Introduction to statistical shape analysis II: Semi-landmarks and beyond

Sara Rolfe

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How many landmarks are enough to characterize shape and size variation?

- Criteria for landmarks to be homologous and reproducible results in very sparse data from images
- For many data sets, this may not be sufficient to capture shape changes, especially along curves or smooth surfaces
- Point-landmark too stringent for effective biometrics in many 3D applications

Watanabe, Akinobu. "How many landmarks are enough to characterize shape and size variation?." PloS one 13.6 (2018): e0198341.

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Image data provides rich phenotype descriptions – how can this be leveraged?

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Landmark types

- Type I: Points with homology provided by a biologically location on the form
- Type II: Points with homology determined by geometric criteria
- Type III: Points with a location dependent on other landmark points

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Landmark types

- Type I: Points with homology provided by a biologically location on the form
- Type II: Points with homology determined by geometric criteria
- Type III: Points with a location dependent on other landmark points
- **Psudolandmarks: Points placed automatically without reference to anatomical landmarks.**

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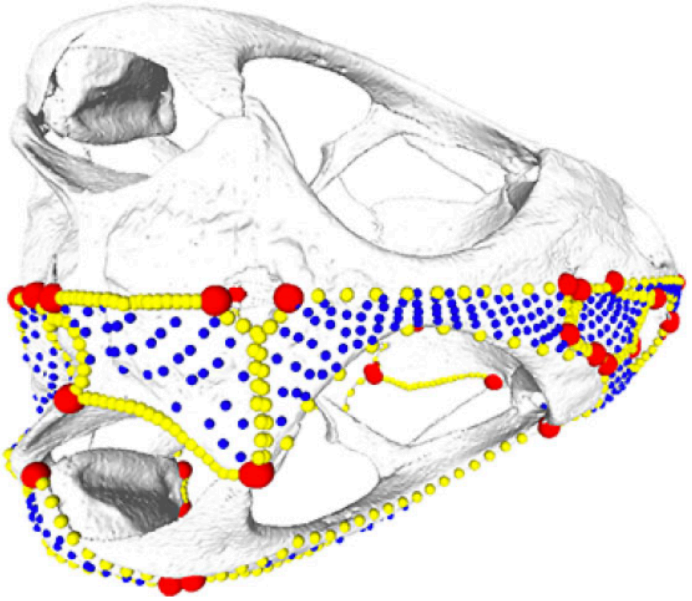
3D semi-landmark placement

- Generally placed on a template
- Equally spaced points are placed along curves
- Surface patches are evenly sampled
- Landmarks can be used to anchor patches or curves



Bardua, C., Felice, R. N., Watanabe, A., Fabre, A. C., & Goswami, A. (2019). A practical guide to sliding and surface semilandmarks in morphometric analyses. *Integrative Organismal Biology*, *1*(1), obz016.

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What is wrong with equidistant samples?

Produce spacing as a by-product of the analysis since the analysis is ignorant of the actual spacing.

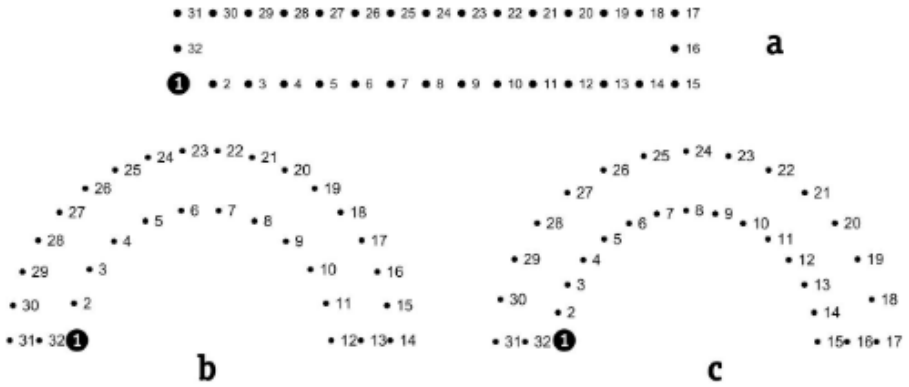

Figure 3. (a) Form with one true landmark in the lower left corner and 31 other points equally spaced along the outline. (b) Bent form with one true landmark (1) and 31 other points in equal spacing. (c) The position of the points now optimizes bending energy.

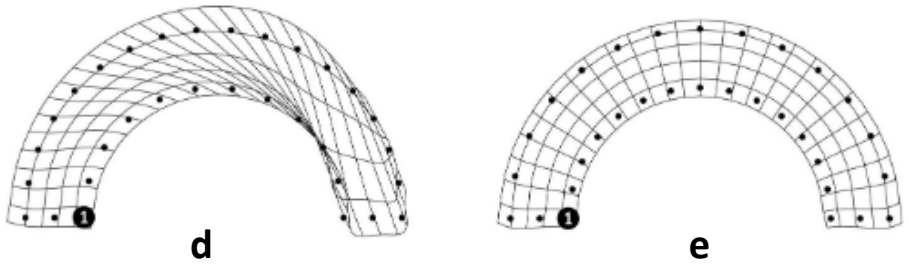

Figure 4. Splines corresponding to Figure 3. (a) Deformation grid from the form in Figures 3a and 3b. (b) Deformation grid from the form in Figures 3a and 3c.

Gunz, Philipp, Philipp Mitteroecker, and Fred L. Bookstein. "Semilandmarks in three dimensions." *Modern morphometrics in physical anthropology*. Springer, Boston, MA, 2005. 73-98.

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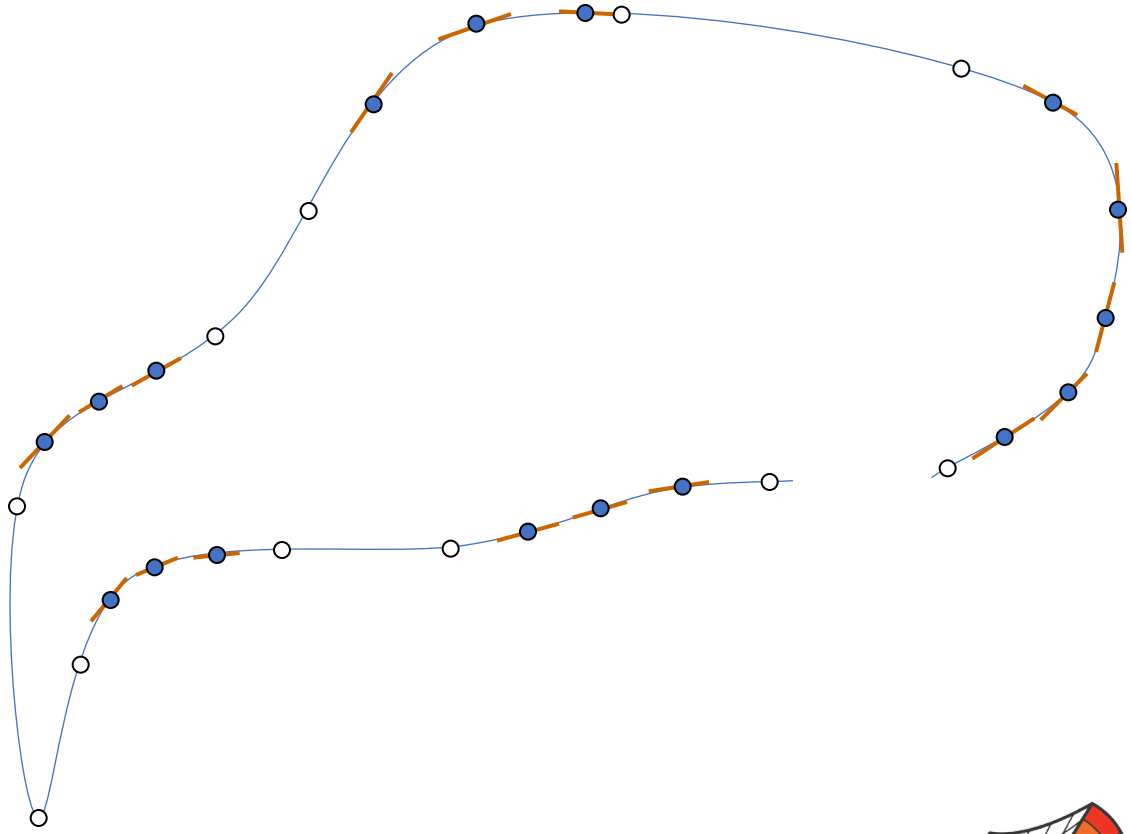
Sliding semi-landmark method

1) Slide semi-landmark points along the surface until they satisfy matching criteria with a single reference specimen
2) Calculate Procrustes average shape
3) Slide semi-landmark points along the surface until they satisfy matching criteria with the Procrustes average
4) Repeat steps 3 and 4 until convergence



Bookstein, Fred L. "Landmark methods for forms without landmarks: morphometrics of group differences in outline shape." *Medical image analysis* 1.3 (1997): 225-243.

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Determining position of sliding semi-landmarks

1) **Minimum bending energy criterion:** select semi-landmark positions that result in the smoothest possible transformation to the mean shape

2) **Procrustes distance criterion:** estimate the tangent to the mean surface for each semi-landmark point and remove the component of the difference between the mean and each specimen that lies along this tangent.

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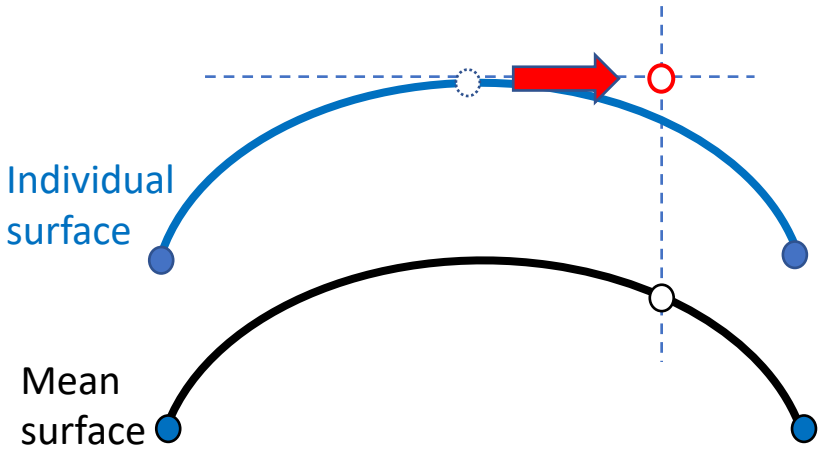
Minimum bending energy criteria



Slide along the surface's tangent structure to the position minimizing the bending energy of the transform between the individual and mean shape.

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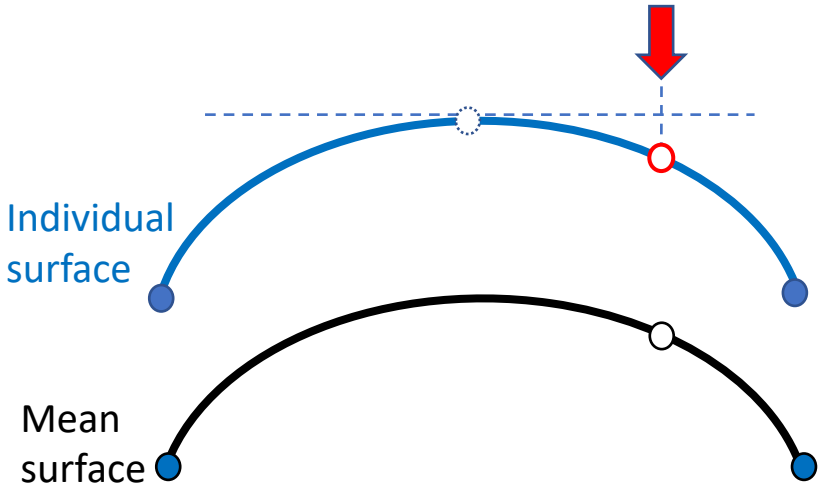
Minimum bending energy criteria



Project the point back to the point back to the surface.

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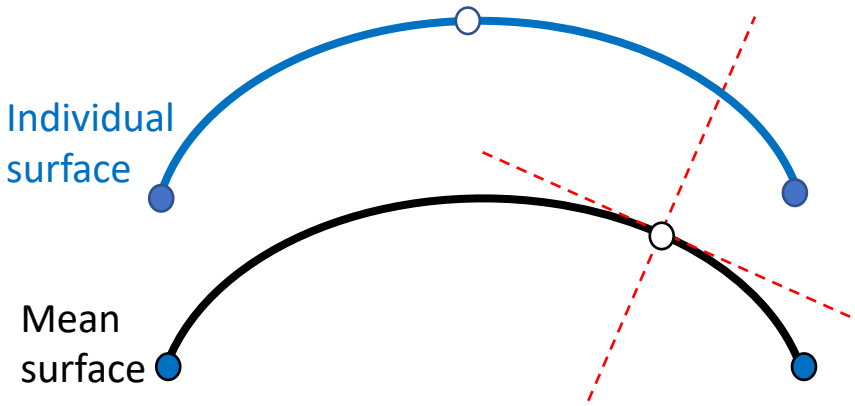
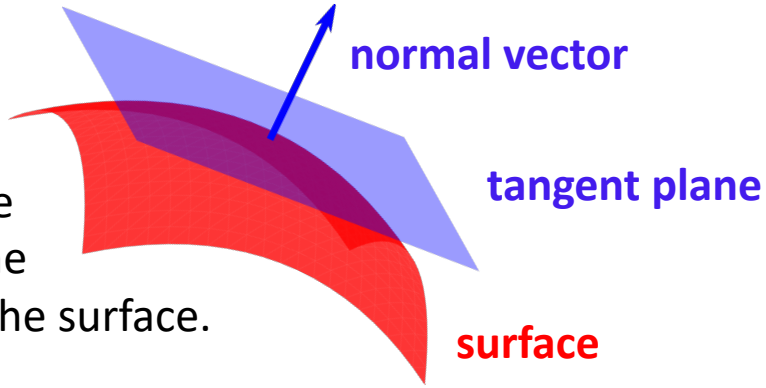
Procrustes distance criteria



Find the normal vector of the reference surface at the landmark point.



A **normal vector** points in the direction perpendicular to the tangent plane at a point on the surface.

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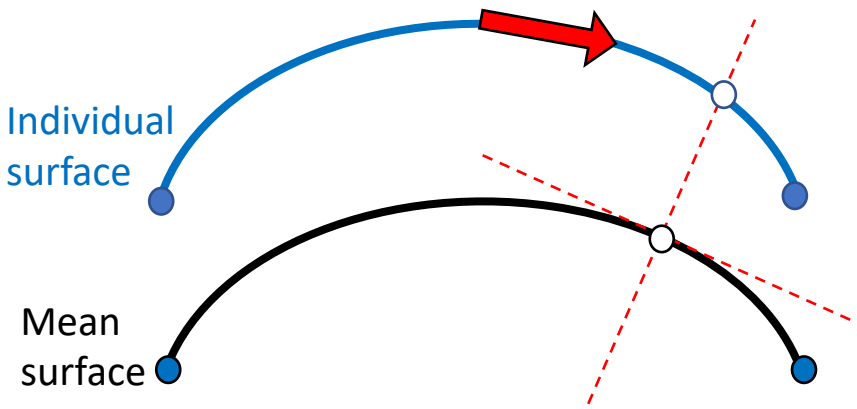
Procrustes distance criteria



Slide the semi-landmark towards the reference surface normal vector.

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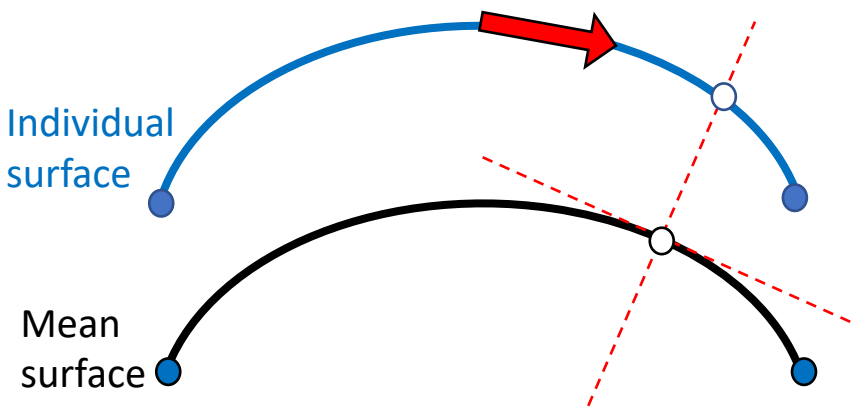
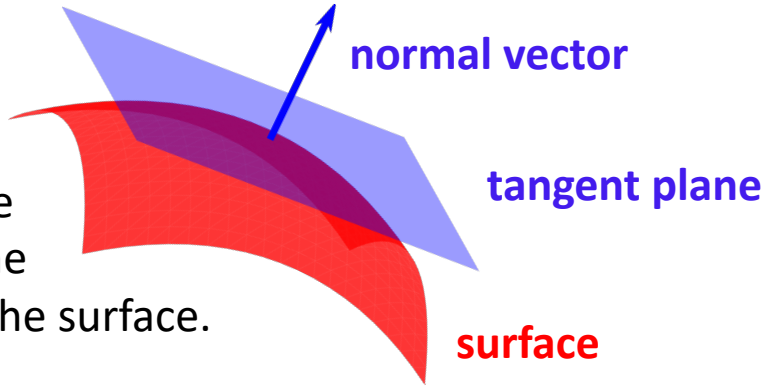
Procrustes distance criteria



Slide the semi-landmark towards the reference surface normal vector.



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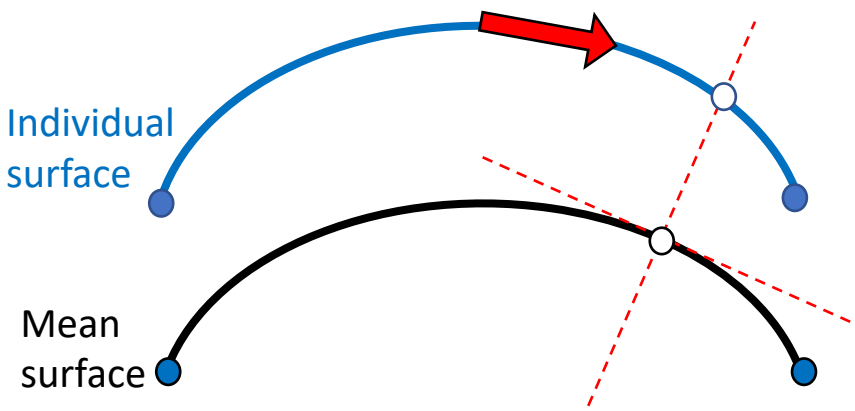
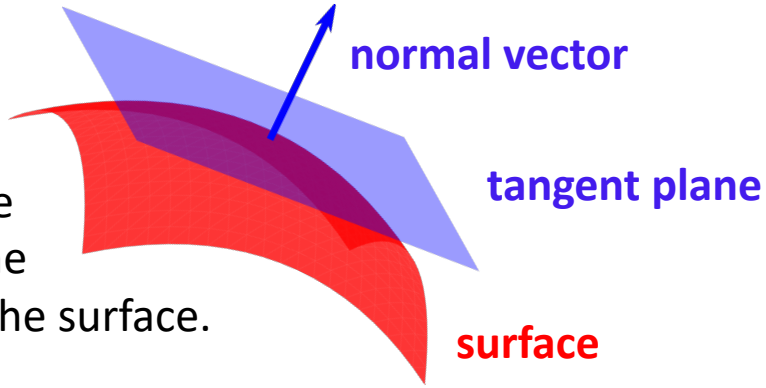
Procrustes distance criteria



Slide the semi-landmark towards the reference surface normal vector.



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Minimum bending energy or Procrustes distance?

- Use different background assumptions
- The difference between the criteria can alter the results when morphological variation in the sample is low
- More noticeable with smaller numbers of semi-landmarks

Perez, S. Ivan, Valeria Bernal, and Paula N. Gonzalez. "Differences between sliding semi-landmark methods in geometric morphometrics, with an application to human craniofacial and dental variation." *Journal of anatomy* 208.6 (2006): 769-784.

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Limitations of semi-landmarks

- Limits to homology
- The method of handling semi-landmarks can influence the results
- The number of semi-landmarks may also influence the results
- Sliding semi-landmark positions are dependent on the dataset. Not possible to compare new shapes without recalculating

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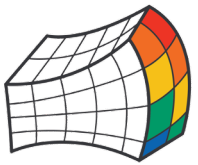
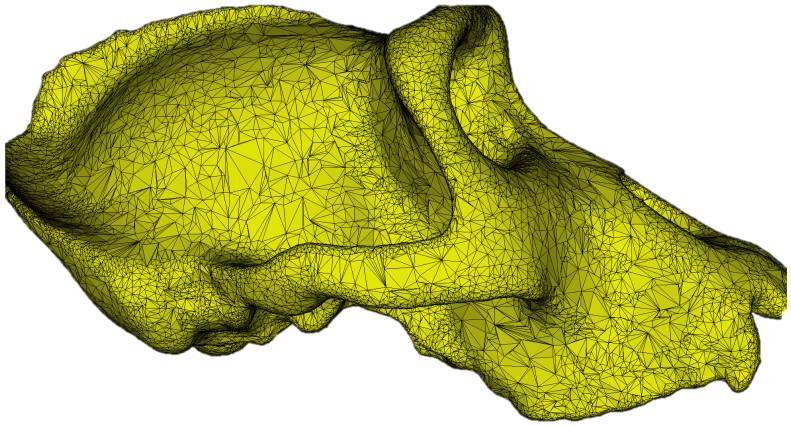
Working with semi-landmarks in 3D

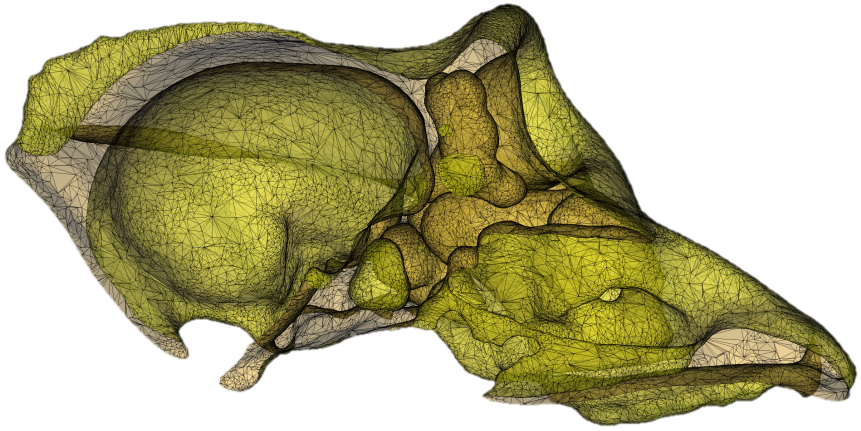


Initial semi-landmark placement

- Generating equally spaced samples on a surface can be surprisingly complex
- SlicerMorph provides flexible tools for generating semi-landmarks and pseudo-landmarks for different data types



Exterior of mesh



Complex internal structures

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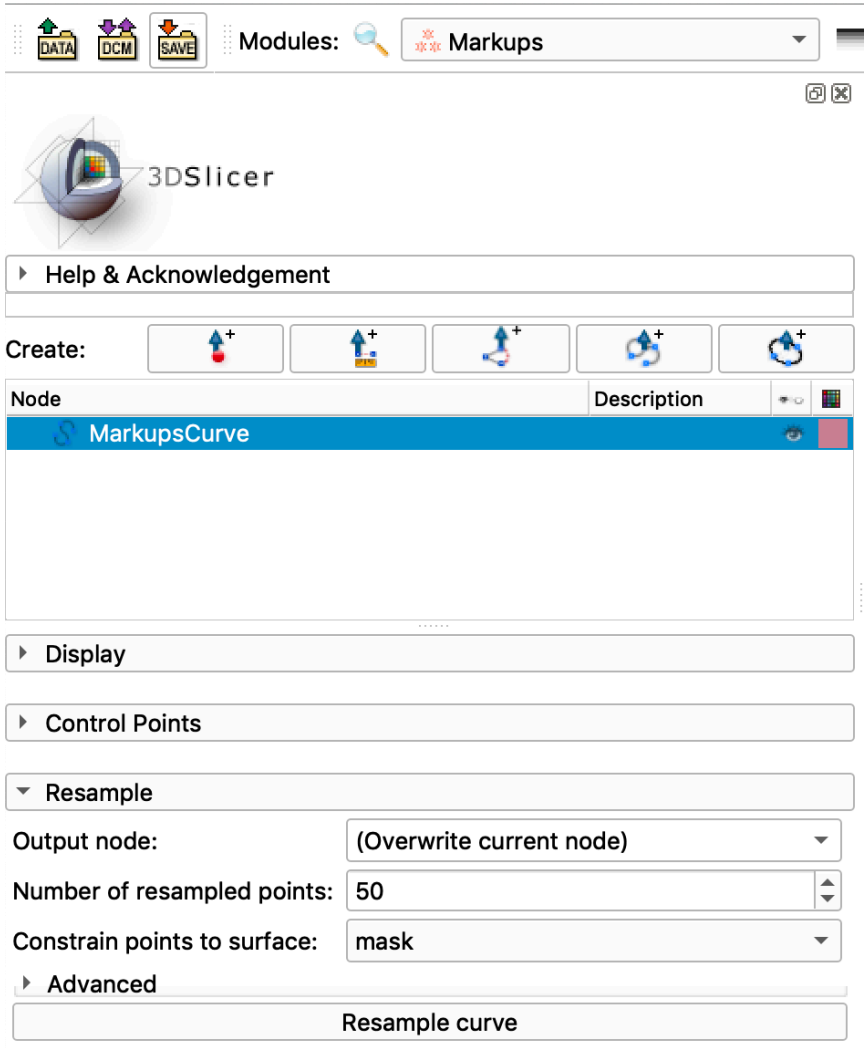
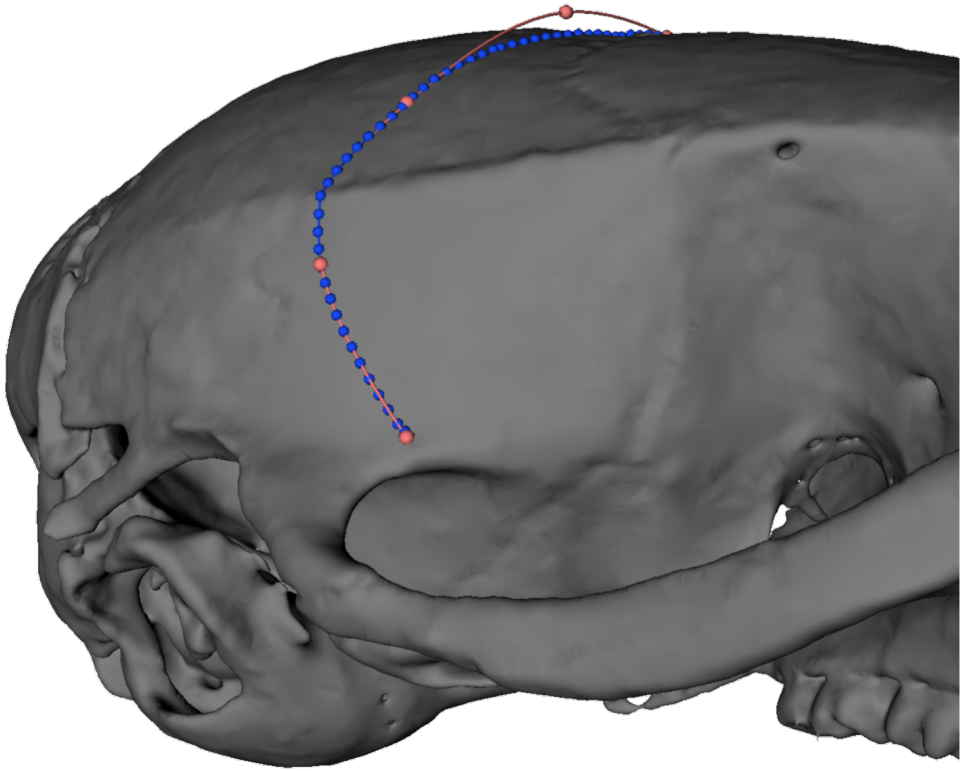
Semi-landmarking: Curves





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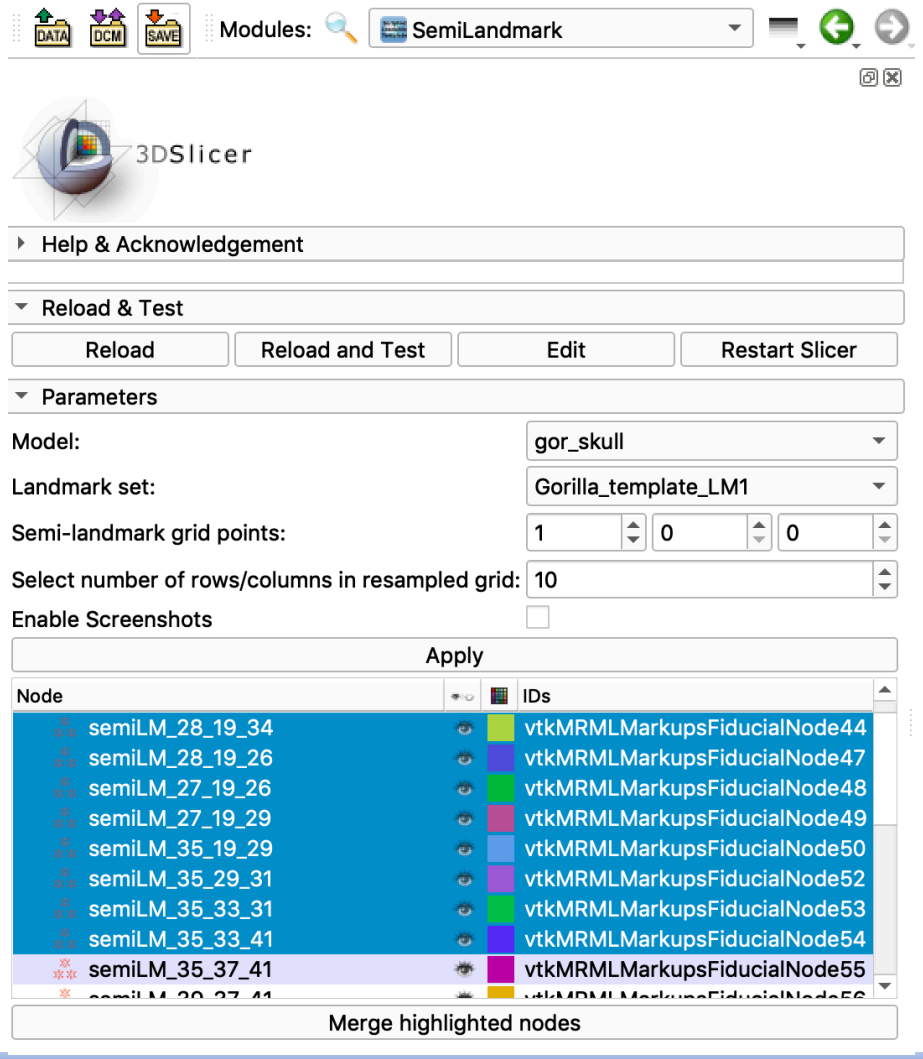
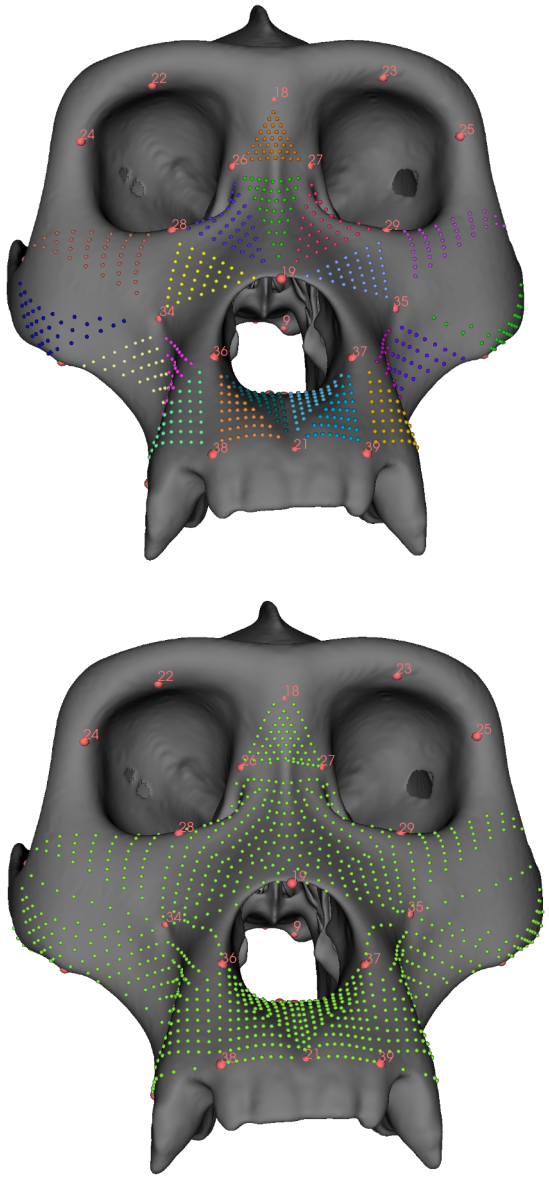
Patch-based placement of semi-landmarks





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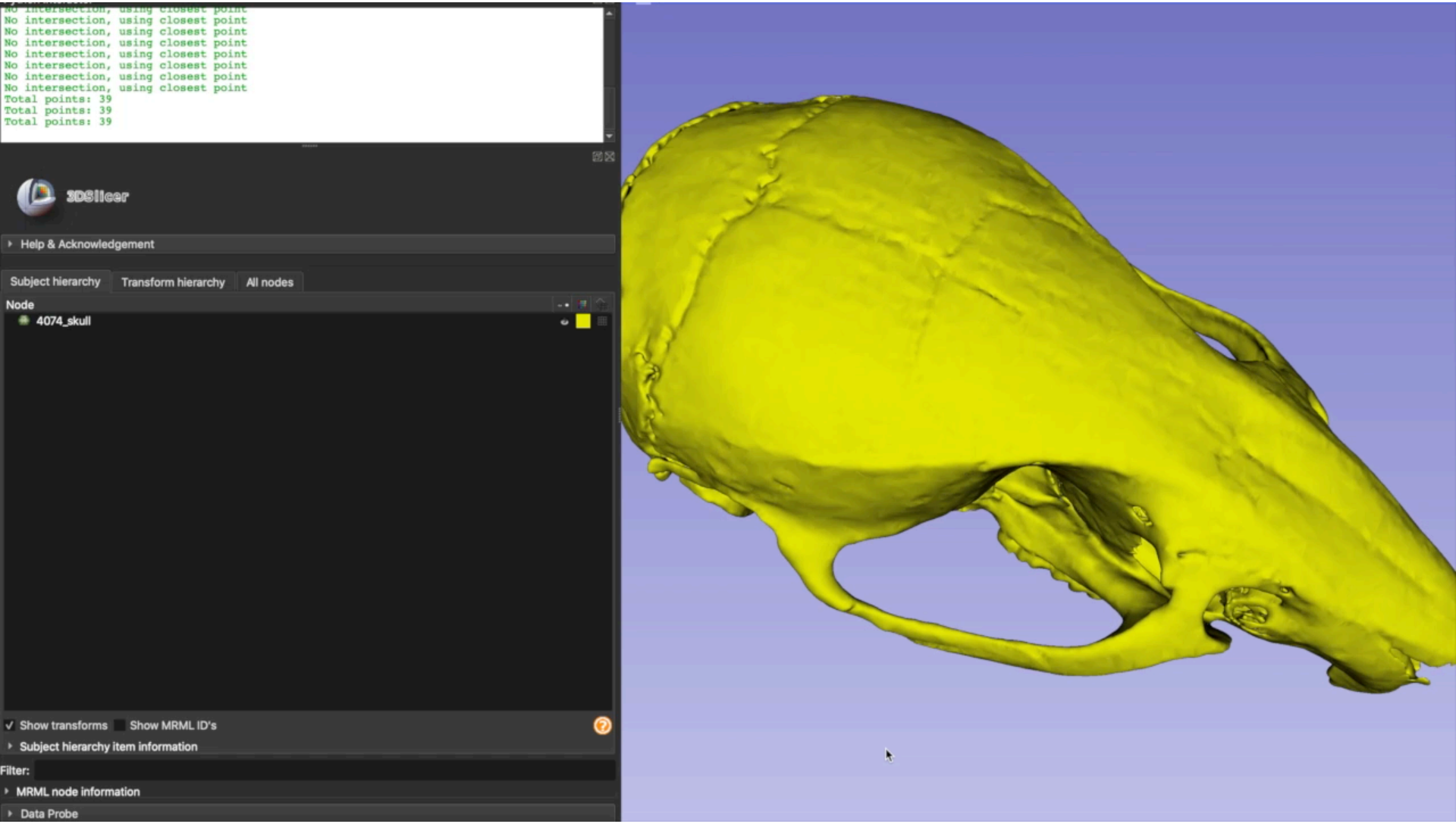
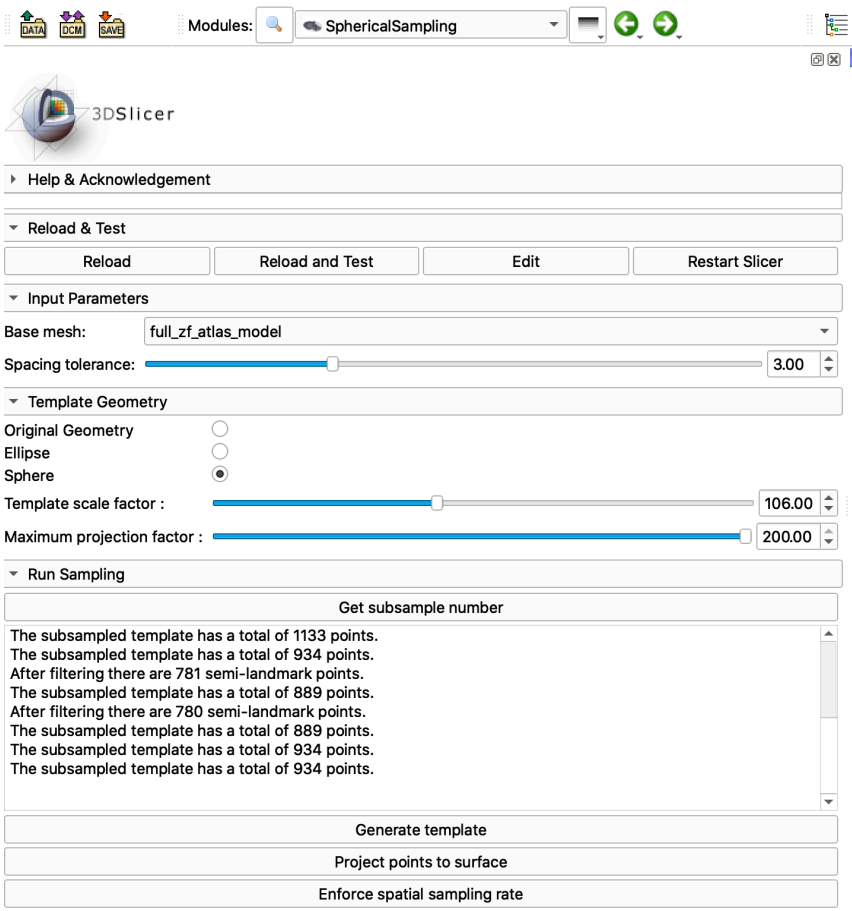
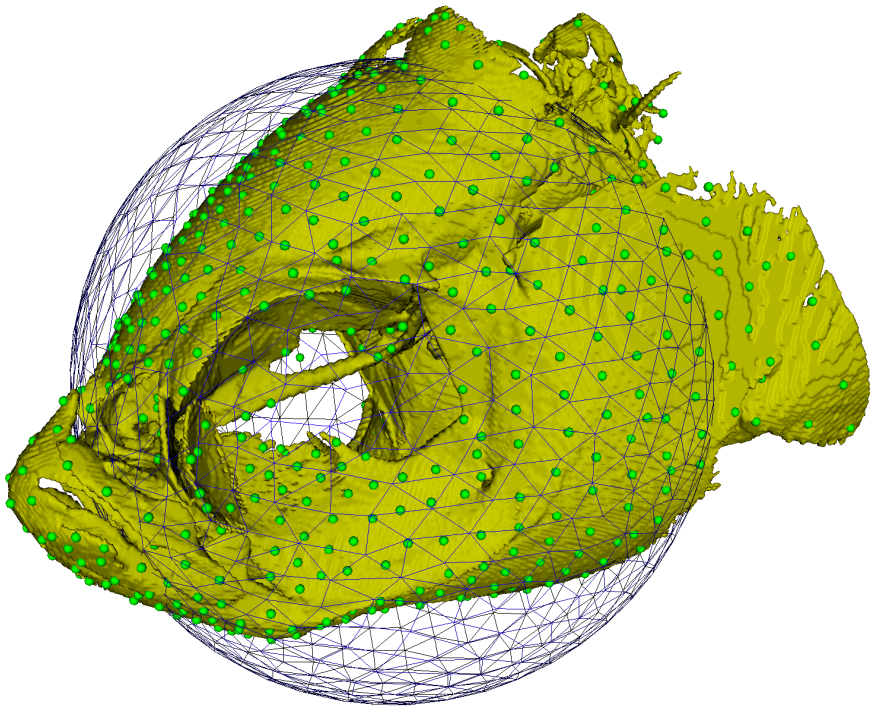
Semi-landmark tools in SlicerMorph



PseudoLMGenerator





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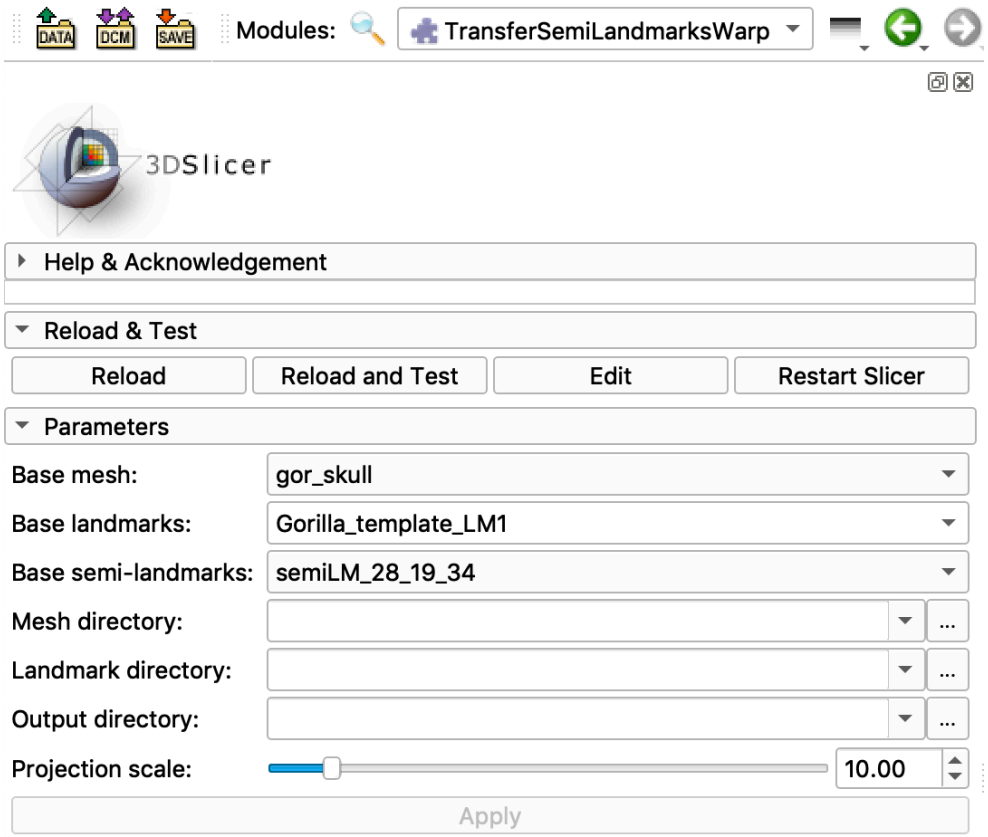
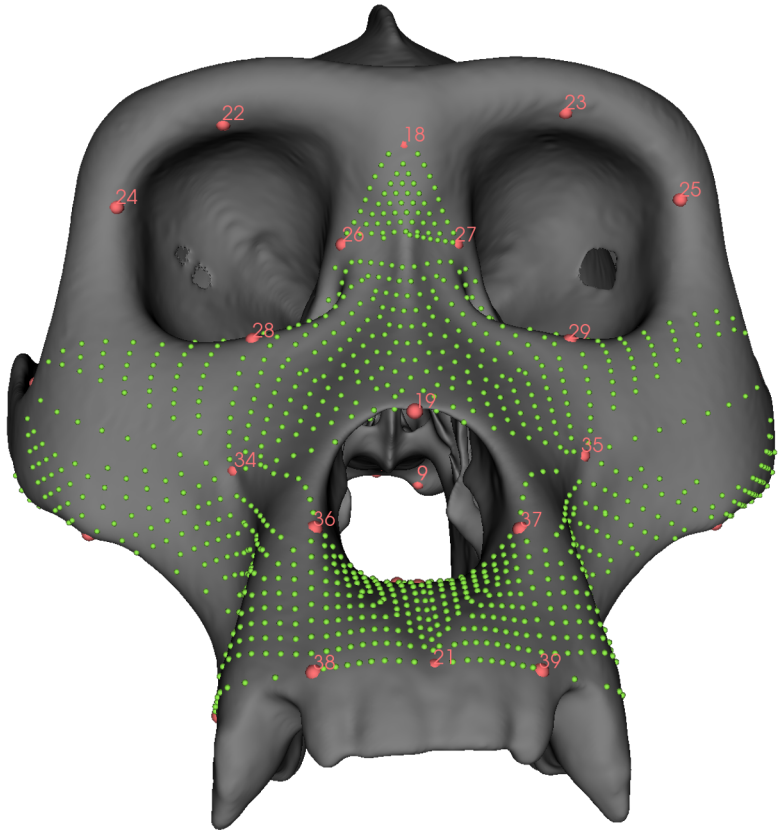
Transferring Semi-landmarks-TPS





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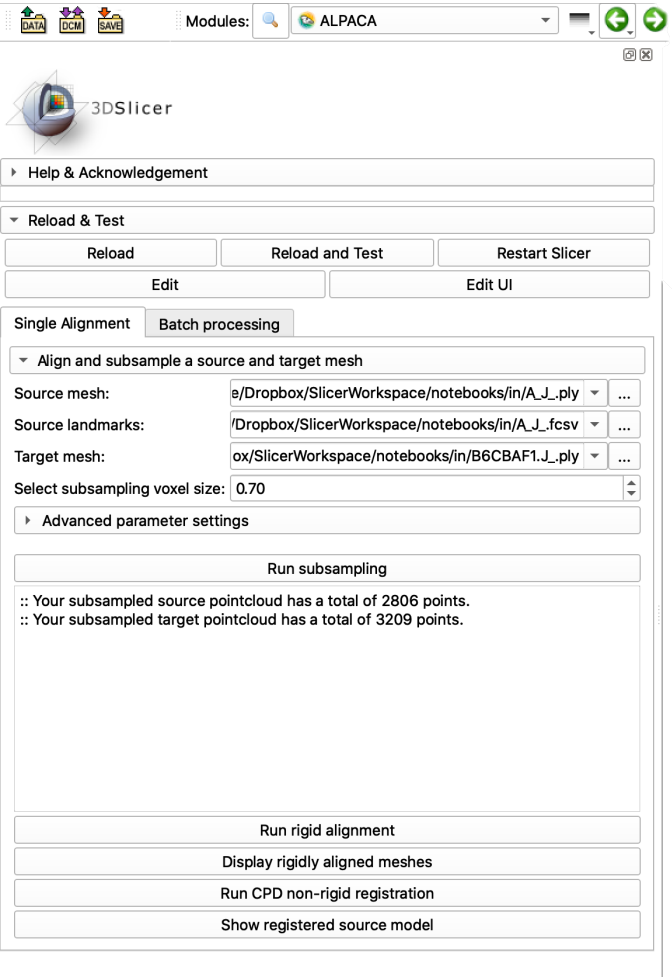
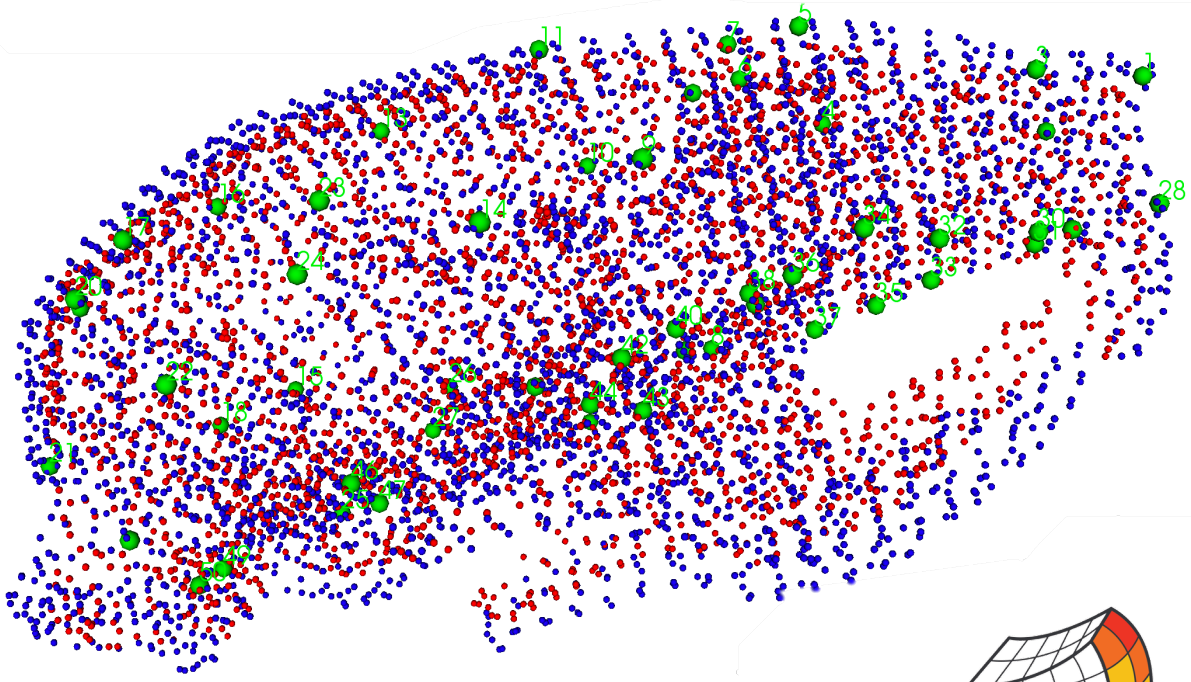
Transferring Landmarks - ALPACA





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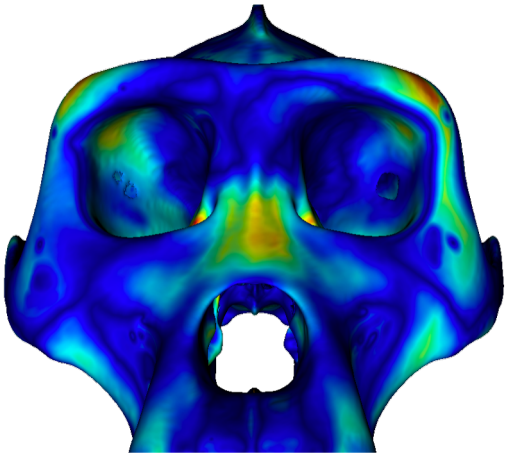
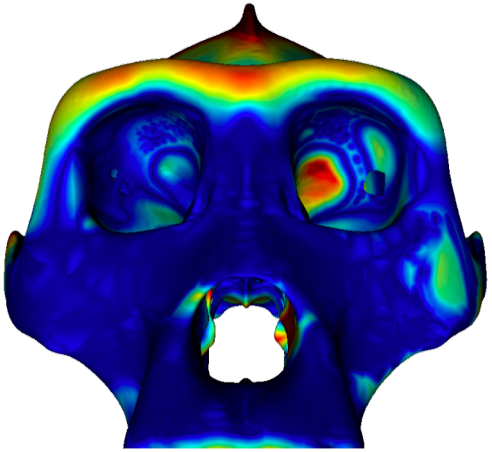
Comparing Semi-landmark methods

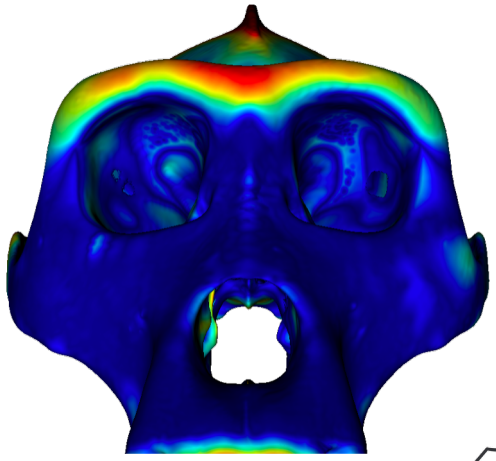
Species	N	Manual landmarks (mm)	Individually placed patch semi-landmarks (mm)	TPS-placed patch semi-landmarks (mm)	Spherical surface sampling (mm)
Gorilla	22	1.267 (SD=0.177)	1.177 (SD=0.162)	1.076 (SD=0.521)	1.124 (SD=0.120)



Manual landmarks only



Individually placed patch semi-landmarks



TPS-placed patch semi-landmarks

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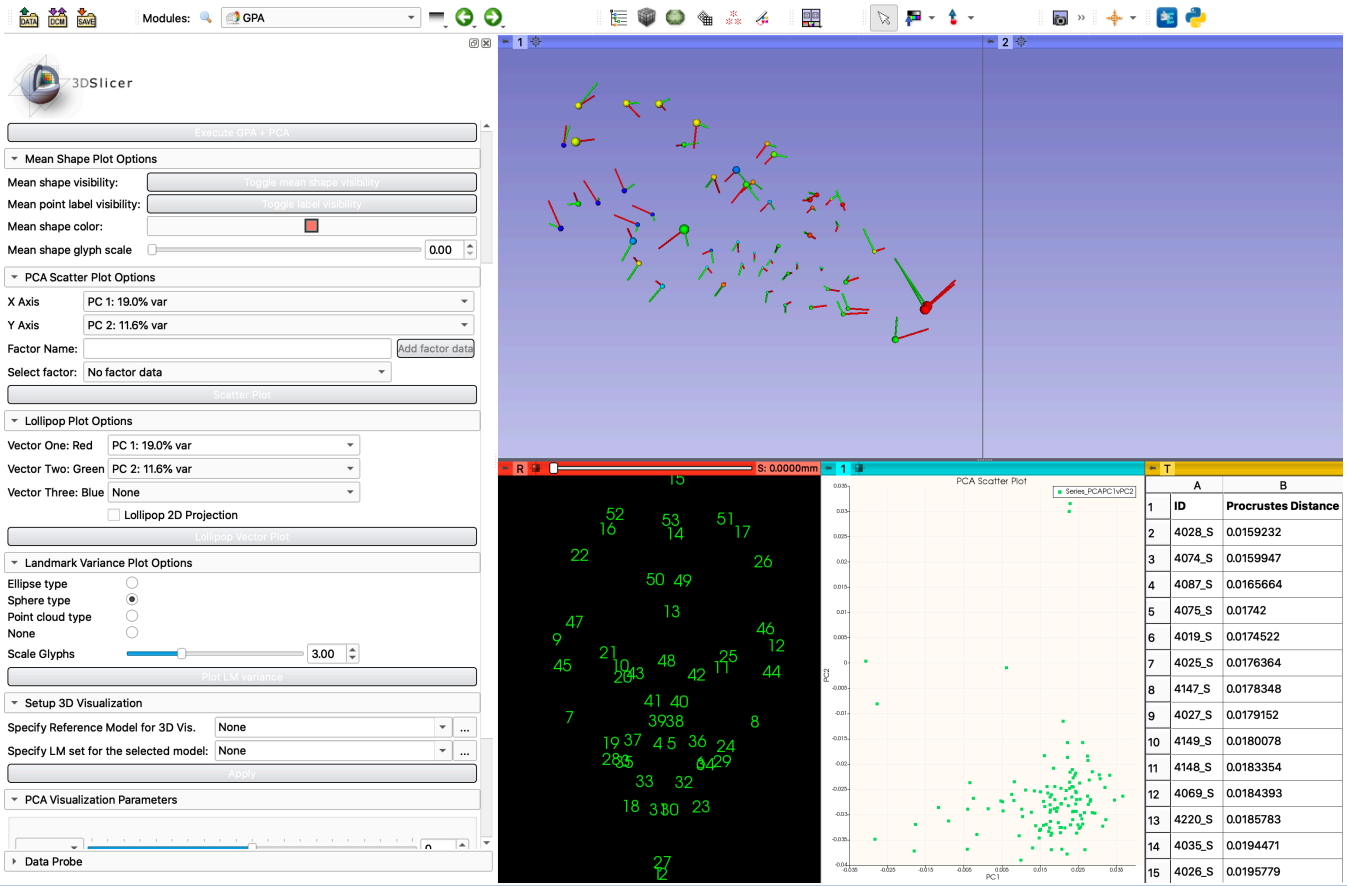
Semi-landmark analysis in SlicerMorph: GPA

The SlicerMorph GPA module supports standard GPA/PCA analysis and visualization



	A	B
1	ID	Procrustes Distance
2	4028_S	0.0159232
3	4074_S	0.0159947
4	4087_S	0.0165664
5	4075_S	0.01742
6	4019_S	0.0174522
7	4025_S	0.0176364
8	4147_S	0.0178348
9	4027_S	0.0179152
10	4149_S	0.0180078
11	4148_S	0.0183354
12	4069_S	0.0184393
13	4220_S	0.0185783
14	4035_S	0.0194471
15	4026_S	0.0195779

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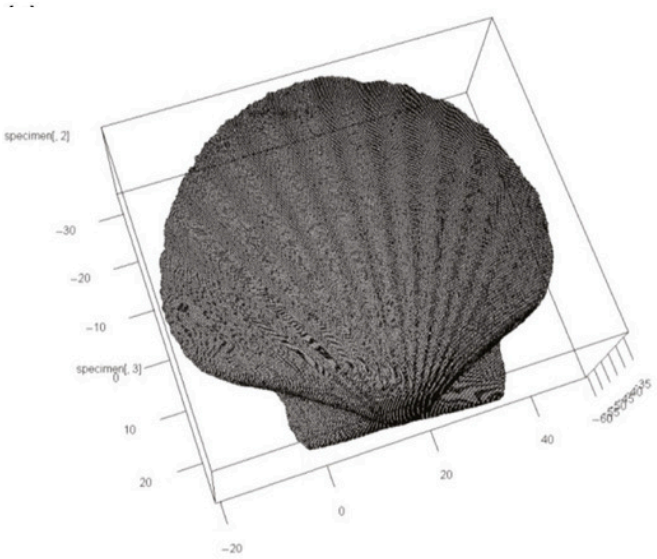
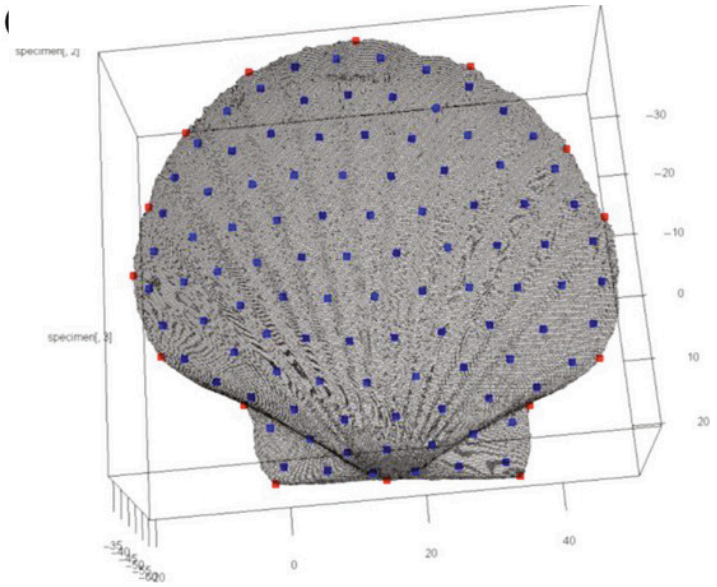
Semi-landmark analysis in R: Morpho and Geomorph

R Toolboxes Morpho and Geomorph for morphometric analysis provide support for transferring, sliding, and analyzing semi-landmarks





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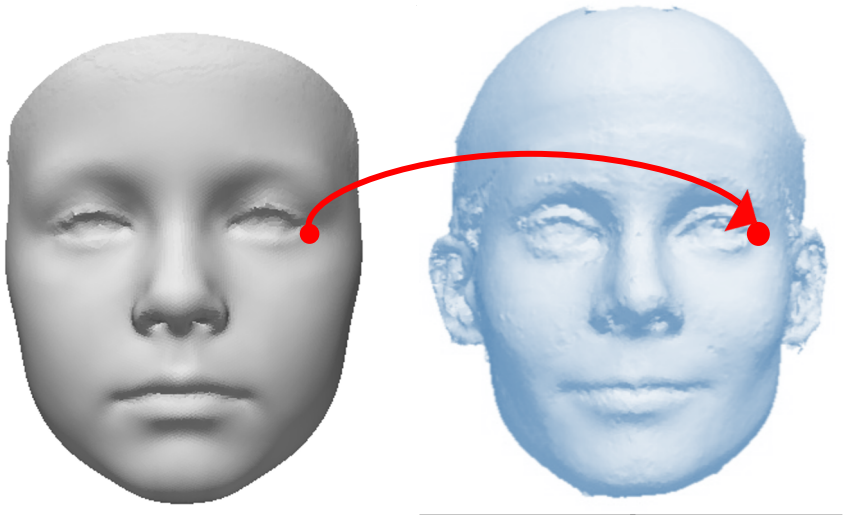
Beyond Semi-Landmarks

Deformation-based morphology (DBM)

- Calculate or select a base mesh
- Establish point correspondences between the base mesh and all meshes in data set
- Vertices of the base mesh define a new set of dense surface landmarks



Base mesh Sample image

Hutton, T. J., Buxton, B. F., Hammond, P. (2001). "Dense surface point distribution models of the human face," in Proceedings IEEE Workshop on Mathematical Methods in Biomedical Image Analysis (MMBIA 2001) (Kauai, HI).

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Limitations of DBM

- No guarantee of homology
- Results need to be interpreted with respect to initial alignment
- High dimensional data output
- Computationally intensive
- Quality of the mapping of the point correspondences between the base mesh and individuals should be assessed

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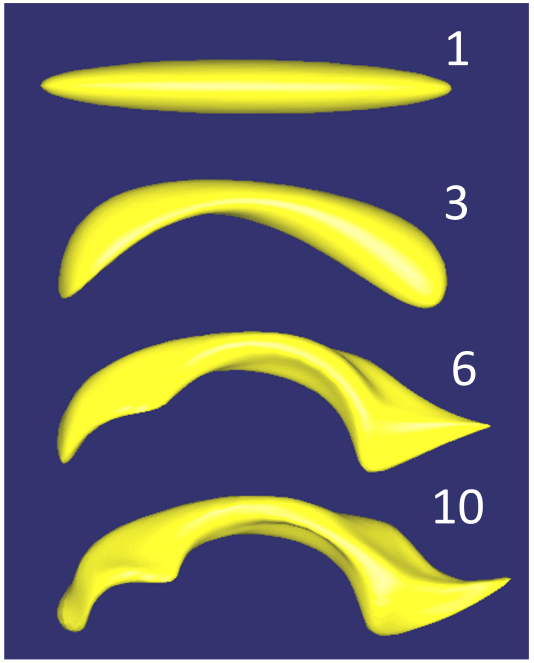
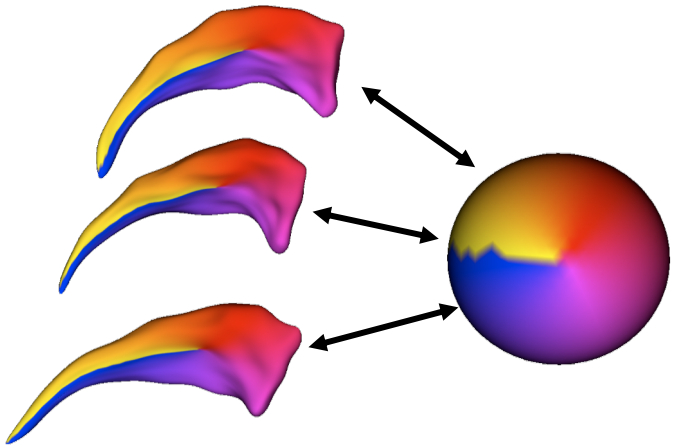
Spherical harmonic representation and point distributed models (SPHARM-PDM)





SPHARM description is computed from the mesh and its spherical parameterization

Styner, Lieberman, Pantazis, Gerig: Boundary and Medial Shape Analysis of the Hippocampus in Schizophrenia, Medical Image Analysis, 2004, pp 197-203

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Limitations of SPHARM methods

- Requirement for spherical topology of meshes
- Challenging for complicated or noisy data sets
- Developed for high N of shapes with similar morphology – should preform a quality assessment to check for correspondence issues

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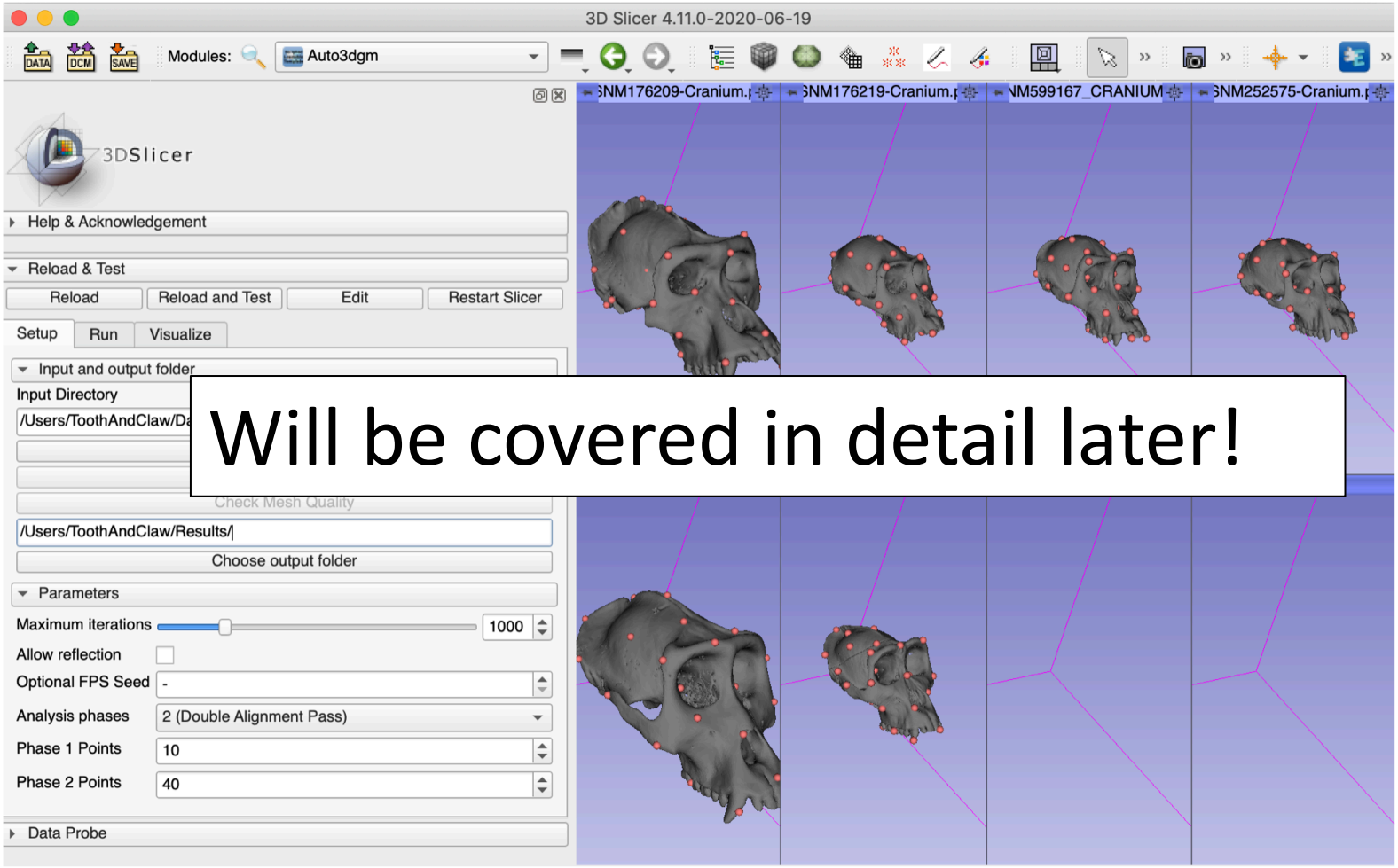
Auto3DGM



Will be covered in detail later!

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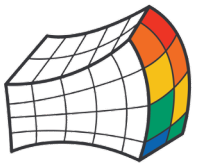
Questions?



Resources

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Watanabe, Akinobu. "How many landmarks are enough to characterize shape and size variation?." PloS one 13.6 (2018): e0198341.

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Bookstein, Fred L., and William DK Green. "A feature space for edgels in images with landmarks." *Journal of Mathematical imaging and vision* 3.3 (1993): 231-261.

Cutting, Court, et al. "A three-dimensional smooth surface analysis of untreated Crouzon's syndrome in the adult." *The Journal of craniofacial surgery* 6.6 (1995): 444-453.

Andresen, Per Rønsholt, and Mads Nielsen. "Non-rigid registration by geometry-constrained diffusion." *Medical Image Analysis* 5.2 (2001): 81-88.

Ekrami, Omid, et al. "Measuring asymmetry from high-density 3D surface scans: An application to human faces." *PloS one*13.12 (2018): e0207895.

Darvann, Tron A., et al. "Automated quantification and analysis of facial asymmetry in children with arthritis in the temporomandibular joint." *2011 IEEE International Symposium on Biomedical Imaging: From Nano to Macro*. IEEE, 2011.

Styner, Lieberman, Pantazis, Gerig: Boundary and Medial Shape Analysis of the Hippocampus in Schizophrenia, Medical Image Analysis, 2004, pp 197-203

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