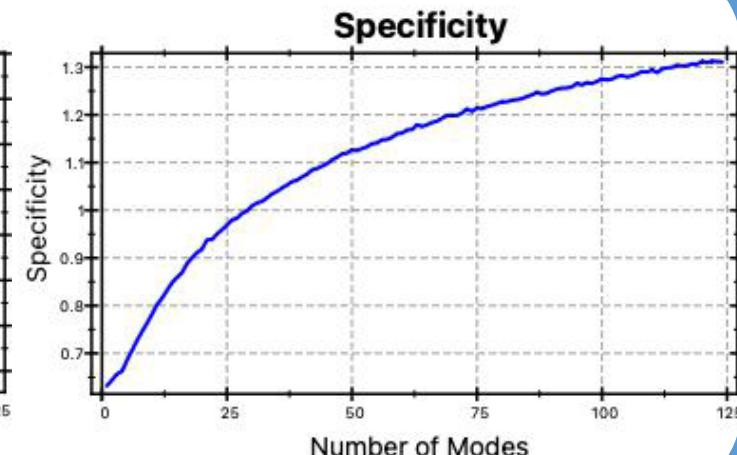
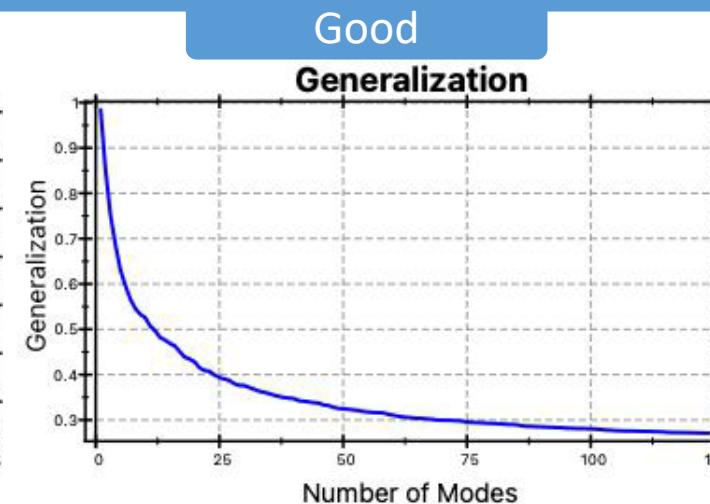
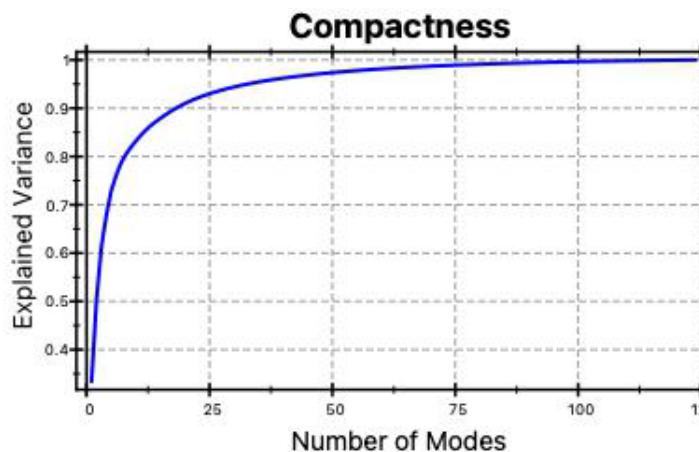
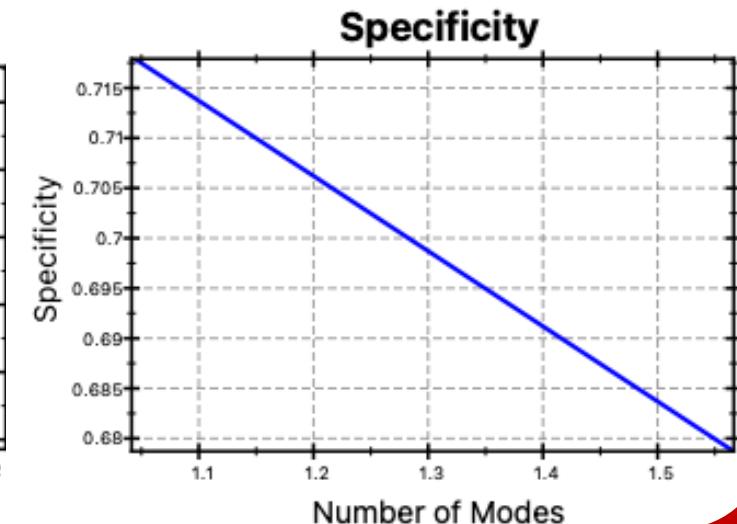
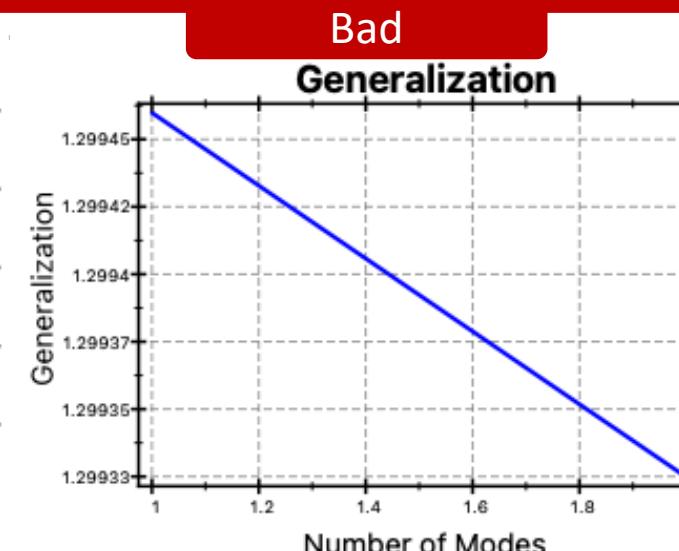
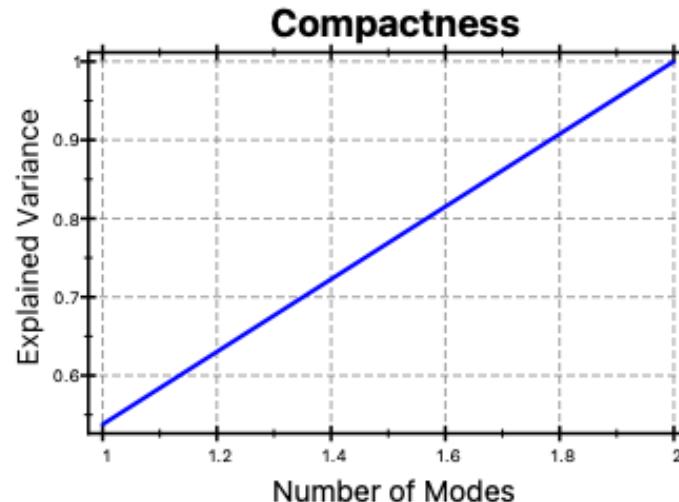
# ShapeWorks Studio – Principal Component Analysis

Analyze

- PCA



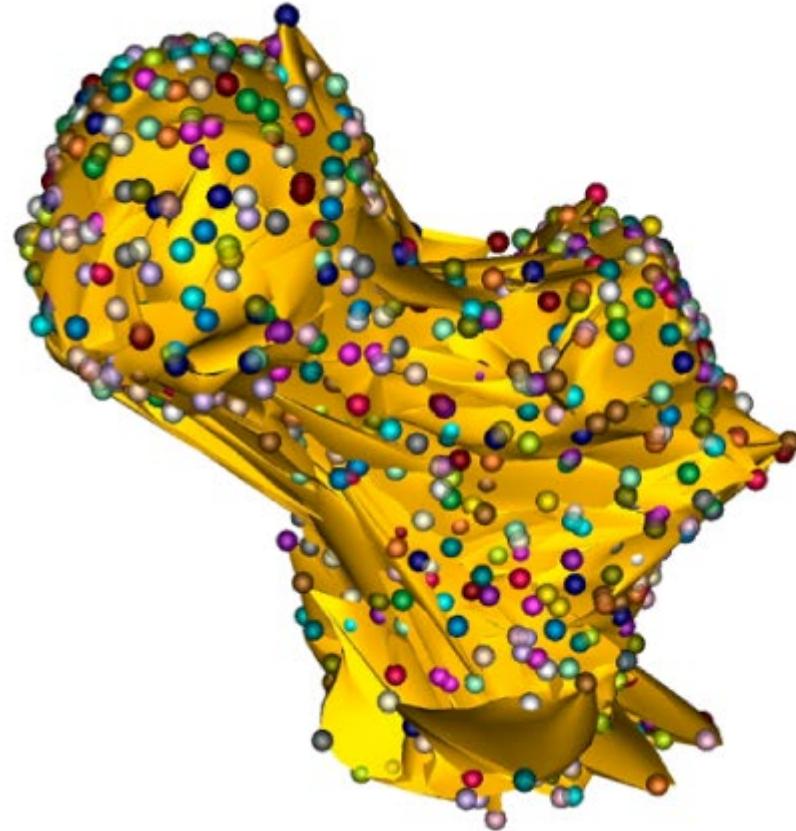
# What makes good correspondence?



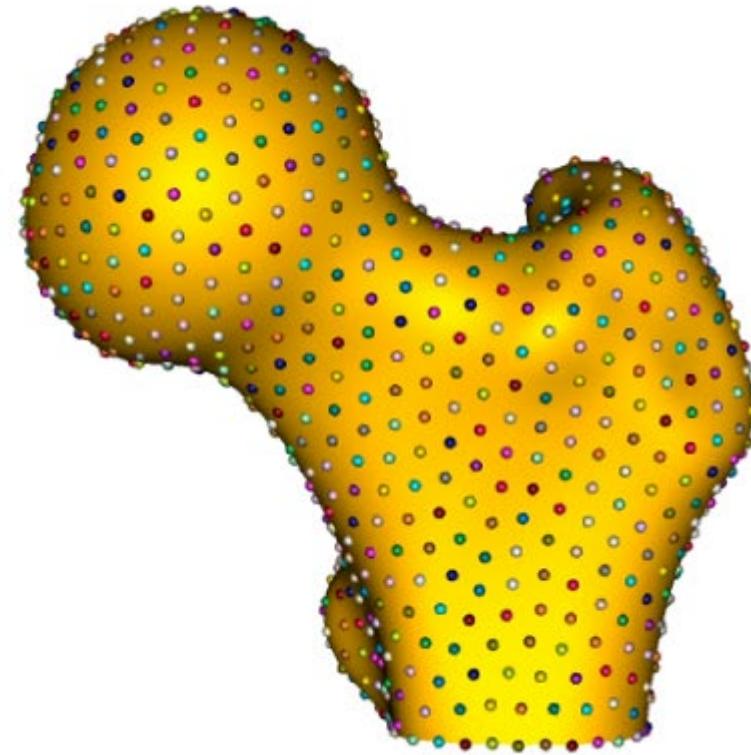


# What makes a good model?

Anatomically Correct Surface Reconstructions



Poor  
Correspondence

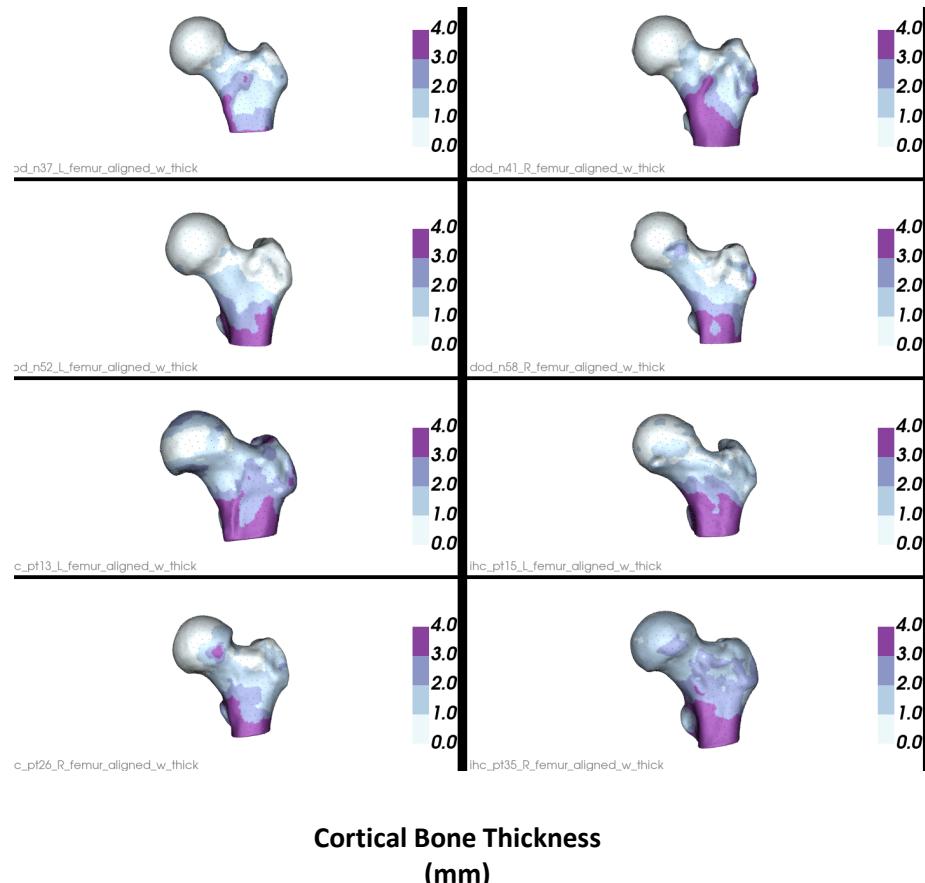


Good  
Correspondence

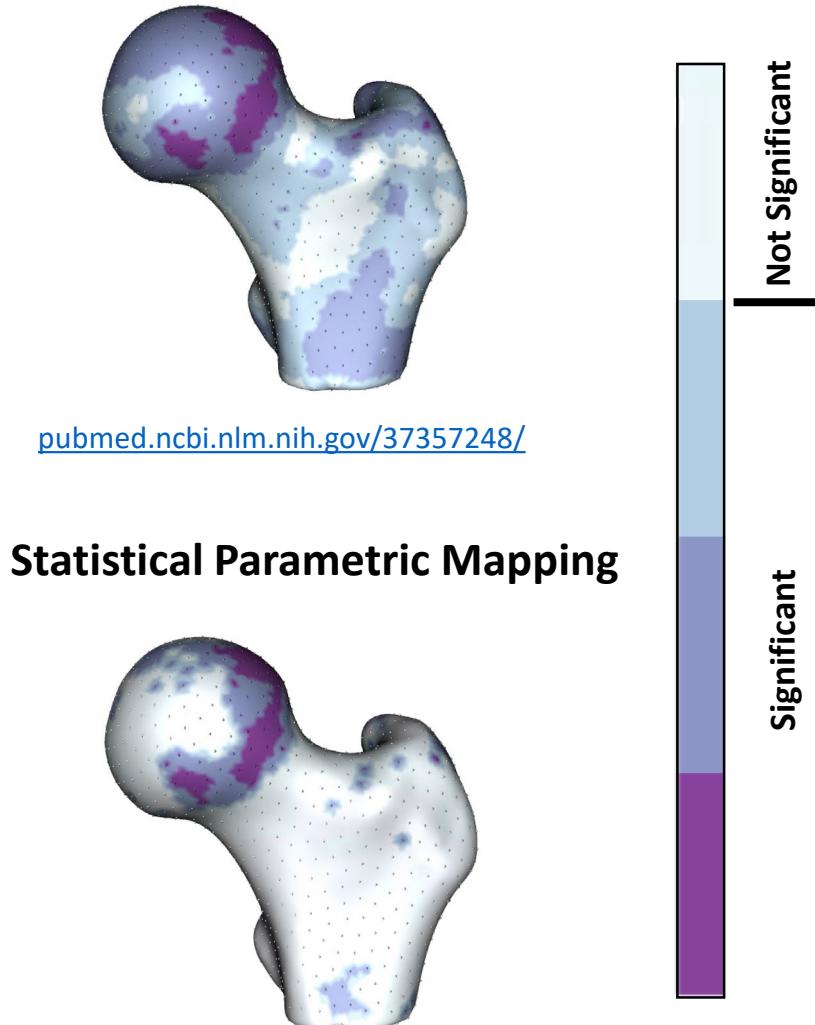


# Advanced Analysis Using Feature Maps

## Feature Maps



## Network Analysis



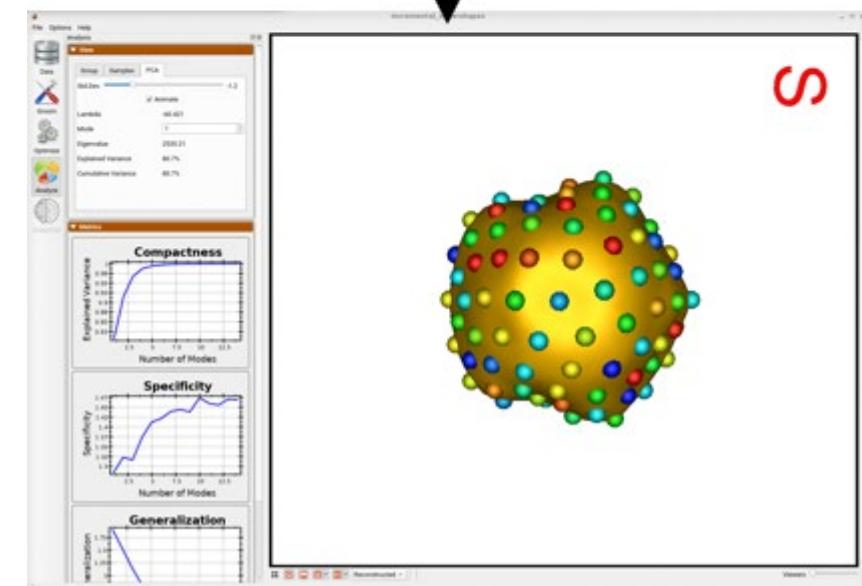
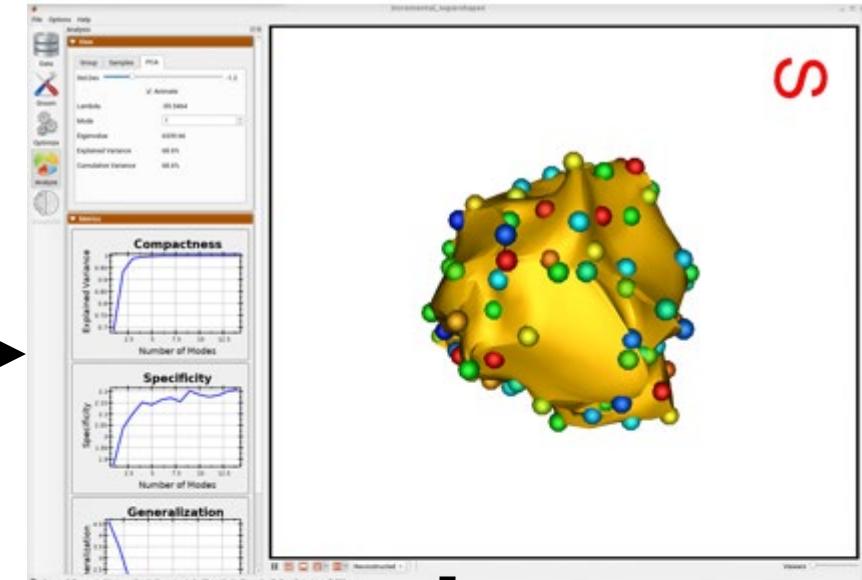
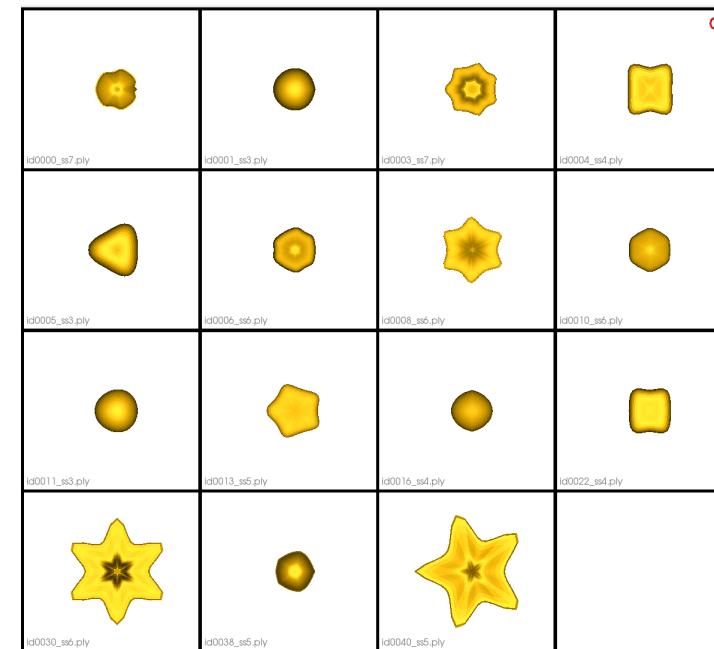
# Incremental Modeling

## Uses

Dataset:  
very large

or

small but highly variable



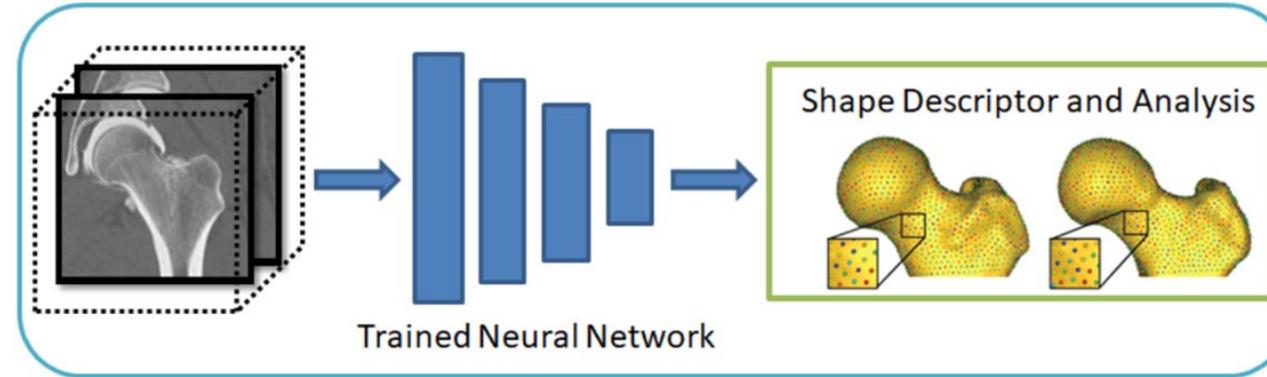
1. Optimize the model on a small subset of shapes
2. Use the mean of the local particles as landmarks to initialize the particles on new surfaces
3. Repeat until all surfaces have been optimized

**Benefit:** More compact shape model with better correspondence





# ShapeWorks Developments – DeepSSM



## Why DeepSSM?

- **Less Labor:** Does not require segmentation, only a bounding box around the anatomy of interest in the image
- **End-to-end:** Does not require separate grooming or optimization steps
- **Faster Results:** Once a DeepSSM network has been trained, it can be used to predict the shape model on a new image





# Directions for Installation

## URL



[sciinstitute.github.io/ShapeWorks/](https://sciinstitute.github.io/ShapeWorks/)



### ShapeWorks

Home

Getting Started >

For Users ▾

[How to Install ShapeWorks?](#)

[How to Cite ShapeWorks?](#)

## GitHub



[github.com/SCIIInstitute/ShapeWorks](https://github.com/SCIIInstitute/ShapeWorks)





# Test Dataset

## Femur SSM Dataset



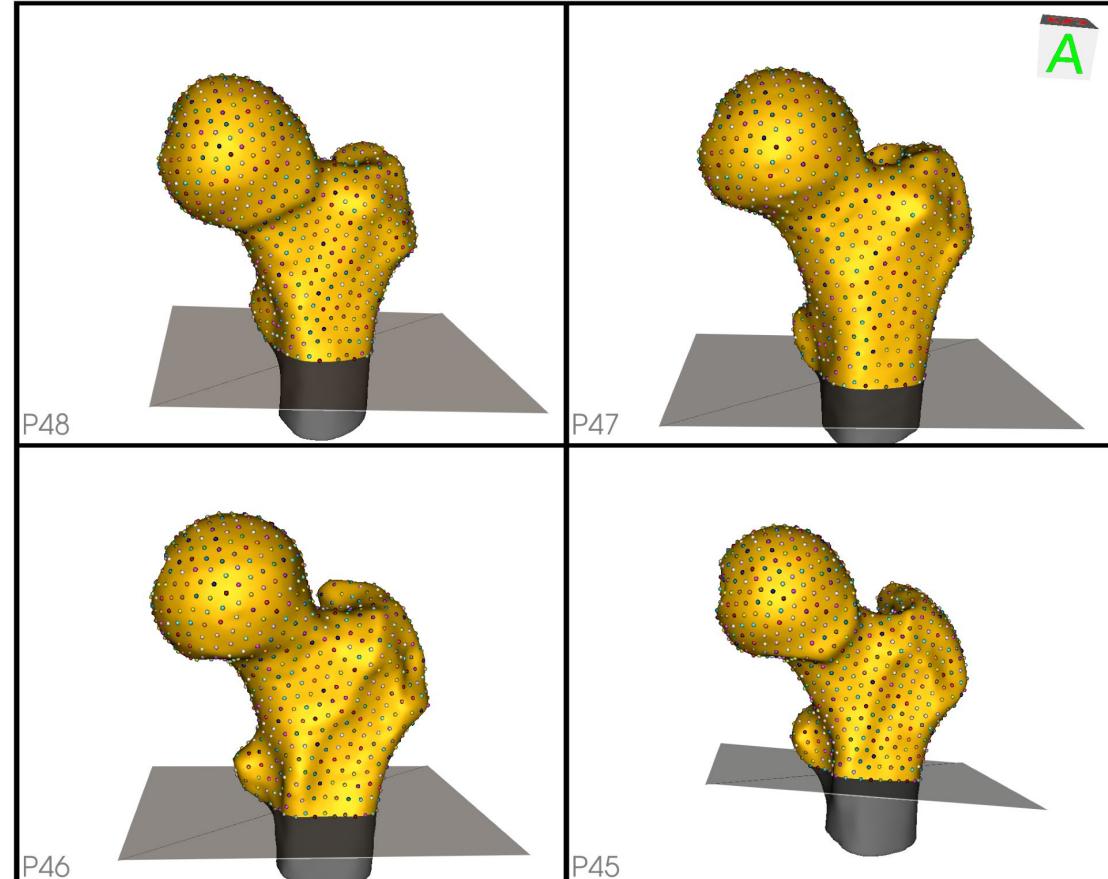
[github.com/Anderson-Research-Group/Femur SSM Example](https://github.com/Anderson-Research-Group/Femur_SSM_Example)



## Cam Morphology and Sex-Based Differences in the Proximal Femur Anatomy of Collegiate Athletes Without Hip Pain: A 3-Dimensional Statistical Shape Modeling Analysis

Bergen Braun <sup>1 2</sup>, Joseph D Mozingo <sup>2</sup>, Penny R Atkins <sup>3</sup>, K Bo Foreman <sup>2 4</sup>, Allan K Metz <sup>2</sup>,  
Stephen K Aoki <sup>2</sup>, Travis G Maak <sup>2</sup>, Andrew E Anderson <sup>1 2 3 4</sup>

[pubmed.ncbi.nlm.nih.gov/39931634/](https://pubmed.ncbi.nlm.nih.gov/39931634/)



# Workshop Example



Femur\_SSM\_Example / SSM\_Exercise /

Femur\_SSM\_Example Public

Name

main 1 Branch 0 Tags

RichLisonbee ready

OJSM\_2025\_Braun\_Model

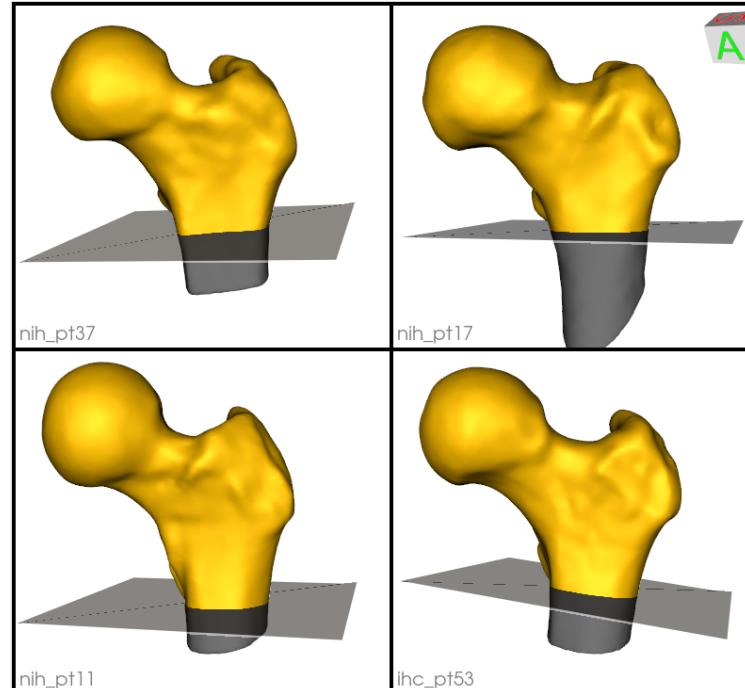
SSM\_Exercise

SSM\_Workshop\_Example\_Solution\_Femur.xlsx

SSM\_Workshop\_Exercise\_Femur.xlsx

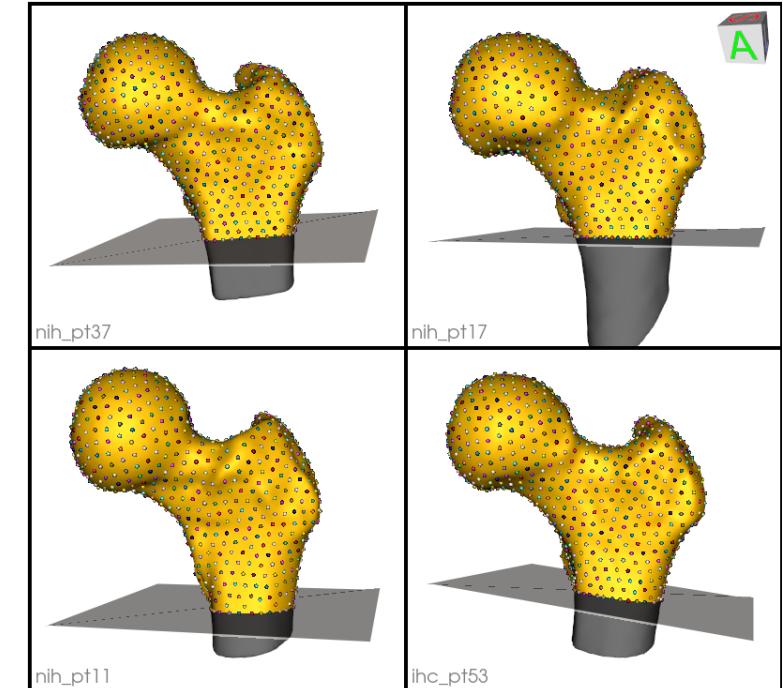
## Example

- ShapeWorks Project File (.xlsx)  
*SSM\_Workshop\_Exercise\_Femur.xlsx*
- Groomed Models (.vtk)
- Cutting Planes (.json)



## Solution

- ShapeWorks Project File (.xlsx)  
*SSM\_Workshop\_Example\_Solution\_Femur.xlsx*
- Mean Models (.stl)
- Correspondence Models (.particles)



# Workshop Example – Exercise



Get Data from GitHub



Load Project File

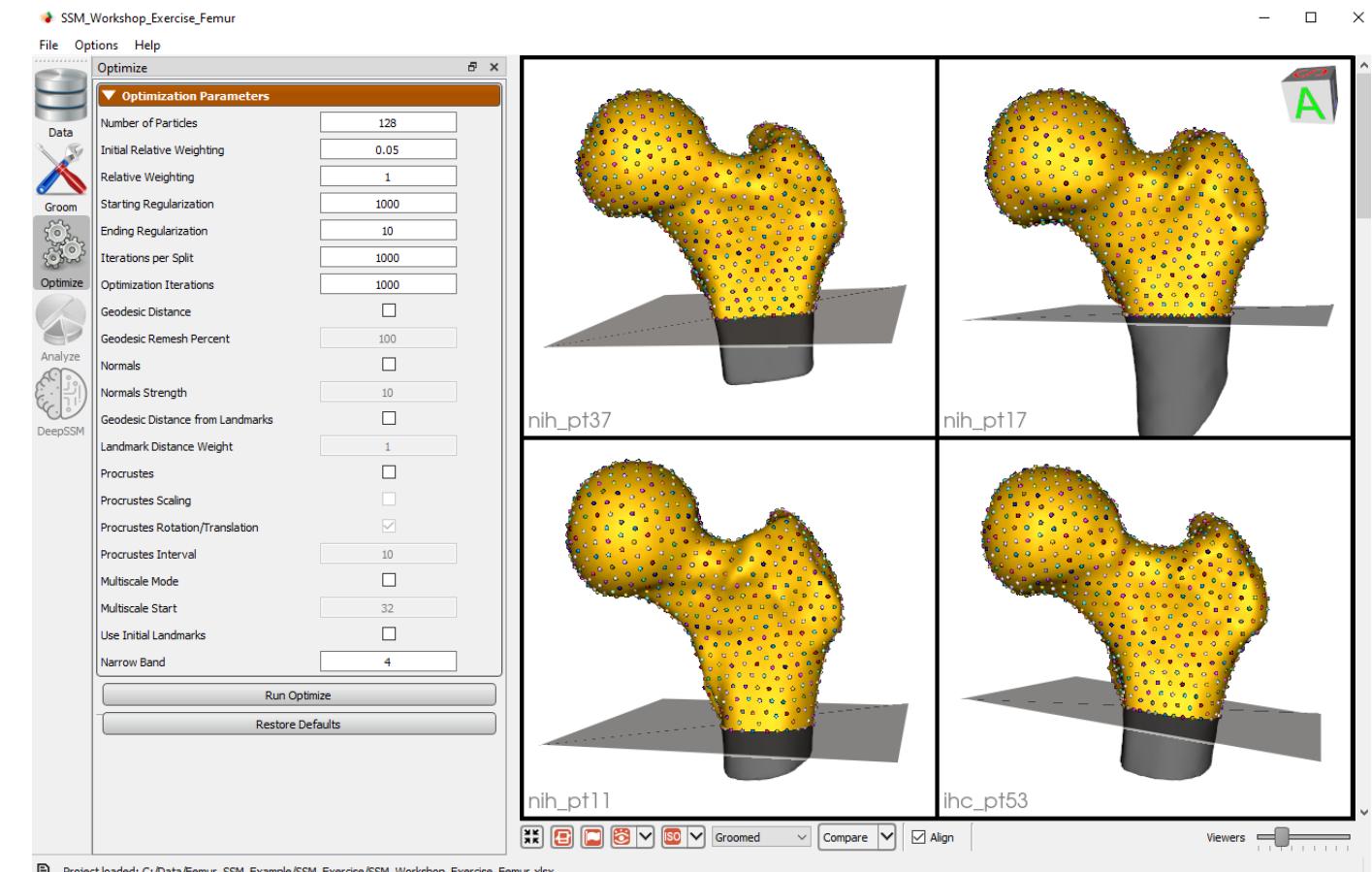
*SSM\_Workshop\_Exercise\_Femur.xlsx*



Play around with parameters



Optimize



# Workshop Example – Exercise



Get Data from GitHub



Load Project File

*SSM\_Workshop\_Exercise\_Femur.xlsx*

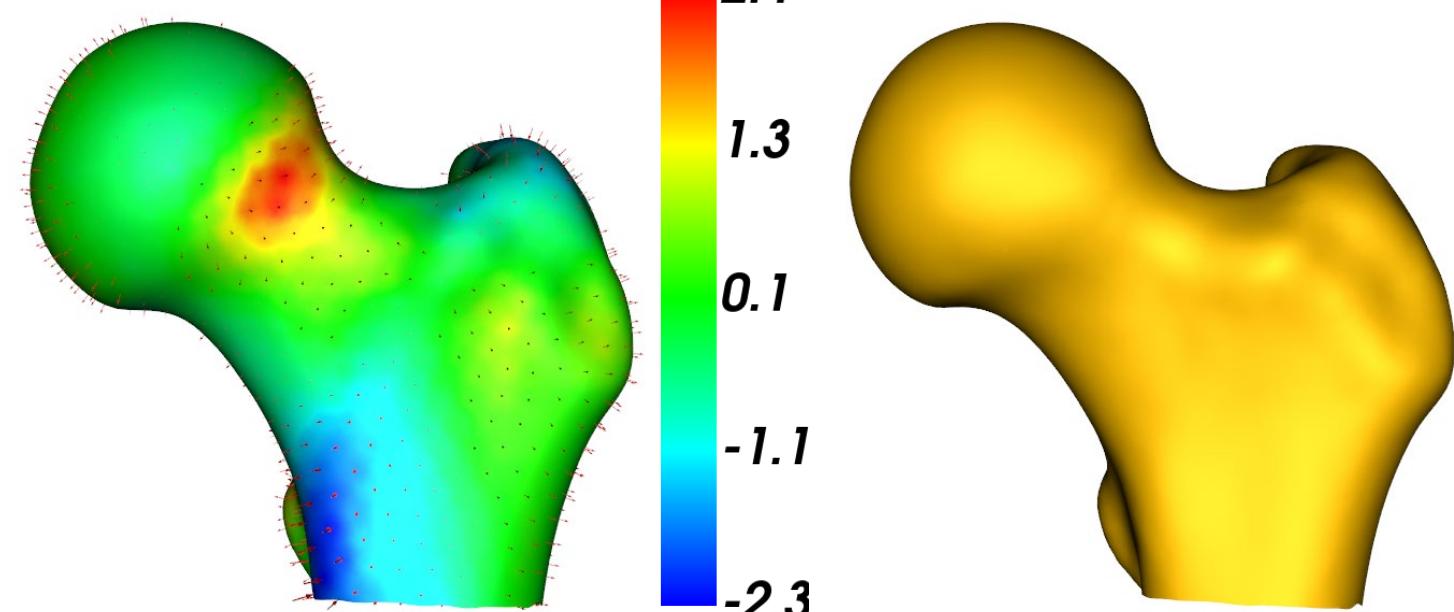
Optimize

Compare your mean models



ShapeWorks

*Mean Shape Differences*



- Built-in, quick, and easy
- Less control of figure presentation
- Can only compare project models

# Workshop Example – Exercise



Get Data from GitHub



Load Project File

*SSM\_Workshop\_Exercise\_Femur.xlsx*

Play around with parameters

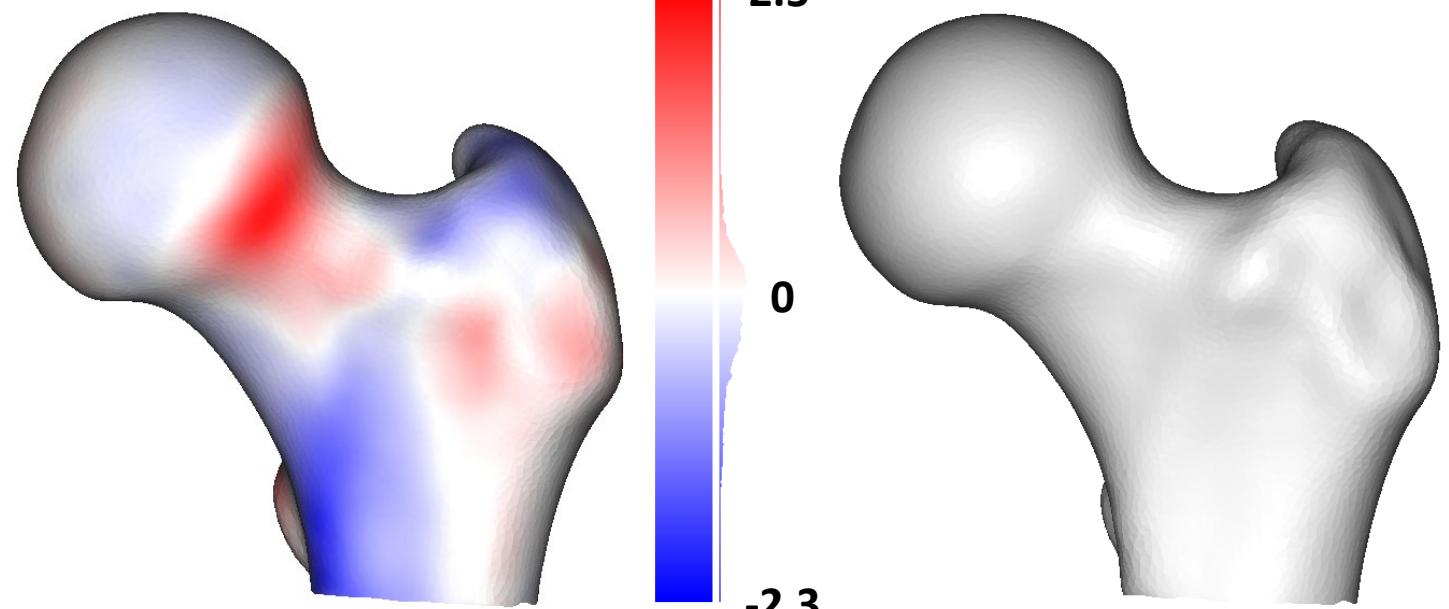
Optimize

Compare your mean models



CloudCompare

*Mean Shape Differences*



- Quick and easy to use
- More control of figure presentation
- Can compare any surface or cloud

# Workshop Example – Exercise



Get Data from GitHub



Load Project File

*SSM\_Workshop\_Exercise\_Femur.xlsx*

Play around with parameters

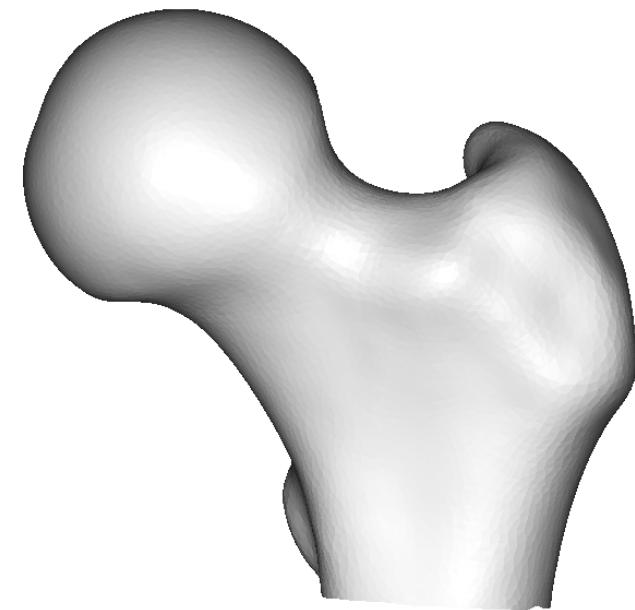
Optimize

Compare your model to example

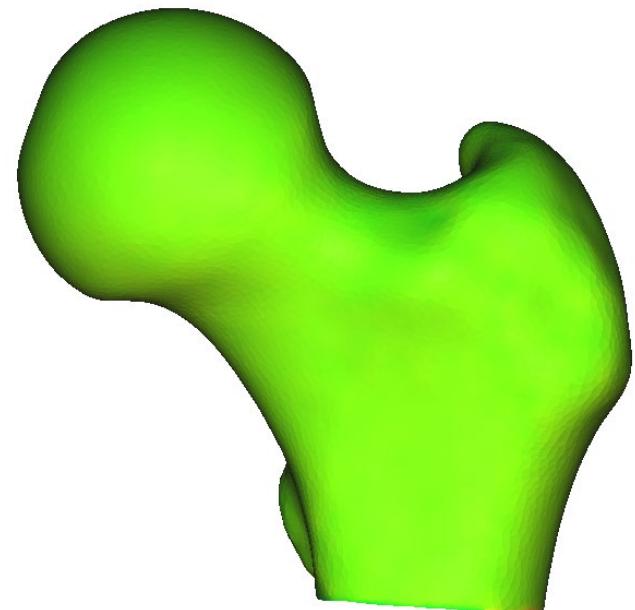


CloudCompare

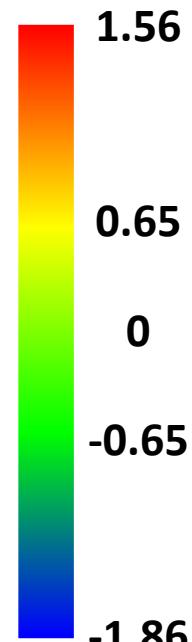
*Model Shape Differences*



Solution



Solution  
with x2 relative weights





# May Workshop

## New Users

- Try and optimize femur dataset
- Want more examples?
  - ShapeWorks has use cases
- Start your SSM project

## Current Users

- Debug and Troubleshooting Help
- What are next steps?
  - What more would you like to know?
    - Pre-processing steps
    - Optimization issues
    - Morphometric analyses

Bring:

- ShapeWorks Projects
- Questions or Issues





# ShapeWorks User Meetings

## Office Hours

- Every other week
- Next meeting is on Tuesday April 1st at 2 PM MDT
  - Email us in advance for an invite





# Thank you! Questions?



## Acknowledgements



NIBIB U24EB029011

NIBIB R01EB016701

NIAMS R01AR076120

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NIGMS P41GM103545

R24 GM136986

## Acknowledgements



NIH R01AR077636

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NIH U24EB029011

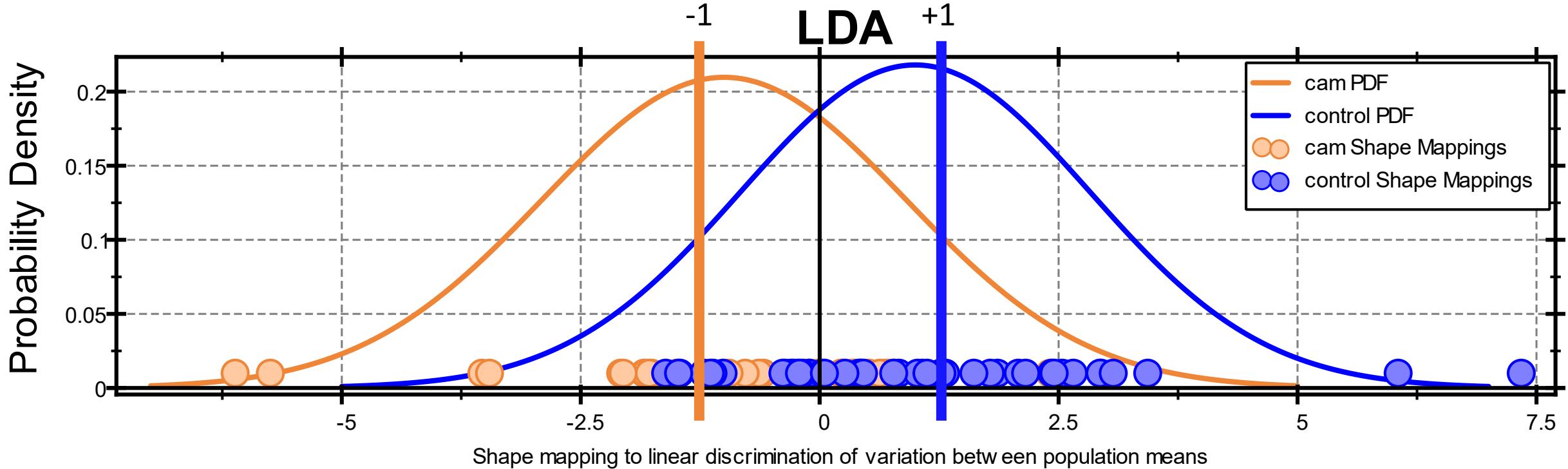
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# ShapeWorks Studio – Linear Discriminant Analysis



# SLIDE TITLE

