

Statistical Shape Analysis of Human Infant Skull

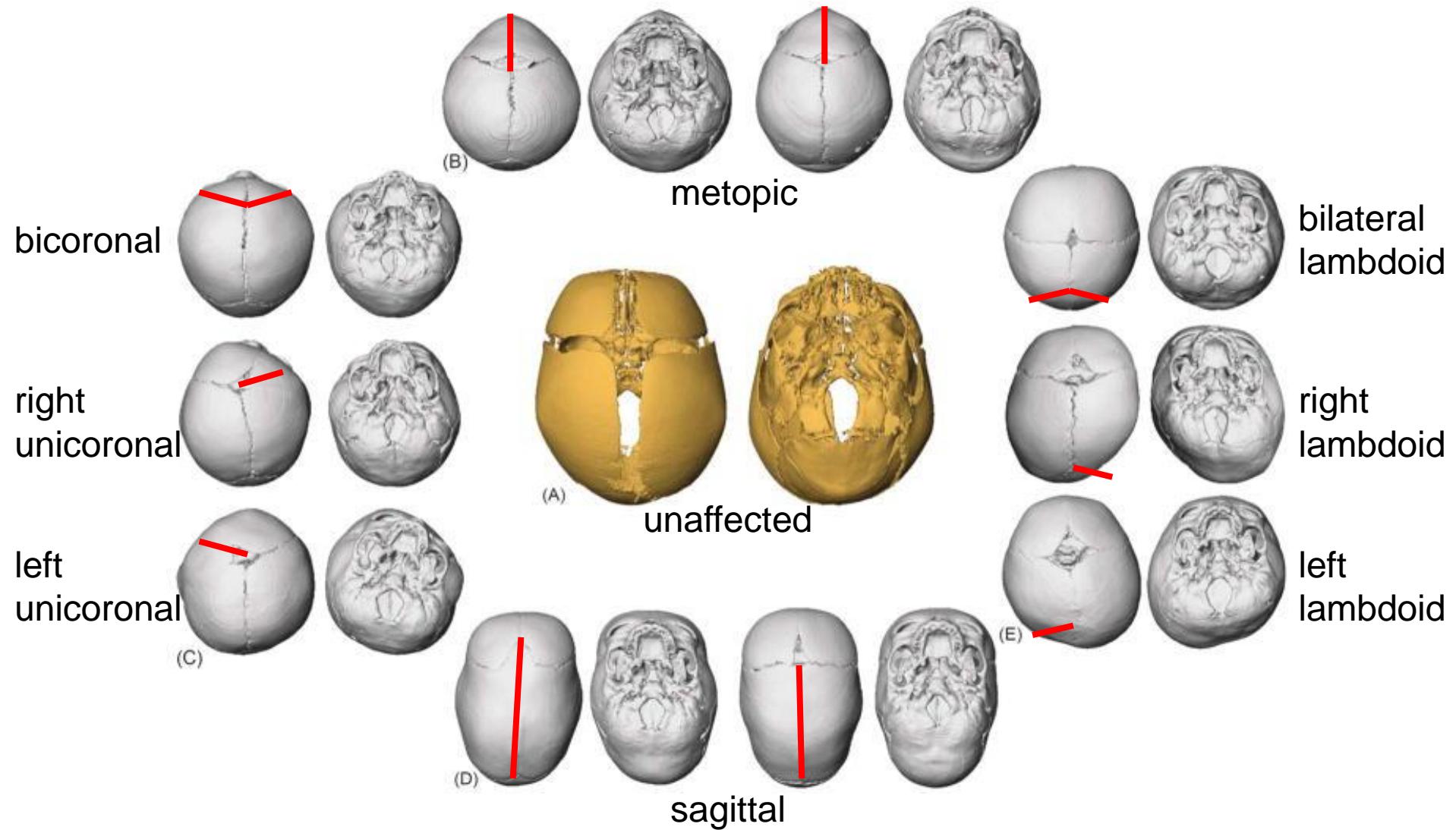
Ezgi Mercan

Murat Maga

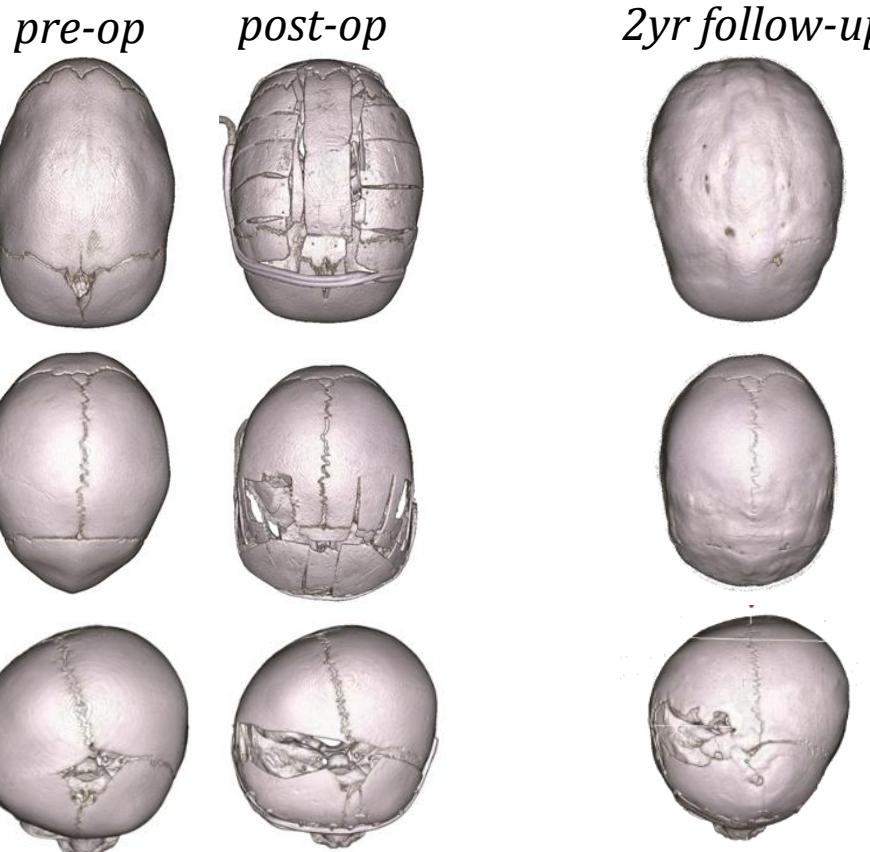
Richard Hopper



Skull Shape in Craniosynostosis: A Complex Phenotype



Cranial Reconstruction

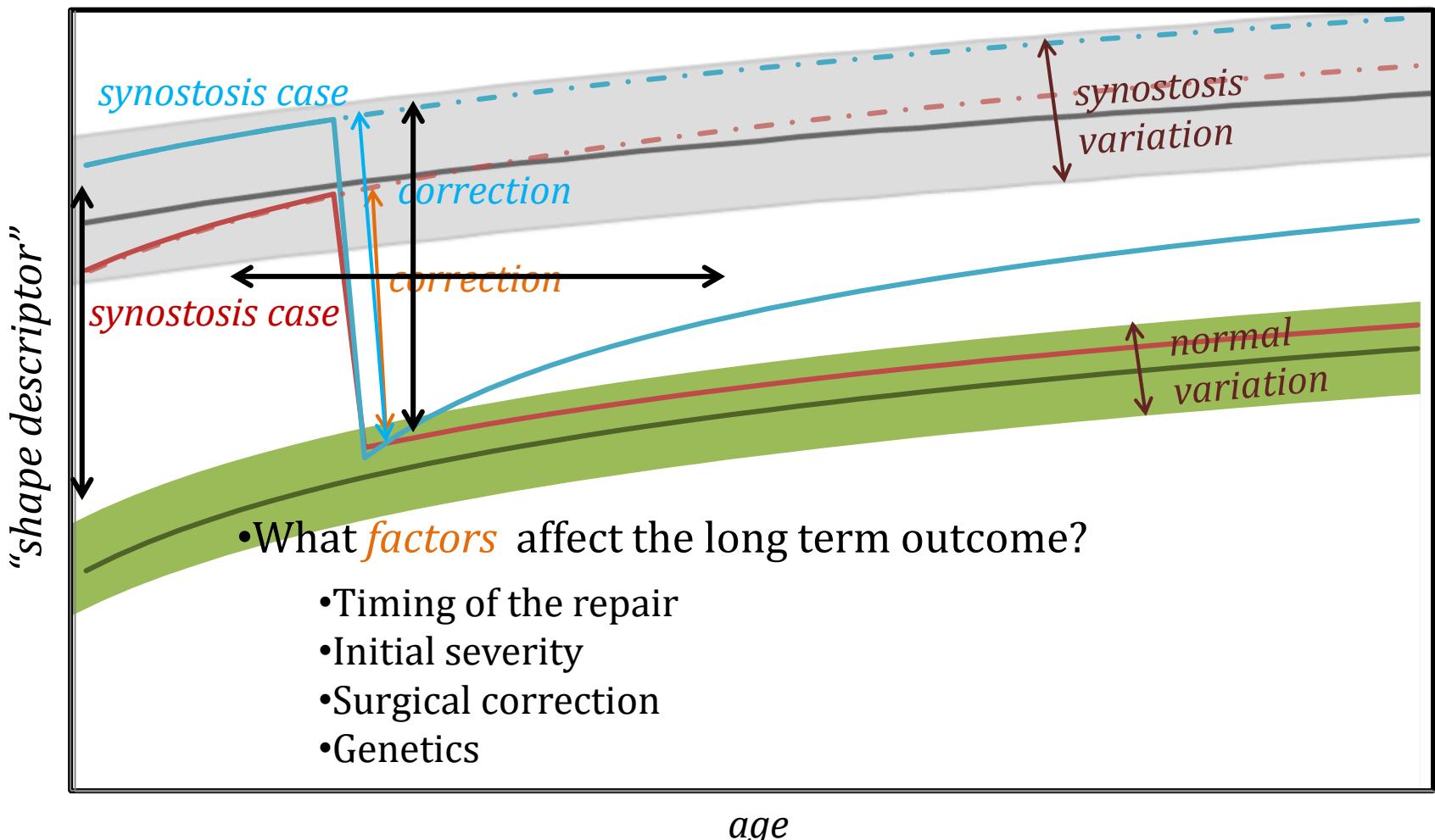


Shape Maintenance

- What *changes* are due to growth ?
- What *factors* affect the long term outcome?
 - Timing of the repair
 - Initial severity
 - Individual characteristics
- How does the skull *grow* in different diagnoses?

Goal: minimal surgical intervention

Hypothetical Growth



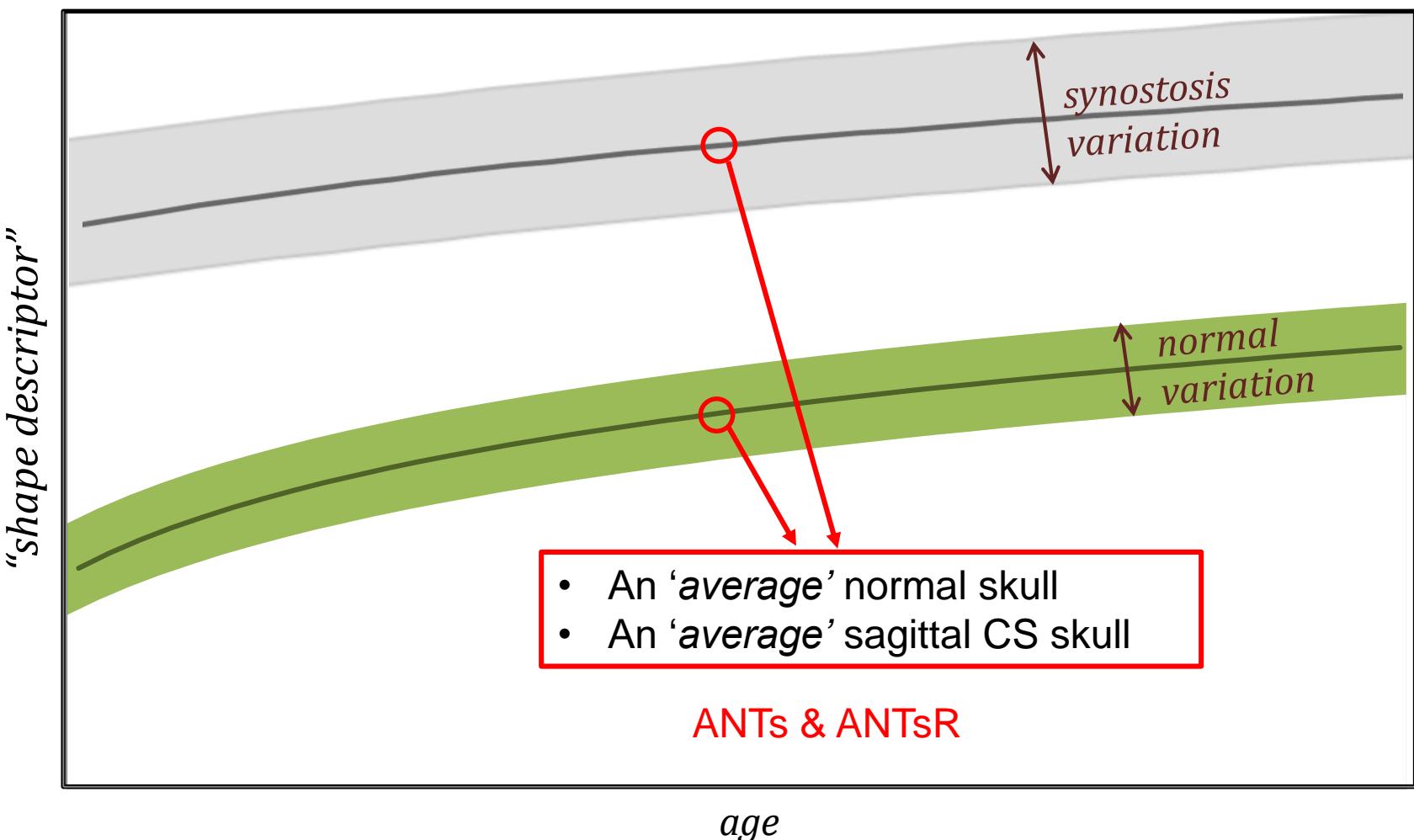
Outline

Template Building

Growth Modeling

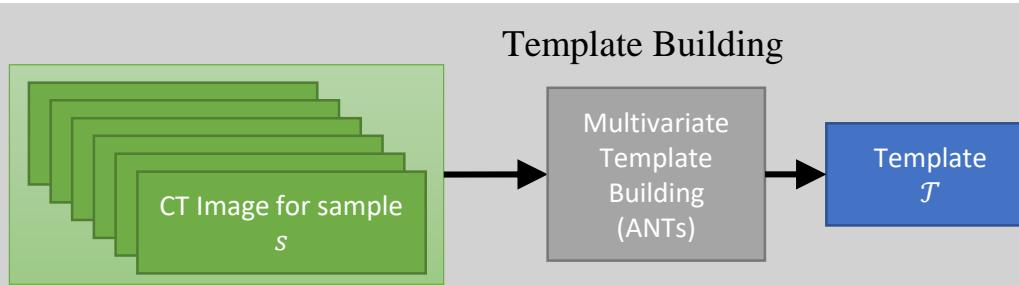
Suture Closure Analysis

Hypothetical Growth



- Avants BB, Tustison NJ, Song G, Gee JC (2009) ANTs: open-source tools for normalization and neuroanatomy, *TransacMed Imagins Penn Image Comput Sci Lab*.
- Avants BB, Tustison NJ, Song G, Cook PA, Klein A, Gee JC (2011) A reproducible evaluation of ANTs similarity metric performance in brain image registration, *Neuroimage* 54(3), 2033-2044.

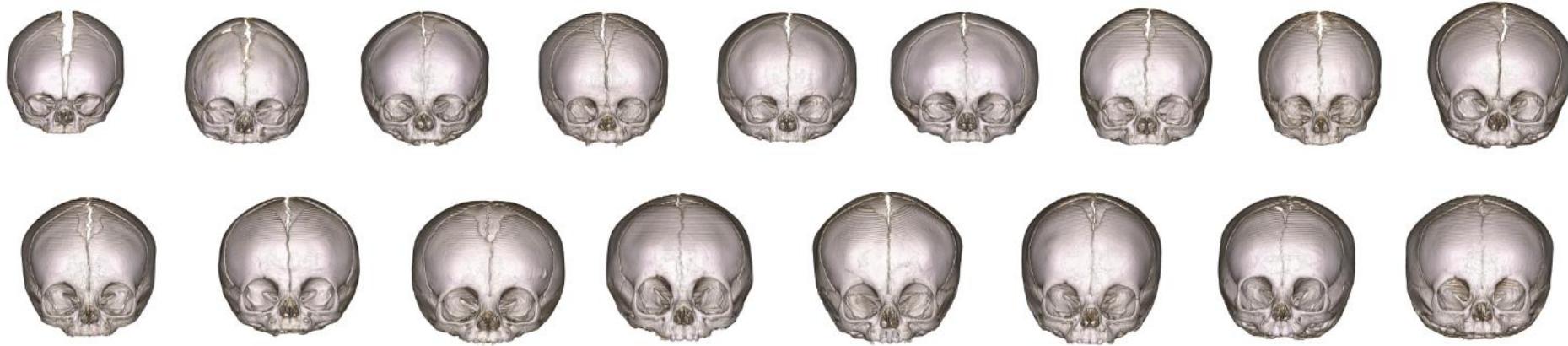
Outline



Growth Modeling

Suture Closure Analysis

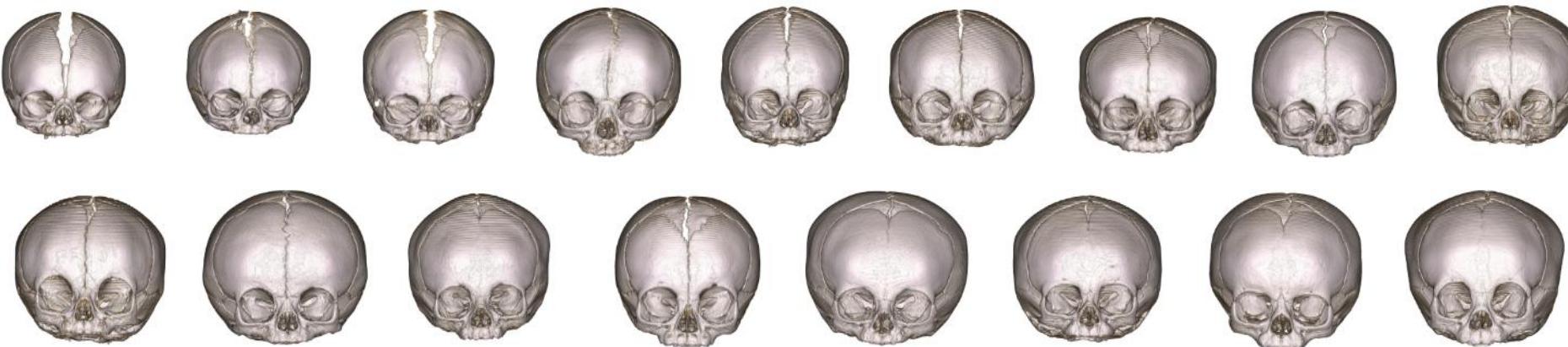
Data



N = 34 normal samples (17 male and 17 female)

N = 81 sagittal CS samples (62 male and 19 female)

0-6 months old



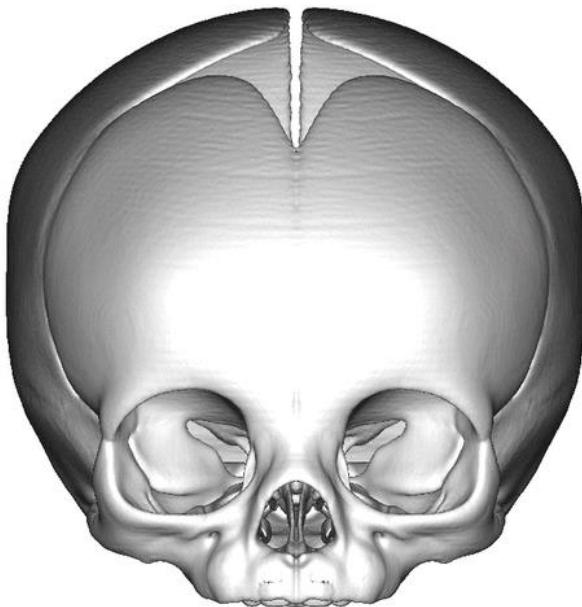
Pre-processing

1 Ⓛ

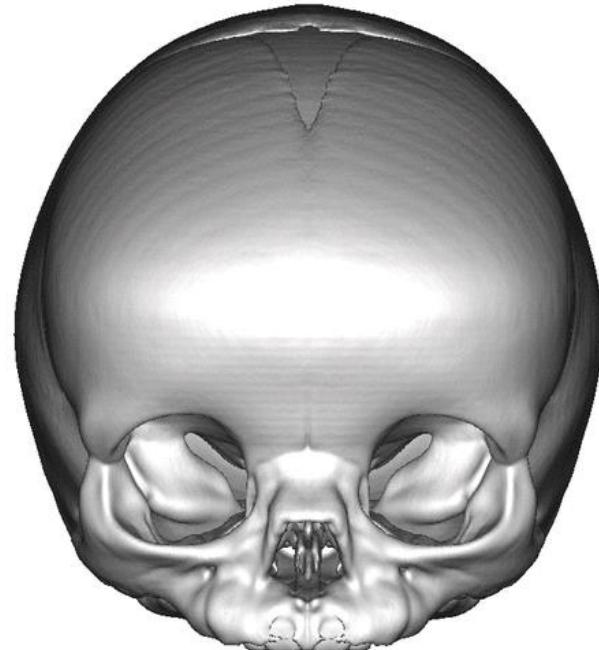


Population Templates

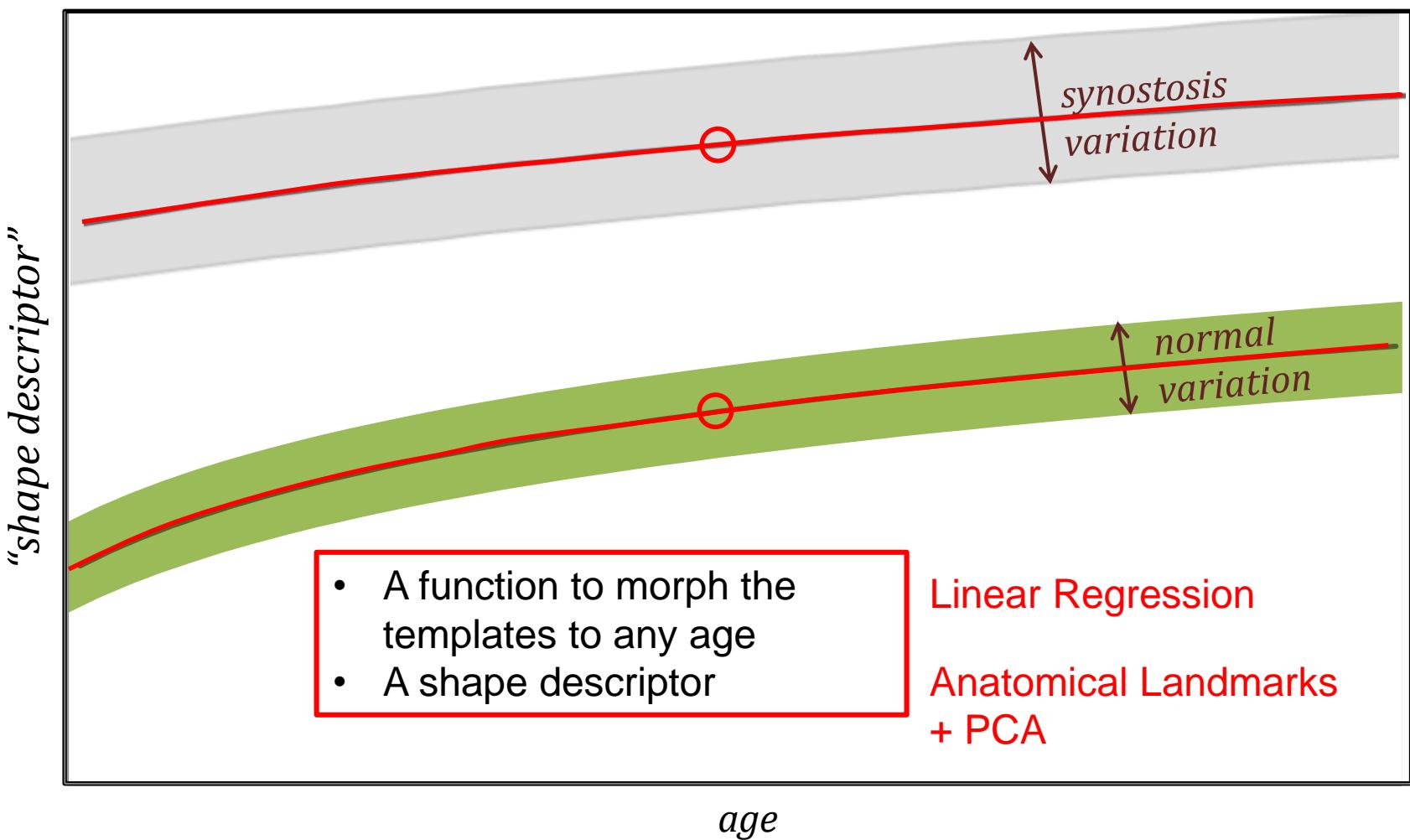
Normal Infant Template



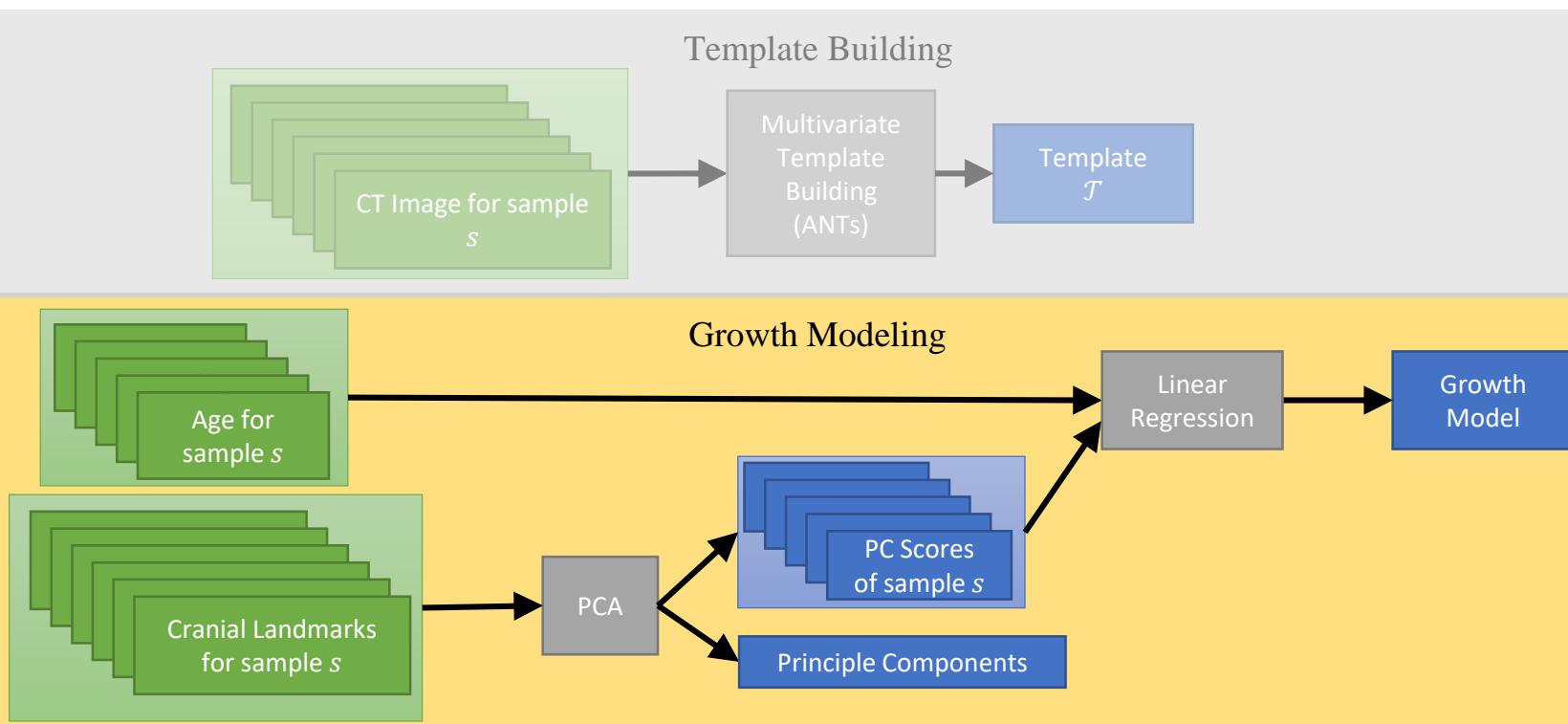
Sagittal CS Template



Hypothetical Growth

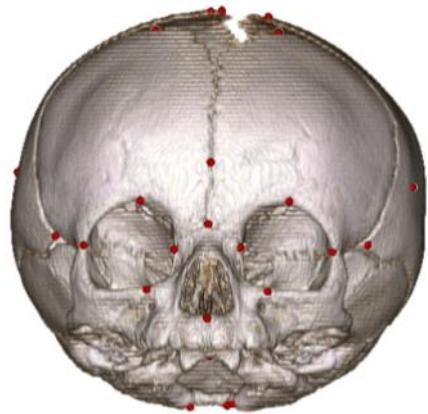
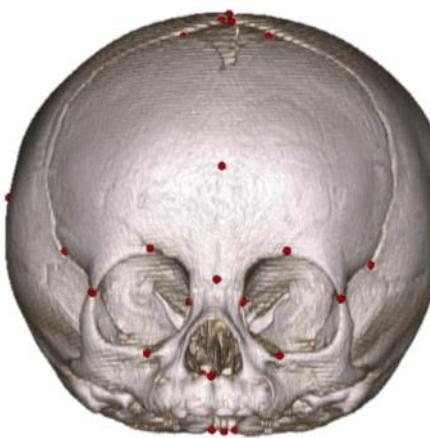
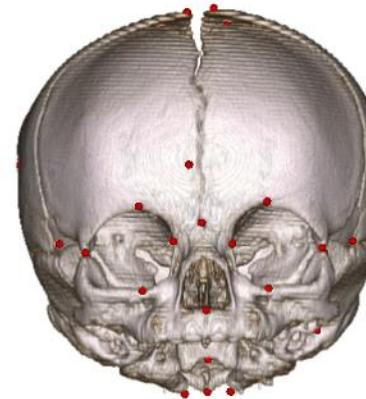
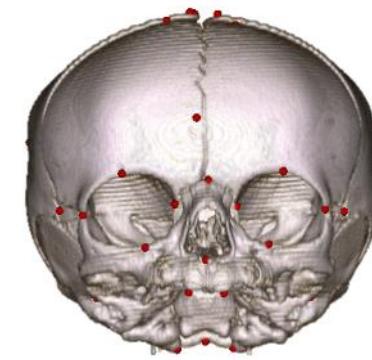


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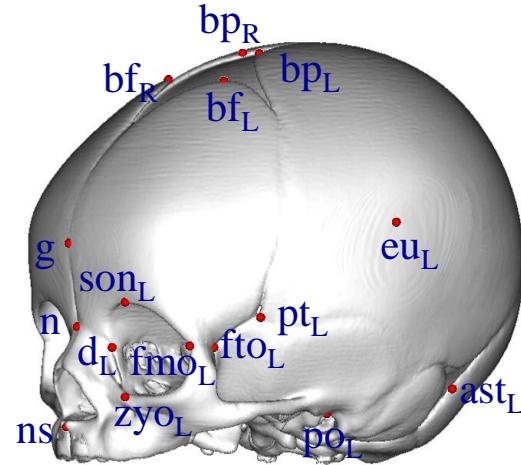
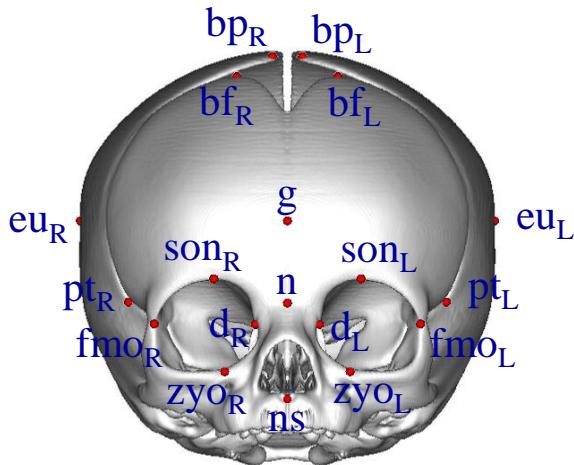
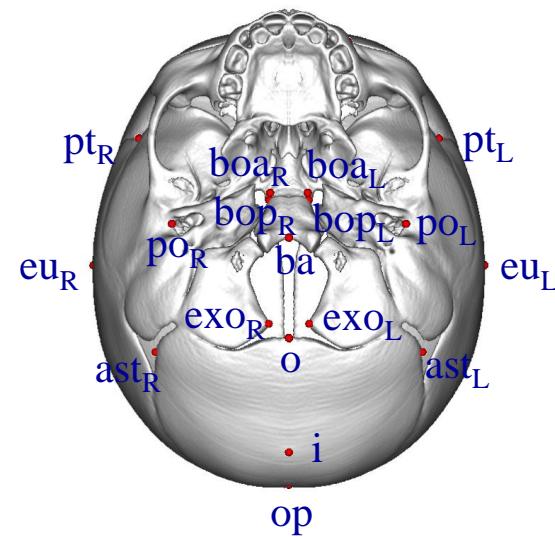
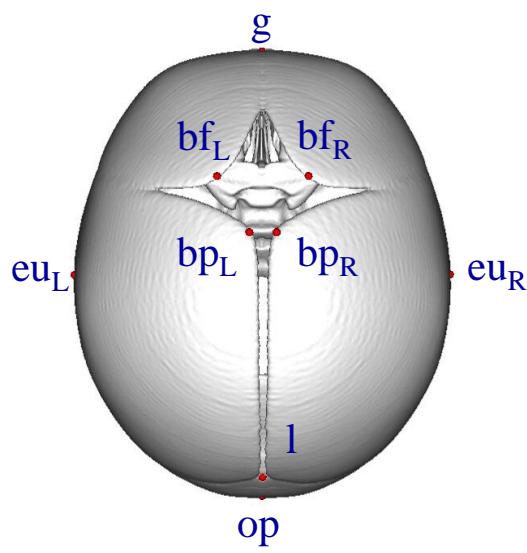


Suture Closure Analysis

Growth Modeling

 age_1  age_2  age_3  age_4

Landmarks



Growth Modeling

landmark.position ~ age + error

- We have 38 3D landmarks = $38 \times 3 = 114$ linear regression models.
- Landmark positions are not independent from each other.
- PCA

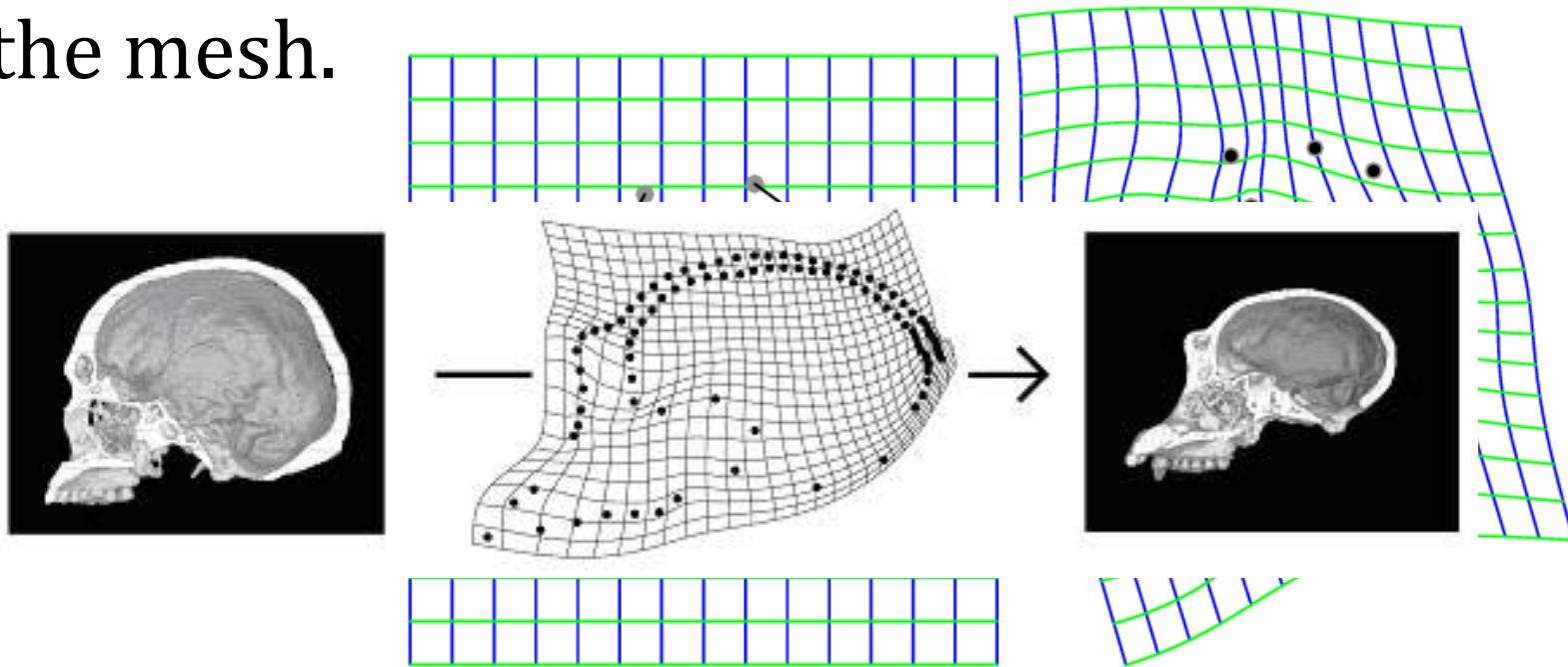
Growth Modeling

PC. scores ~ age + error

- PCA is also helpful with dimensionality reduction and noise removal.
- First 20 PCs explained 90% of the variation.
- 114 => 20
- Each PC is a linear combination of all landmarks.

Thin Plate Splines

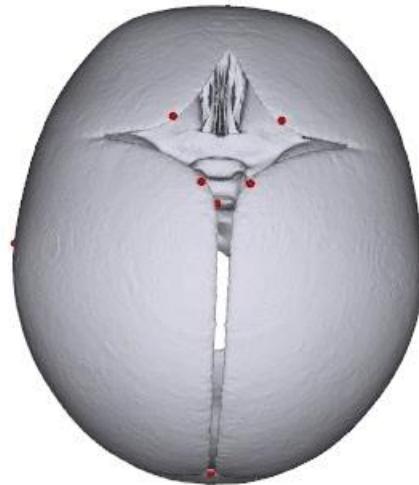
- It is an interpolation and smoothing technique.
- Using predicted landmark points, we *warp* the mesh.



- Bookstein, FL (1989) Principal Warps: Thin-Plate Splines and the Decomposition of Deformations, *IEEE Transactions on Pattern Analysis and Machine Intelligence* 11(6), 567-585.

Growth Models

Normal Infant Template



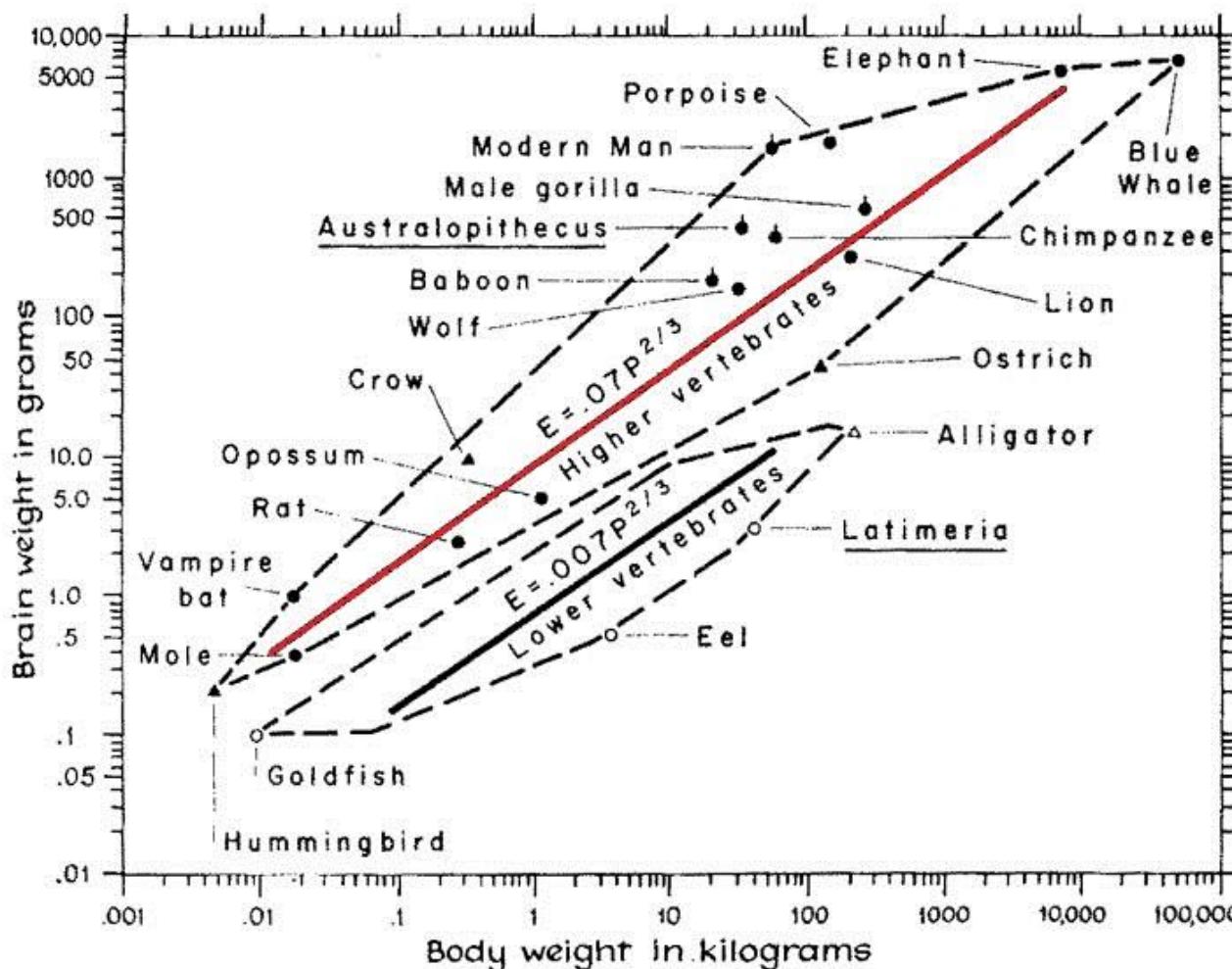
Sagittal CS Template



Allometry

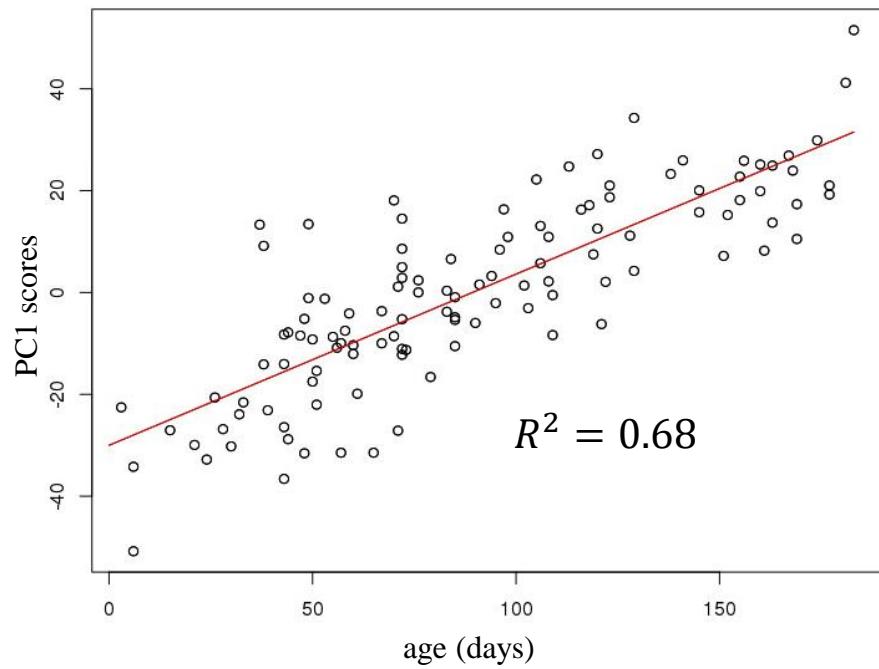
- The relationship between *size* and *shape*
- Should we remove PC1?
- Infant skull doubles in size by the first 6 months.
- Size is part of the variable (*growth*) we are interested in.

Allometry

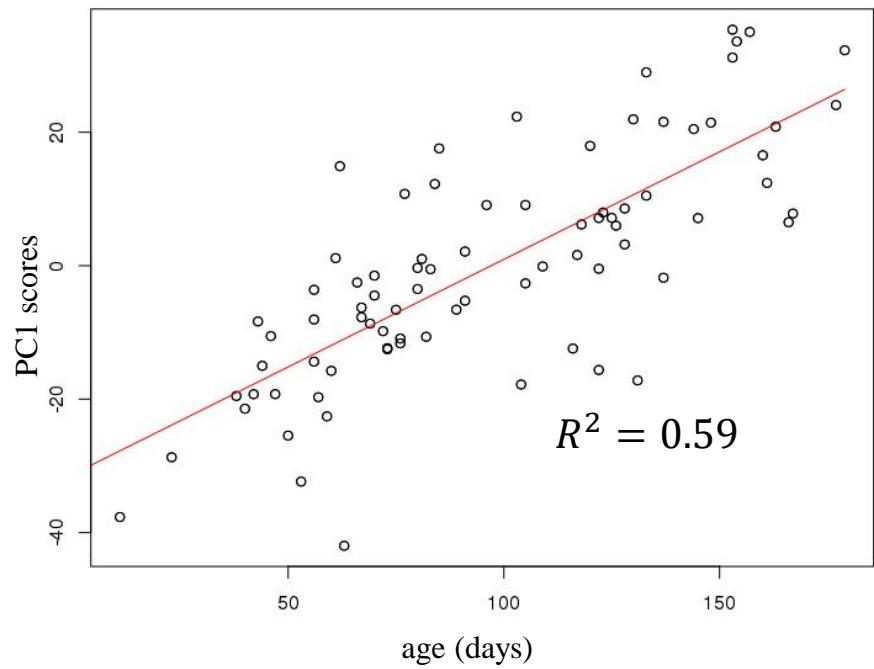


Dominant Shape Changes: PC1

Normal Control Cohort

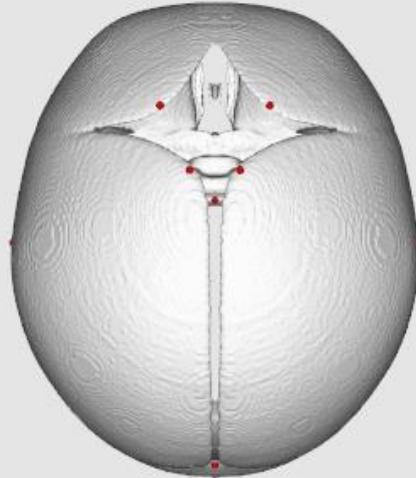


Sagittal Synostosis Cohort

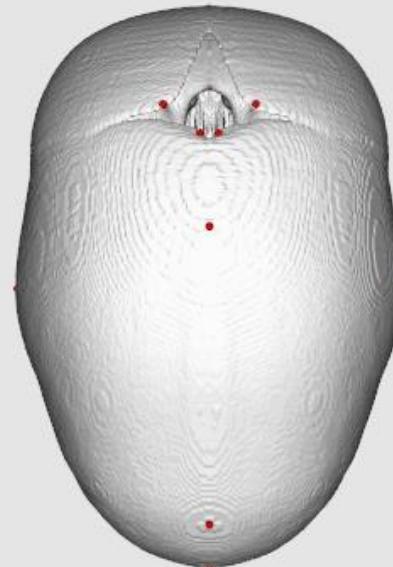


Dominant Shape Changes: PC1

Normal Infant Template

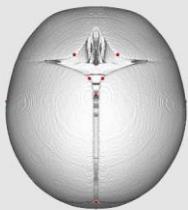
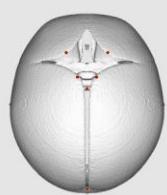


Sagittal CS Template



First 5 PCs

Normal Infant Template



PC1

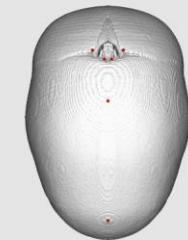
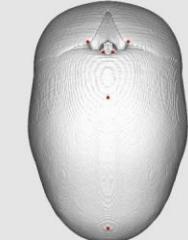
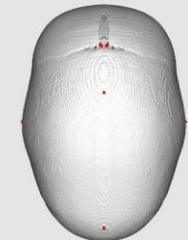
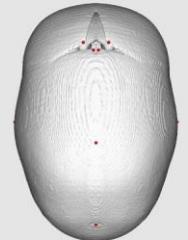
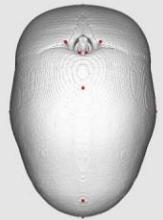
PC2

PC3

PC4

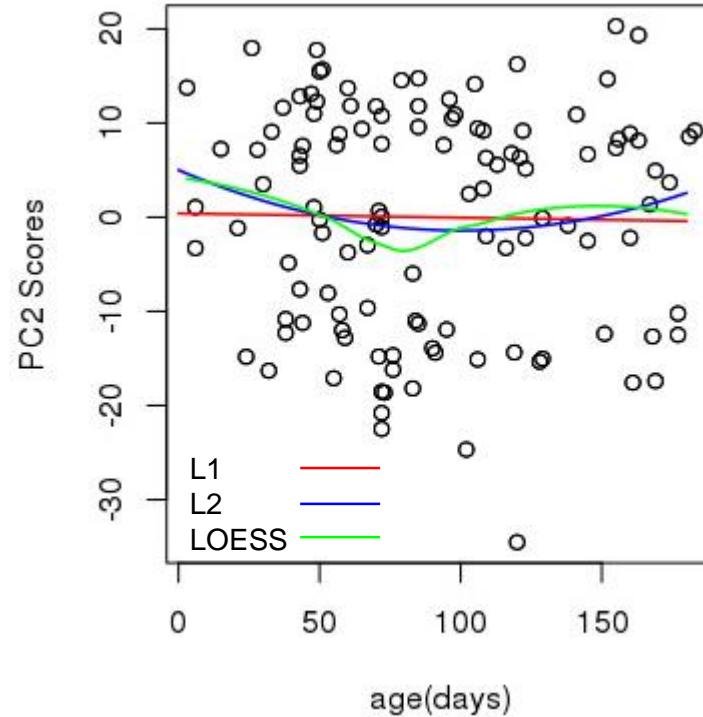
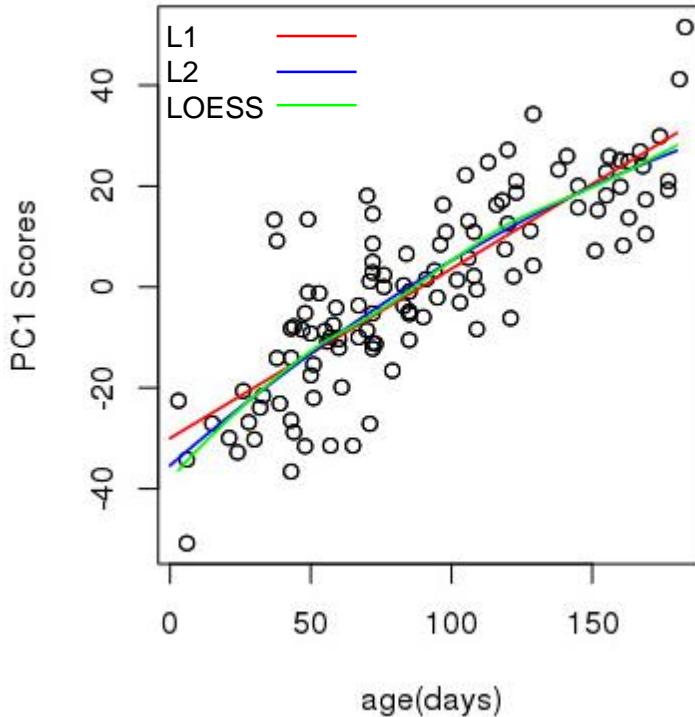
PC5

Sagittal CS Template

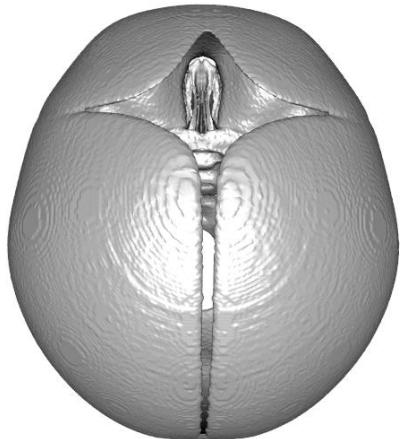
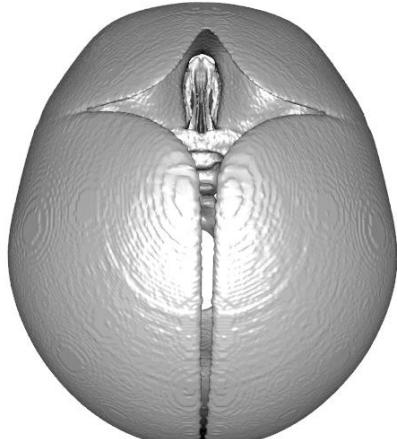
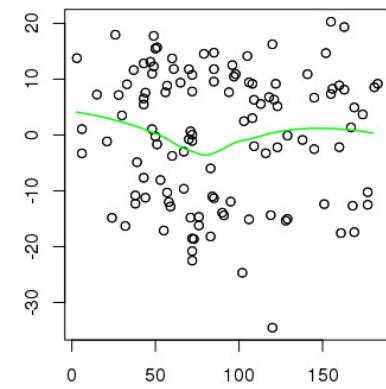
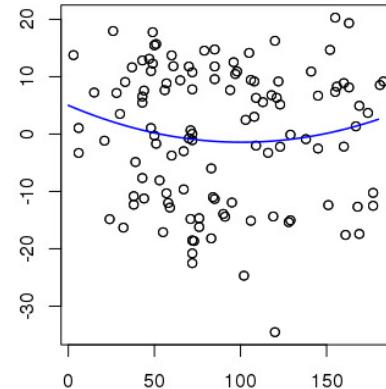
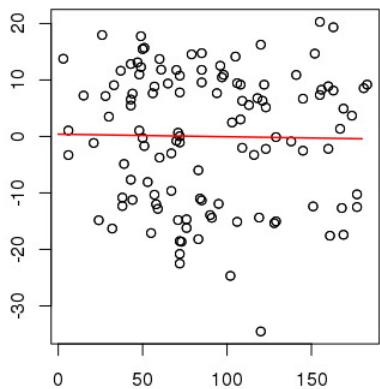
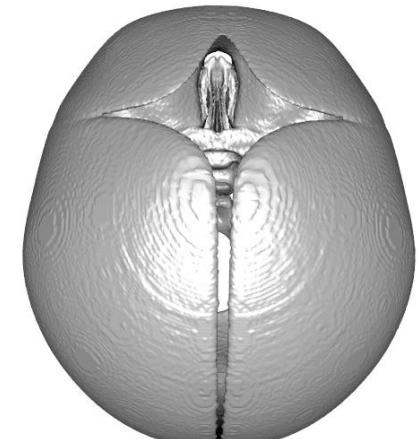


Why Linear Regression

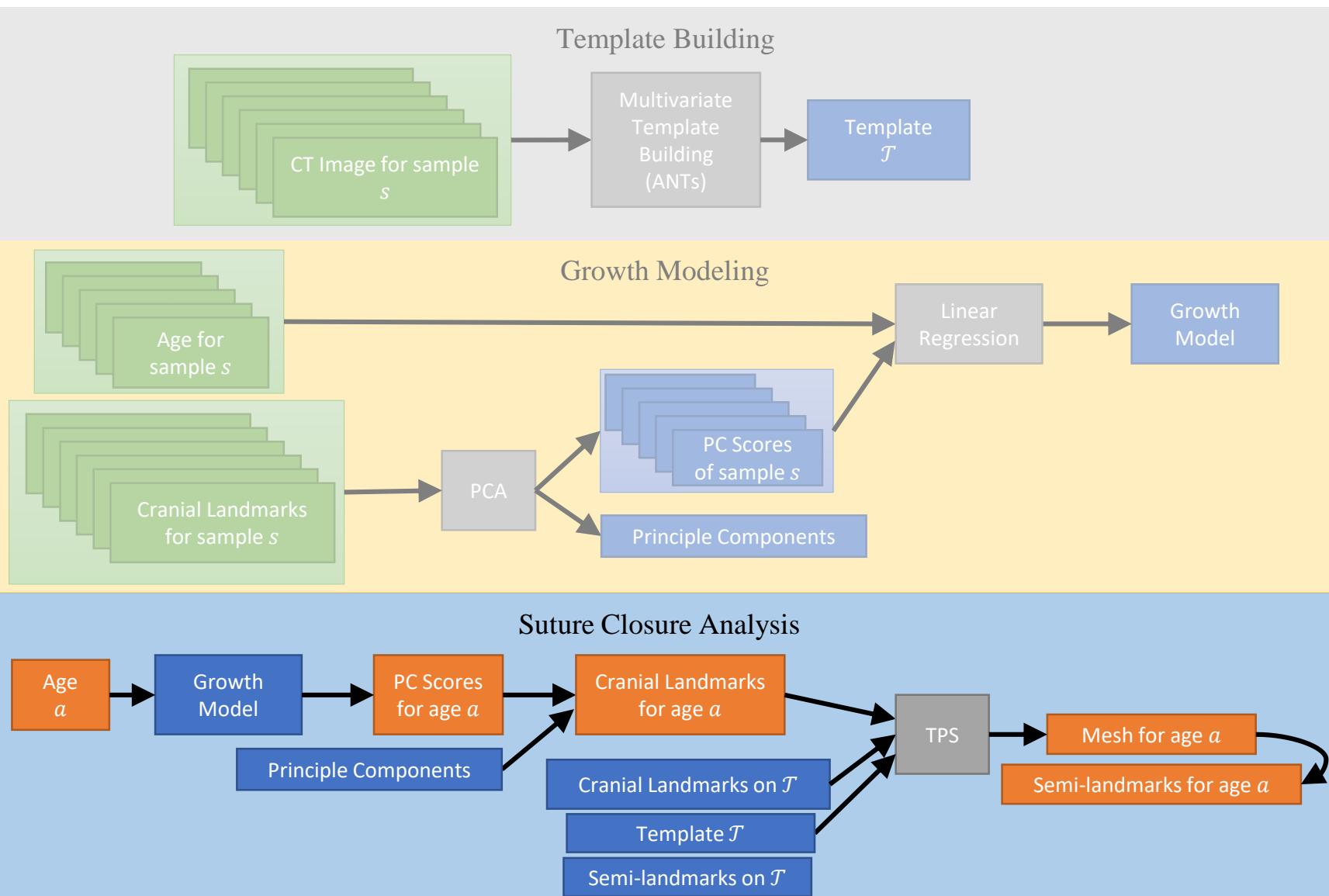
- L1 generalizes well, does not overfit and has only 2 parameters to learn.



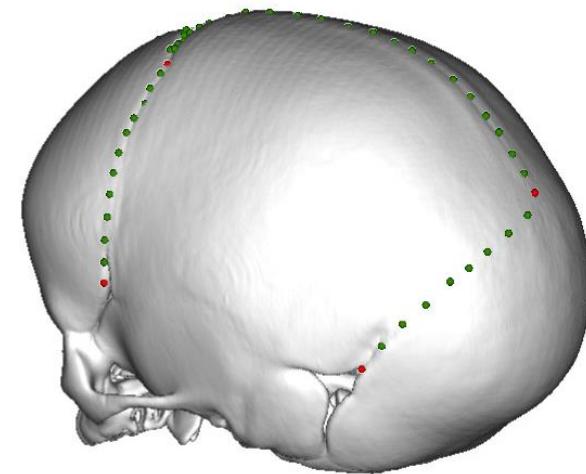
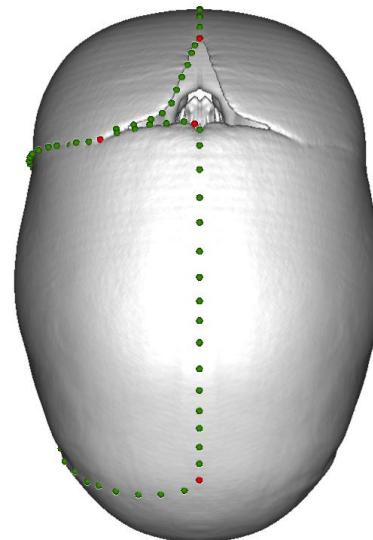
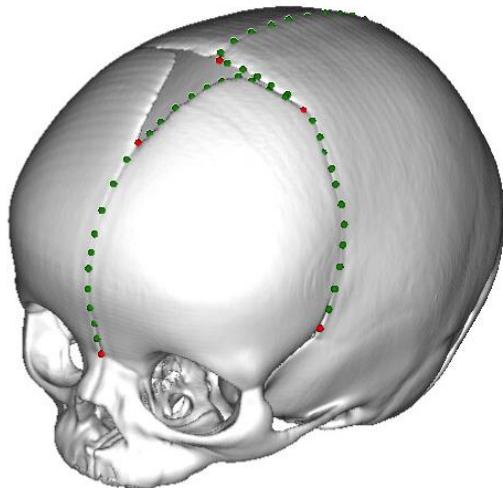
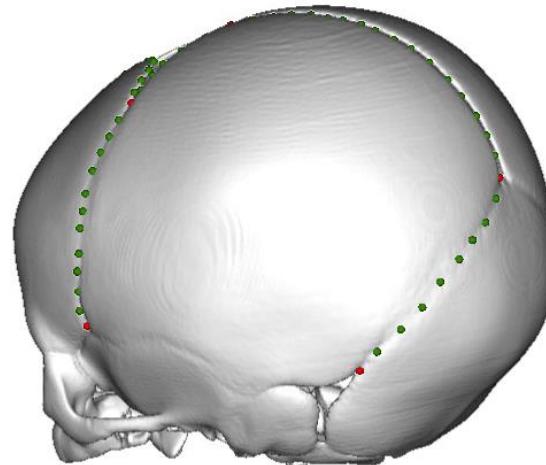
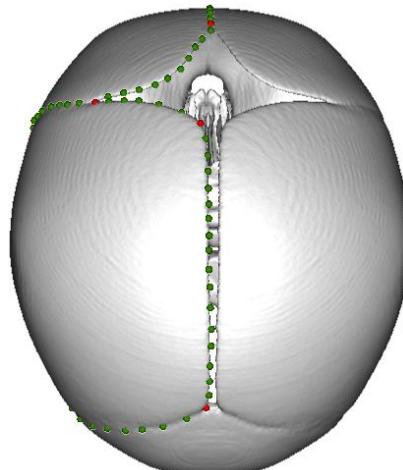
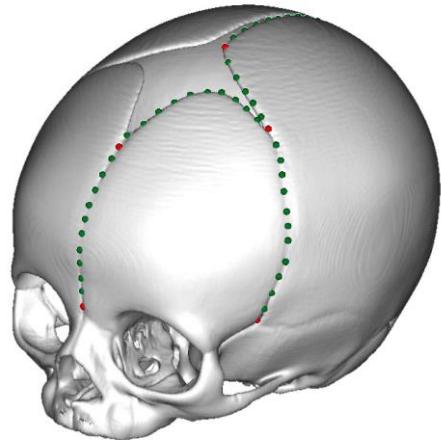
Why Linear Regression

L1**L2****LOESS**

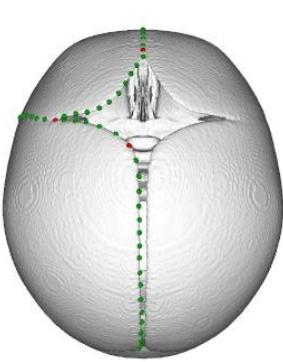
Outline



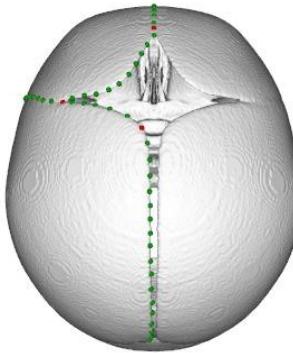
Suture Semi-landmarks



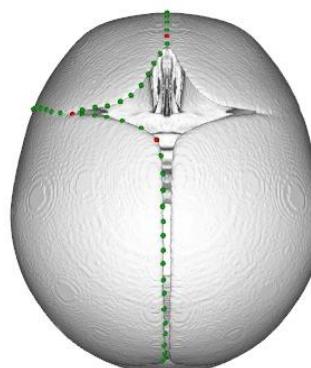
Suture Semi-landmarks



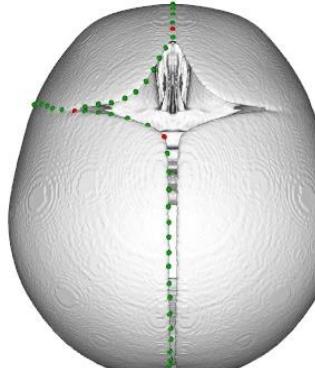
11 days



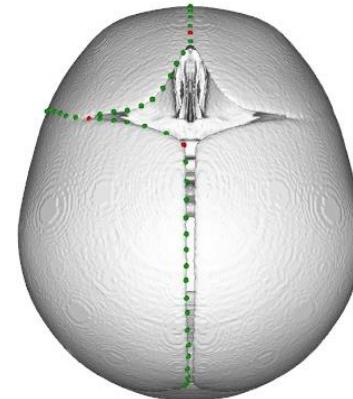
53 days



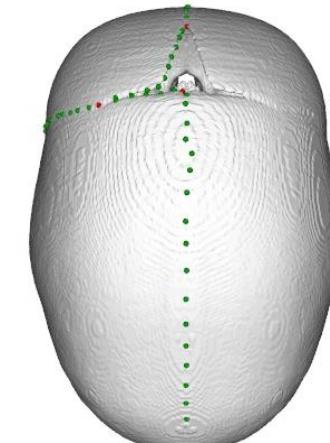
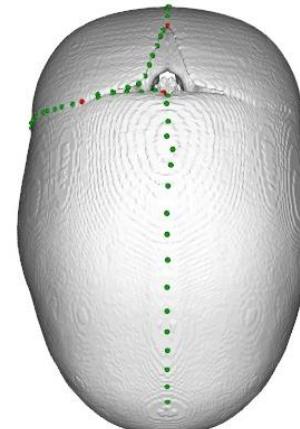
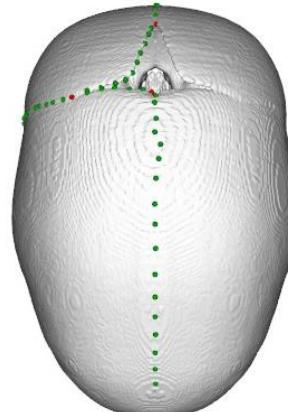
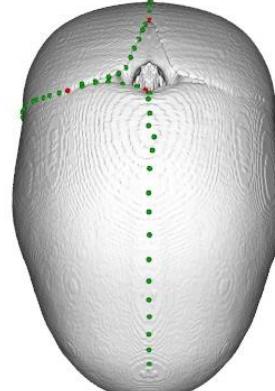
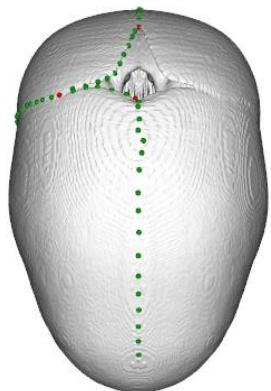
95 days



137 days

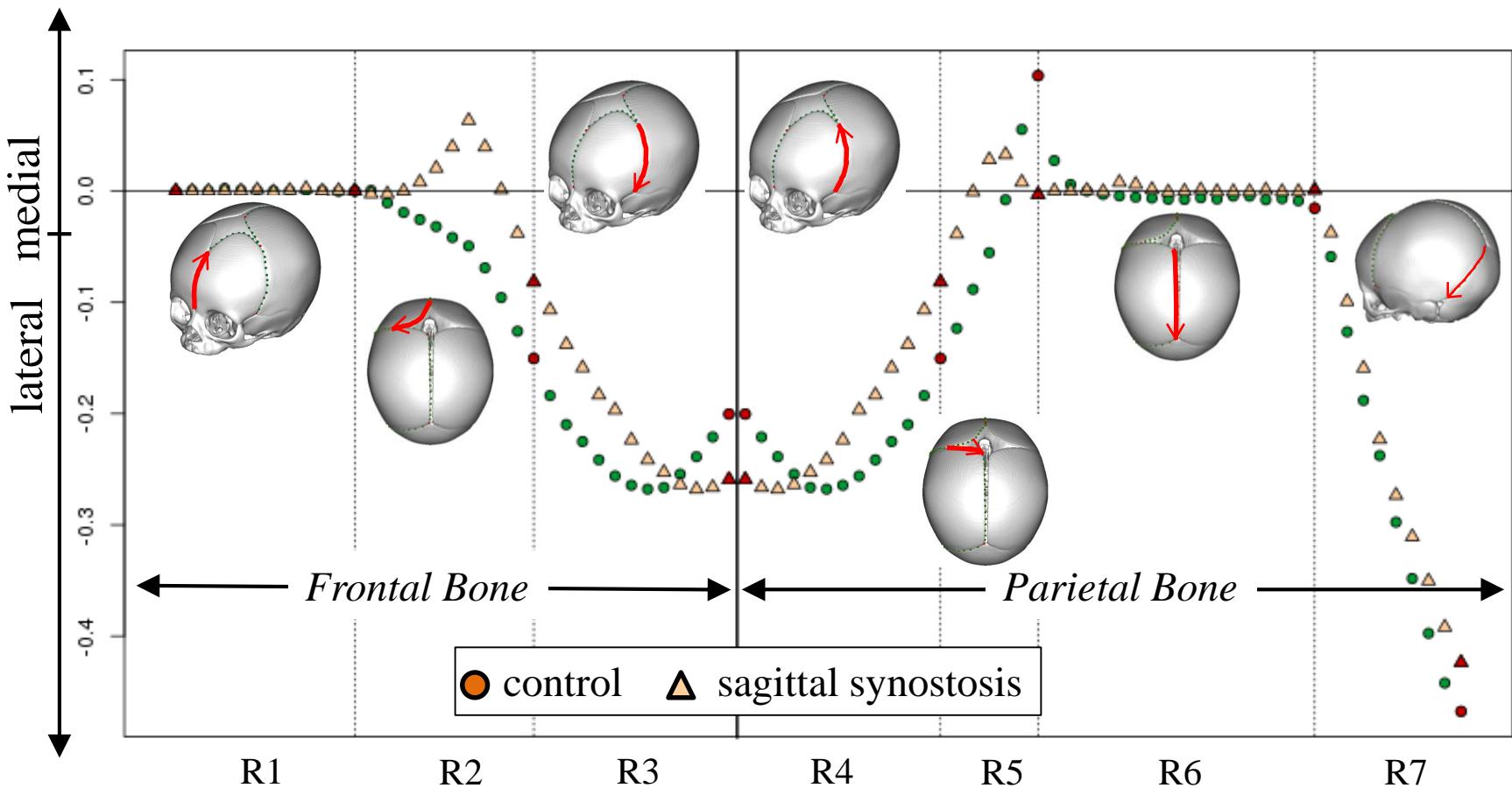


179 days



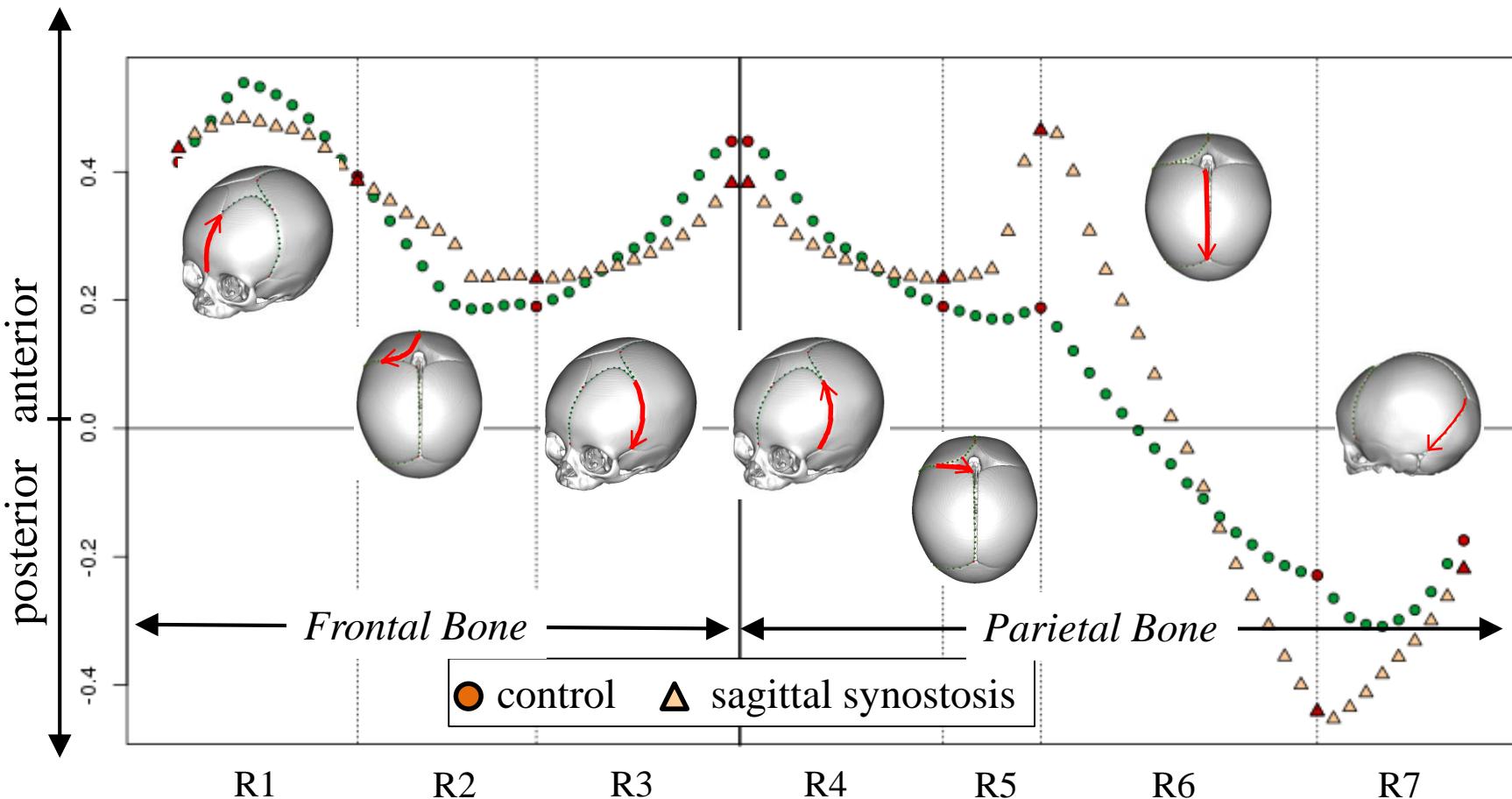
Mediolateral Displacement

(mm/week)

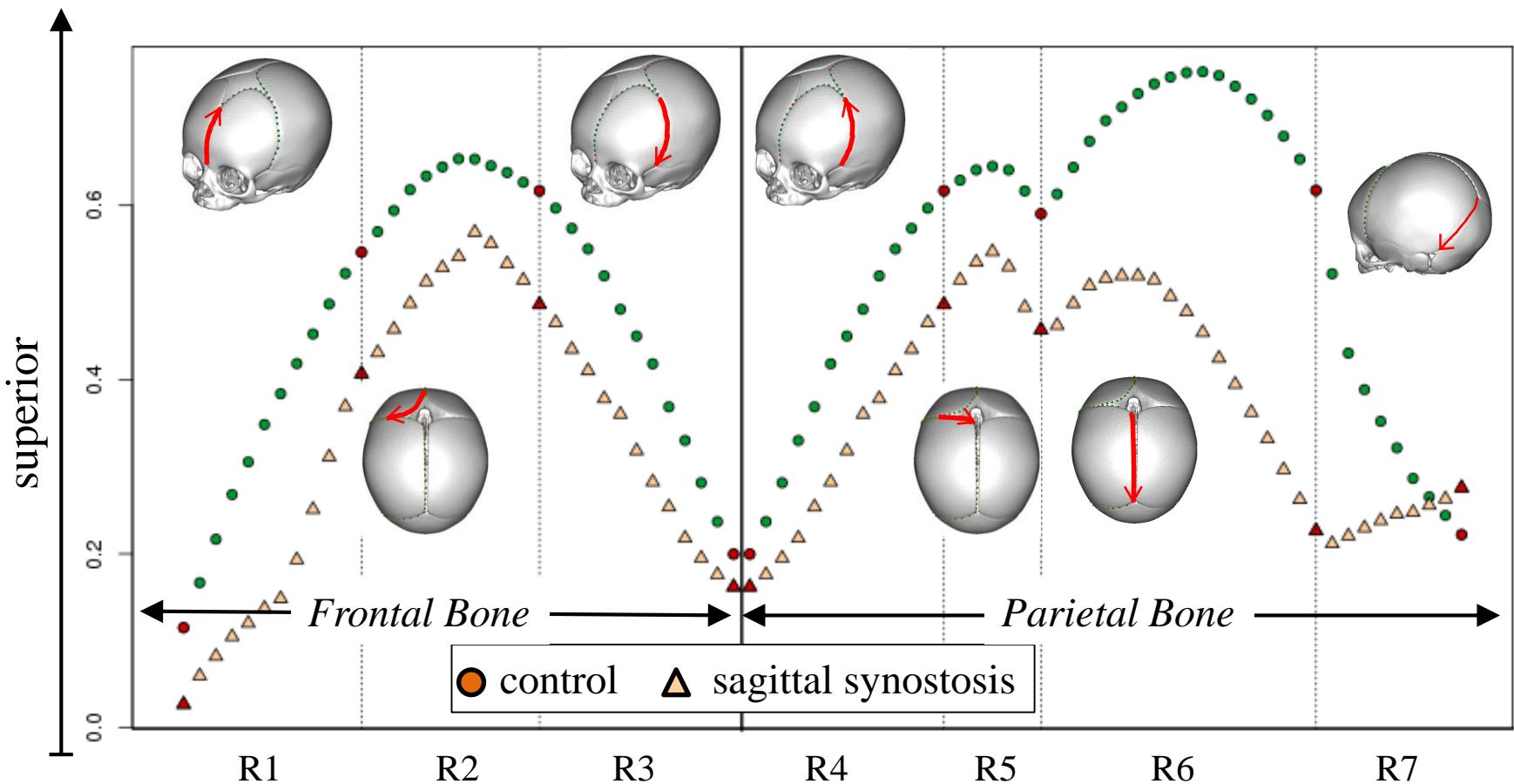


Anteroposterior Displacement

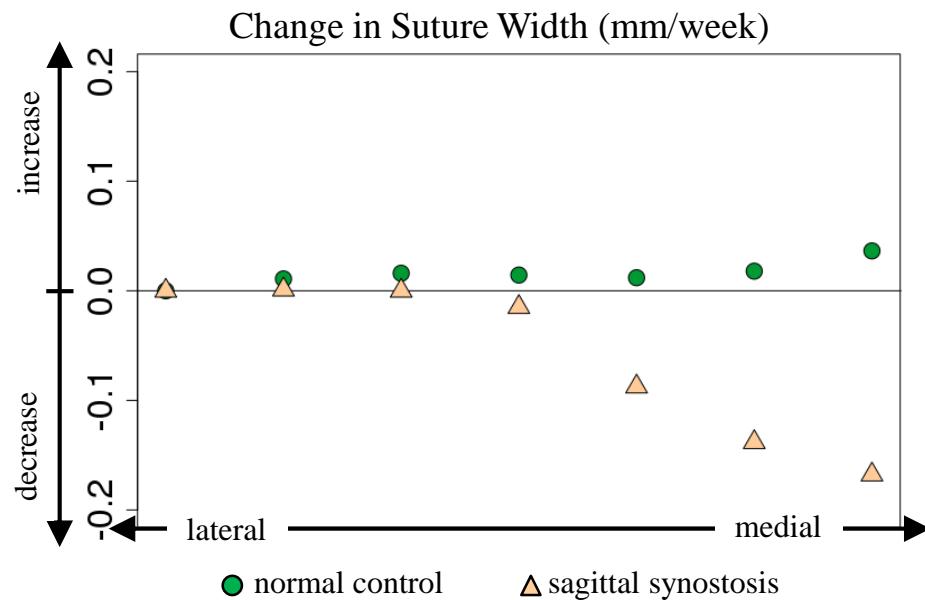
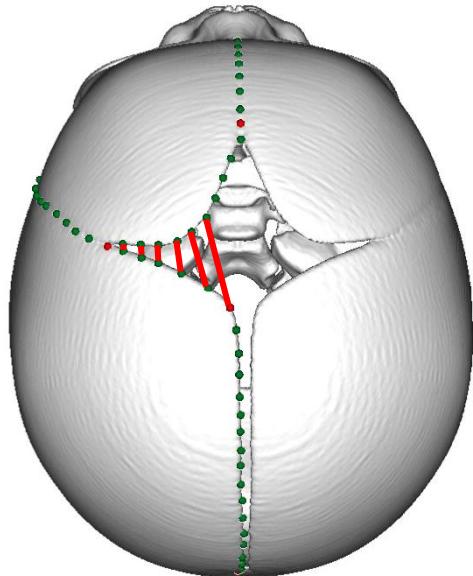
(mm/week)



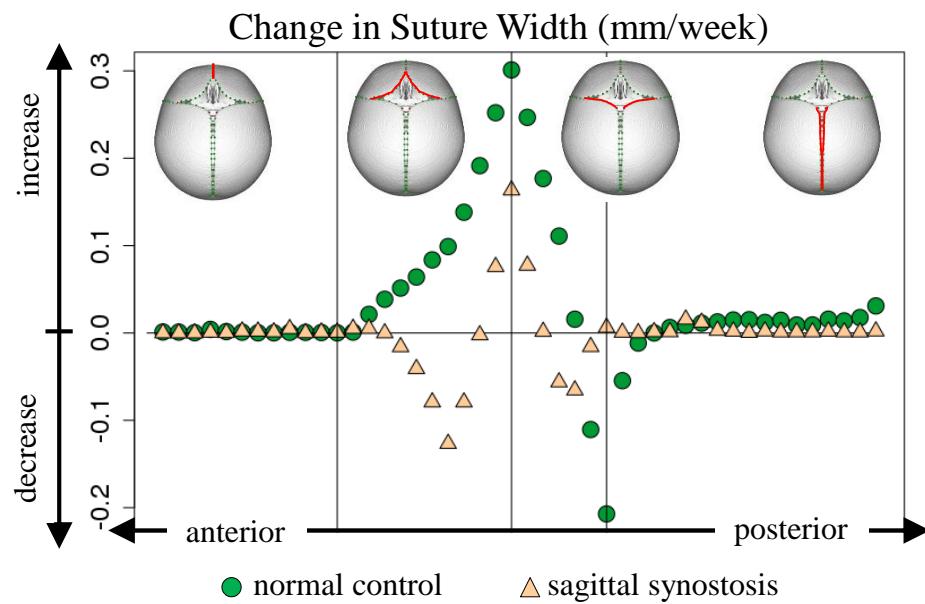
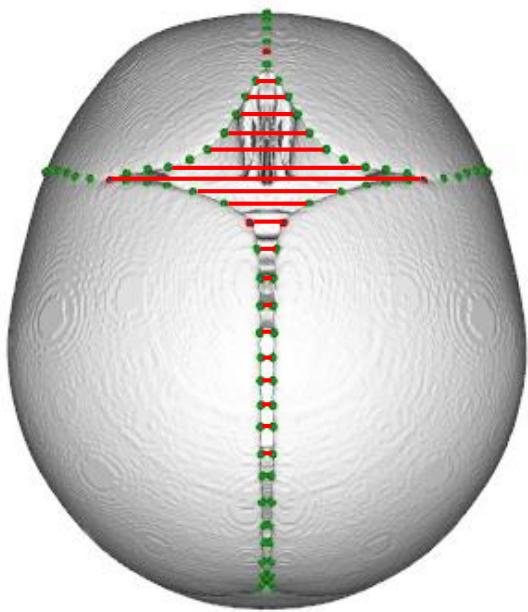
Superoinferior Displacement



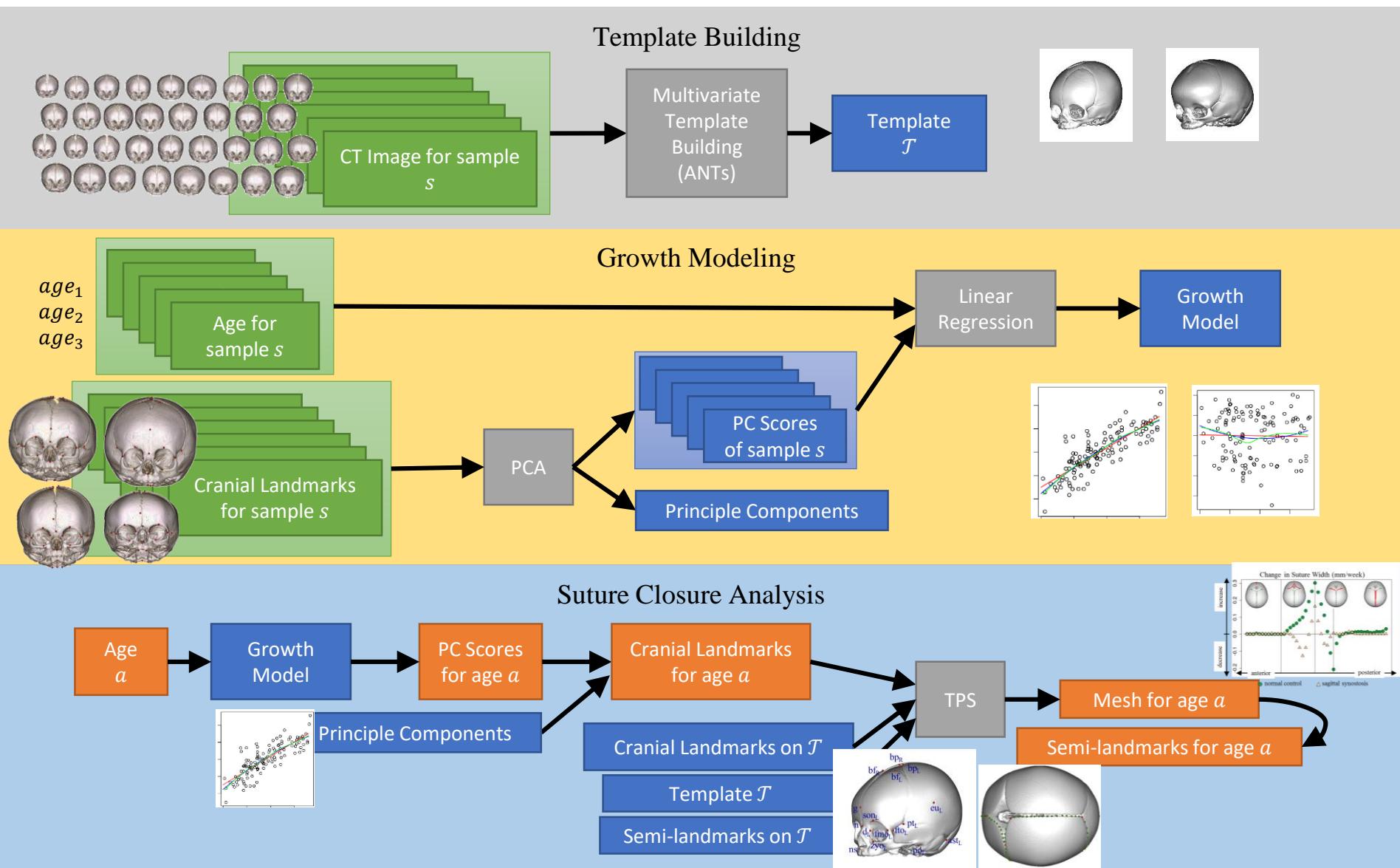
Suture Closure



Suture Closure



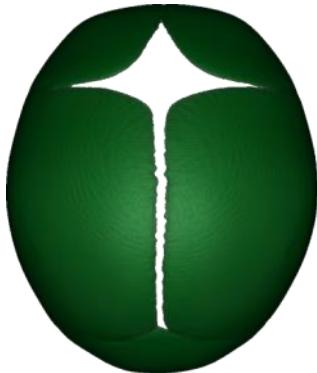
Recap



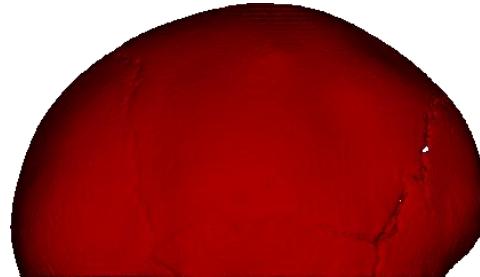
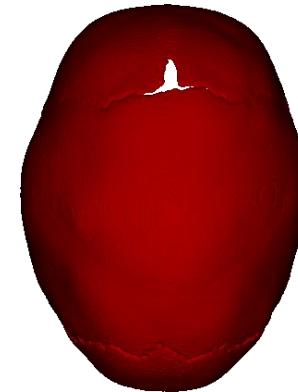
What else can you do with templates and diffeomorphic registration

BEYOND GROWTH

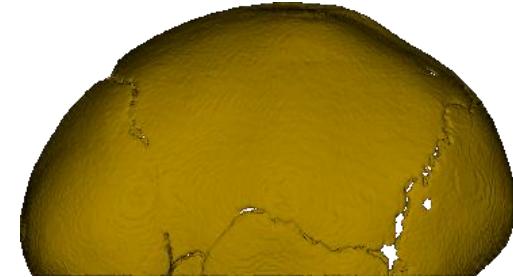
Shape Description



normal template

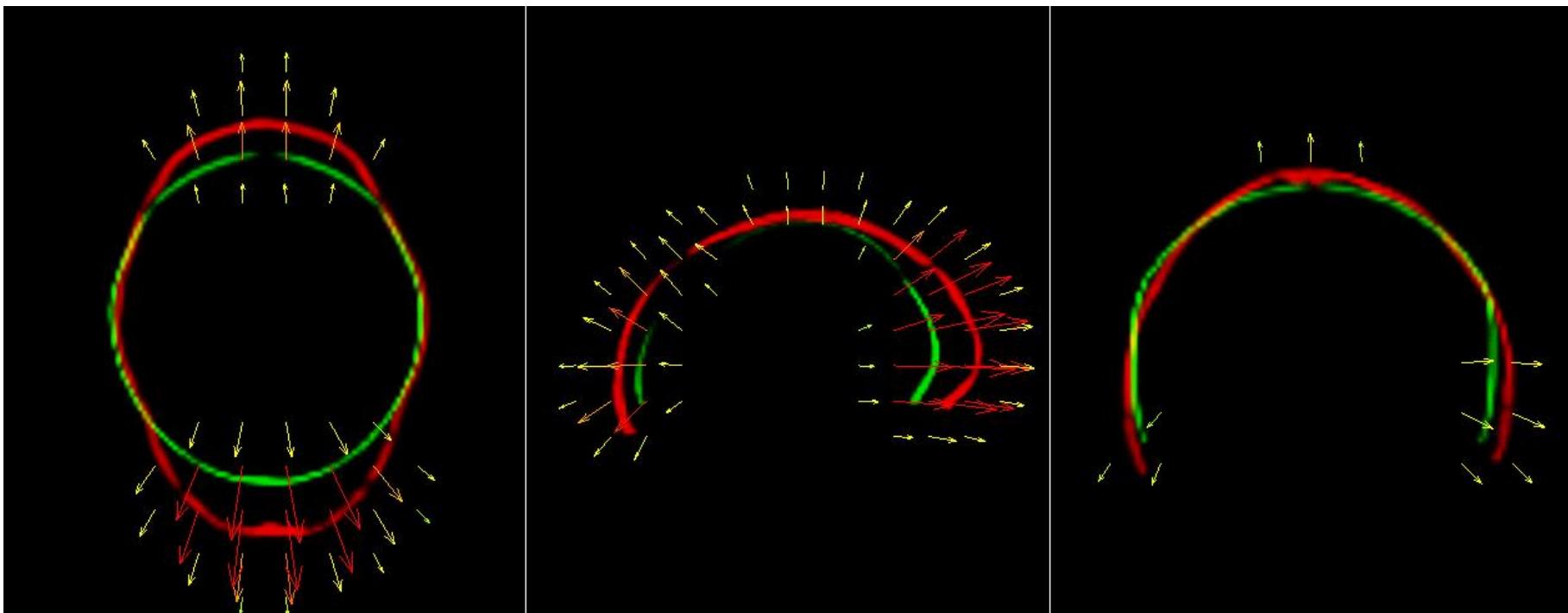
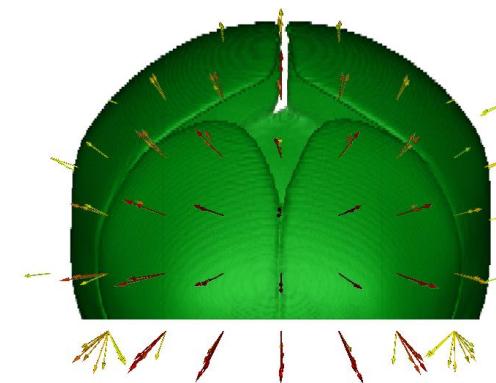
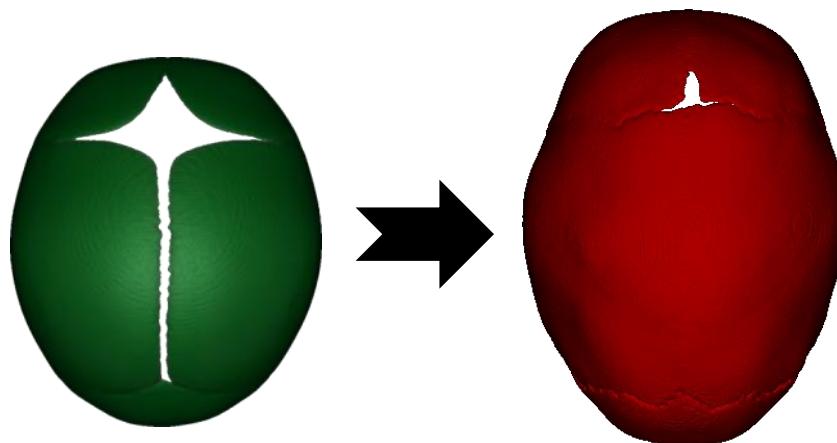


sagittal sample1

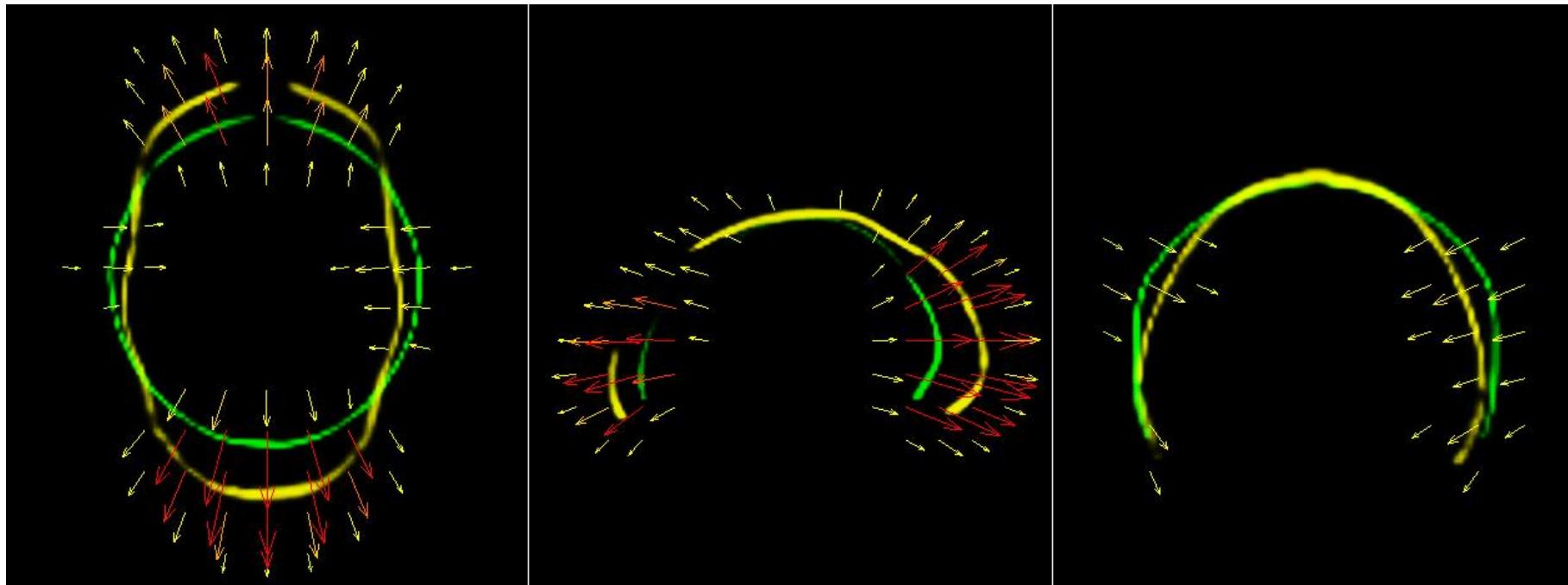
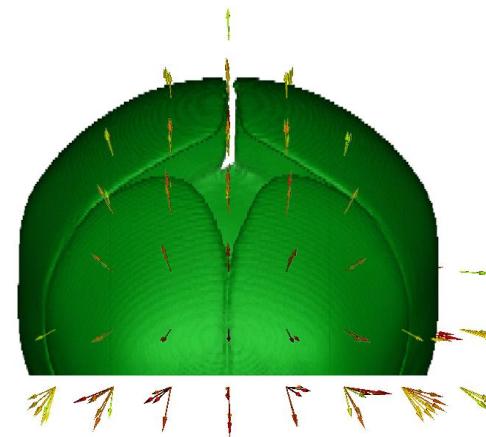
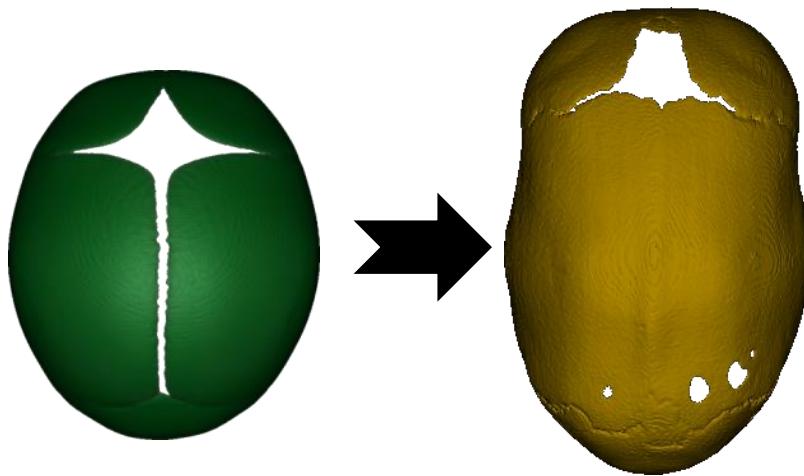


sagittal sample2

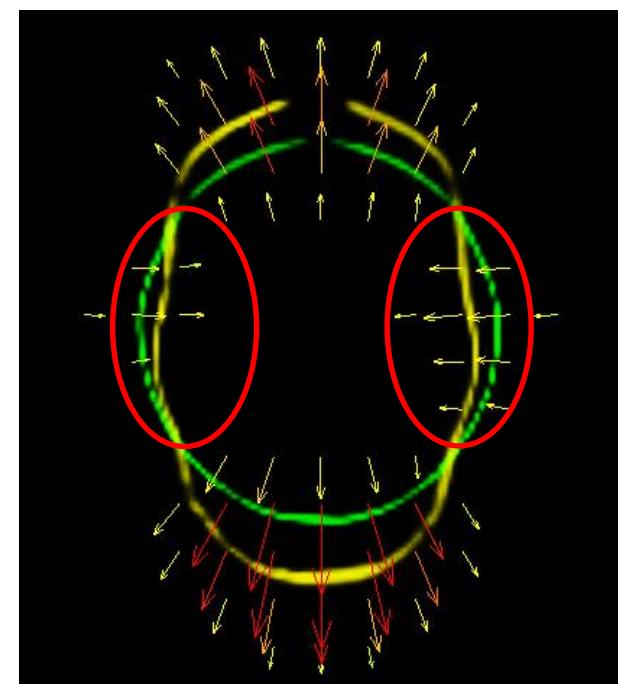
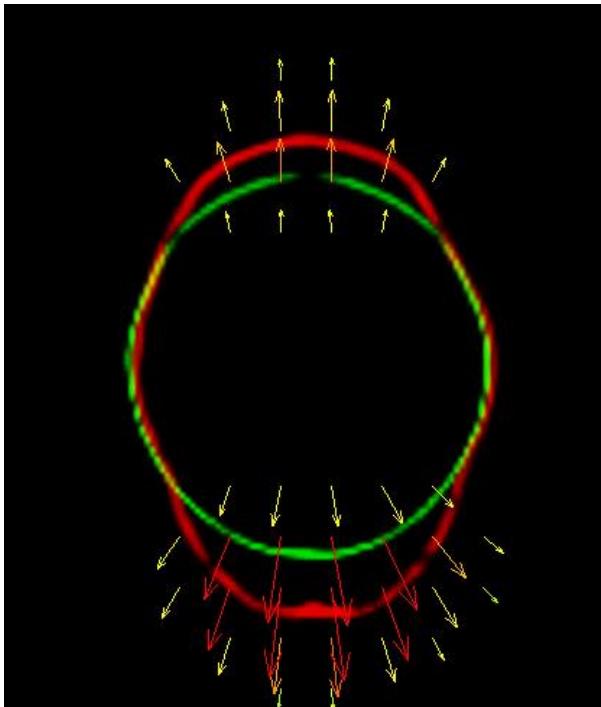
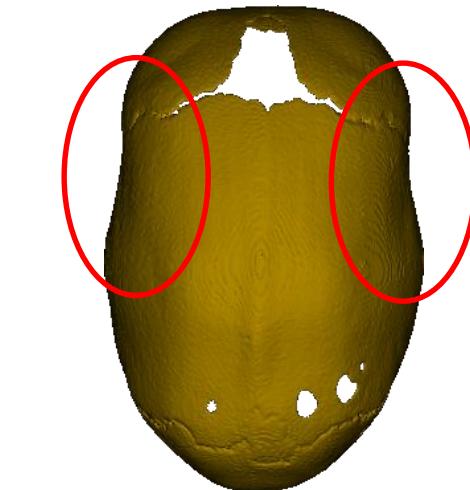
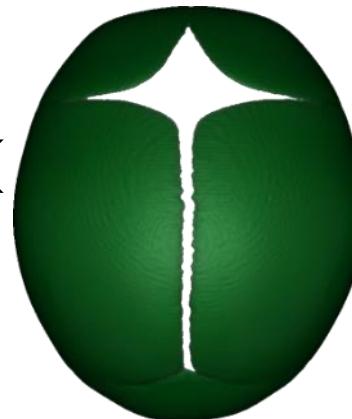
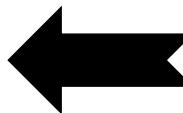
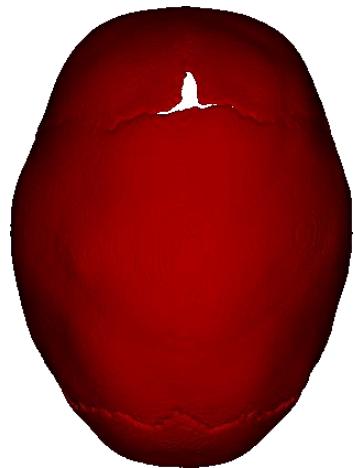
Shape Description



Shape Description



Shape Description



PEDIATRIC/CRANIOFACIAL

Identifying Reproducible Patterns of Calvarial Dysmorphology in Nonsyndromic Sagittal Craniosynostosis May Affect Operative Intervention and Outcomes Assessment

Rodney E. Schmelzer, M.D.

Chad A. Perlyn, M.D.

Alex A. Kane, M.D.

Thomas K. Pilgram, Ph.D.

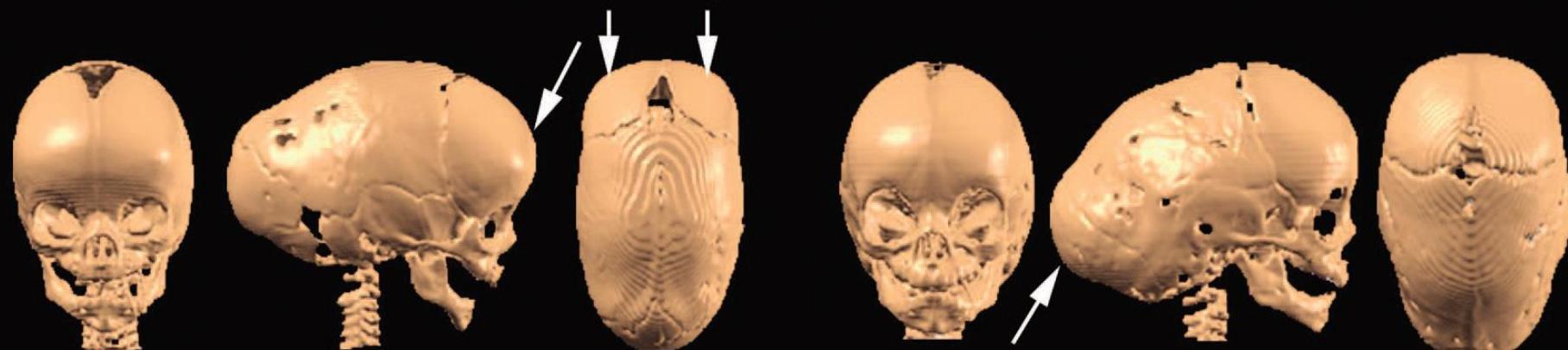
Daniel Govier

Jeffrey L. Marsh, M.D.

St. Louis, Mo.

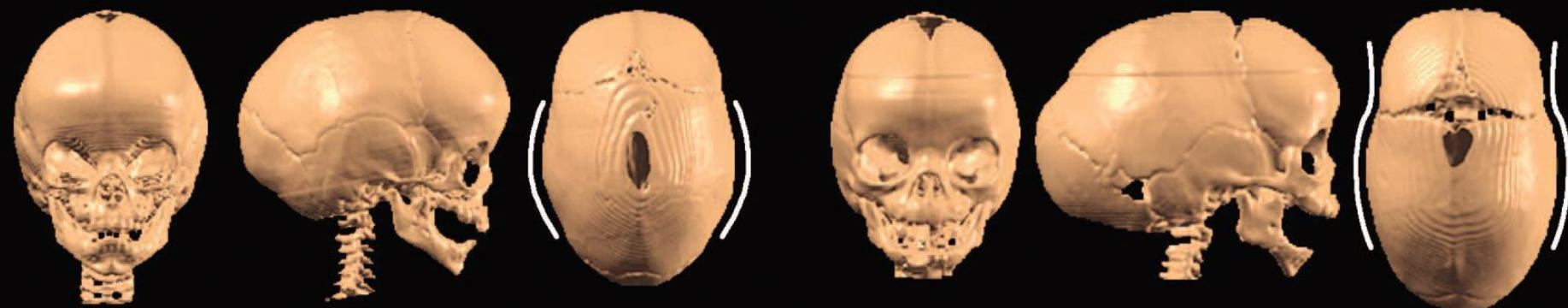
Background: The authors tested the premise that there are four distinctive patterns of calvarial dysmorphology in nonsyndromic sagittal craniosynostosis that can be reproducibly recognized.

Methods: Twenty-nine computed tomographic scan data sets of infants met the following criteria: nonsyndromic sagittal craniosynostosis, age younger than 12 months, and satisfactory computed tomographic data. Osseous reformations were constructed in the anteroposterior, right lateral, and vertex projections for each patient. From these images, four templates—coronal constriction, occipital



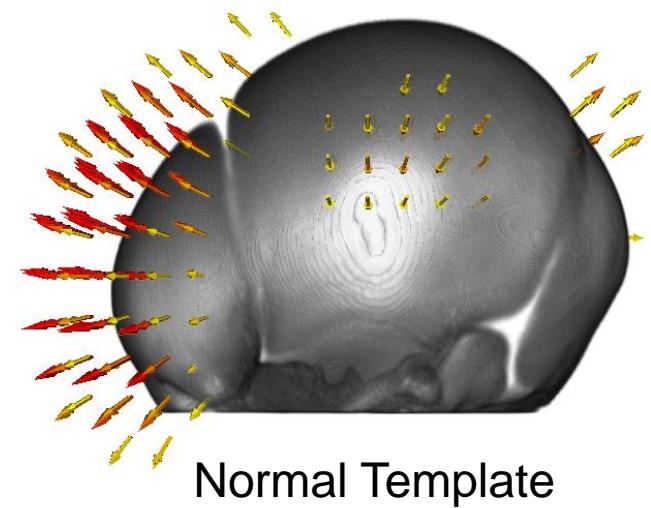
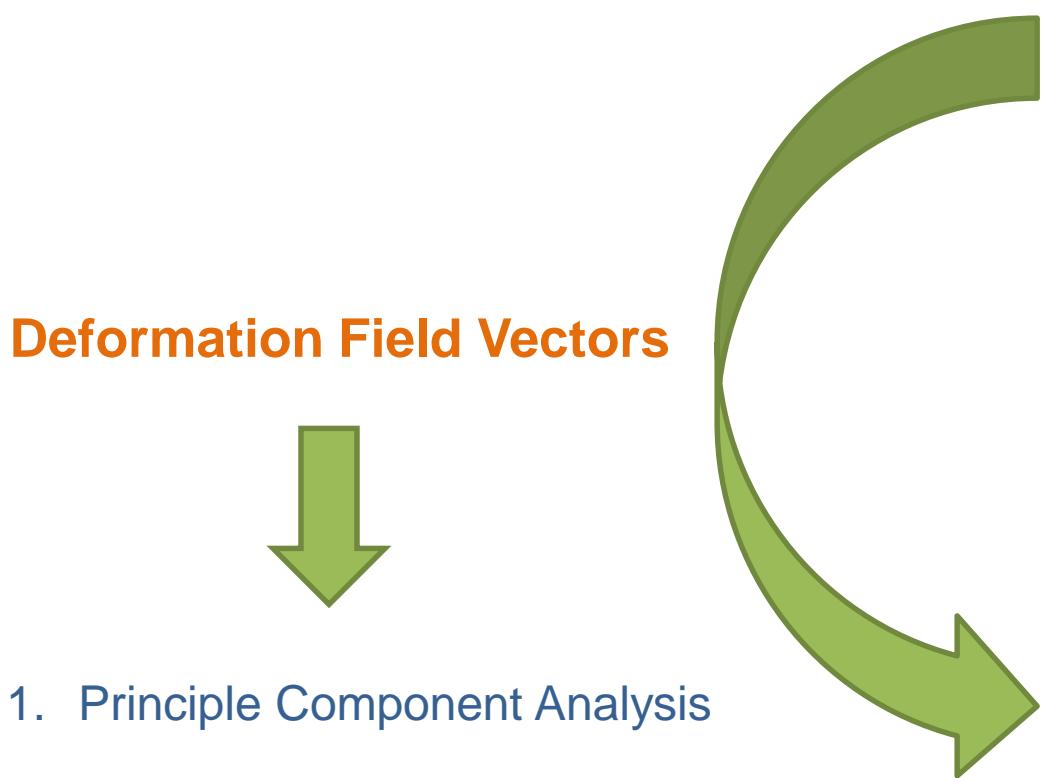
Bifrontal Bossing

Occipital Protuberance

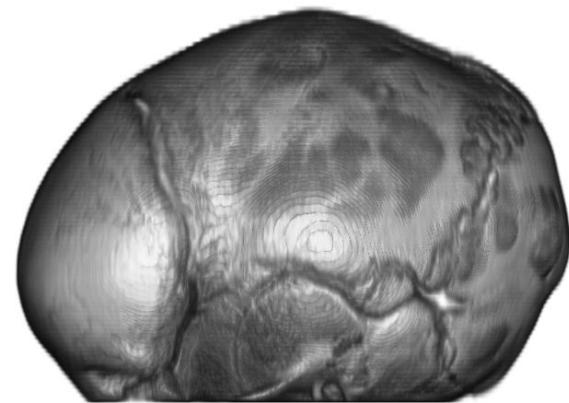


Bitemporal Protrusion

Coronal Constriction



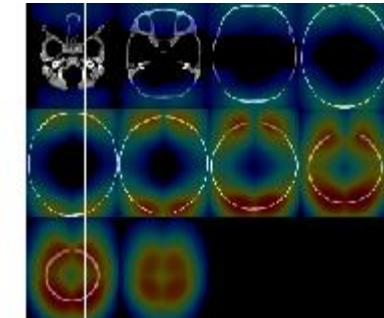
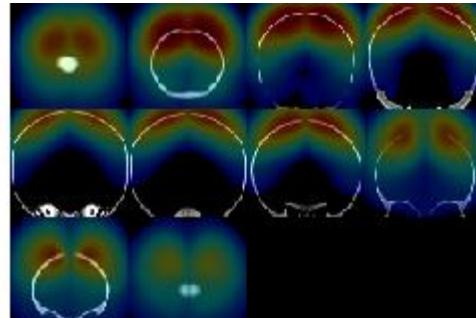
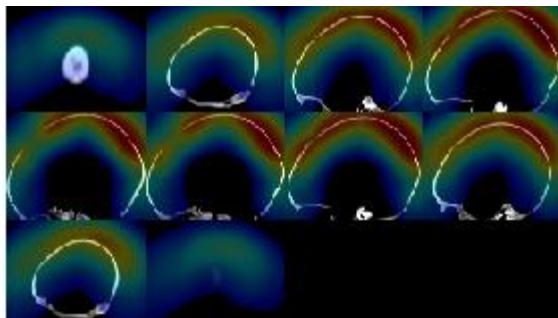
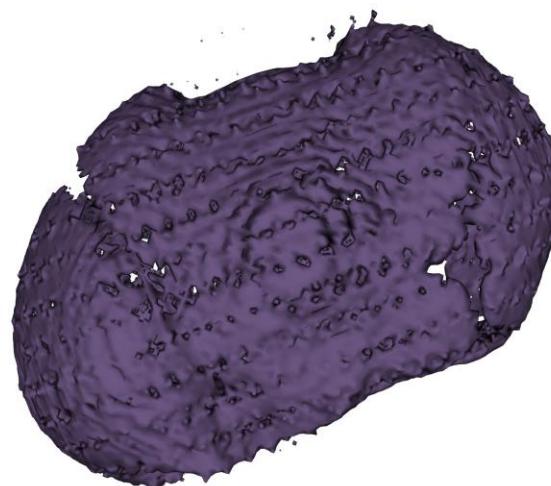
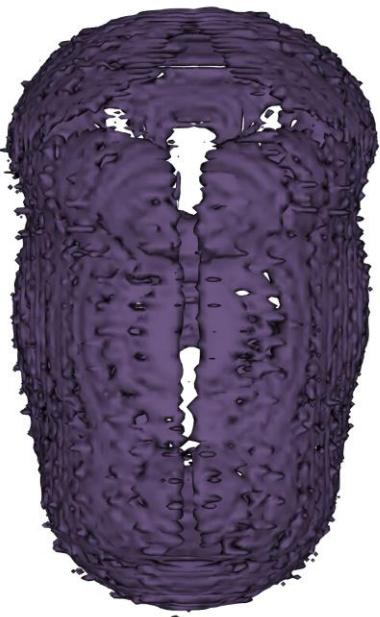
Normal Template



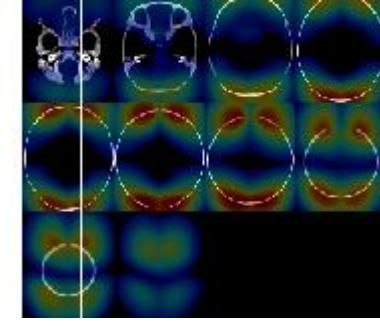
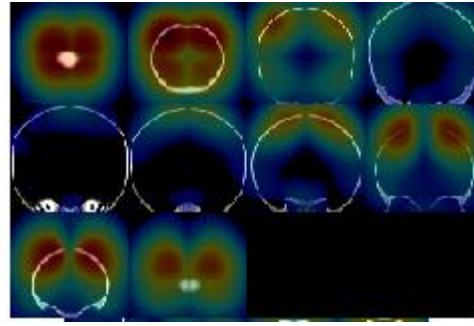
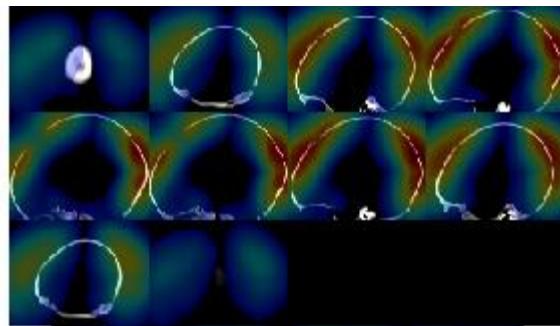
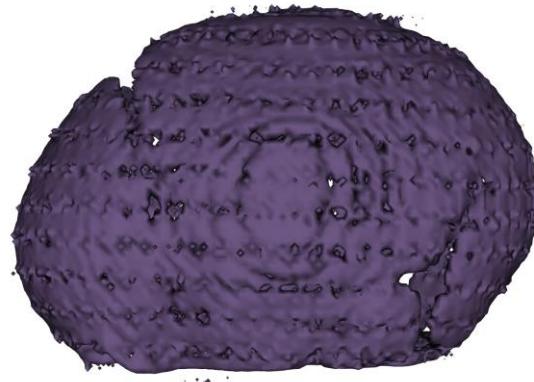
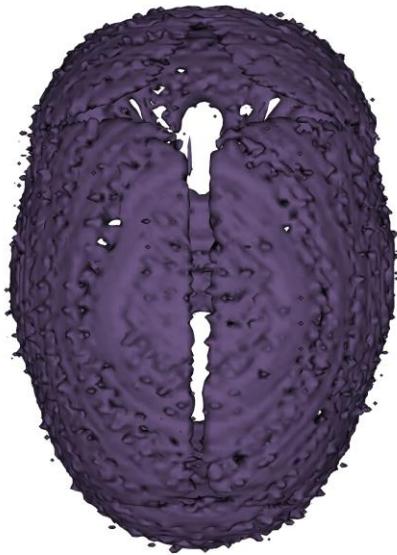
Sagittal Sample

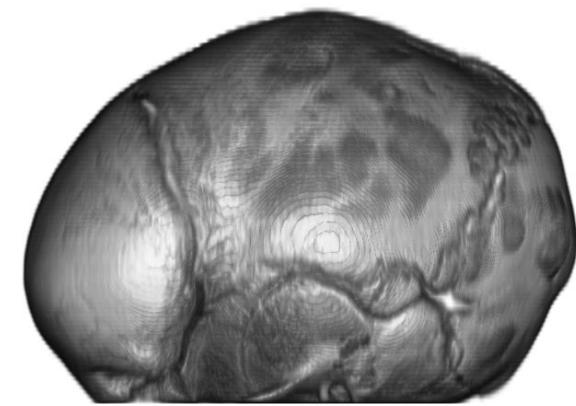
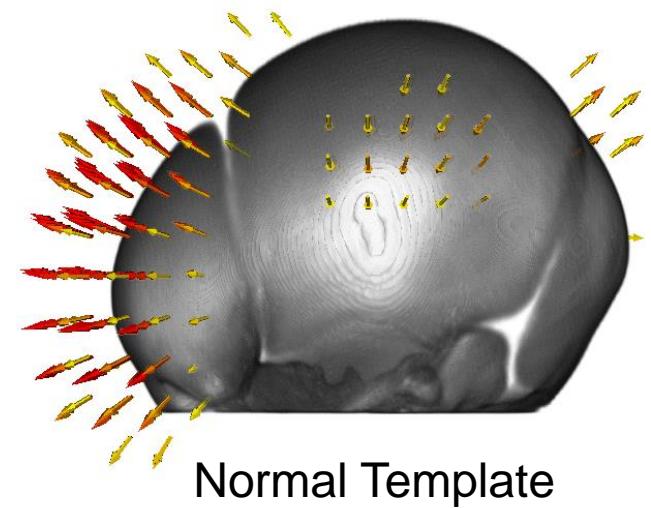
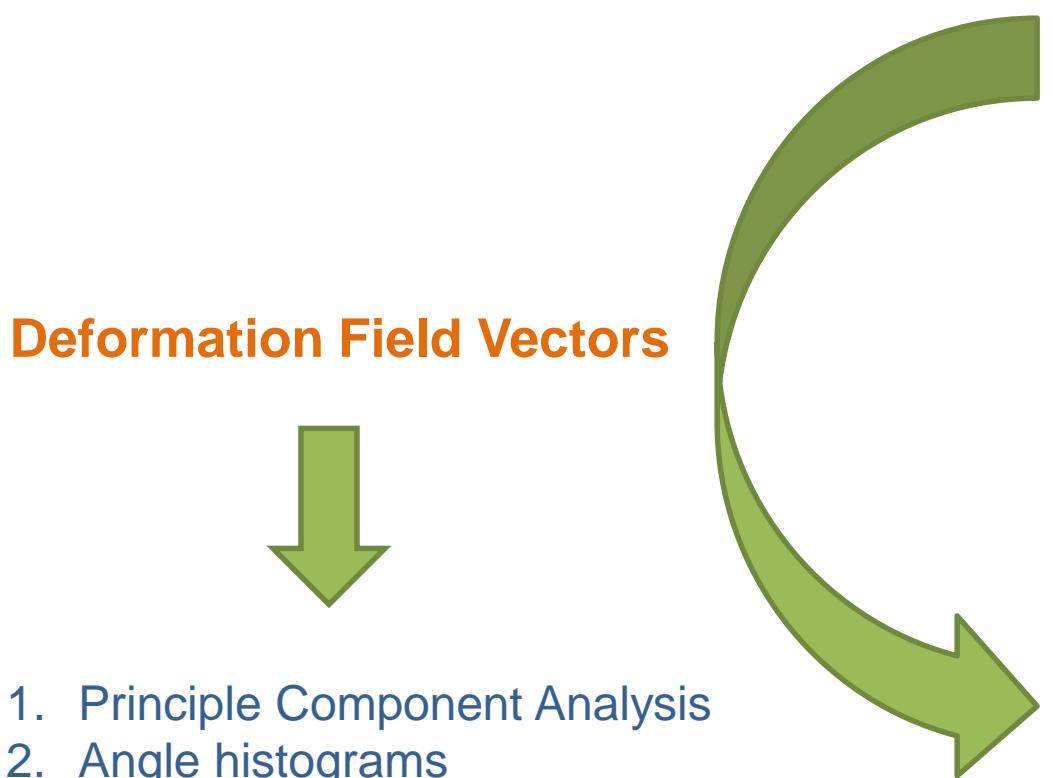
1. Principle Component Analysis

PC1

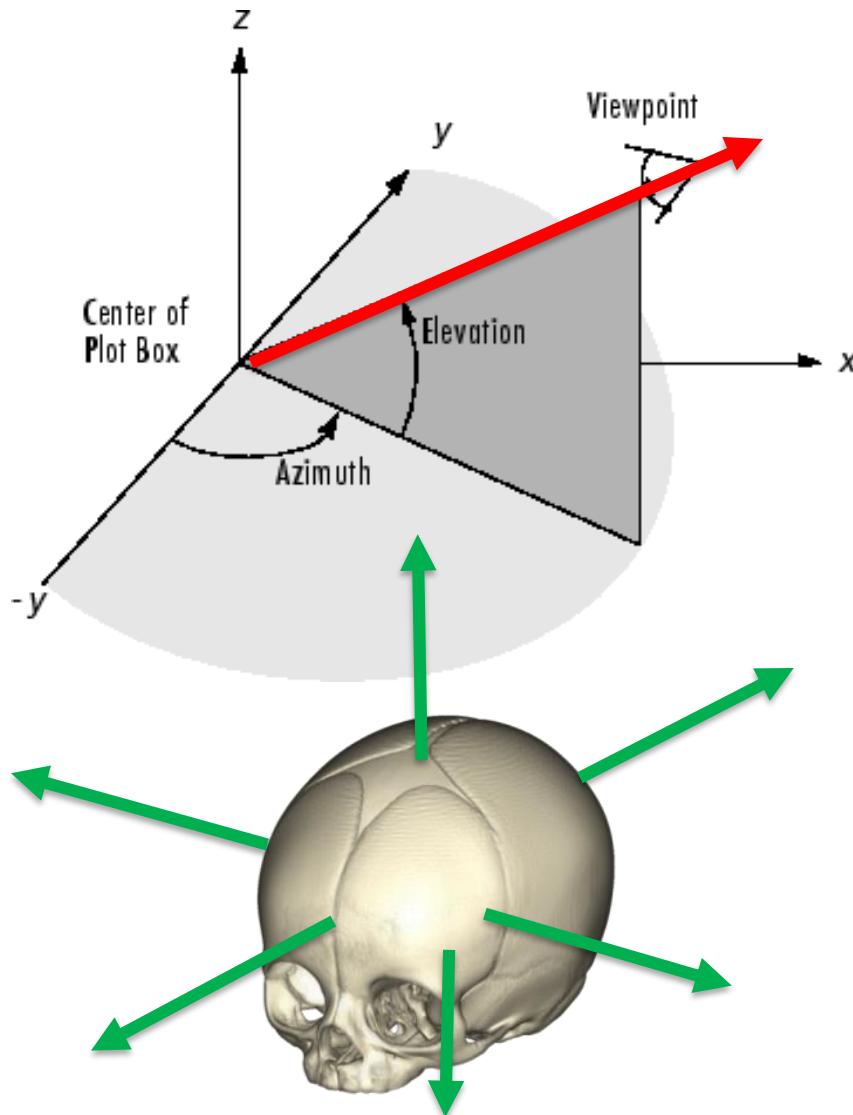


PC2

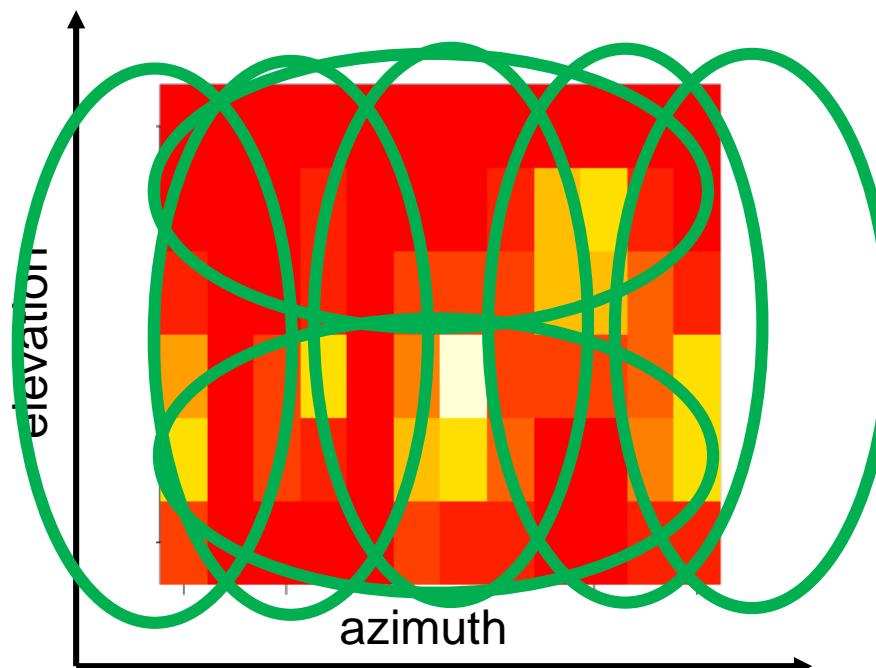




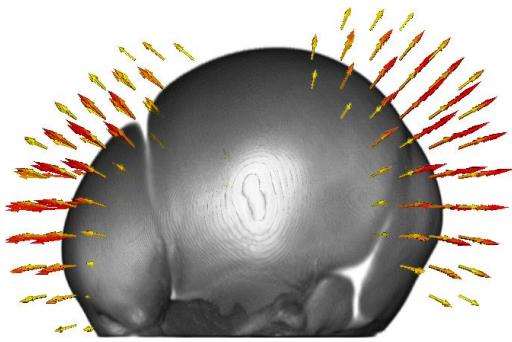
Angle Histograms



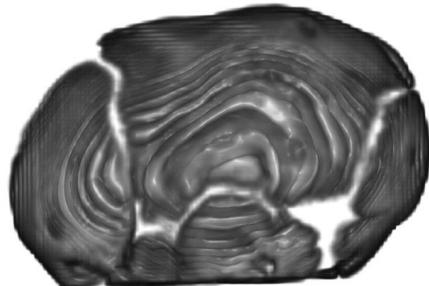
Generate a 2D histogram based on the azimuth and elevation angles of 3D deformation vectors.



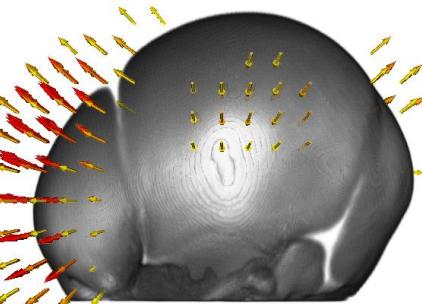
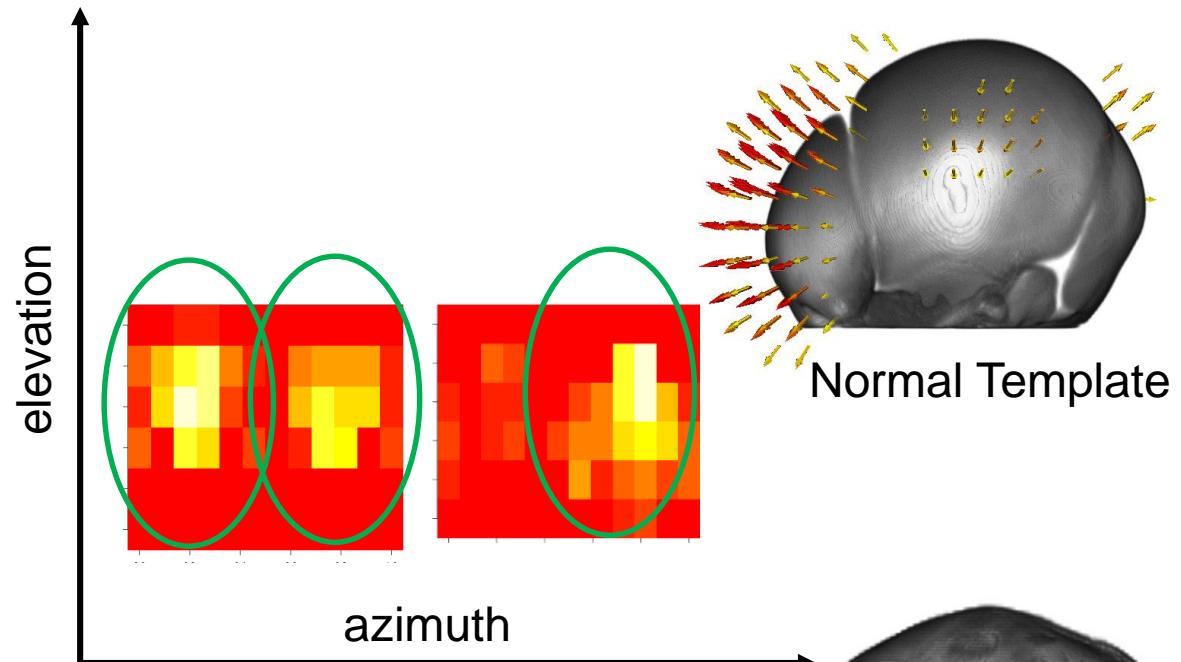
Angle Histograms



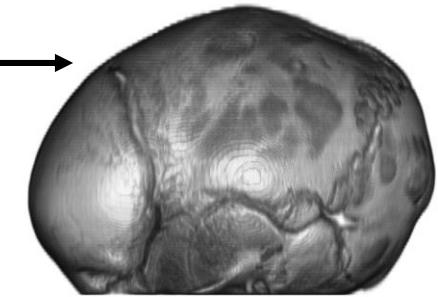
Normal Template



Sagittal Sample



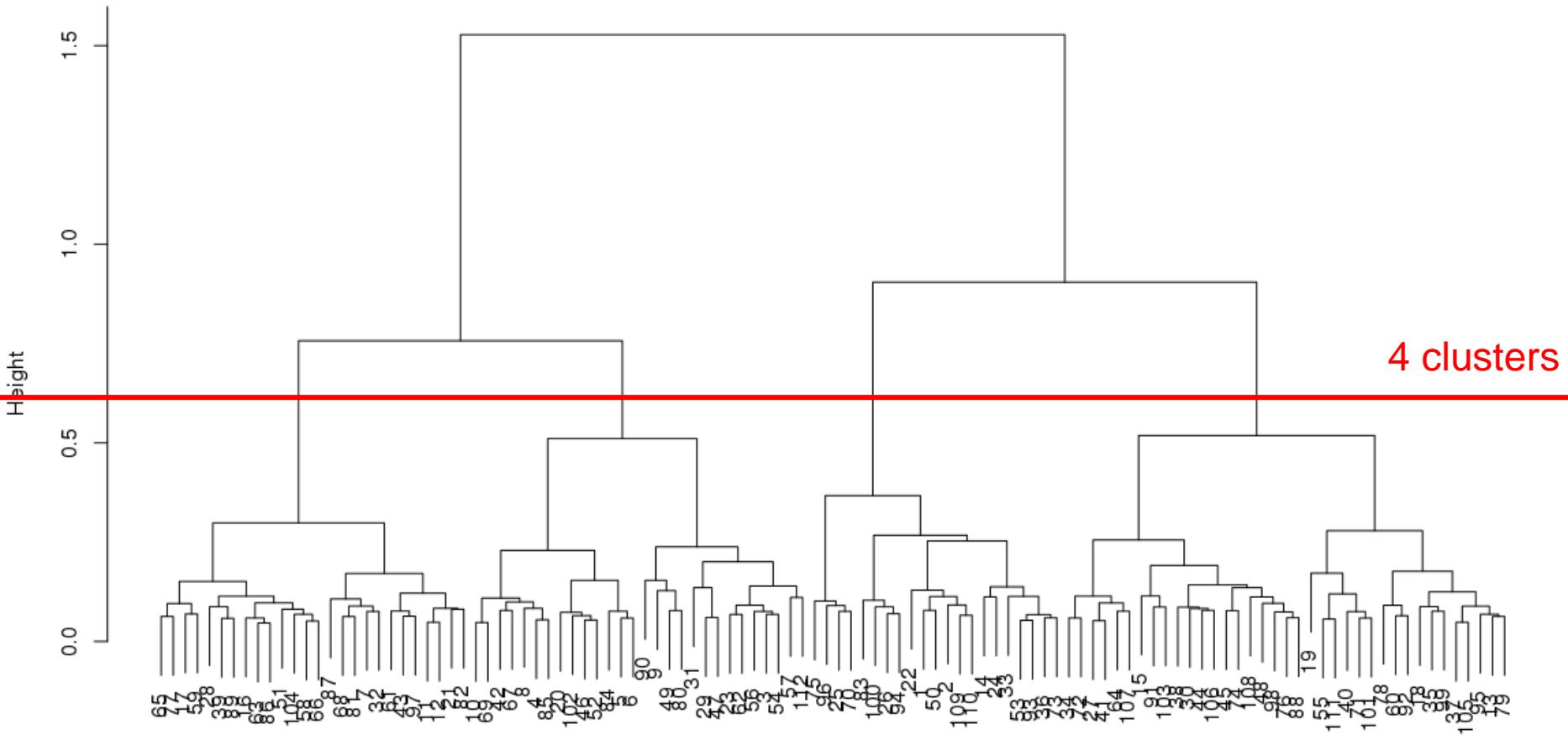
Normal Template



Sagittal Sample

Clustering - Angle Histograms

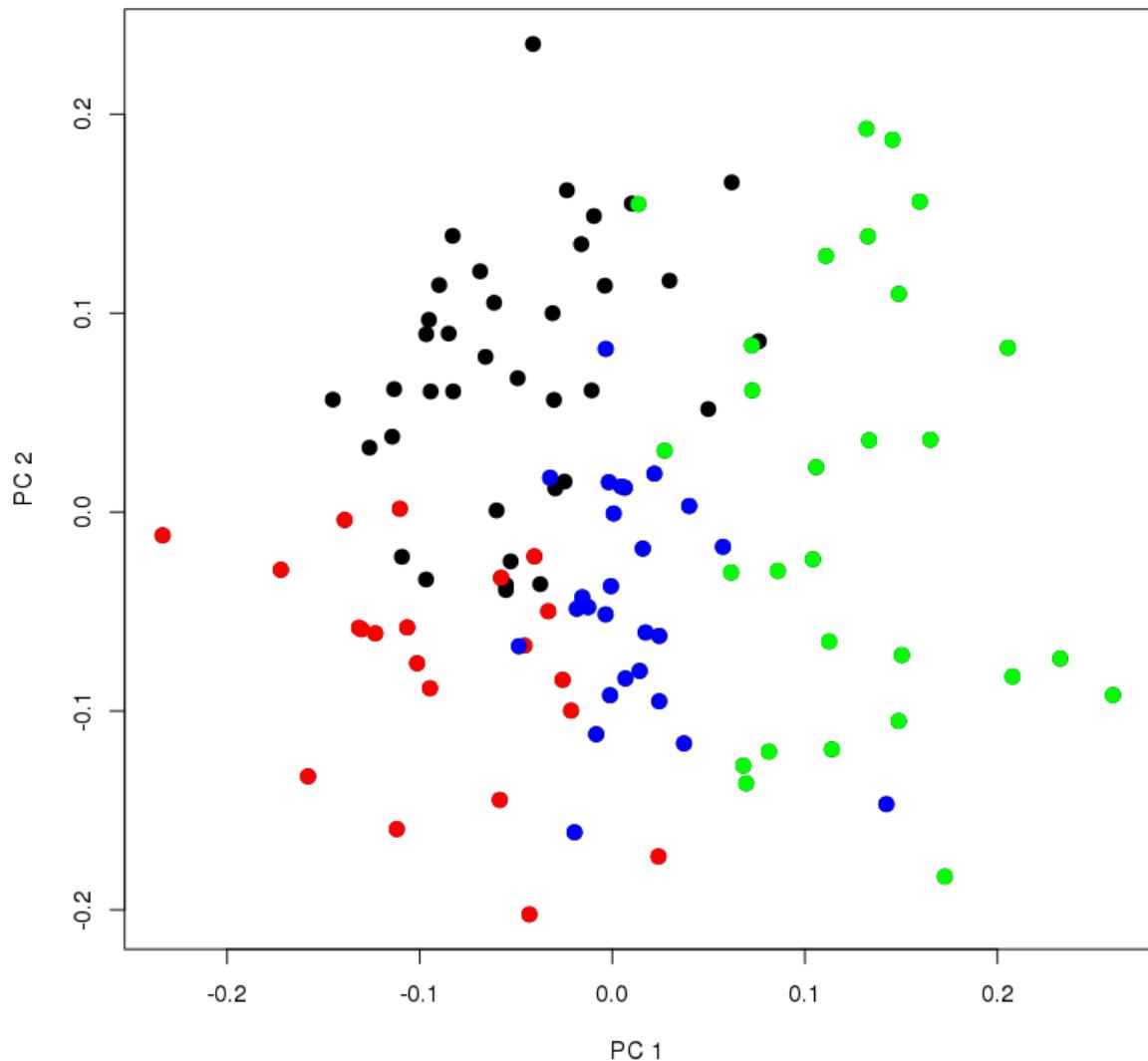
Cluster Dendrogram



Sanity Check

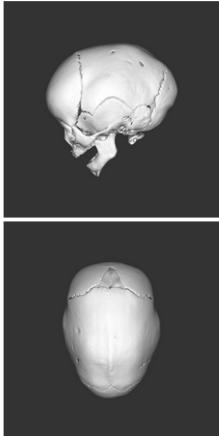
Do principle components capture the same clusters?

Yes!



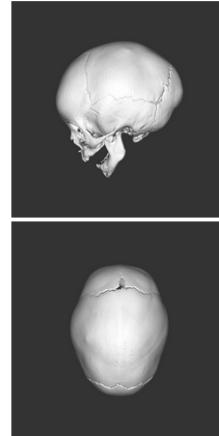
Observed Phenotypes

CT0407547



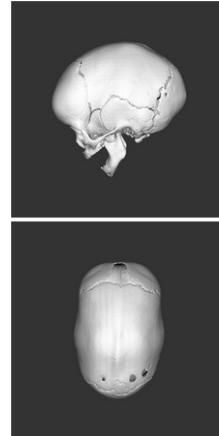
Bifrontal bossing : 0 1 2
Occipital protuberance : 0 1 2
Bitemporal protusion : 0 1 2
Coronal constrictions : 0 1 2
Saddle : 0 1 2

CT0408969



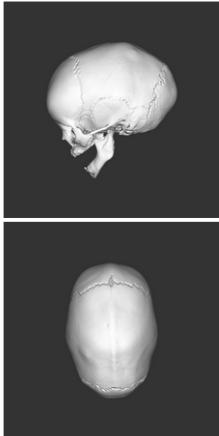
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Occipital protuberance : 0 1 2
Bitemporal protusion : 0 1 2
Coronal constrictions : 0 1 2
Saddle : 0 1 2

CT0411107



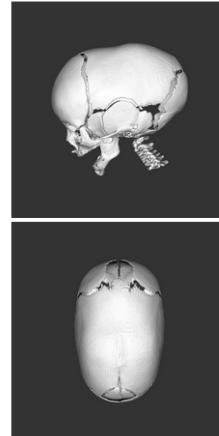
Bifrontal bossing : 0 1 2
Occipital protuberance : 0 1 2
Bitemporal protusion : 0 1 2
Coronal constrictions : 0 1 2
Saddle : 0 1 2

CT0411214



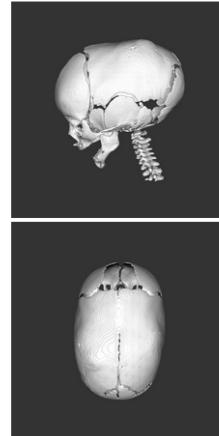
Bifrontal bossing : 0 1 2
Occipital protuberance : 0 1 2
Bitemporal protusion : 0 1 2
Coronal constrictions : 0 1 2
Saddle : 0 1 2

CT0501524



Bifrontal bossing : 0 1 2
Occipital protuberance : 0 1 2
Bitemporal protusion : 0 1 2
Coronal constrictions : 0 1 2
Saddle : 0 1 2

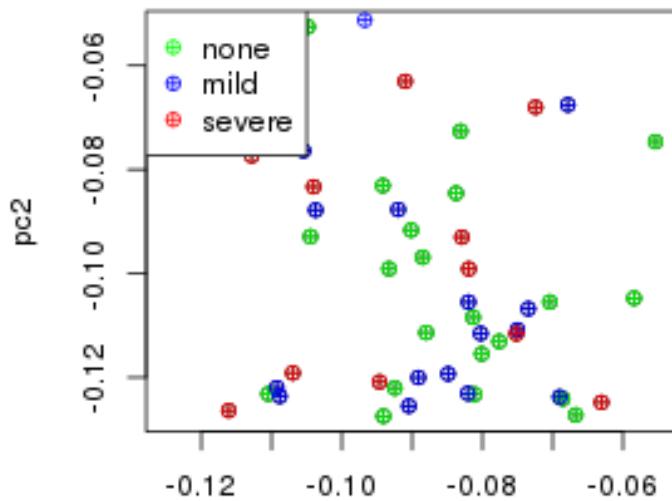
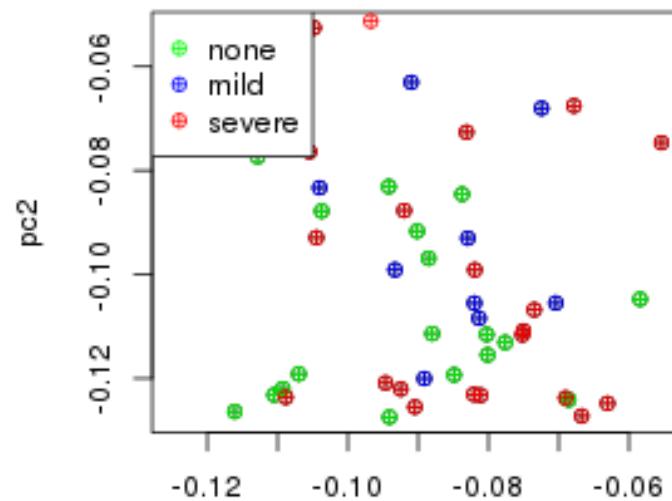
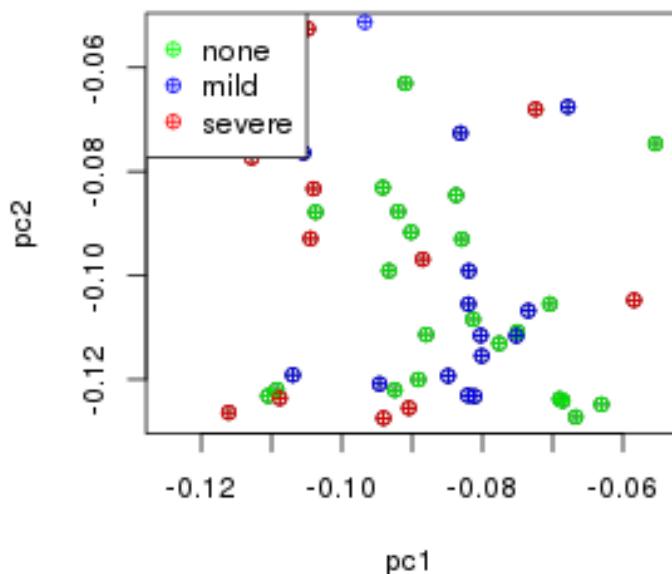
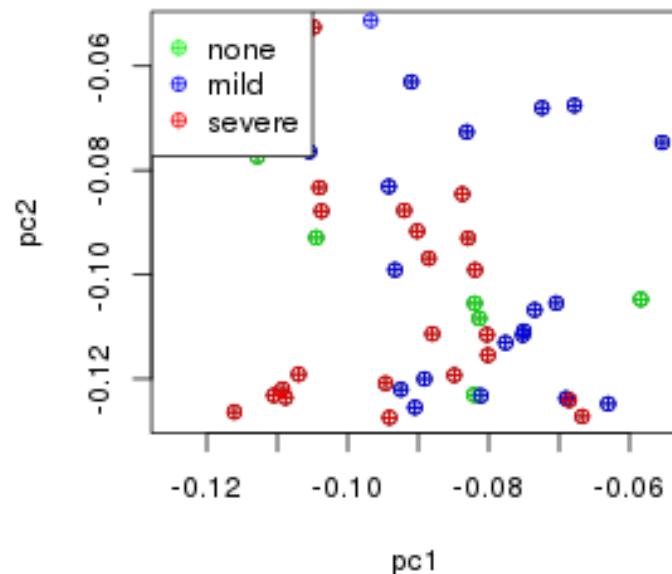
CT0501526



Bifrontal bossing : 0 1 2
Occipital protuberance : 0 1 2
Bitemporal protusion : 0 1 2
Coronal constrictions : 0 1 2
Saddle : 0 1 2

Collected rankings from
a surgeon
N=48

Can computed clusters
capture the observed
phenotypes?

bifrontal.bossing**Bitemporal.protusion****No****coronal.constriction****occipital protuberance**

Recovering observed phenotypes

- Observed phenotypes are mixture of the 4 published
 - More clusters
 - More ranking
- Are observed phenotypes reliable?
- Our approach is unsupervised
 - Try a supervised approach: learn from surgeon rankings

Recovering observed phenotypes

- We deformed all sagittals to a normal template
 - Deform to a sagittal template?
- Parameter search

Recovering observed phenotypes

- Maybe more than 4 phenotypes?
- Clinical relevance of phenotypes
 - Shape maintenance
 - Initial severity

Papers of Interest

1. Flaherty K, Singh N, Richtsmeier JT (2016) Understanding craniosynostosis as a growth disorder, *Wiley Interdiscip Rev Dev Biol* 5(4), 429-459.
2. Li Z, Park BK, Liu W et al. (2015) A statistical skull geometry model for children 0-3 years 579 old, *PLoS ONE* 10(5).
3. Andresen PRØ, Bookstein FL, Conradsen K, ErsbØll BK, Marsh JL, Kreiborg S. Surface-bounded growth modeling applied to human mandibles. *IEEE Trans Med Imaging*. 2000;19(11):1053-1063.
4. Herlin C, Largey A, DeMatteï C, Daurès JP, Bigorre M, Captier G. Modeling of the human fetal skull base growth: Interest in new volumetrics morphometric tools. *Early Hum Dev*. 2011;87(4):239-245.
5. Libby J, Marghoub A, Johnson D, Khonsari RH, Fagan MJ, Moazen M. Modelling human skull growth: a validated computational model. *J R Soc Interface*. 2017.
6. Avants BB, Tustison NJ, Song G, Gee JC (2009) ANTS: open-source tools for normalization and neuroanatomy, *TransacMed Imagins Penn Image Comput Sci Lab*.
7. Avants BB, Tustison NJ, Song G, Cook PA, Klein A, Gee JC (2011) A reproducible evaluation of ANTs similarity metric performance in brain image registration, *Neuroimage* 54(3), 2033-2044.