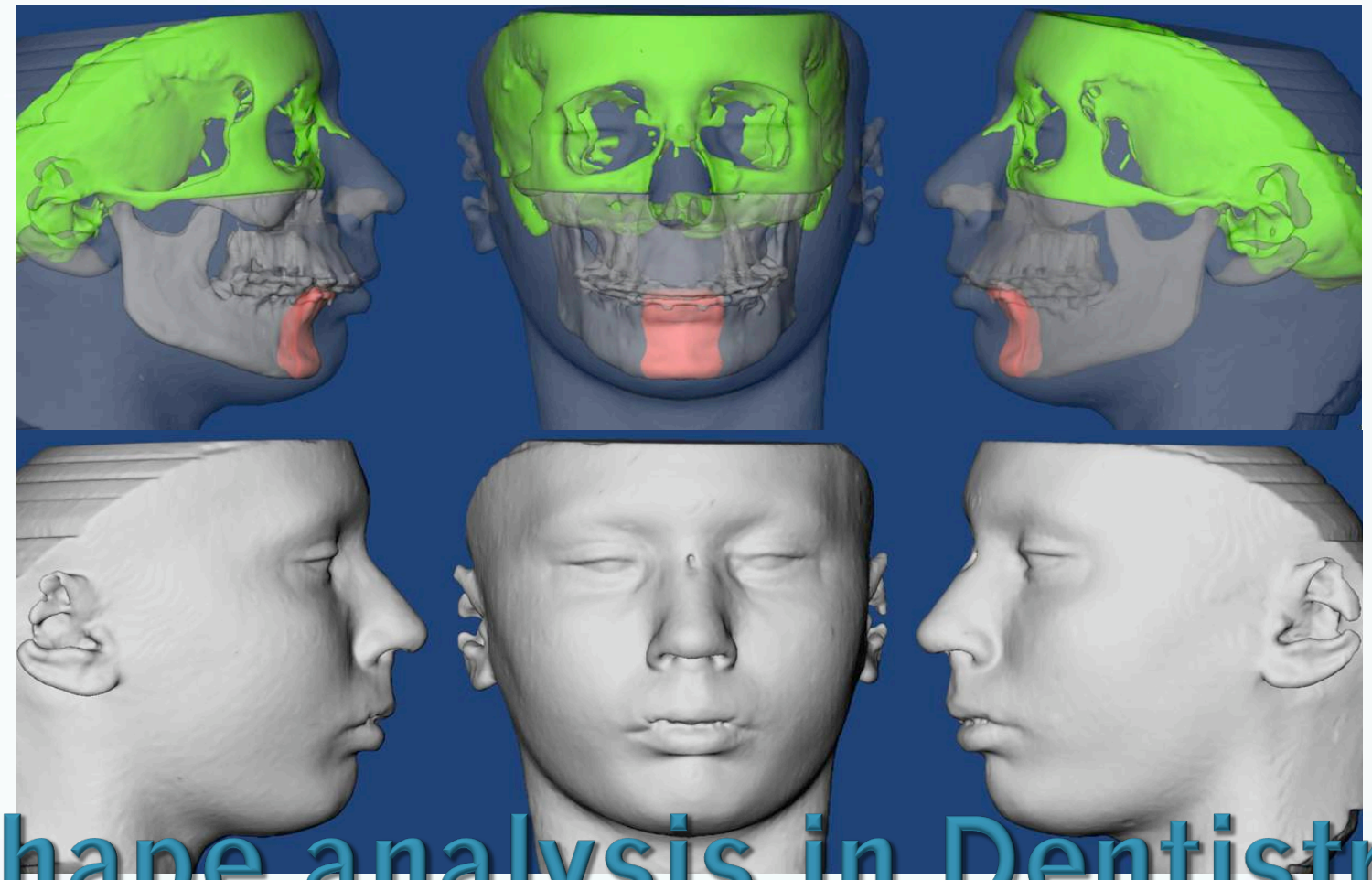

Shape analysis in Dentistry

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Departments of Computer Science and Orthodontics

Shape and Stats Seminar Friday 30th October 2009

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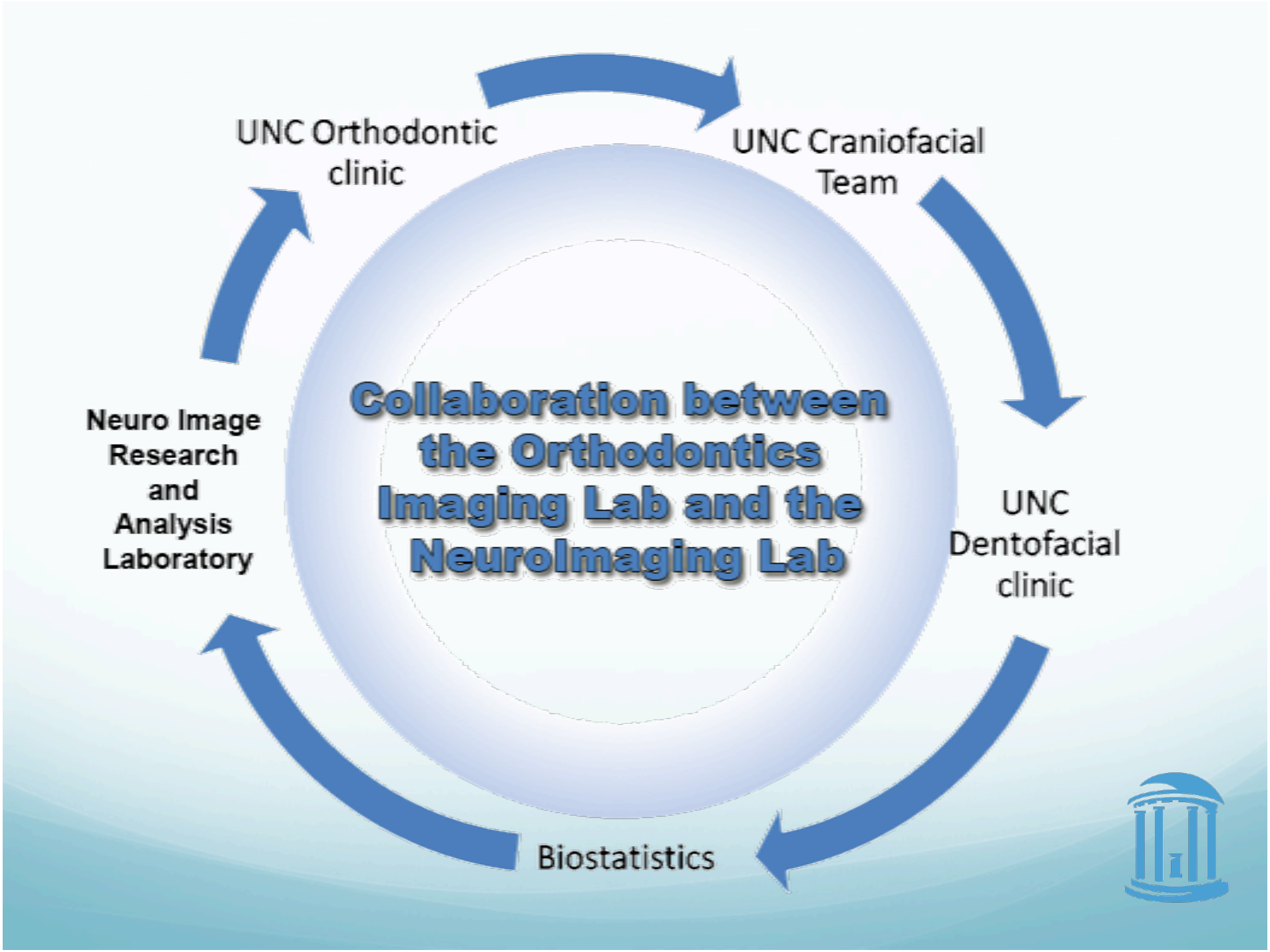
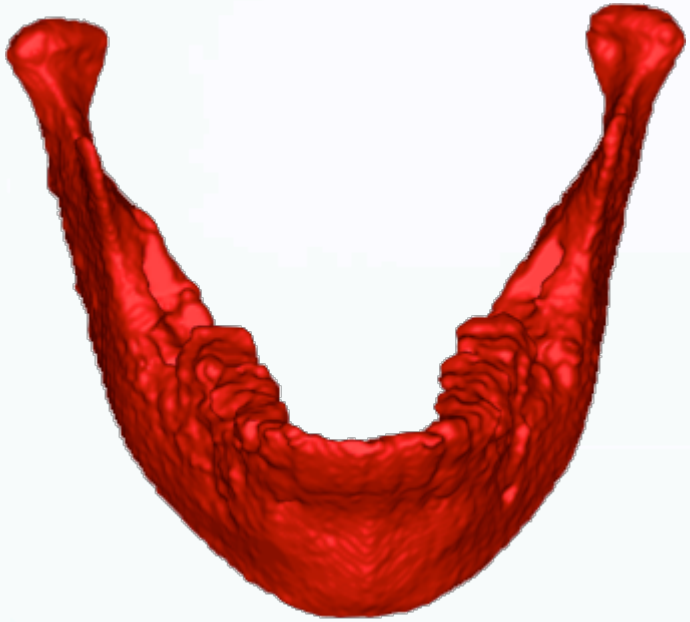
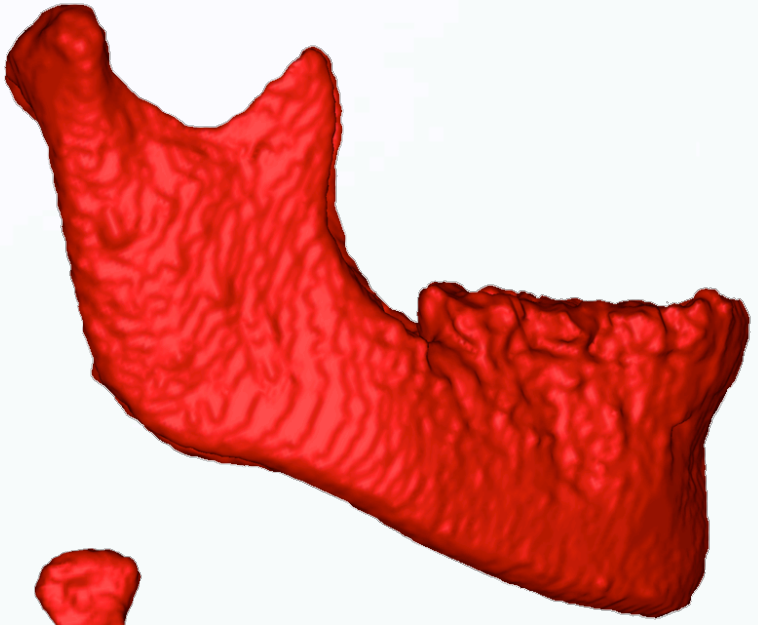
- Clinical application of Statistical Shape Analysis in Dentistry
  - Temporomandibular joint disease and osteoarthritis (ISBI 2010 Short validation paper – R01 proposal)
  - Orthonagtic surgery (IJCARS Journal paper – R03)
  - Asymmetry studies (Master & PhD proposal – Abeer Alhadidi)
- Dentistry not Orthodontics: Dental radiology, surgery *and* orthodontics
- Active discussion talk!!


UNC Orthodontic clinic
UNC Craniofacial Team
UNC Dentofacial clinic
Biostatistics
Neuro Image Research and Analysis Laboratory
Collaboration between the Orthodontics Imaging Lab and the NeuroImaging Lab

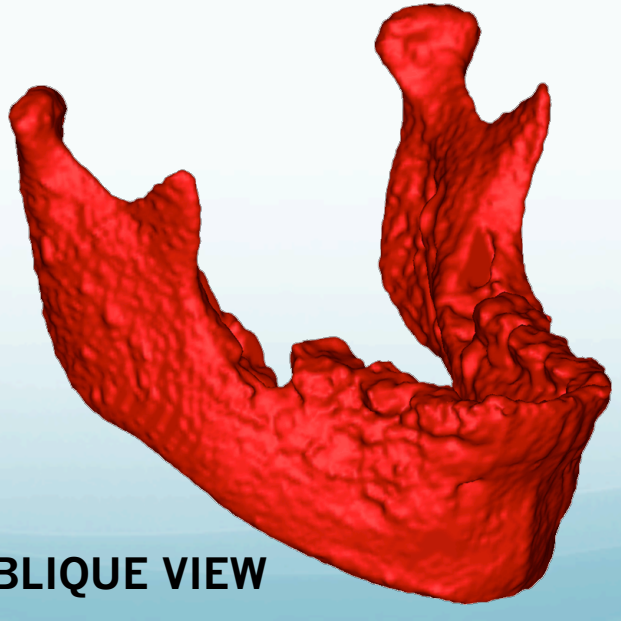
Mandibular Anatomy



ANTERIOR VIEW



LATERAL VIEW

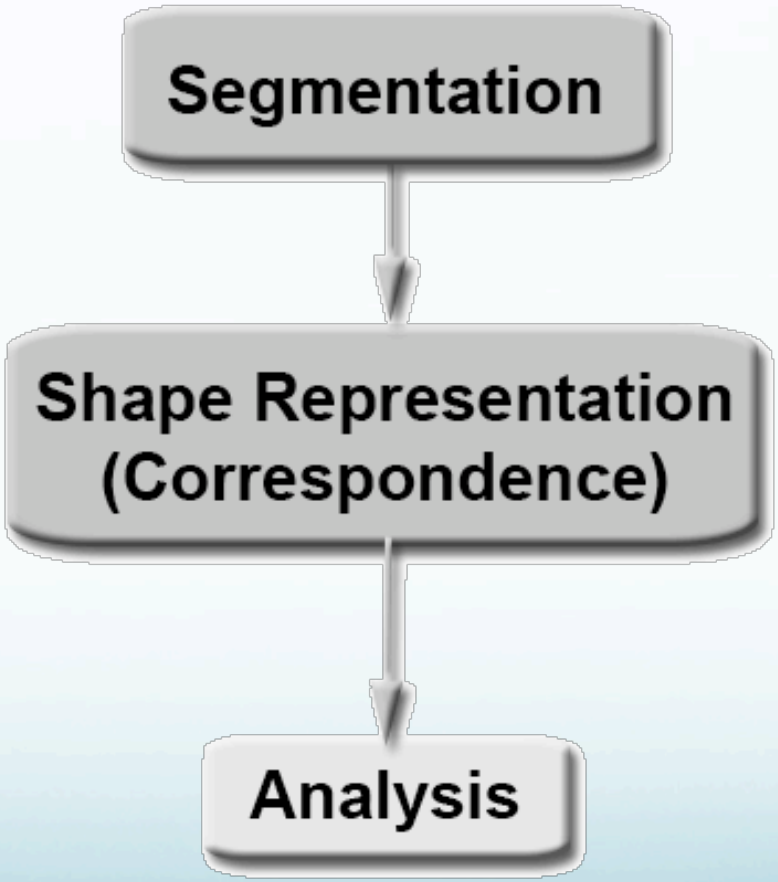


LATERAL OBLIQUE VIEW

Methods

Shape Correspondence
Statistical Shape Analysis

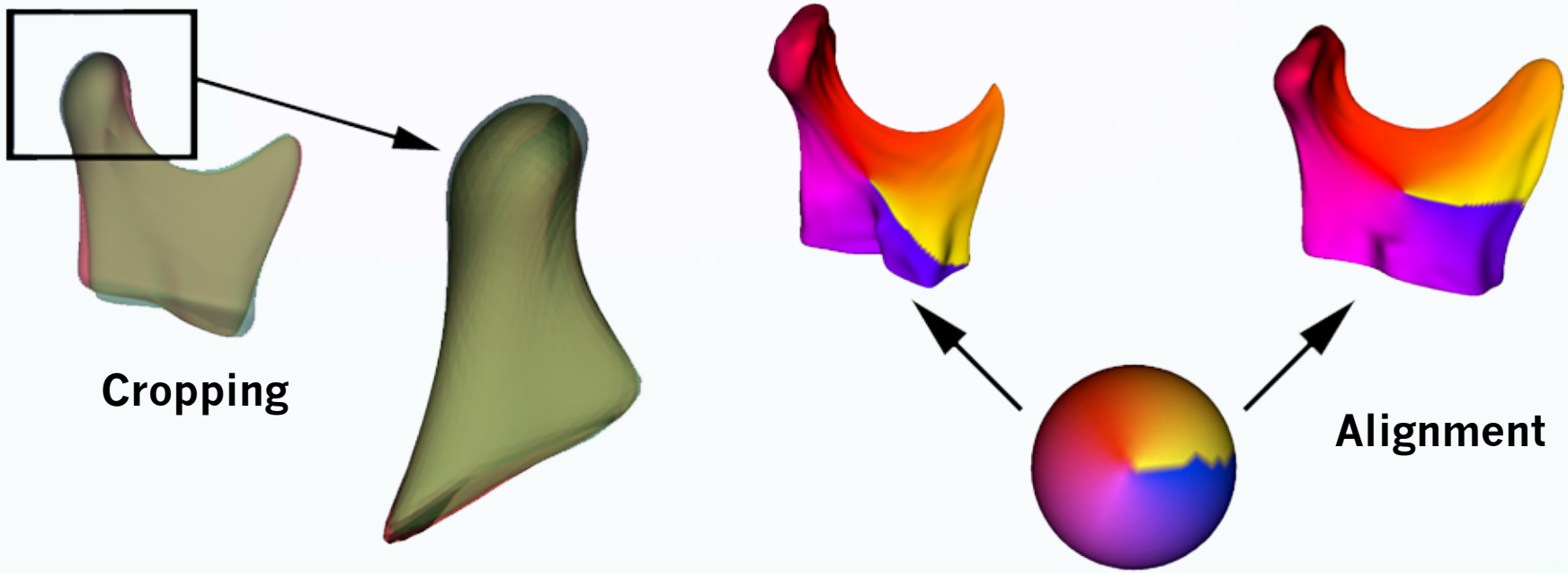
Shape Analysis (I)

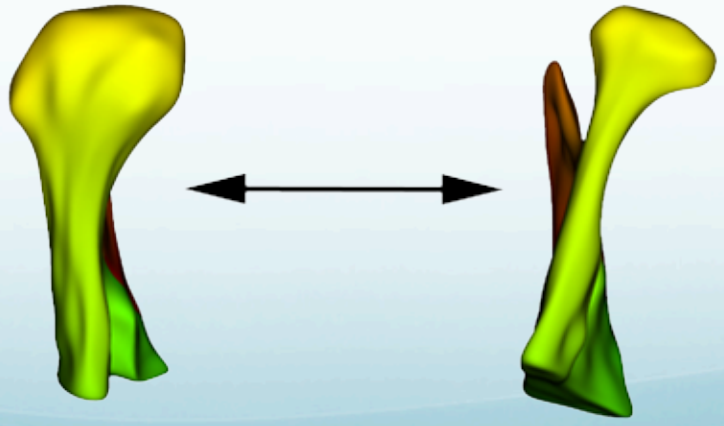


Shape Analysis (II)

- For each clinical application,
  - Shape representation
  - Appropriate correspondence
    - Pose normalization
    - Parameters
    - ...
  - Statistical analysis:
    - What is clinically relevant?
- Forever on-going research

Shape Analysis (III)

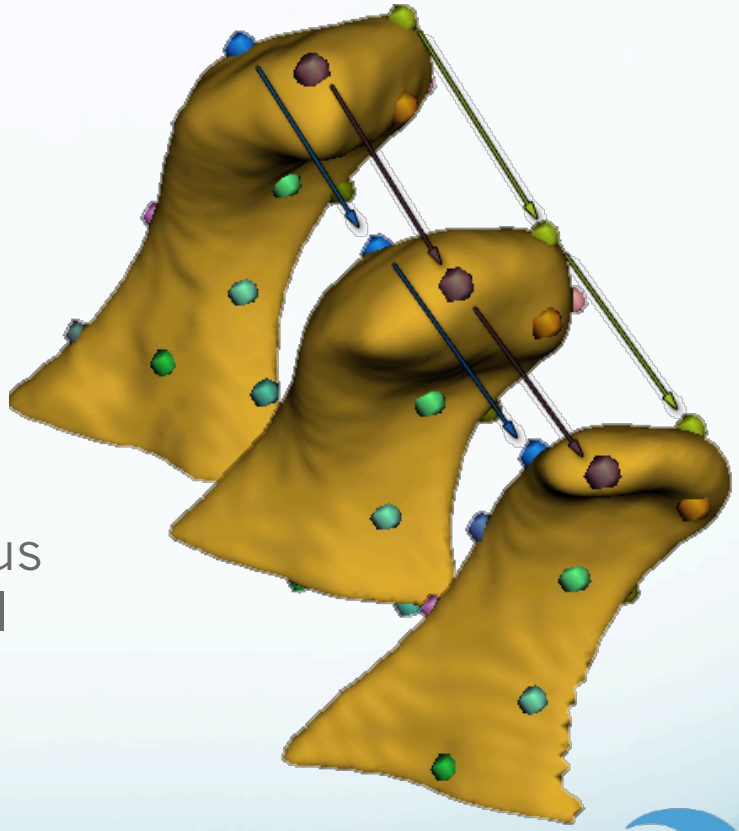




... and more ...

Shape Correspondence (I)

- Definition of correspondence influences directly analysis
- Correspondence frameworks:
  - Anatomical correspondence
    - Landmarks
  - Functional correspondence
    - In brain morphometry i.e. locus responsible for same neuronal functionality
  - *Geometry correspondence*
    - *Ridges, critical points*



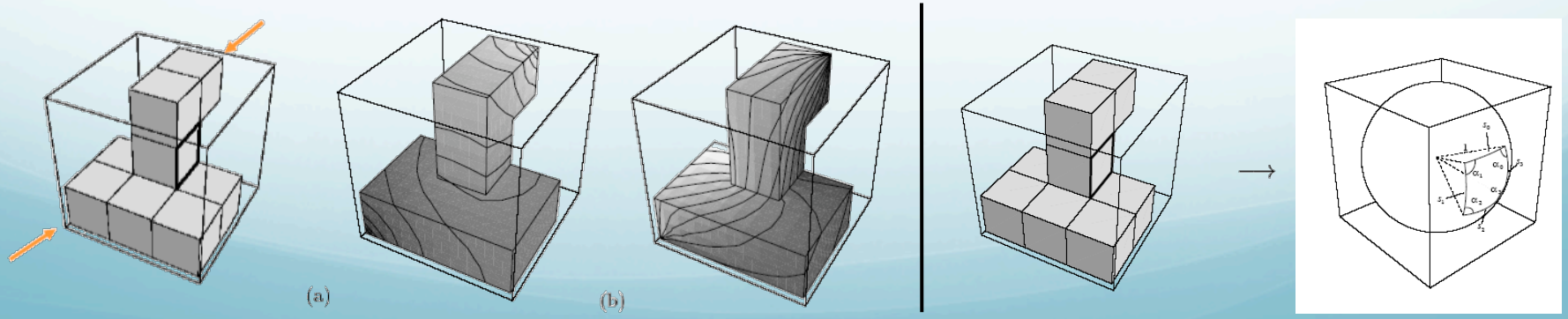
Shape Correspondence (II)

- Different geometric correspondence options
  - Matching of template surface geometry
    - Curvature + Location
    - Meier, Medical Imaging 02
  - *Spherical optimization can be well-defined*
    - *Parameterization based correspondence → Optimize over (φ,ϕ), evaluate on surface*
  - Population based:
    - Entropy-based Particle Systems - Cates, IPMI 07
    - Ipek Oguz

"Shape Modeling and Analysis with Entropy-Based Particle Systems" J Cates, P T Fletcher, M Styner, M Shenton, R Whitaker. IPMI 2007, LNCS 4584, pp. 333-345, 2007.
"Parameter space warping: shape-based correspondence between morphologically different objects" Meier, D. Fisher, E. IEEE Transactions on Medical Imaging, 2002

SPHARM (I): Parameterization

- Spherical topology
- Two parameters, longitude and latitude (φ,ϕ).
- Mapping of surface to unit sphere
  - Difficult, no unique ordering of points in 3D
  - Initialize with heat equation mapping
  - Optimization for equal area ratio mapping with minimal angular distortion



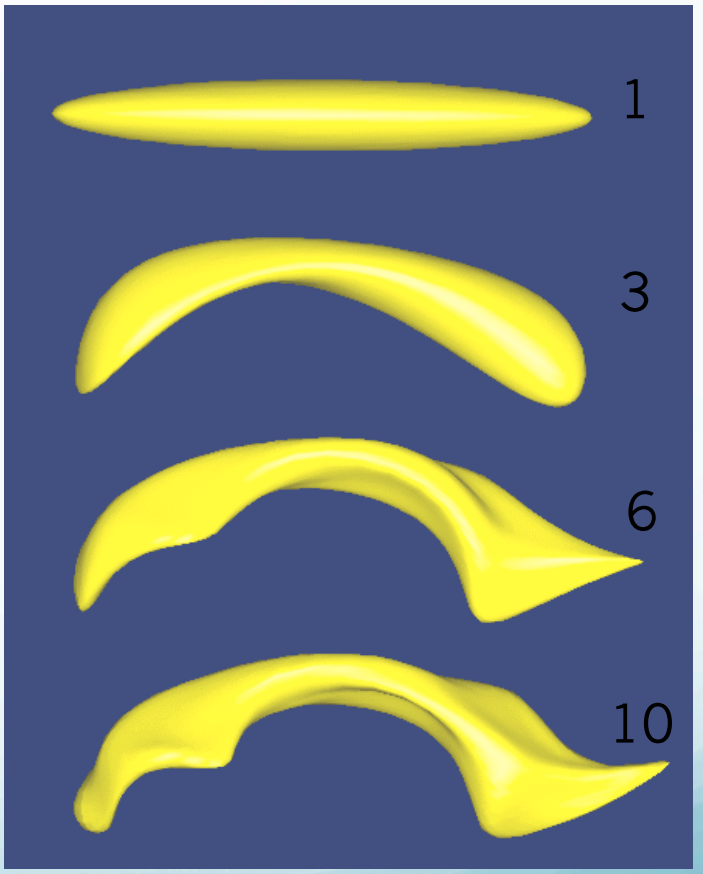
SPHARM (II): Representation

- Hierarchical description
- Spherical harmonics basis

1. Surface & Parameterization
2. Fit coefficients of parameterized basis functions to surface
3. Reconstruct object →PDM

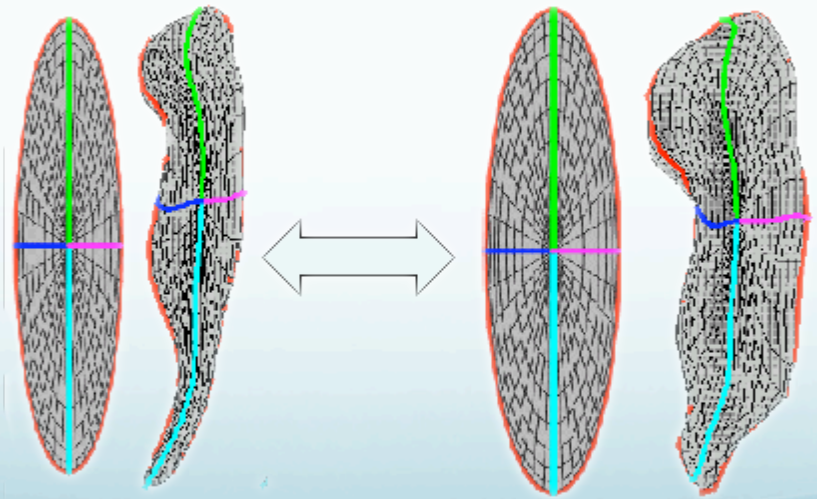
$$\begin{matrix} x \\ y \\ z \end{matrix} \rightarrow \boldsymbol{r}(\theta,\phi) = \begin{pmatrix} x(\theta,\phi) \\ y(\theta,\phi) \\ z(\theta,\phi) \end{pmatrix}$$

$$\boldsymbol{r}(\theta,\phi) = \sum_{k=0}^{K} \sum_{m=-k}^{k} \boldsymbol{c}_k^m \boldsymbol{Y}_k^m(\theta,\phi) \rightarrow \boldsymbol{c}_k^m = \begin{pmatrix} c_{xk}^m \\ c_{yk}^m \\ c_{zk}^m \end{pmatrix}$$



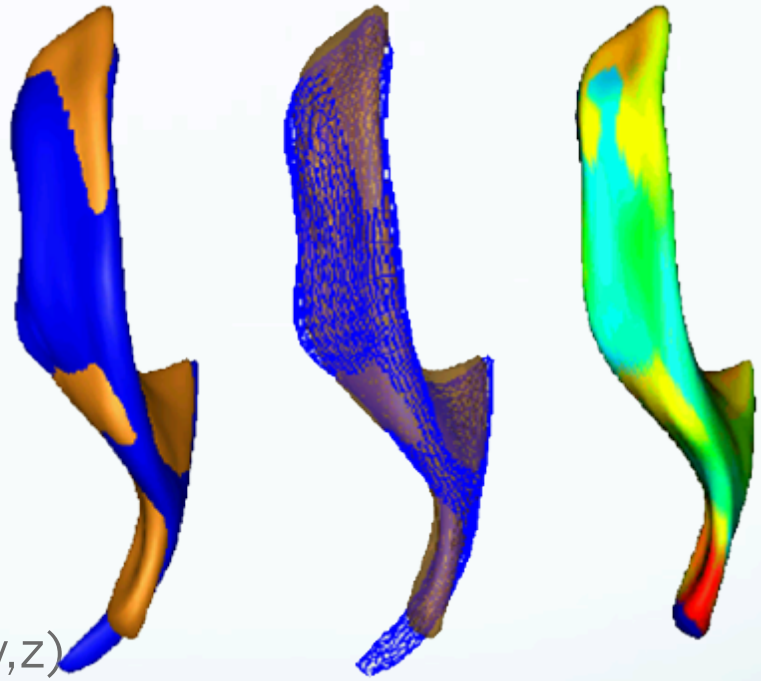
SPHARM (III): Correspondence

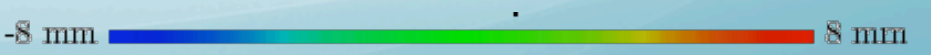
- Correspondence by same parameterization
  - Area ratio preserving through optimization
  - Location of meridian and equator
- Normalize the pose: poles and axis of first order ellipsoid



Statistical Analysis

- Surfaces with
  - Correspondence
  - Pose normalized
- Analyze shape features
  - Features per surface point
  - Univariate
    - Distance to template
    - Thickness
  - Multivariate, point locations (x,y,z)
- Results displayed by means of diverse color-coded maps

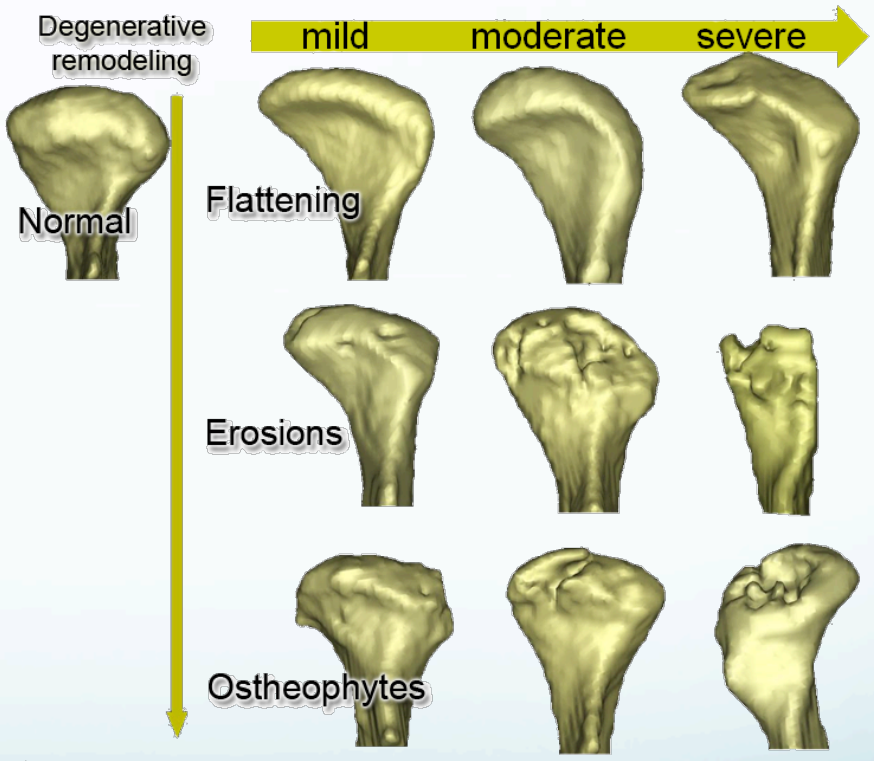




Temporomandibular joint disease and osteoarthritis

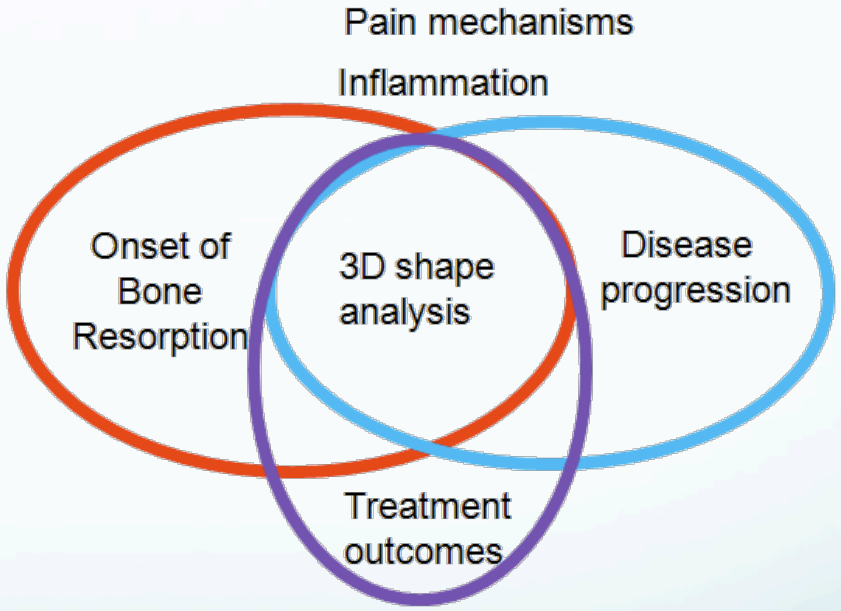
TMJ OA Studies (I)

- Shape analysis used to localize and quantify the condylar morphological differences in the progression of the Temporomandibular Joint Osteoarthritic disease.
- 3D models obtained from CBCT → visualize the progression of degenerative change and levels of severity.
- Progression (flattening, erosions and osteophytes) of degenerative change versus levels of severity.



TMJ OA Studies (II)

- **Groupwise studies** → localize and quantify the condylar morphological differences among diseased and healthy population.
- **Correlation studies** → help to elucidate the interactions between condylar morphology, inflammation and pain pathways.
- **Longitudinal studies** → **treatment planning and evaluation of treatment outcomes.**

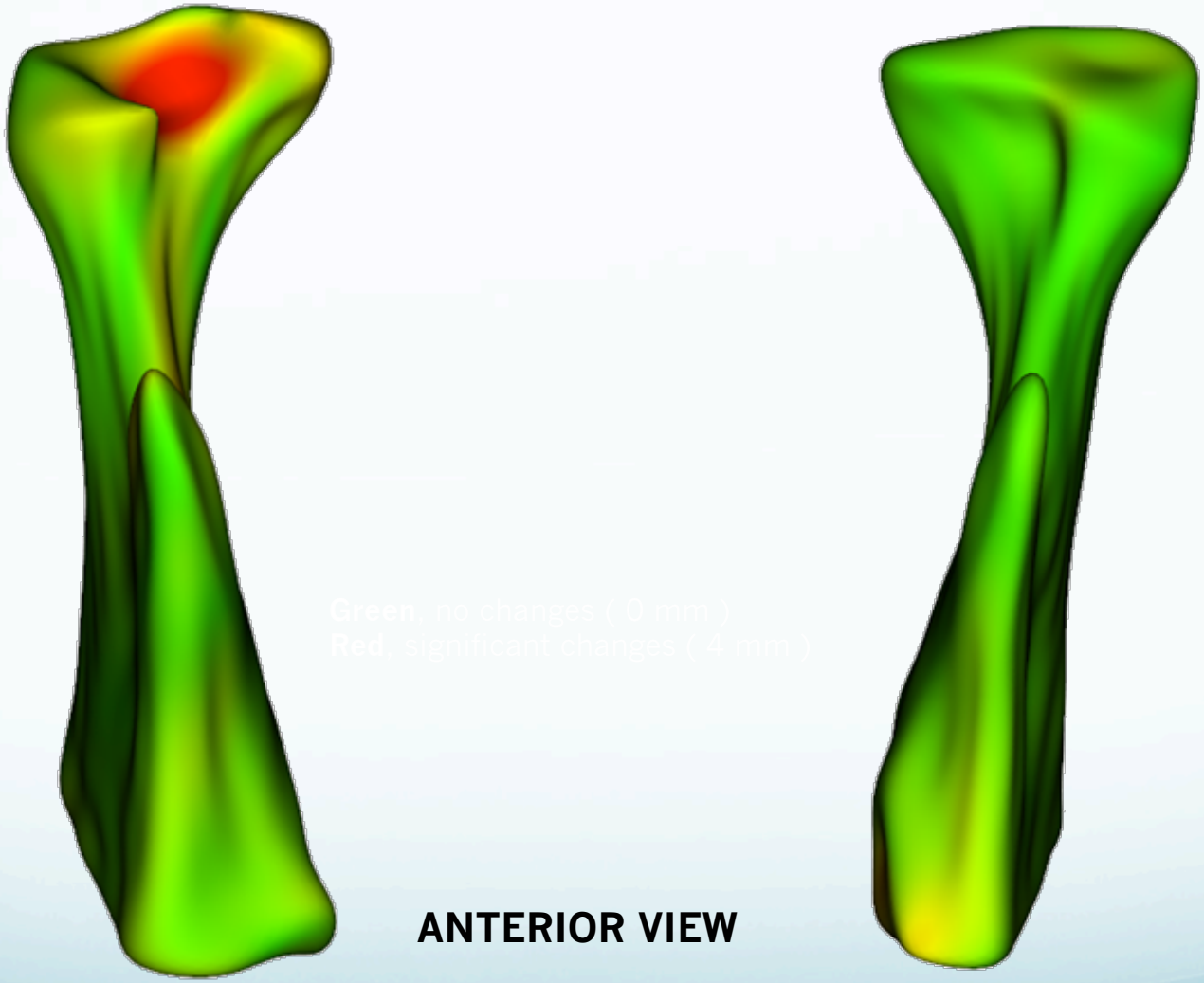


"Condylar Resorption in Subjects with TMJ Osteoarthritis" Lucia H.S. Cevidanes, Anna-Kari Hajati, Beatriz Paniagua, David G. Walker, Martin Styner, Pei Feng Lim. *Submitted to the* Journal of Dental Research, 2009

TMJ OA Longitudinal Analysis

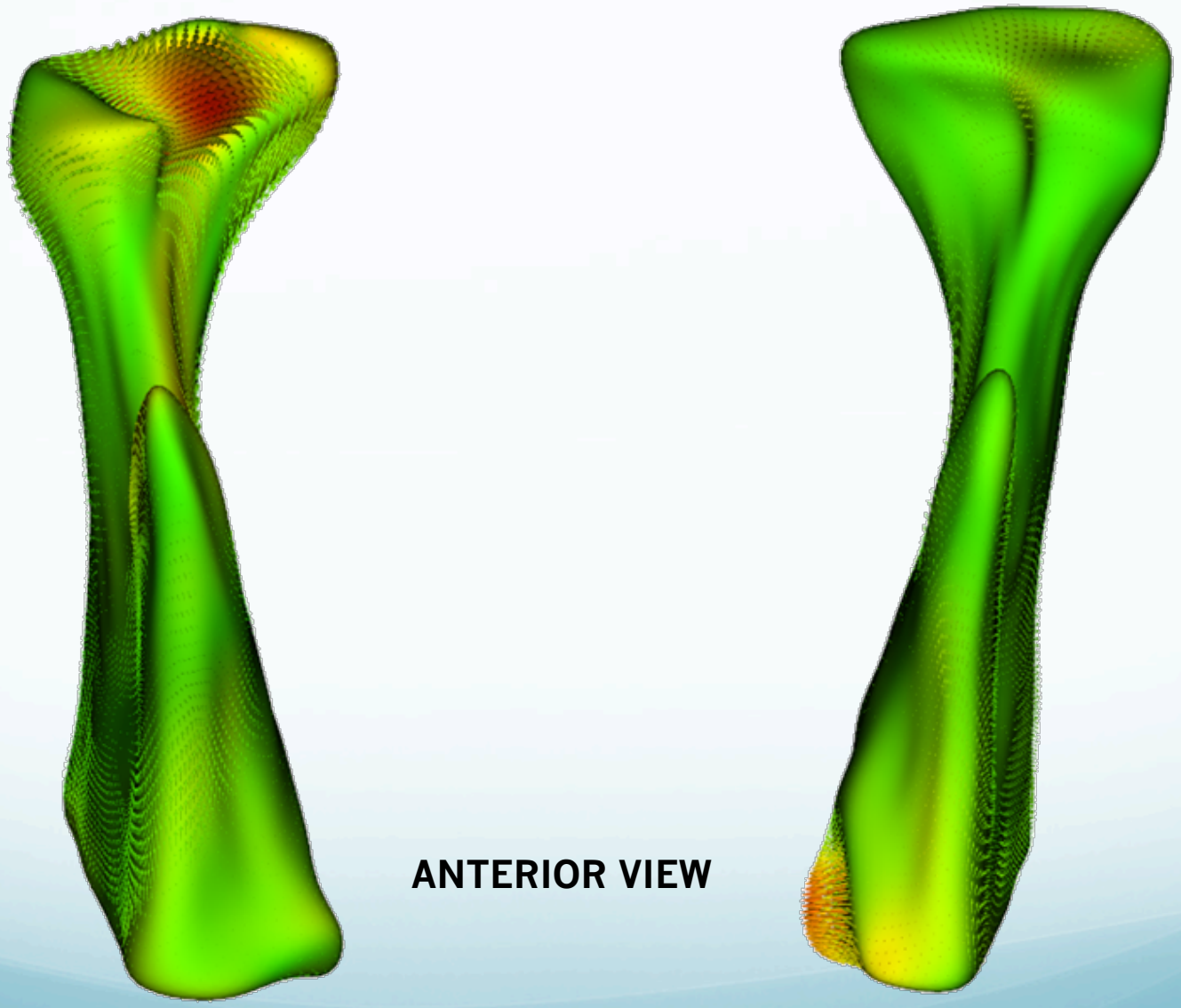
- Objectives:
  - Documentation of the progression of the disease after treatment
  - Find correspondence between the models generated at a baseline and a two years follow-up.
- Results: Vector maps, magnitude maps for clinical evaluation

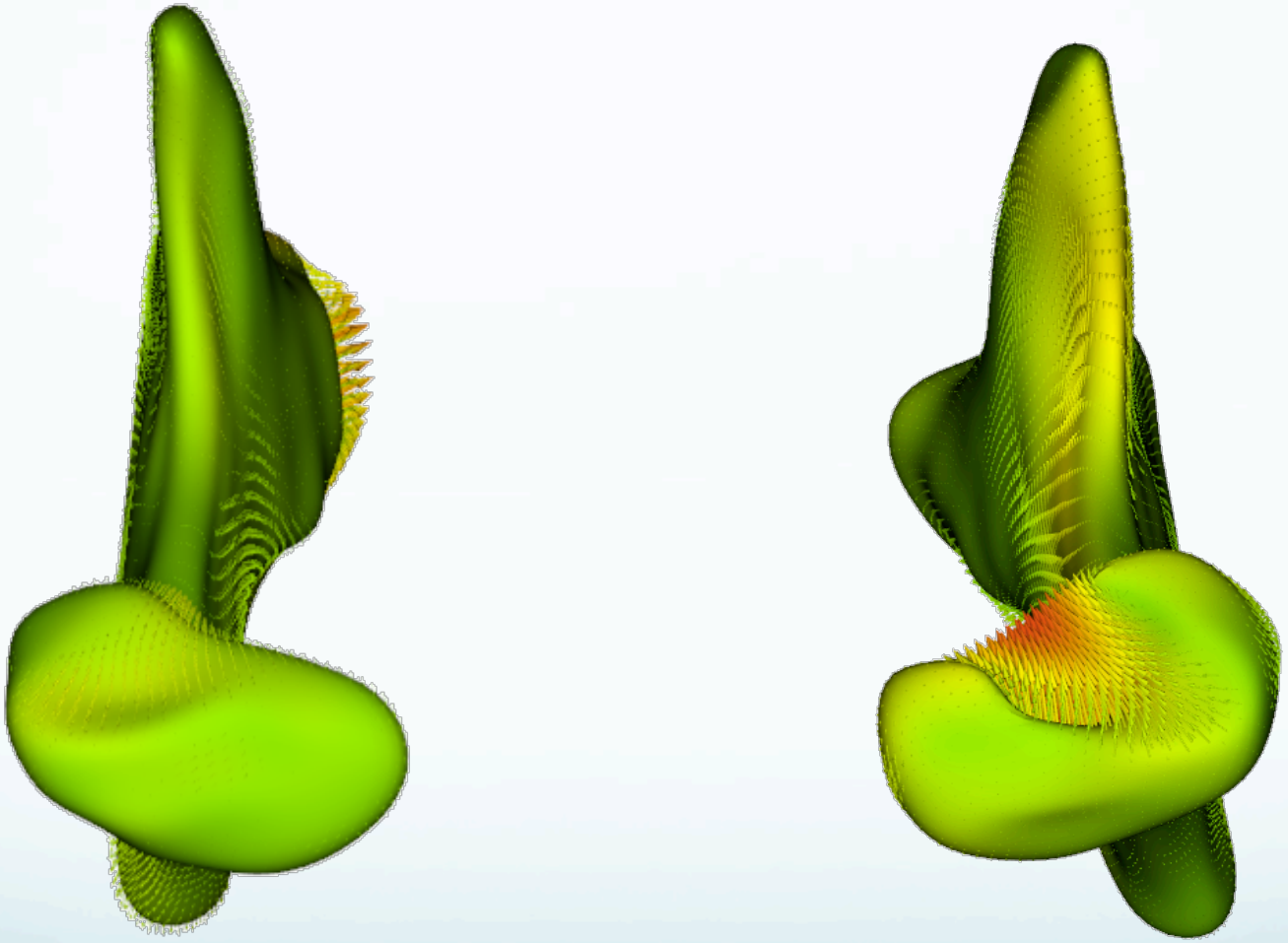
Measurements: Distance Maps



SUPERIOR VIEW

Measurements: Vector Maps





SUPERIOR VIEW

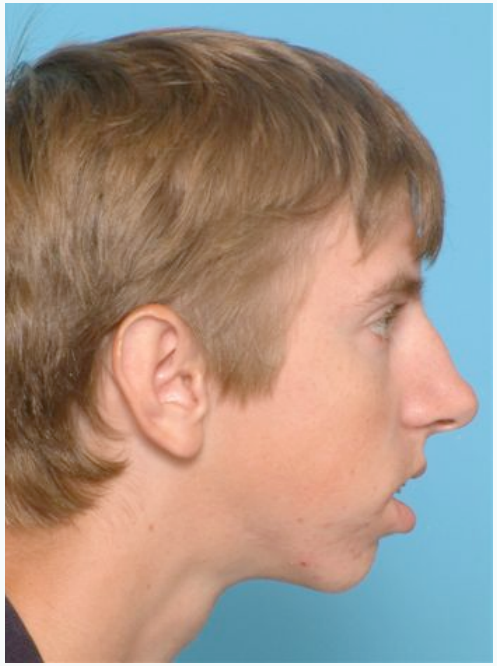
Clinical Case

2001

(12 yo)

2004

(15 yo)

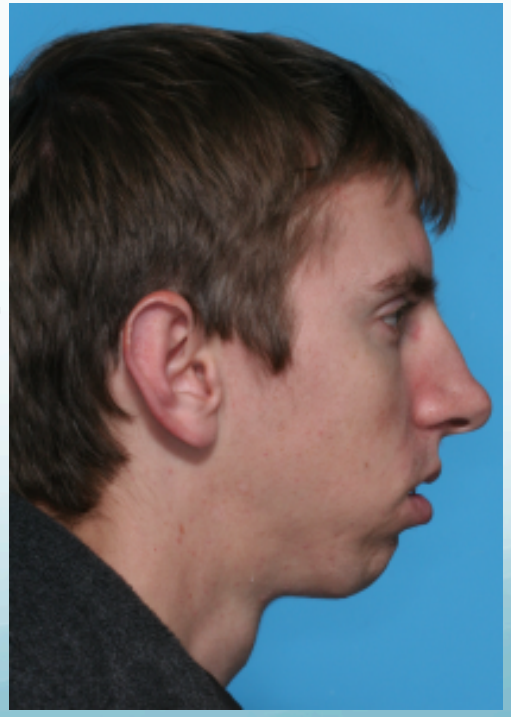


2005

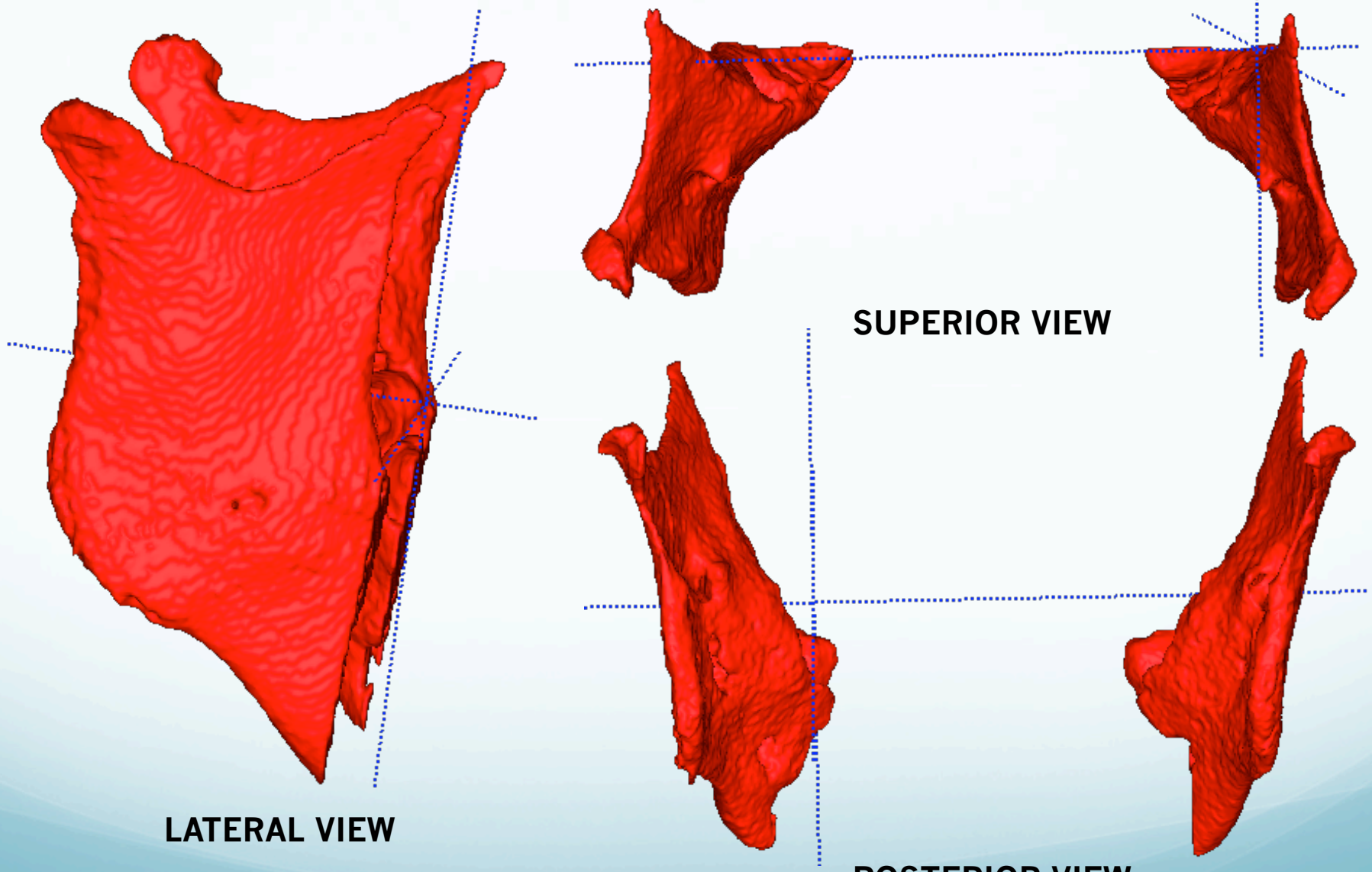
(17 yo)

2007

(19 yo)

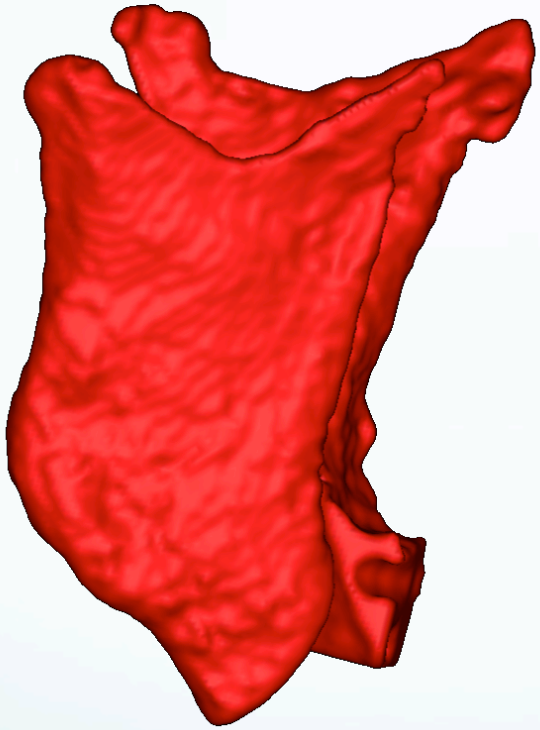


CBCT 3D models – 8/05



ITK-SNAP - *www.itksnap.org*

CBCT 3D models – 11/07



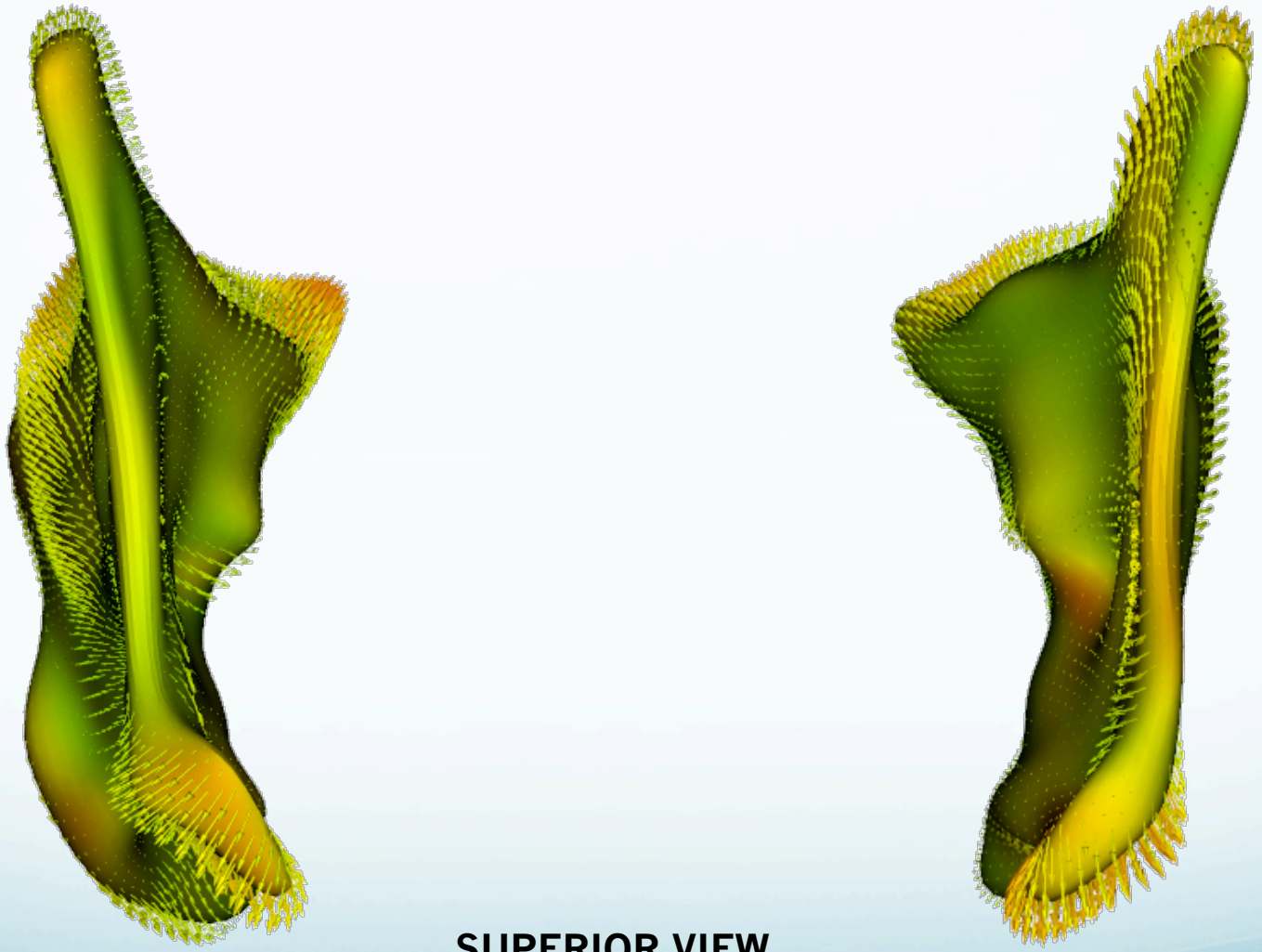
LATERAL VIEW

SUPERIOR VIEW

POSTERIOR VIEW

ITK-SNAP - *www.itksnap.org*

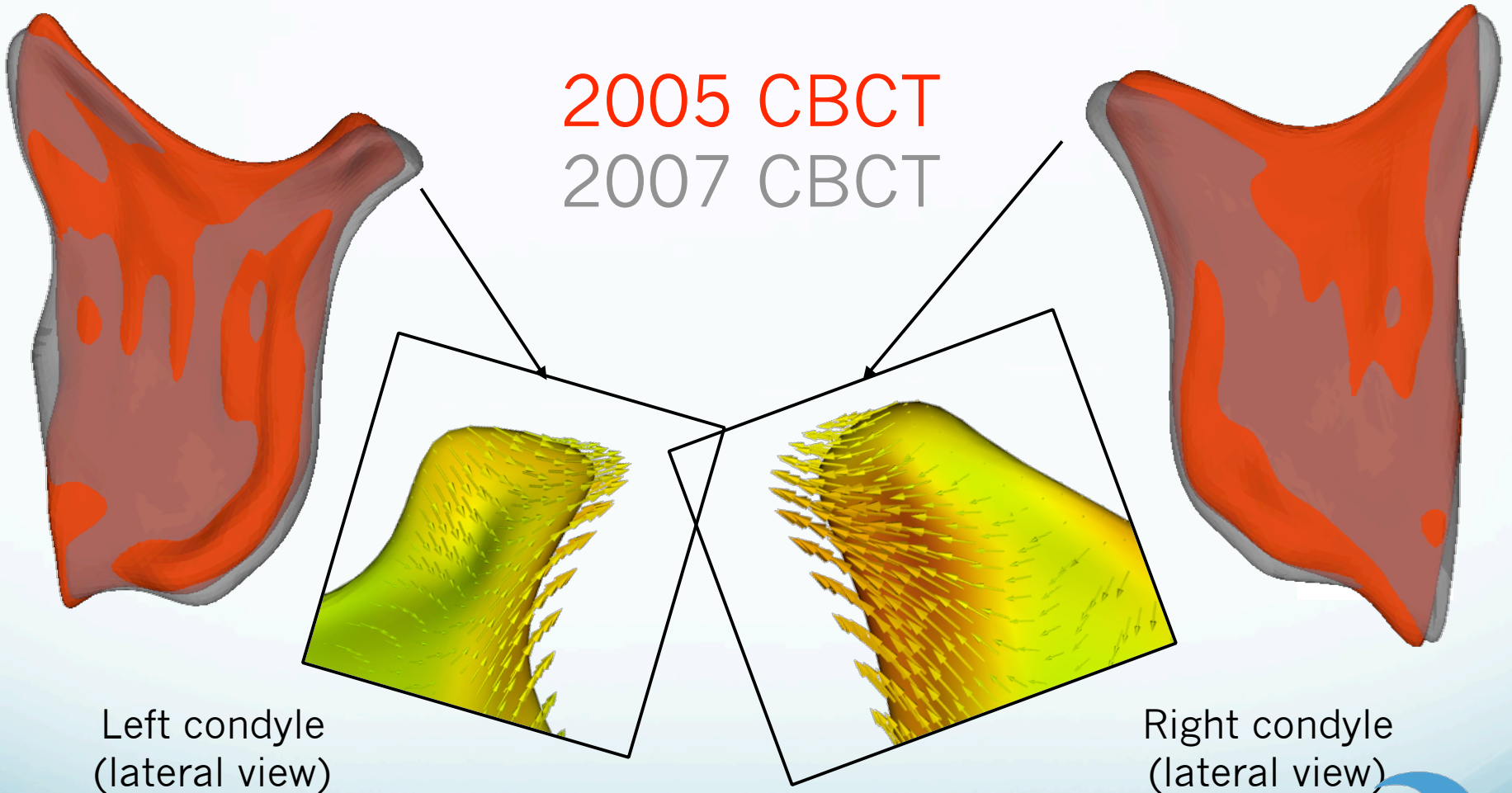
Vector maps



SUPERIOR VIEW

0mm 3mm

Semi-transparent overlays



SPHARM+PDM software - http://www.ia.unc.edu/dev/download/shapeAnalysis

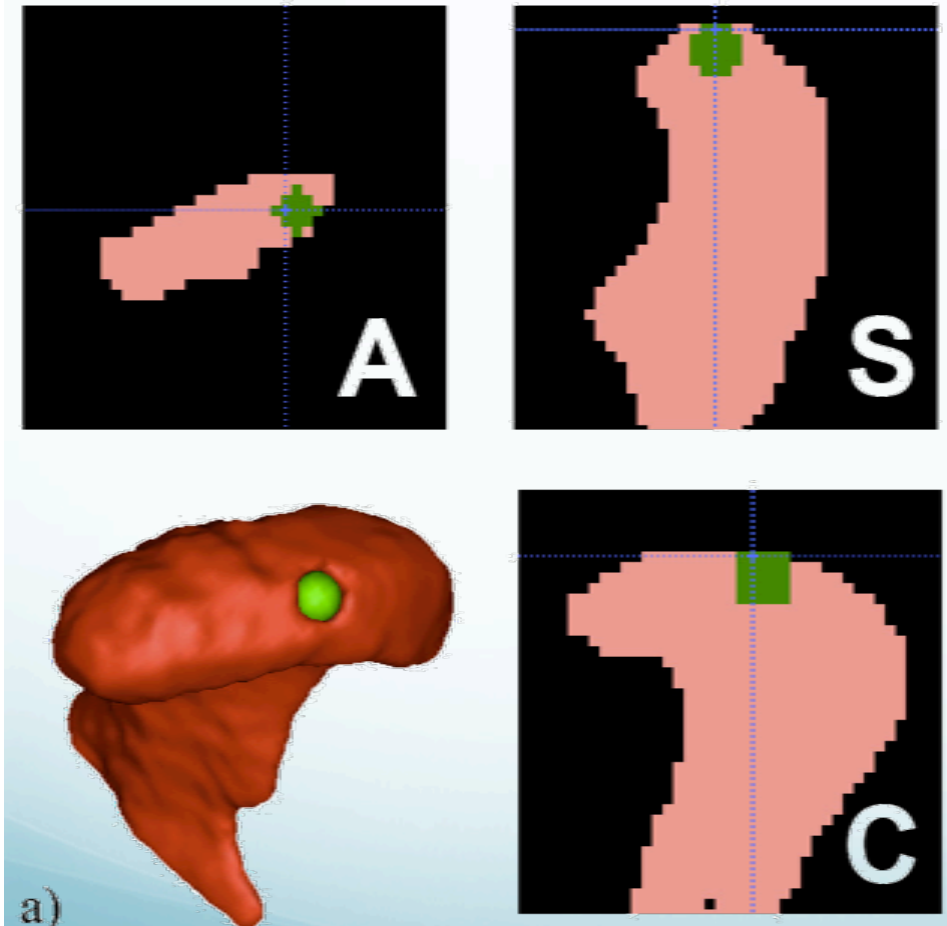
Slicer3 - http://www.slicer.org/

ISBI 2010

ISBI2010: Validation Shape Analysis

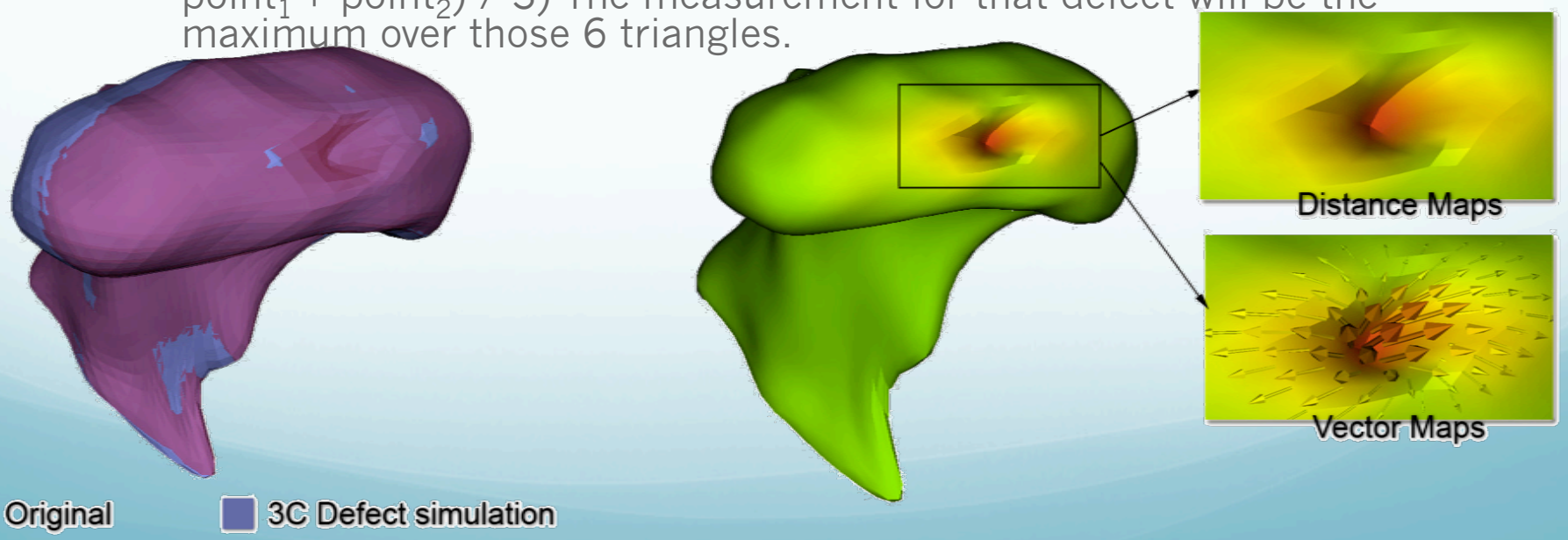
- There is no validated method for the quantification of discrete changes in joint morphology.
- **Proposal**:
  - Use **simulated bone resorption** to study condylar morphological variation.
  - Agreement between the simulated defects and the shape analysis measurements within 0.5mm (the image's spatial resolution).
  - 179 discrete bony defects measuring 3mm and 6mm
  - SPHARM shape correspondence was used to localize and quantify morphological differences.
  - The size of each simulated defect was analyzed and the values obtained compared to the true defect size.

Simulated bone resorption



Shape Correspondence & Measurements

- SPHARM correspondent models
- Defect measurement:
  1. Absolute difference maps between each resorption 3D model and the original 3D model.
  2. Selection of ROIs.
  3. ROI absolute differences map.
  4. Maximum difference in the ROI-differences map and its six neighbor triangles. Then, the value for each one of the 6 triangles was found for the maximum point neighborhood. (triangle value = ($point_0$+ $point_1$ + $point_2$) / 3) The measurement for that defect will be the maximum over those 6 triangles.



Statistical Analysis

- Statistical methods:
  1. **Probability** that the difference between the sample mean and the hypothesized mean is less than 0.5 mm
  2. **95% CI**, interval with 95% confidence in which we can state that true mean of falls within the interval
  3. **95% PI**, estimate of an interval that a future observation of a random variable (if any) would fall with certain probability

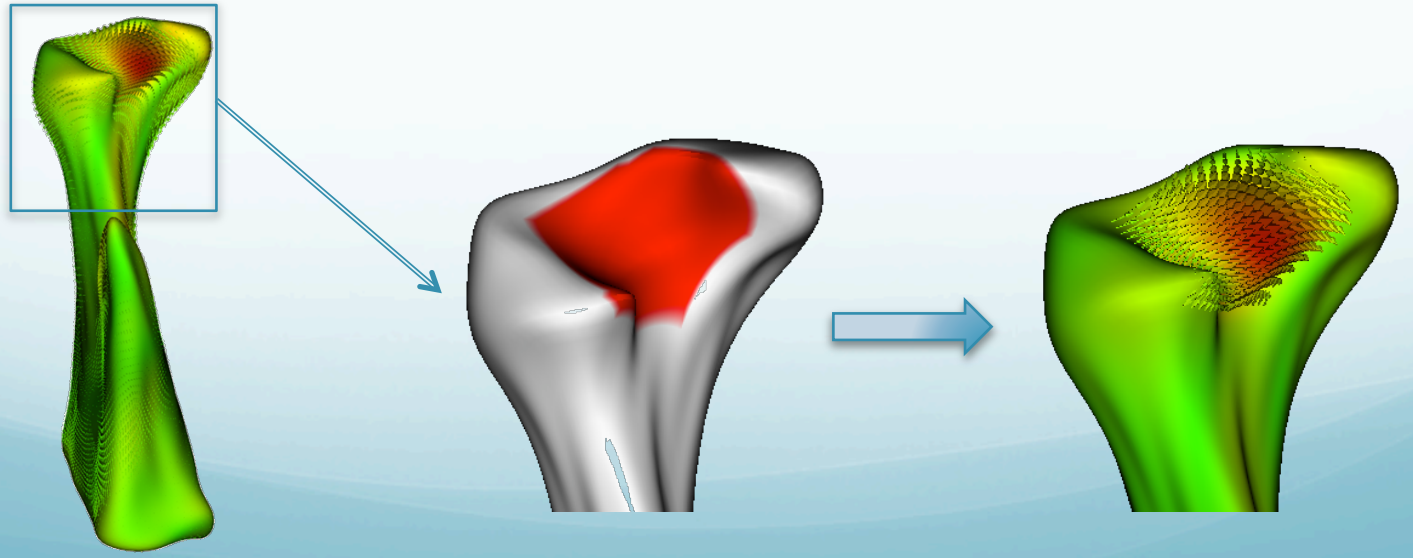
- **Results**: right and left condyles grouping and defects grouping.

Left Condyles	$3C$	$3M$	$3L$	$3CML$	$6C$
$P(\lvert\bar{X}-\mu_0\rvert) < 0.5$	0.9999	1.0000	1.0000	0.9999	0.9987
95% CI	(2.7093,3.1302)	(2.8859,3.2482)	(2.6265,3.0233)	(2.7045,3.1081)	(6.0639,6.5703)
95% PI	(1.9786,3.8608)	(2.2570,3.8770)	(1.9158,3.7340)	(2.0038,3.8088)	(5.4400,7.1942)
Right Condyles	$3C$	$3M$	$3L$	$3CML$	$6C$
$P(\lvert\bar{X}-\mu_0\rvert) < 0.5$	1.0000	0.9998	0.9999	1.0000	0.9303
95% CI	(2.4947,2.8685)	(2.4681,2.9218)	(2.4272,2.8370)	(2.5240,2.8218)	(5.2333,6.3620)
95% PI	(1.8457,3.5175)	(1.7063,3.6837)	(1.7156,3.5486)	(2.0412,3.3046)	(4.4154,7.1800)

Defects	3mm Avg	6mm Avg
$P(\lvert\bar{X}-\mu_0\rvert) < 0.5$	1	1
95% CI	(2.6686,2.9188)	(5.9905,6.3583)
95% PI	(2.2204,3.3670)	(5.5374,6.8114)

Future work: Clinical Application

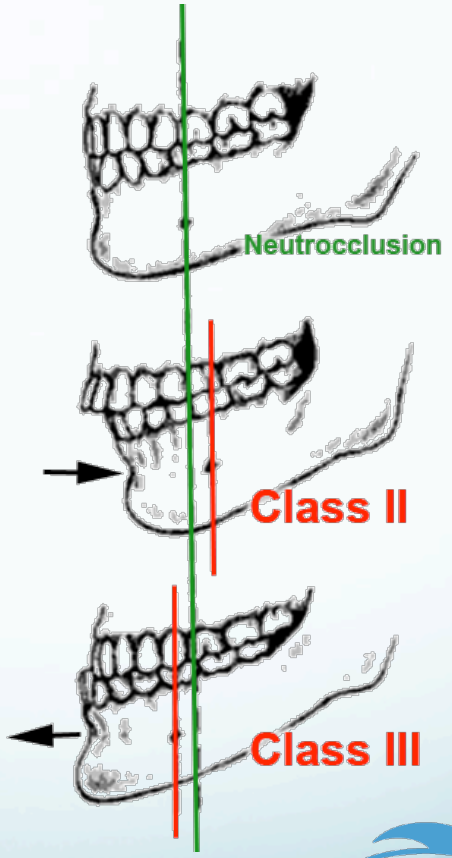
- We need to come out with some meaningful measurement for analyzing and quantifying the progression of the disease in a certain patient.
  - Treatment design
  - Progression follow-up (different time points)
- Combined measurement (?) Size of degeneration (i.e. #points ROI) and shape differences.



Orthonagtic surgery
(IJCARS Journal)

Orthonagthic Surgery (I)

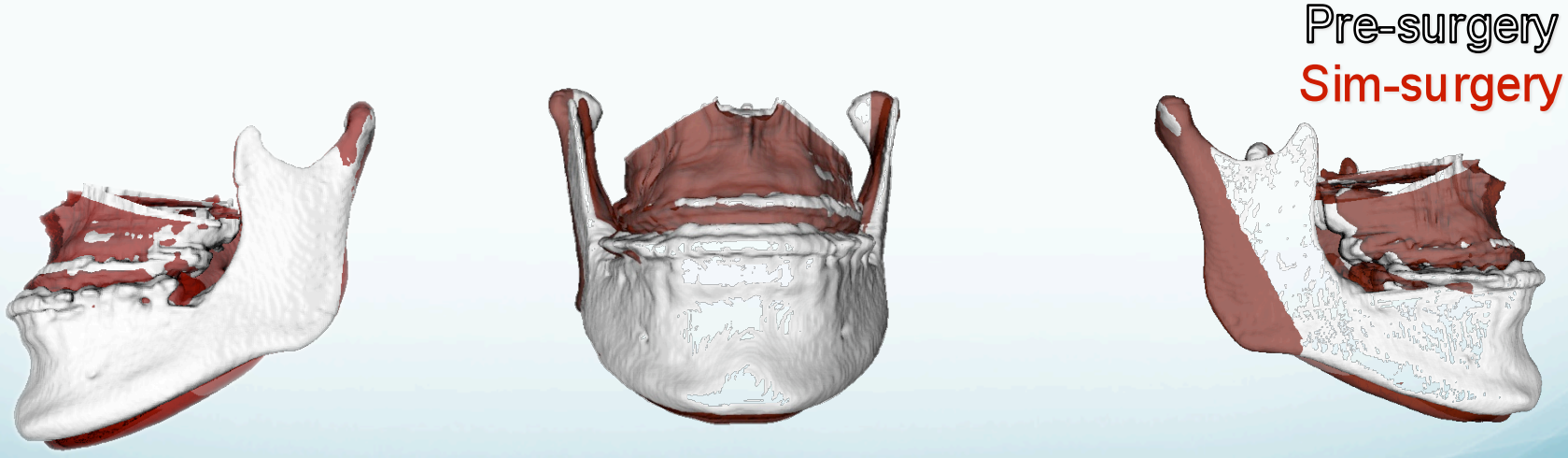
- Test the variability of surgeon surgery outcomes compared with virtual surgery models. Before, Iterative Closest Points.
- **Data** → Existing dataset of 20 cases of pre-surgery and simulated-surgery CBCT images.
- Is Shape Correspondence able to measure virtual surgery outcomes??



"Craniofacial Surgery" Seth Thaller, Joe I. Garri, James P. Bradley, Henry K. (INT) Kawamoto Contributor Henry K. (INT) Kawamoto. CRC Press, 2007

Orthognathic Surgery (II)

- CranioMaxilloFacial (CMF) application software. Developed and validated at the M.E. Müller Institute for Surgical Technology and Biomechanics, University of Bern, Switzerland.
- For each case, simulated surgery outcomes will be created, to compare with the imaging data acquired prior surgery.



LEFT SAGITAL VIEW **ANTERIOR VIEW** **RIGHT SAGITAL VIEW**

"3D Surgical Planning and Navigation for CMF Surgery " Chapuis J, Rudolph T, Borgeson B, De Momi E, Pappas I, Hallermann W, et al. SPIE Medical Imaging, San Diego, California, USA. 2004 February.

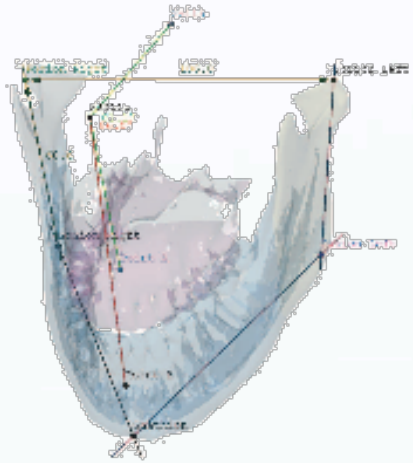
CranioMaxilloFacial Software

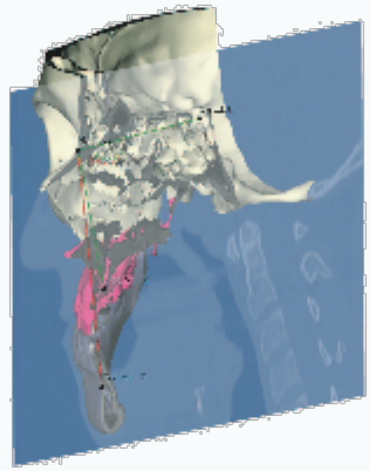
a) Landmarks, distances, angles, lines for 3D cephalometry

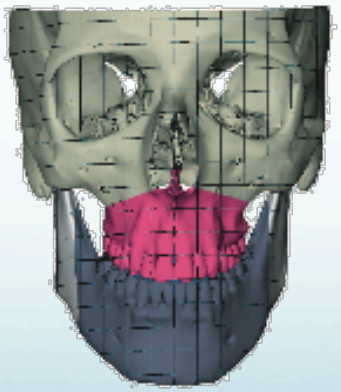
b) Reference planes with superimposition of CT slices and model clipping

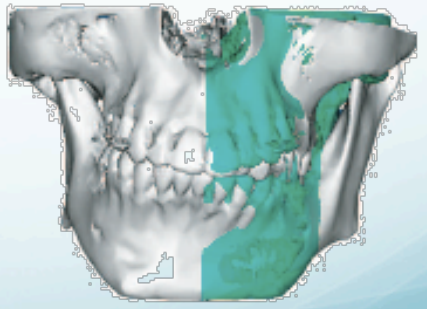
c) Super imposed grids for quick evaluation of facial proportions

d) Semi-transparent overlay of the contra lateral side, mirrored using the mid-sagittal plane.



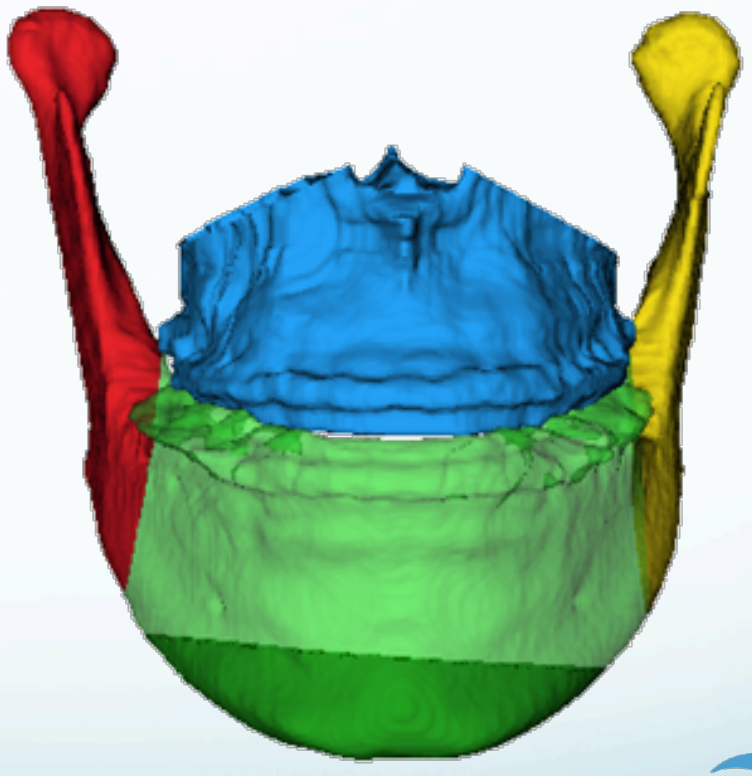






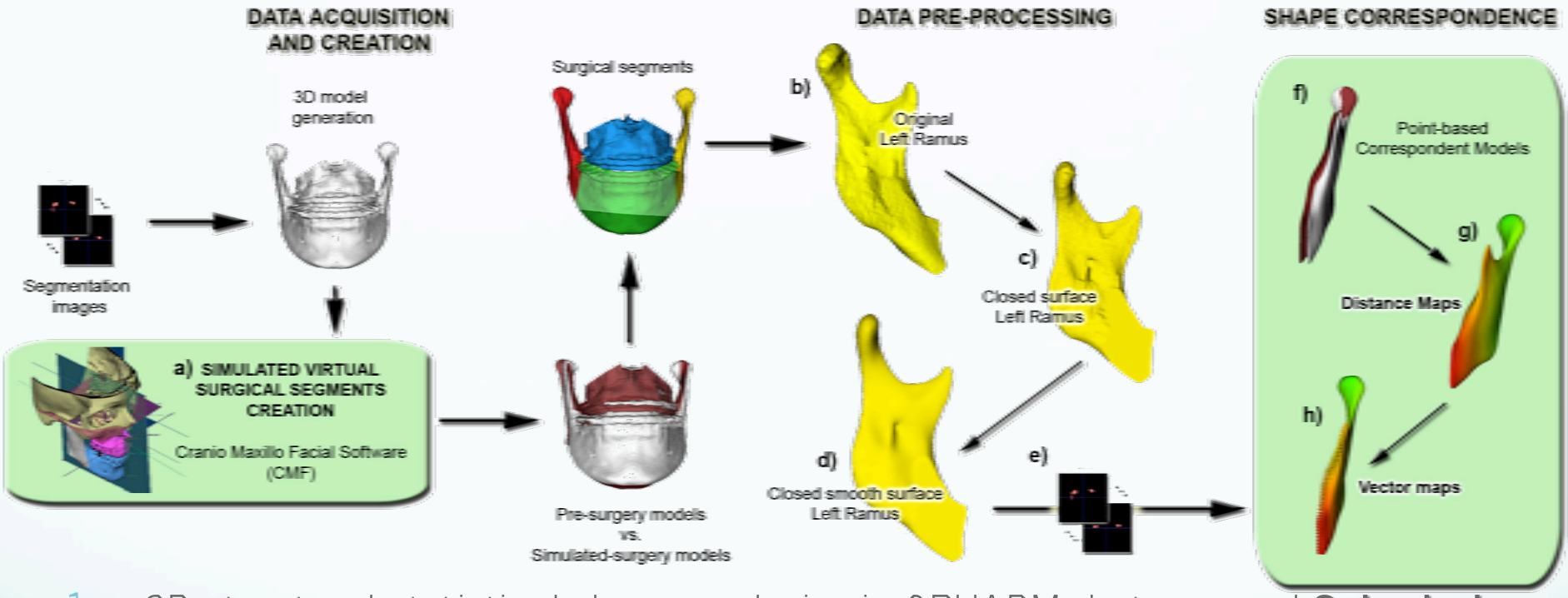
Virtual Osteotomies

- Depending on the surgery each case has different osteotomy cuts.
- Virtual cuts will match planned clinical osteotomy segments.
- Segments → Chin, Left Ramus, Right Ramus, Mandibular Body, Maxillary Body.



"Principles of Surgery" I. Schwartz., Single Volume. McGraw-Hill Professional, 7 edition, 1998.

Shape Correspondence

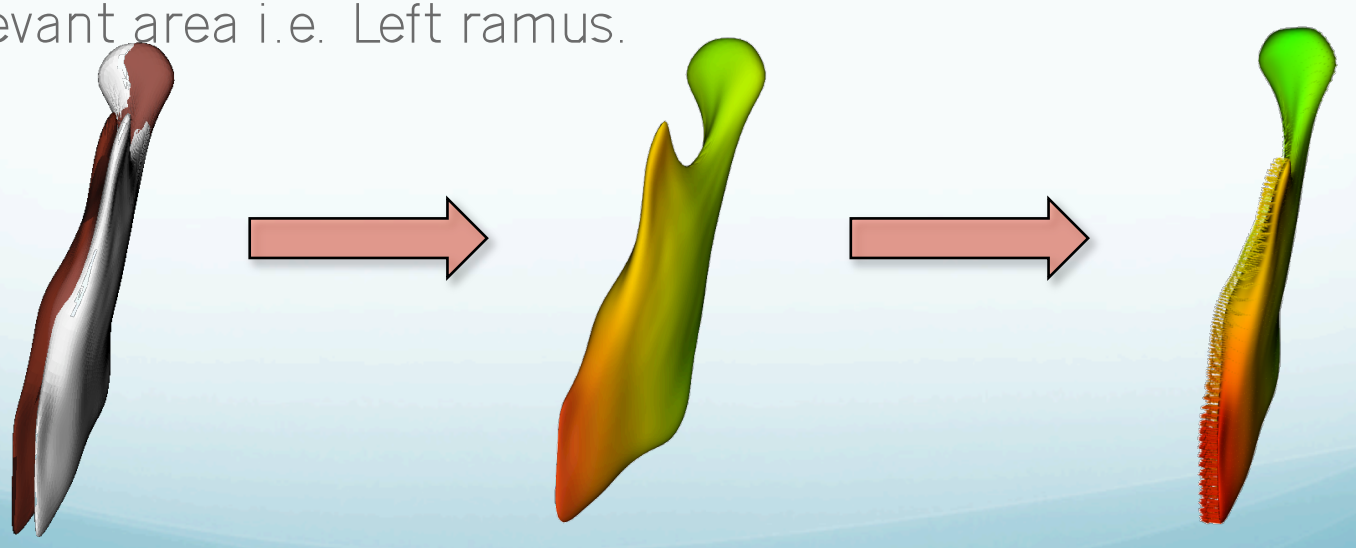


1. 3D structural statistical shape analysis via SPHARM, but we need **Spherical Topology**.
2. After performing virtual osteotomy cuts in CMF → Closure procedure.
3. Smoothing procedure → simplify the ridges and waves of the segments.
4. Recover segmentations → Scan Convert.

Shape Analysis (I)

- **Shape Correspondence** → Find correspondent point-based model computation (SPHARM) in pre-surgery and virtual post-surgery segments. In this application no alignment is used, since rotation and translation information is needed in the study.

- **Statistical Analysis** → Distance maps and vector maps are computed, showing local shape displacements for each relevant area i.e. Left ramus.



PRE and POST surgery correspondent models

DISTANCE MAPS

VECTOR MAPS

Shape Analysis (II)

- The six degrees of freedom(DOF) of jaw movements with surgical osteotomy cuts (3 translation axes and 3 axes for rotations) cannot be measured with 2D x-rays or by the 3D ICP method.
- Distance maps, vector maps.
- Further analysis is needed to capture the six DOF → **Procrustes alignment**.
- Geometric transformation $\Phi(n)$ that best maps the shape changes between pre-surgery and virtual post-surgery point-based correspondent models.

"Pitch, roll, and yaw: describing the spatial orientation of dentofacial traits"Ackerman J, Proffit W, Sarver D, Ackerman M, Kean M. American Journal of Orthodontics and Dentofacial Orthopedics. 3(123):305–310. 2007.

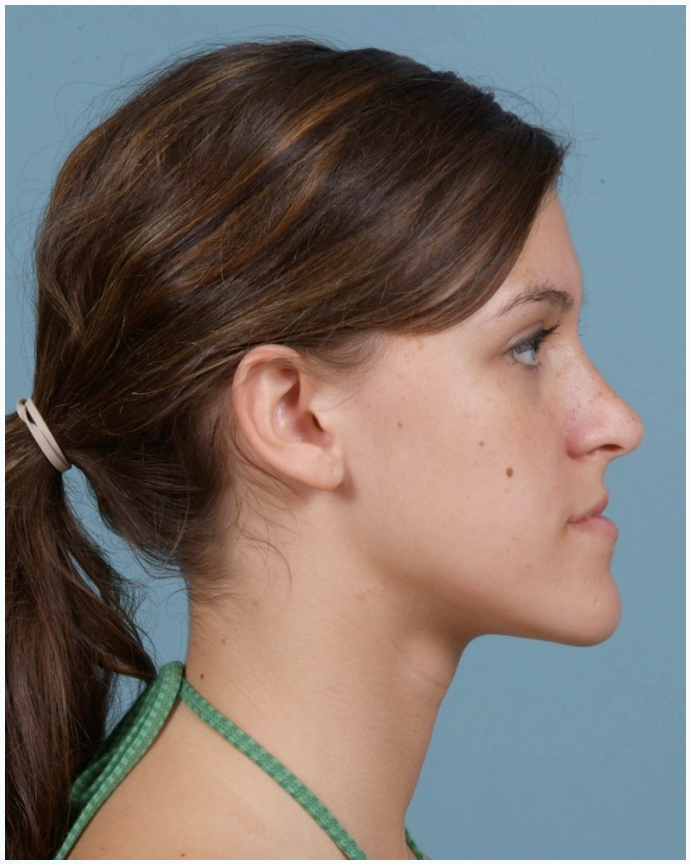
Statistical Analysis

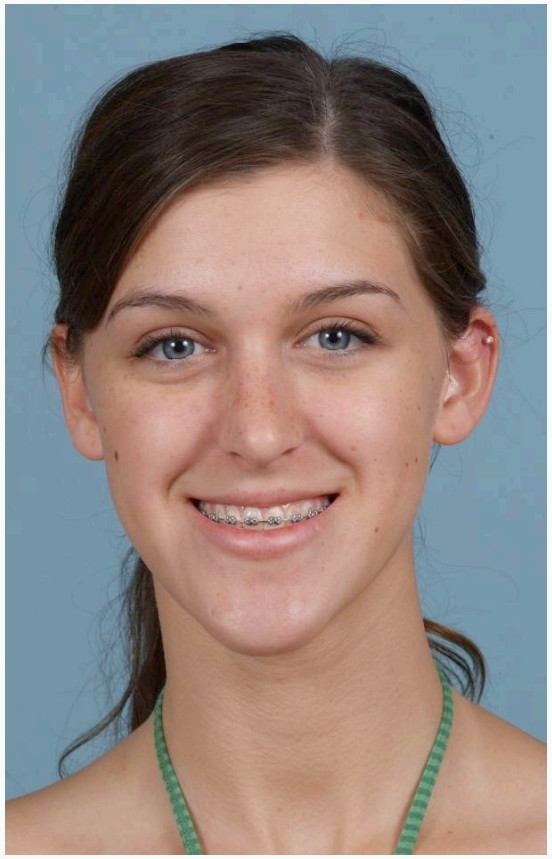
- **Results**: individual segment grouping and global grouping.

	Translation in mm			Rotation in degrees		
	X-plane	Y-plane	Z-plane	X-plane	Y-plane	Z-plane
Chin						
95% CI	(-0.1995,0.1670)	(-1.0589,1.0035)	(-0.8717,0.4948)	(-1.6905,1.9501)	(-0.2362,0.2032)	(-0.4665,0.7406)
95% PI	(-0.4659,0.4343)	(-2.5536,2.4982)	(-1.8622,1.4852)	(-4.3290,4.5886)	(-0.5546,0.5214)	(-1.6155,1.3413)
$\bar{d}$	-0.0158	-0.0277	-0.1885	0.1298	-0.0165	0.1371
$P(\lvert\bar{d}_{tra}\rvert < 0.5) or P(\lvert\bar{d}_{rot}\rvert < 5)$	0.9984	0.7505	0.888	0.9984	0.9999	0.9999
Left Ramus						
95%CI	(-0.0304,0.1376)	(-0.2566,0.0662)	(-0.0742,0.2197)	(-0.6876,0.2033)	(-0.0466,0.00239)	(-0.2716,0.0617)
95%PI	(-0.2935,0.3917)	(-0.7204,0.5366)	(-0.4964,0.6418)	(-1.9674,1.4830)	(-0.1169,0.0727)	(-0.7502,0.5404)
$\bar{d}$	0.0491	-0.0952	0.0727	-0.2422	-0.0221	-0.1049
$P(\lvert\bar{d}_{tra}\rvert < 0.5) or P(\lvert\bar{d}_{rot}\rvert < 5)$	1	0.9999	0.9999	1	1	1
Right Ramus						
95%CI	(-0.2360,0.0565)	(-0.2302,0.0675)	(-0.0691,0.1211)	(-0.0691,0.1305)	(-0.2061,0.0424)	(-0.0612,0.00485)
95%PI	(-0.6371,0.4577)	(-0.6383,0.4755)	(-0.3297,0.3817)	(-0.3428,0.4042)	(-0.5407,0.3831)	(-0.1519,0.0975)
$\bar{d}$	-0.0897	-0.0814	0.026	0.0307	-0.0818	-0.0282
$P(\lvert\bar{d}_{tra}\rvert < 0.5) or P(\lvert\bar{d}_{rot}\rvert < 5)$	0.9999	0.9999	1	1	1	1
Maxillary Body						
95%CI	(-0.0636,0.00483)	(0.1212,0.4376)	(-0.3703,0.1617)	(-0.3545,0.4303)	(-0.2883,0.2874)	(-0.4775,-0.0655)
95%PI	(-0.1862,0.1274)	(-0.4455,1.0043)	(-1.3484,1.1308)	(-1.8360,1.7602)	(-1.3195,1.3185)	(-1.2156,0.6726)
$\bar{d}$	-0.0294	0.2794	-0.1088	0.0379	-0.00046	-0.2715
$P(\lvert\bar{d}_{tra}\rvert < 0.5) or P(\lvert\bar{d}_{rot}\rvert < 5)$	1	0.9999	0.9999	1	1	1
Mandibular Body						
95%CI	(-0.1452,0.0956)	(-0.2980,0.1316)	(-0.2845,0.1746)	(-7.7674,0.9750)	(-0.7181,0.4179)	(-0.8453,0.1368)
95%PI	(-0.4589,0.4093)	(-0.7656,0.6392)	(-0.8826,0.7728)	(-19.1338,12.3514)	(-2.1081,1.8979)	(-2.1249,1.4163)
$\bar{d}$	-0.0248	-0.0632	-0.0549	-3.3912	-0.1501	-0.3543
$P(\lvert\bar{d}_{tra}\rvert < 0.5) or P(\lvert\bar{d}_{rot}\rvert < 5)$	0.9999	0.9998	0.9994	0.9716	1	1

	Translation in mm			Rotation in degrees		
	X-plane	Y-plane	Z-plane	X-plane	Y-plane	Z-plane
All segments						
95% CI	(-0.0574,0.0194)	(-0.0539,0.1577)	(-0.1192,0.0554)	(-1.2752,0.1466)	(-0.1974,0.1442)	(-0.3038,0.0106)
95% PI	(-0.1951,0.1571)	(-0.4330,0.5368)	(-0.4321,0.3683)	(-3.8221,2.6935)	(-0.8094,0.7562)	(-0.8670,0.5738)
$\bar{d}$	-0.019	0.0519	-0.0319	-0.5643	-0.0266	-0.1466
$P(\lvert\bar{d}_{tra}\rvert < 0.5) or P(\lvert\bar{d}_{rot}\rvert < 5)$	1	1	1	1	1	1

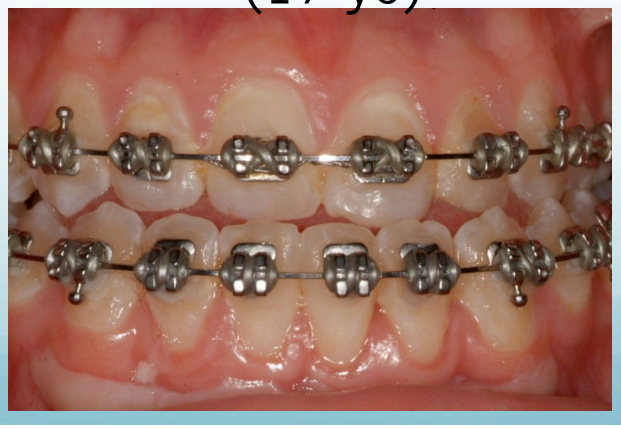
Clinical Case





06/21/05

(17 yo)


09/13/05

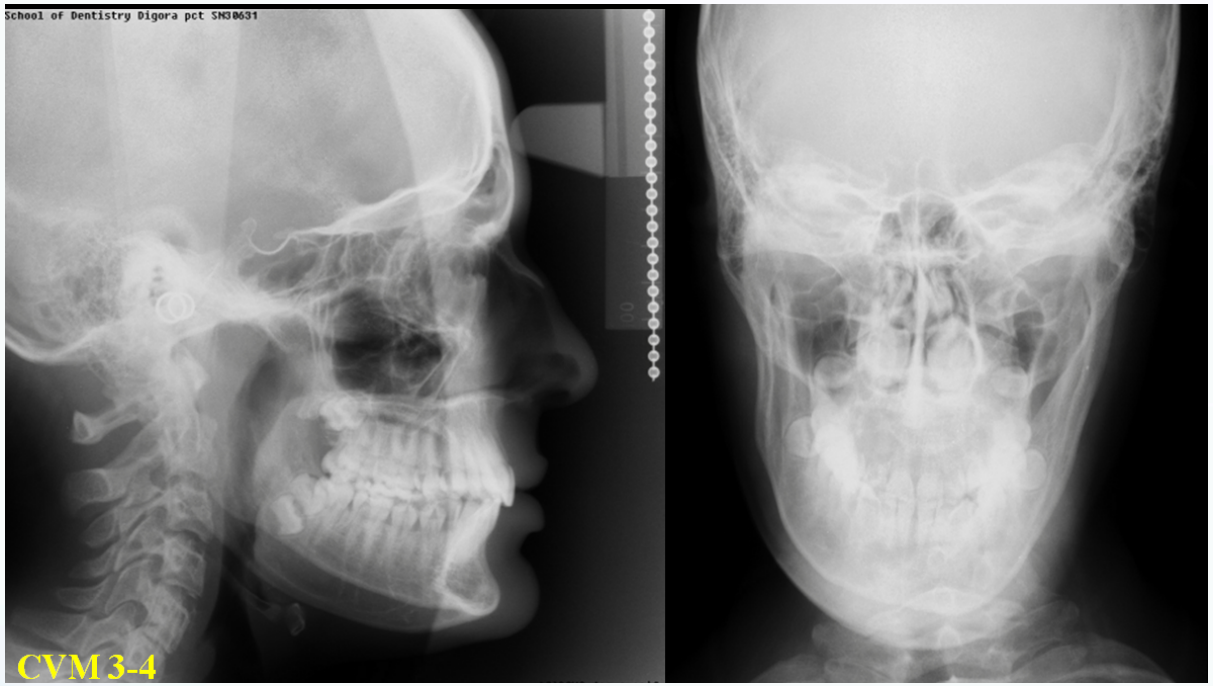
Other projects
(Asymmetry)

Asymmetry Studies (I)

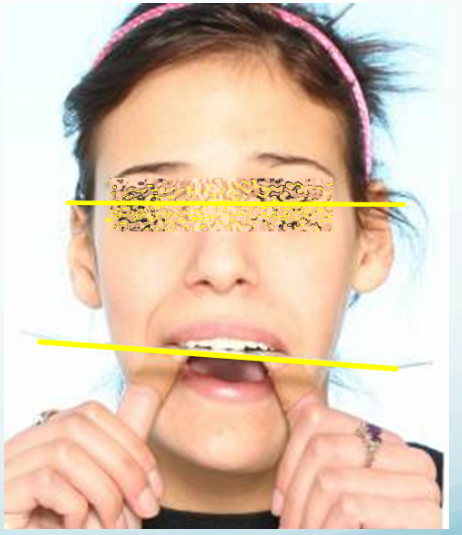
- Facial asymmetry is observed in 21-67% of patients who complain of skeletal discrepancies (Class II, Class III).
- Proper assessment and quantification of the differences between the right and the left sides are crucial for diagnosis, treatment planning and follow up.
- Current limitations of cephalometries, include a 2D visualization of a 3D problem.
- Our proposal involves 3D shape analysis, measuring the distances between the mandible and its mirror as an approach to localize asymmetry and to quantify the left and right differences.

"The prevalence of facial asymmetry in the dentofacial deformities population at the University of North Carolina" Severt TR, Proffit WR. Int J Adult Orthodon Orthognath Surg 1997;12(3):171-6.

Asymmetry Studies (II)



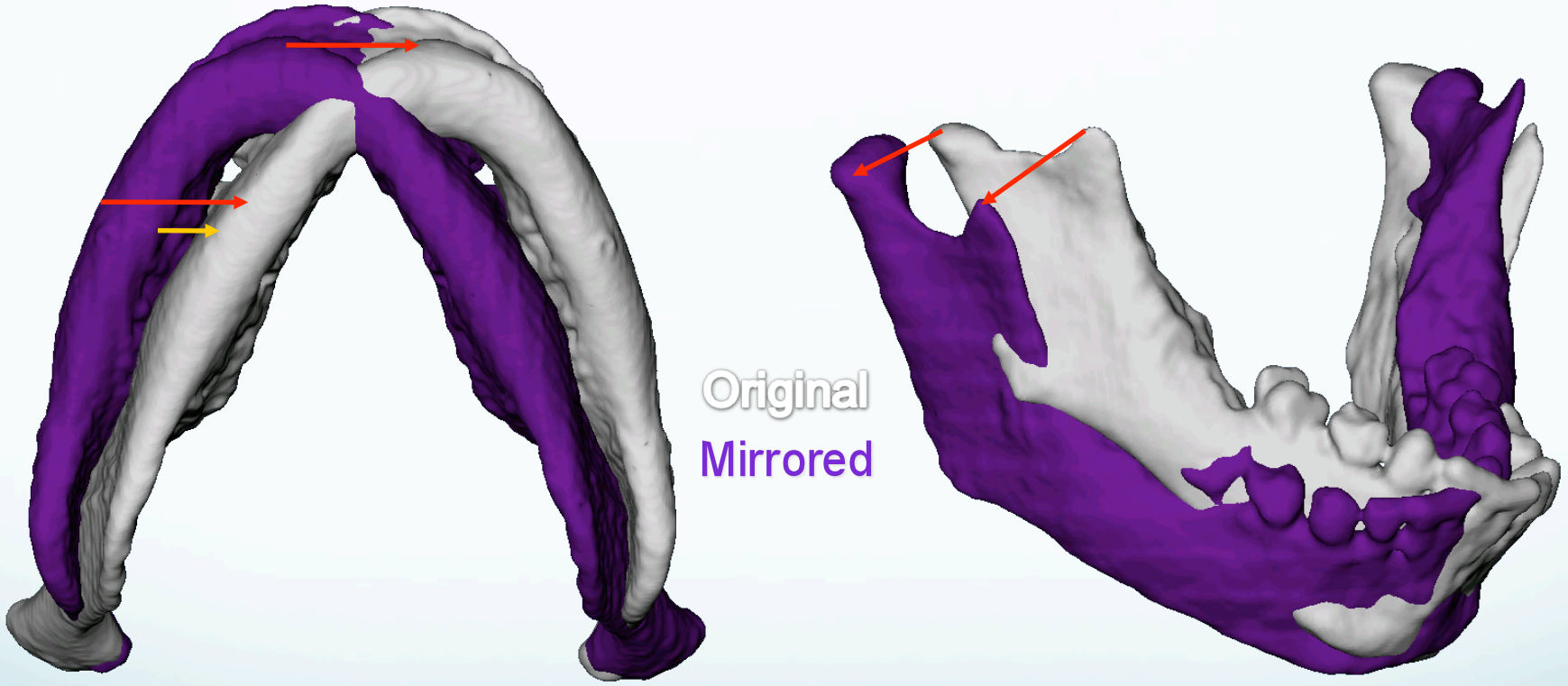
Radiographic information



Occlusal Cant

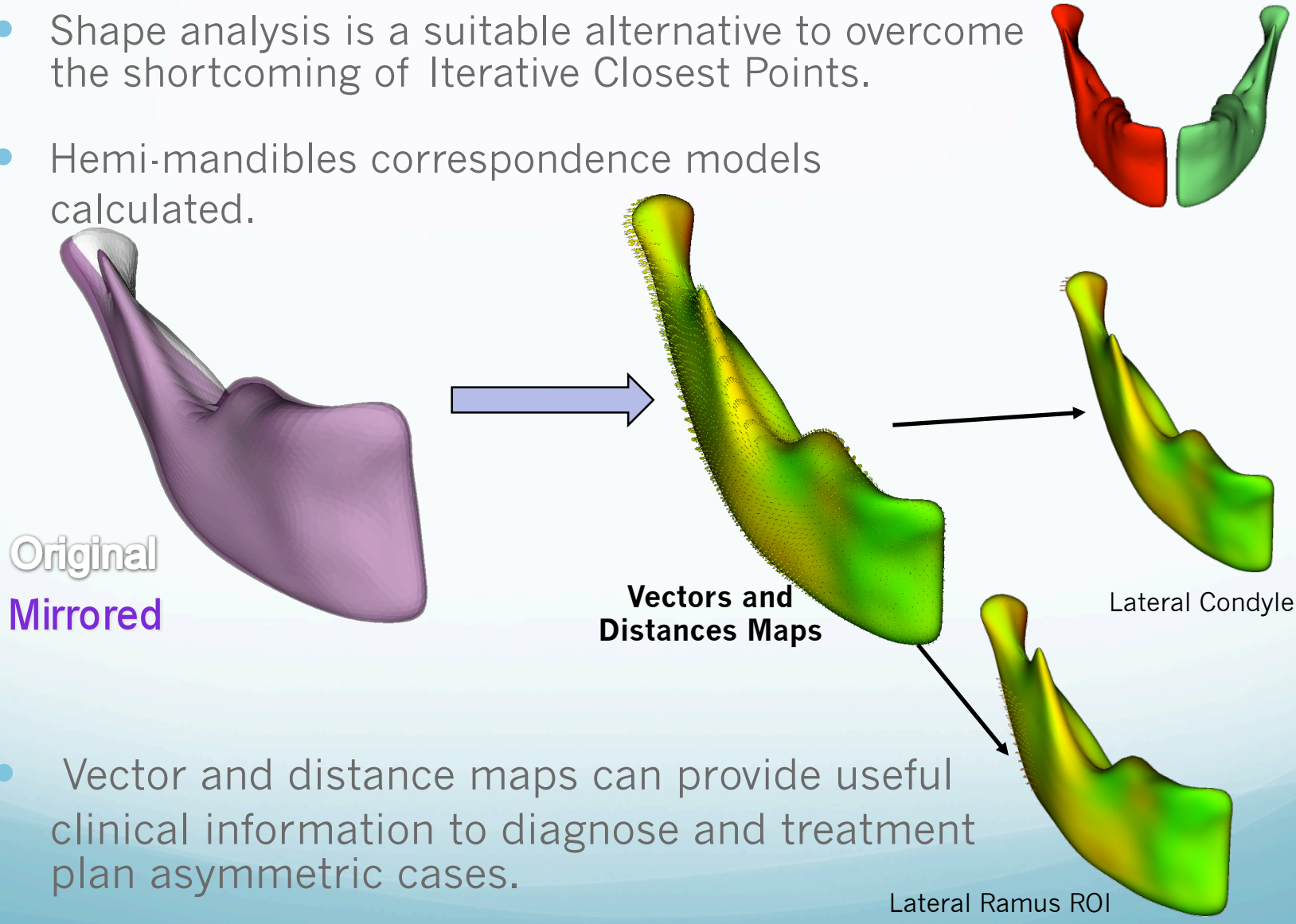
"Encyclopédie médico-chirurgicale, stomatologie: Chirurgice correctrice des malformations ou dysmorphies maxillomandibulaires: avant d'agir"
M. Richter, P. Goudot, F. Laurent, A. Jaquinet, and L. Bidaut. Elsevier, 1997.

Asymmetry Studies (III)



Shape Analysis

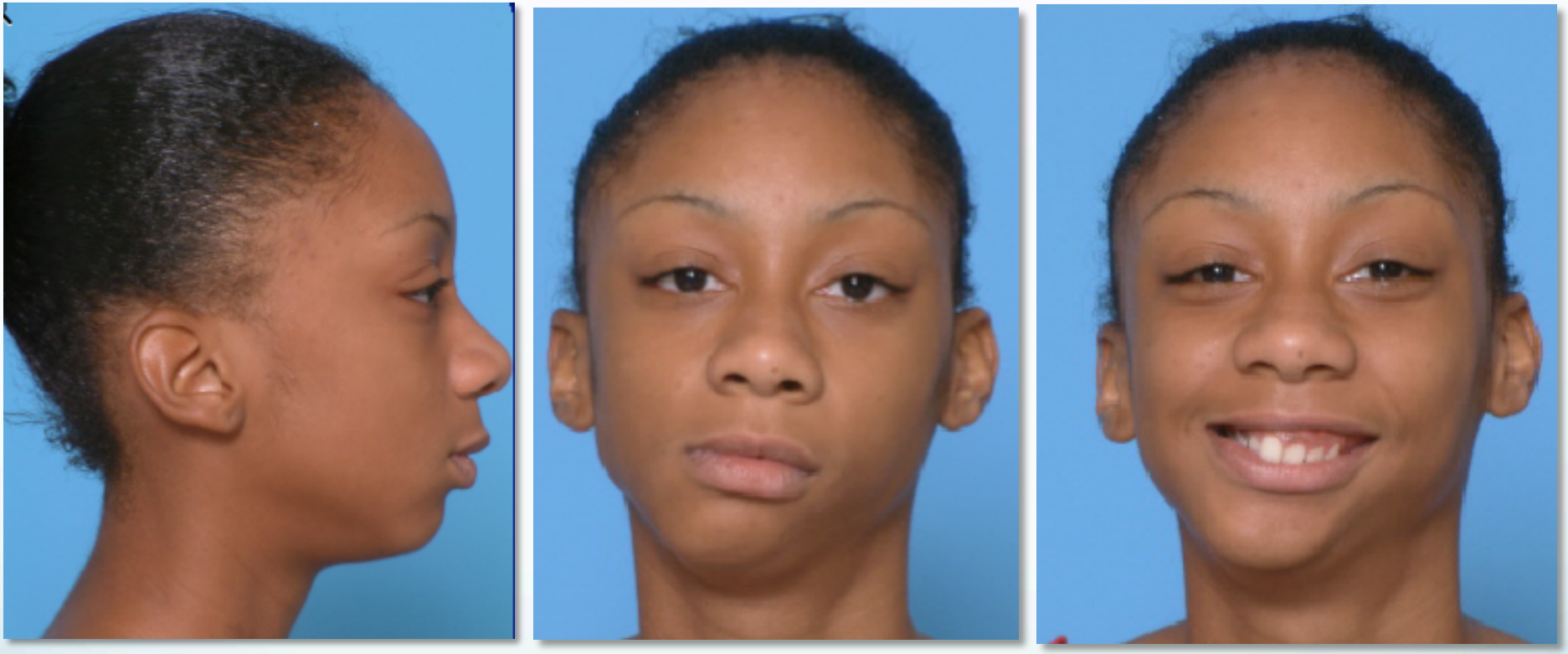
- Shape analysis is a suitable alternative to overcome the shortcoming of Iterative Closest Points.
- Hemi-mandibles correspondence models calculated.



- Vector and distance maps can provide useful clinical information to diagnose and treatment plan asymmetric cases.

Clinical Case

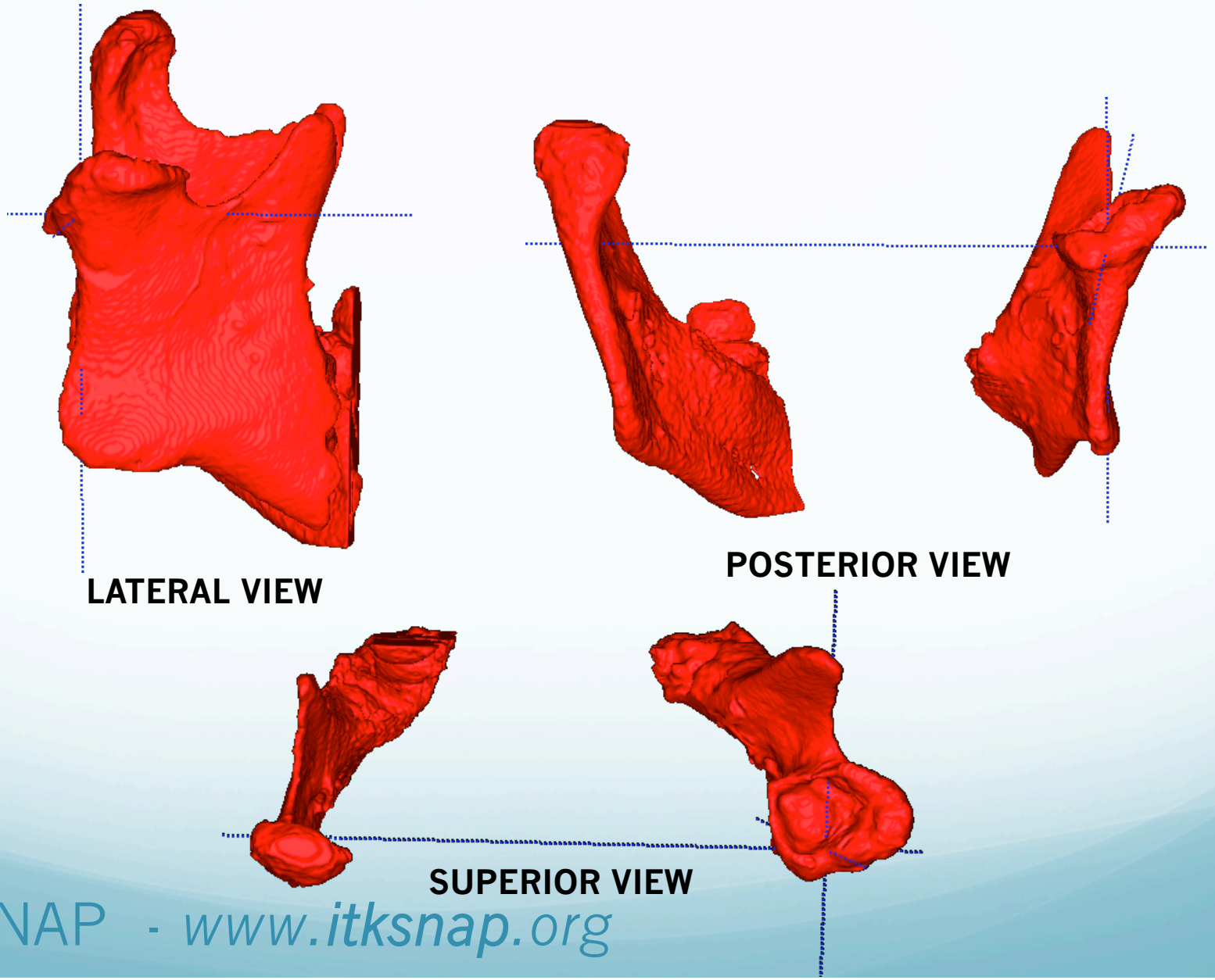
Pre-surgery clinical pictures



2006 (14 yo)

Radiographic information

CBCT 3D models



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Thanks for your attention!!