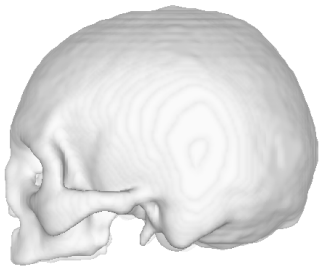
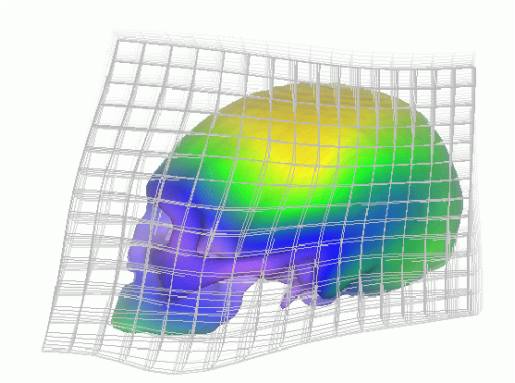
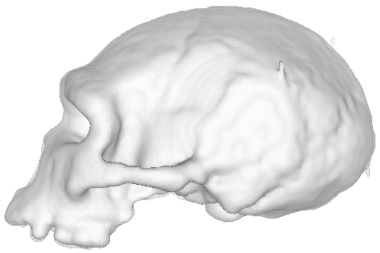
UISPP'2001 - Colloquium on 3D Imaging for Paleoanthropology and Prehistoric Archeology

3D Image Processing for the Study of the Evolution of the Shape of the Human Skull

Presentation of the Tools and Preliminary Results







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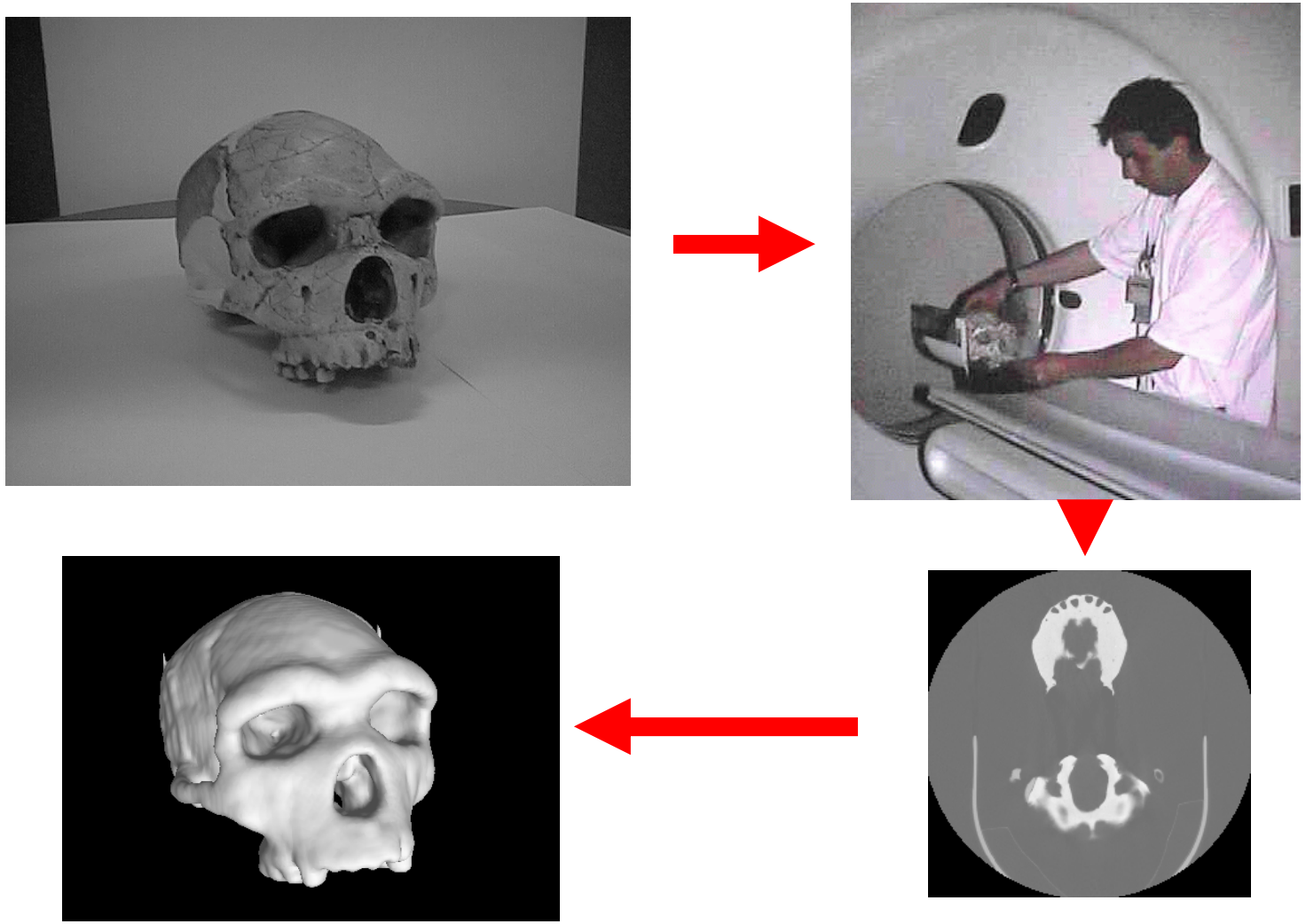
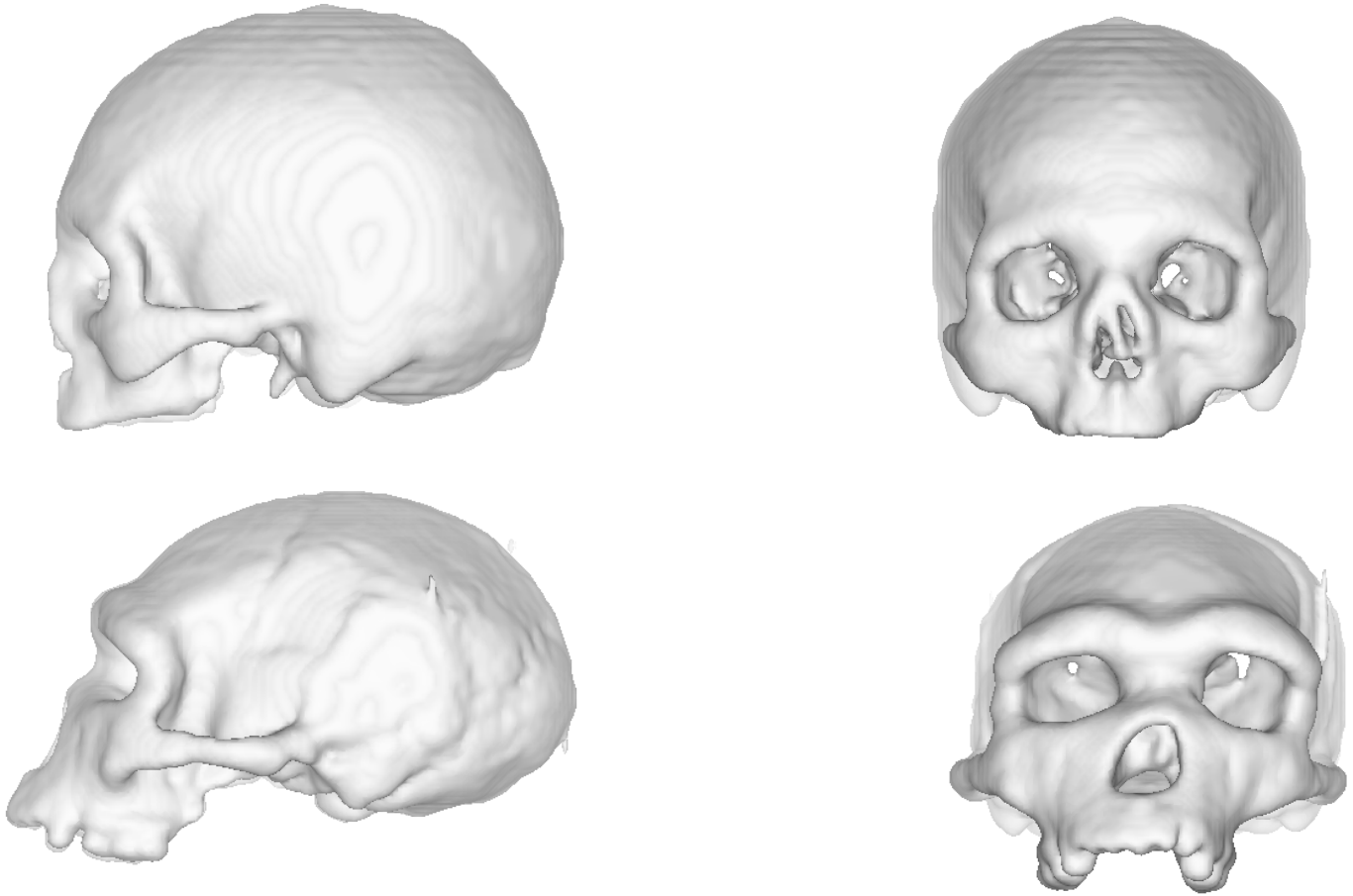
3D scanning of the specimen



- **Modern Man** (specimen without mandible by courtesy of G. Quatrehomme, University of Nice, France)
- **Man of Tautavel** (cast, reconstruction described in [de Lumley, de Lumley & David, *1er congrès de paléontologie humaine* - 1982])
- Specimens scanned with a precision of: **0,5 x 0,5 x 1 mm** (~100 slices of 512 x 512 pixels).

How to study the morphometrical differences between these two skulls?

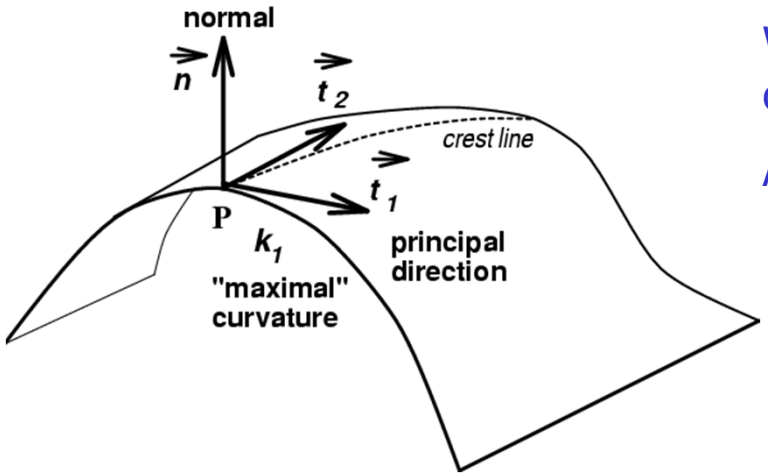


A methodology exists, that consists in **computing and analyzing a 3D deformation function** between the two skulls [Thompson, *On Growth and Form* - 1917] [Bookstein, *Morphometric Tools for Landmark Data* - 1991].
Results are very impressive (e.g. [Ponce de León & Zollikofer, *Nature* - 2001]).

Assess if automatic 3D image processing tools (feature extraction, registration, 3D deformation computation, etc.) can be applied to this methodology.

Step 1: Defining Landmarks (1)

Automatic Extraction of Features Lines

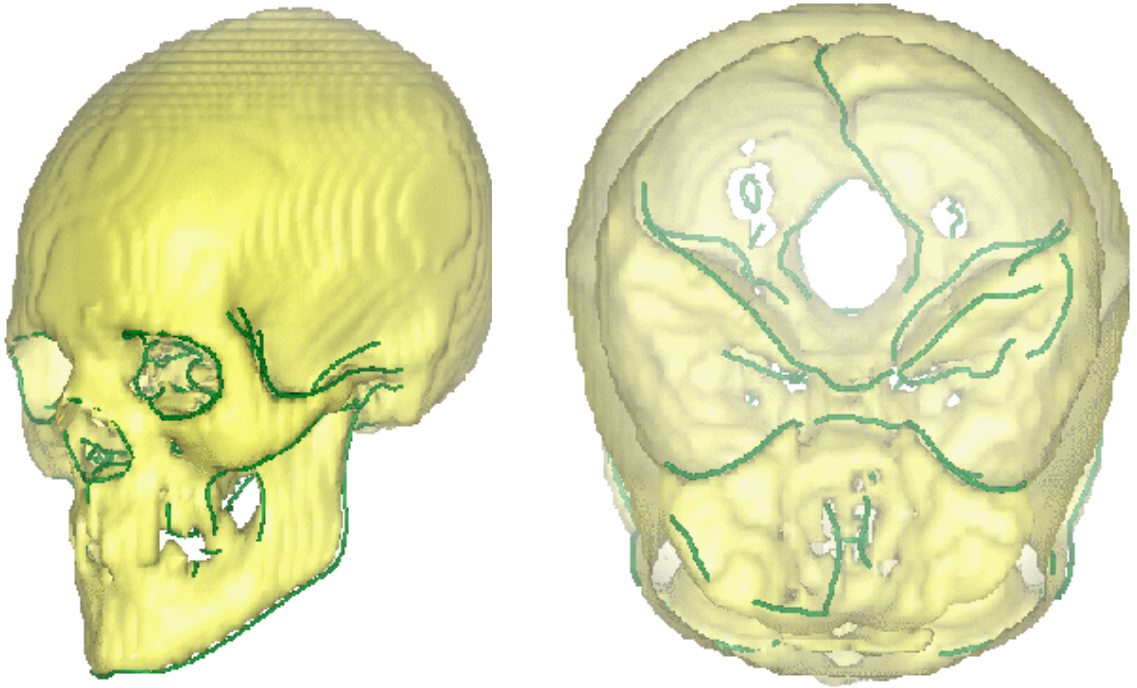


We use **Crest Lines** that correspond to the salient lines on a surface (type II landmark in Bookstein's typology).

At a point P on a surface:

- $\mathbf{k_1}$: maximal principal curvature in absolute value
- $\mathbf{t_1}$: associated principal direction
- **grad k1.t1=0 $\Leftrightarrow$ P is a crest point**

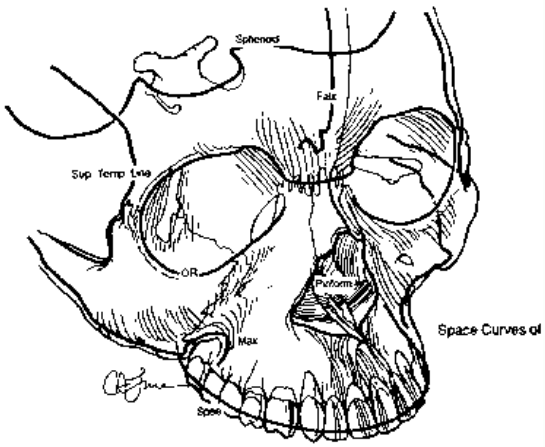
Crest lines are automatically extracted from the 3D image and leads to several hundred lines with several thousand points [Thirion & Gourdon, *Graphical Models & Image Processing* - 1996].

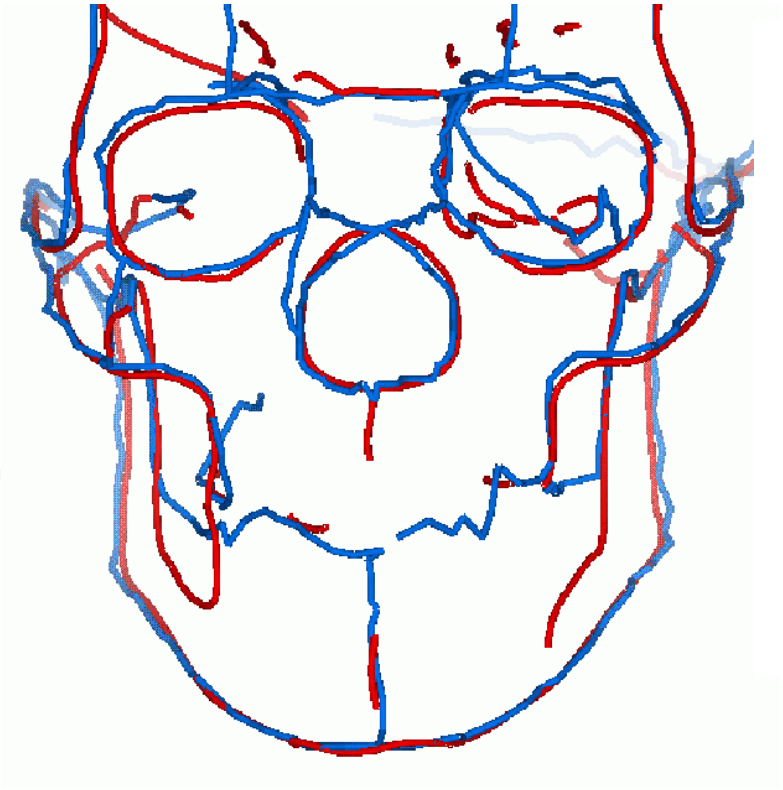


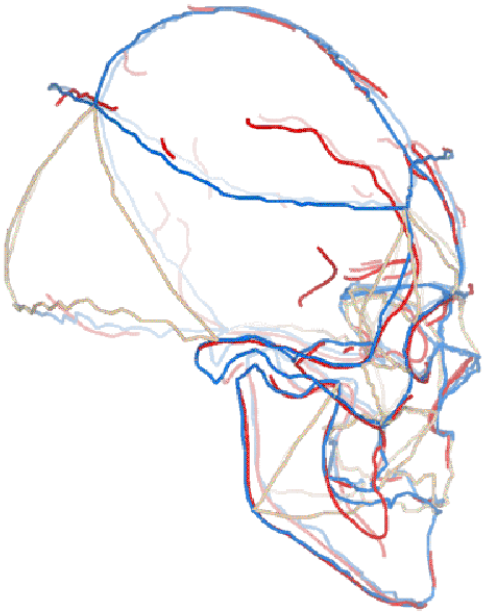
Step 1: Defining Landmarks (2)

An Anatomic Analysis of Crest Lines

Some similar lines, the **Ridge Lines**, extracted under the supervision of an anatomist, have been used as features by some cranofacial surgeons [Bookstein & Cutting, *Cranofacial Morphogenesis and Dysmorphogenesis* - 1988] and paleontologists [Dean, Ph.D. - 1993].





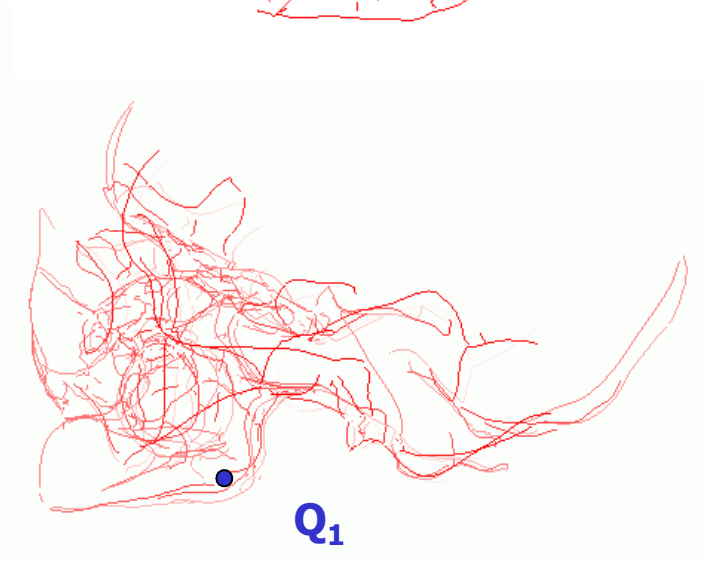


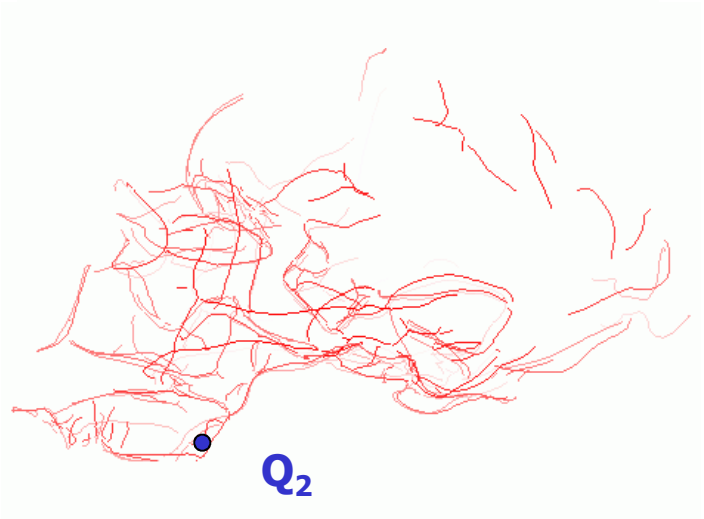
The **Crest Lines** and the **Ridge Lines** are very close

[Thirion, Subsol, Dean, *Visualization in Biomedical Computing* - 1996].

Step 2: Finding Homology

The problem is to find automatically the correspondences between the feature points (e.g. (P_1,P_2) or (Q_1,Q_2)). Many **registration** algorithms exist [Subsol, Thirion & Ayache, *Medical Image Analysis* - 1998].



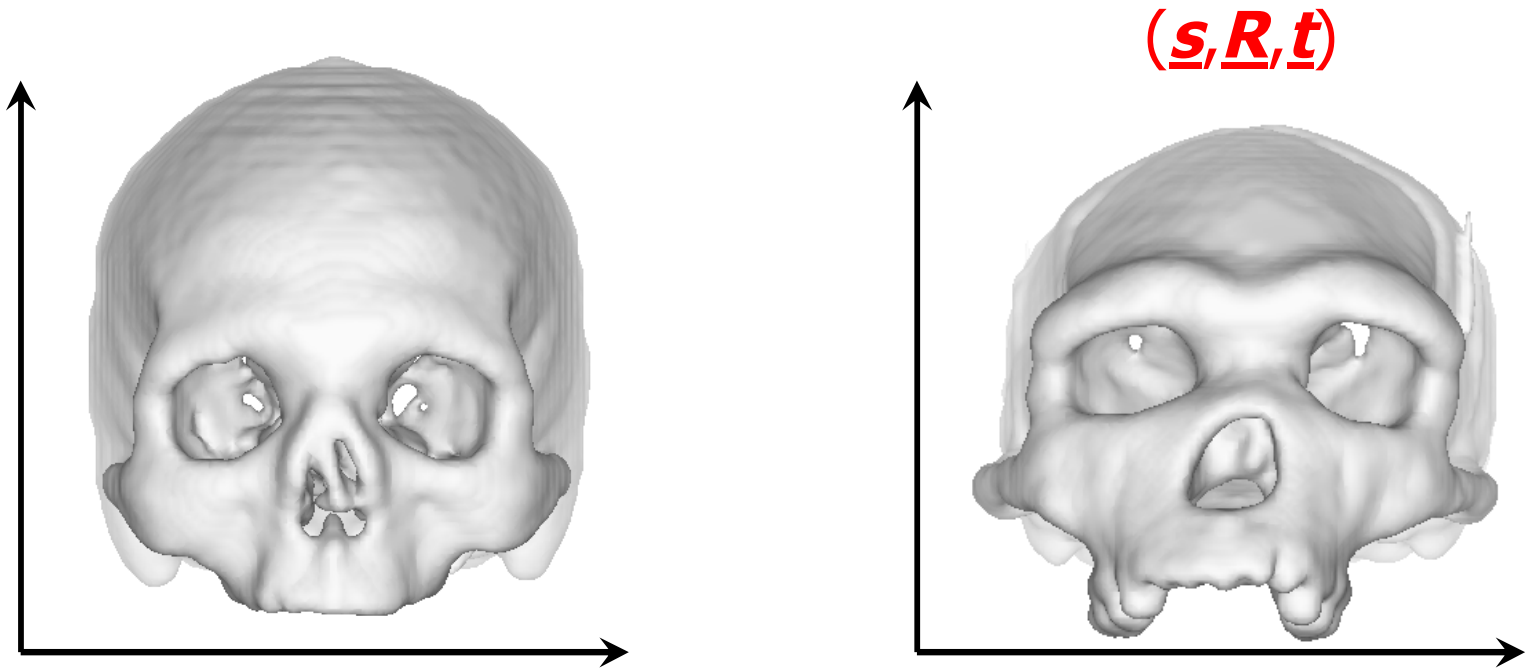


Modern Man: 536 crest lines with 5756 crest points.

Man of Tautavel: 337 crest lines with 5417 crest points.

Step 3: Normalization (1)

Removing differences of position and scaling



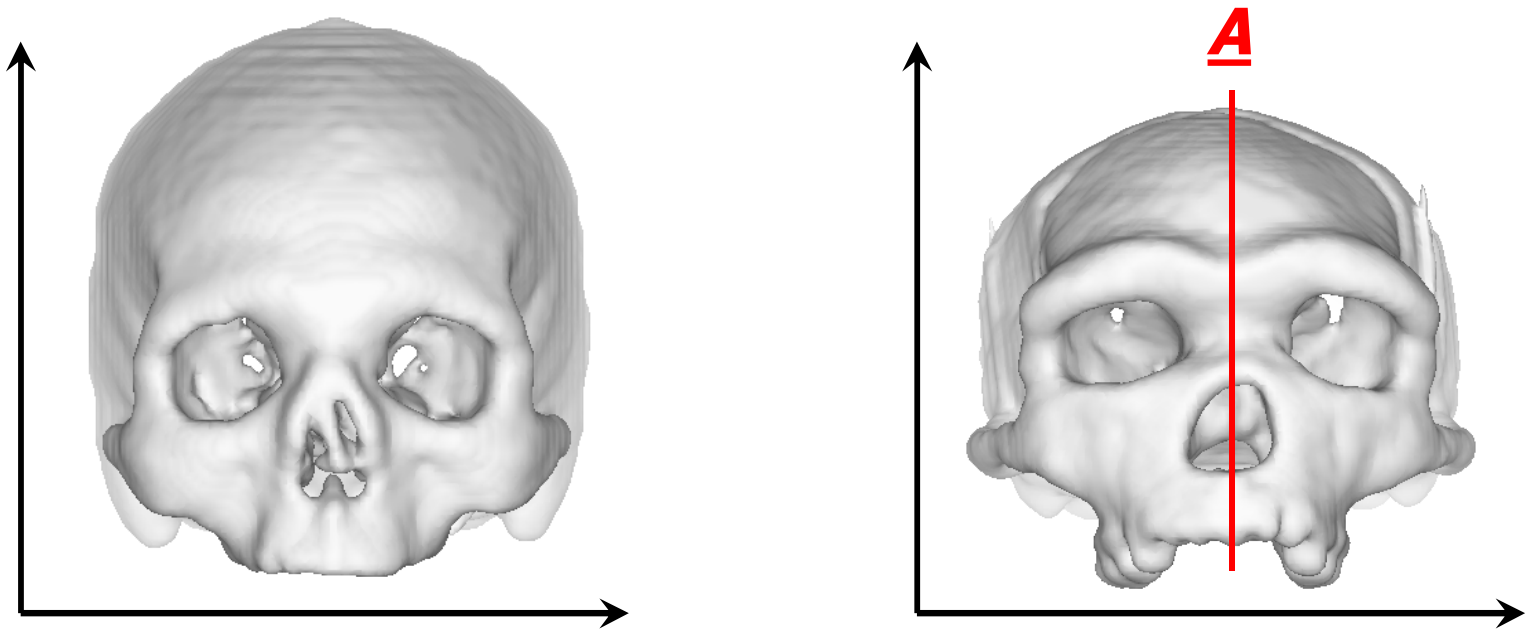
Removes **"non-significant" differences** between the two specimens: difference of position in the acquisition device (rotation $\underline{\boldsymbol{R}}$ +translation $\underline{\boldsymbol{T}}$) or of global size (scaling $\underline{\boldsymbol{s}}$).

Based on pairs of homologous points ($\mathbf{P_i}$,$\mathbf{Q_i}$), several automatic methods exist to compute these transformations. For example, Procrustes or least-square minimization:

$$(\underline{\boldsymbol{s}},\underline{\boldsymbol{R}},\underline{\boldsymbol{t}}) = \text{Argmin}_{(\boldsymbol{s},\boldsymbol{R},\boldsymbol{t})} \sum_i || \boldsymbol{sR}\,\mathbf{P_i} + \boldsymbol{t} - \mathbf{Q_i} ||^2)$$

Step 3: Normalization (2)

What about more complex deformations?



But… do we have to remove other kind of transformations, for example, the taphonomic ones [Ponce de León & Zollikofer, *The Anatomical Record* - 1999].

If yes, **how to model them**?

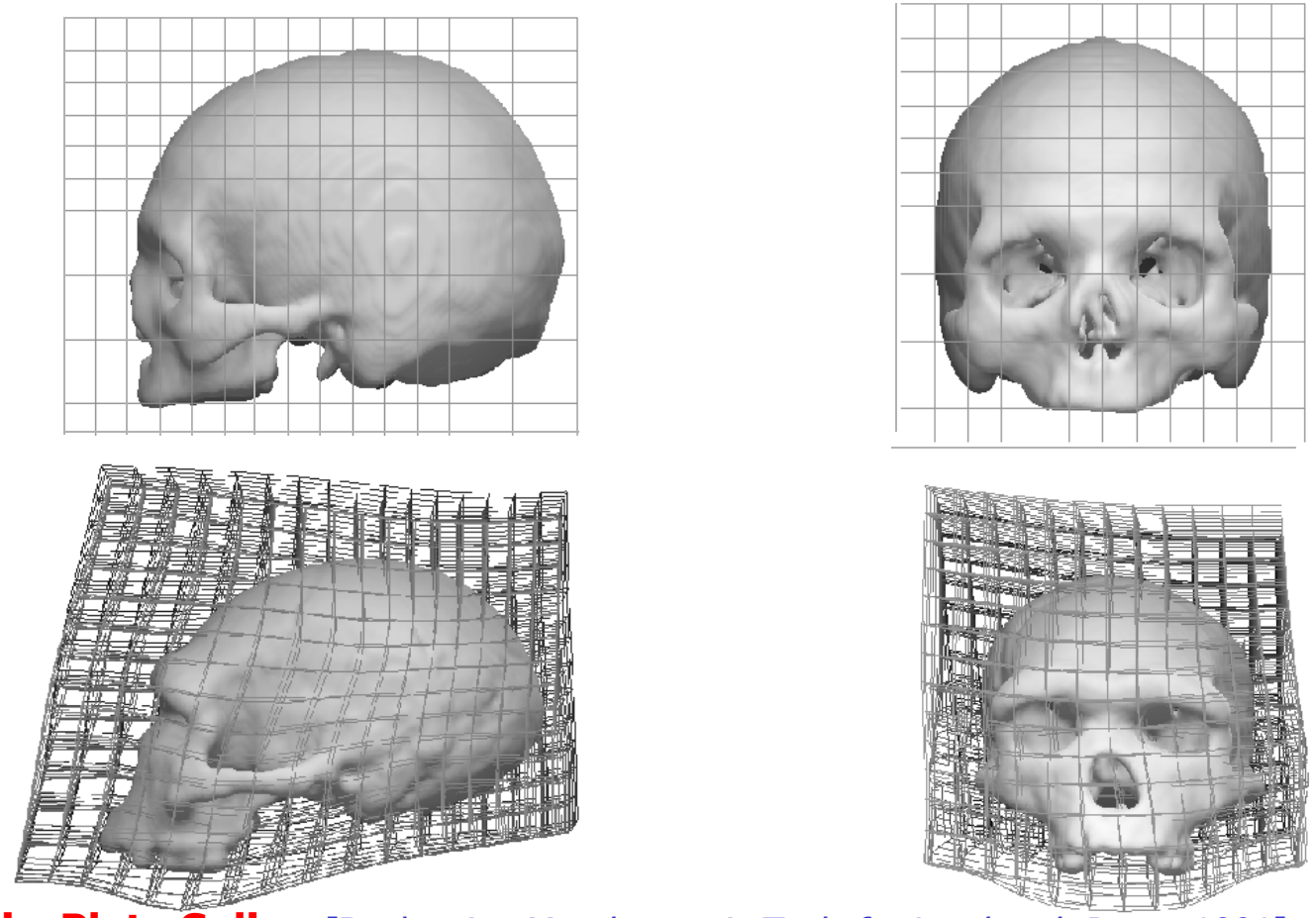
In our example, an affine transformation $\underline{\boldsymbol{A}}$ is computed from the pairs of homologous points:

$$(\underline{\boldsymbol{A}},\underline{\boldsymbol{t}}) = \text{Argmin}_{(\boldsymbol{A},\boldsymbol{t})} \sum_i || \boldsymbol{A}\,\mathbf{P_i} + \boldsymbol{t} - \mathbf{Q_i} ||^2)$$

Step 4: Computing the 3D Transformation

From the pairs of homologous points in the normalized frame ($\mathbf{P'_i}$,$\mathbf{Q'_i}$), it is possible to compute automatically a function $\underline{\boldsymbol{T}}$ that superimposes, at "best", the two specimens.

This requires to define a class $\boldsymbol{C}$ of functions: • that are **computable**, • that have some **regularity** constraints, • whose parameters can be **analyzed** to obtain morphometrical results.



$$\underline{\boldsymbol{T}} = \mathrm{Argmin}_{\boldsymbol{T}} \Sigma_i \, \| \boldsymbol{T}(\mathbf{P'_i}) \mathbf{Q'_i} \|^2 + \rho \int\int (\partial^2 \boldsymbol{T}/\partial x^2) + (\partial^2 \boldsymbol{T}/\partial x \partial y) \ \ldots$$

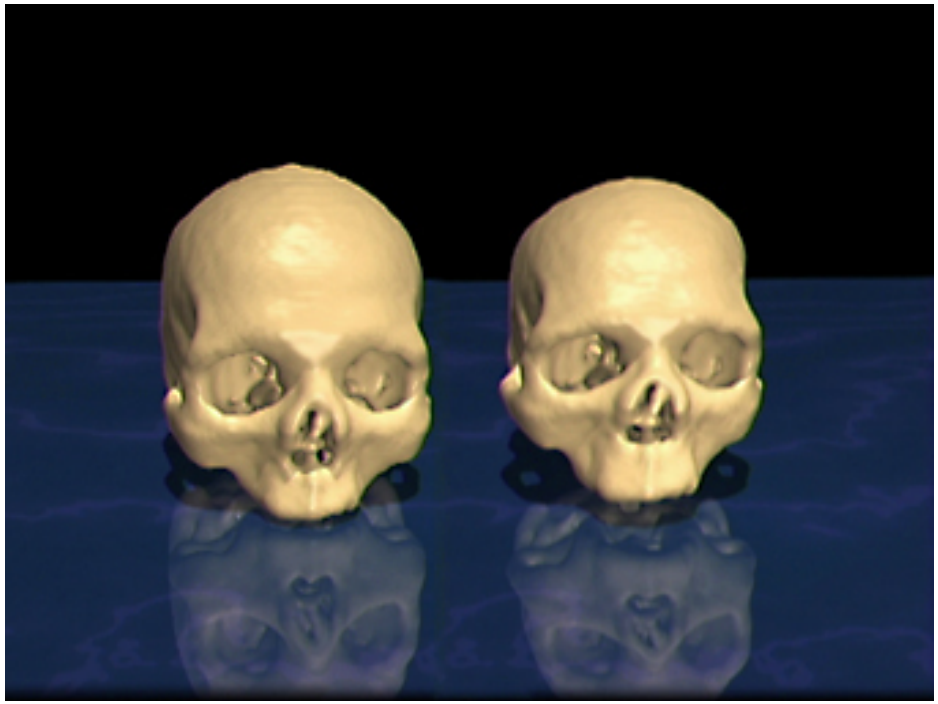
Thin-Plate Spline [Bookstein, *Morphometric Tools for Landmark Data* - 1991] or variants (e.g. approximation instead of interpolation [Declerck, Subsol, Thirion, Ayache - *CVRMed* - 1995]) are very often used but this class of functions has no real biological or anatomical meaning.

Step 5: Qualitative Analysis

Created for *Homo Erectus to Conquer the World* exhibition at Musée de l'Homme in Paris (March 1999 - April 2000).

Video: **3D Imagery and Paleontology**

Shape differences between the skull of Modern Man and that of Tautavel Man



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Alain Silvestre, Gérard Subsol

Production; INRIA © 1999

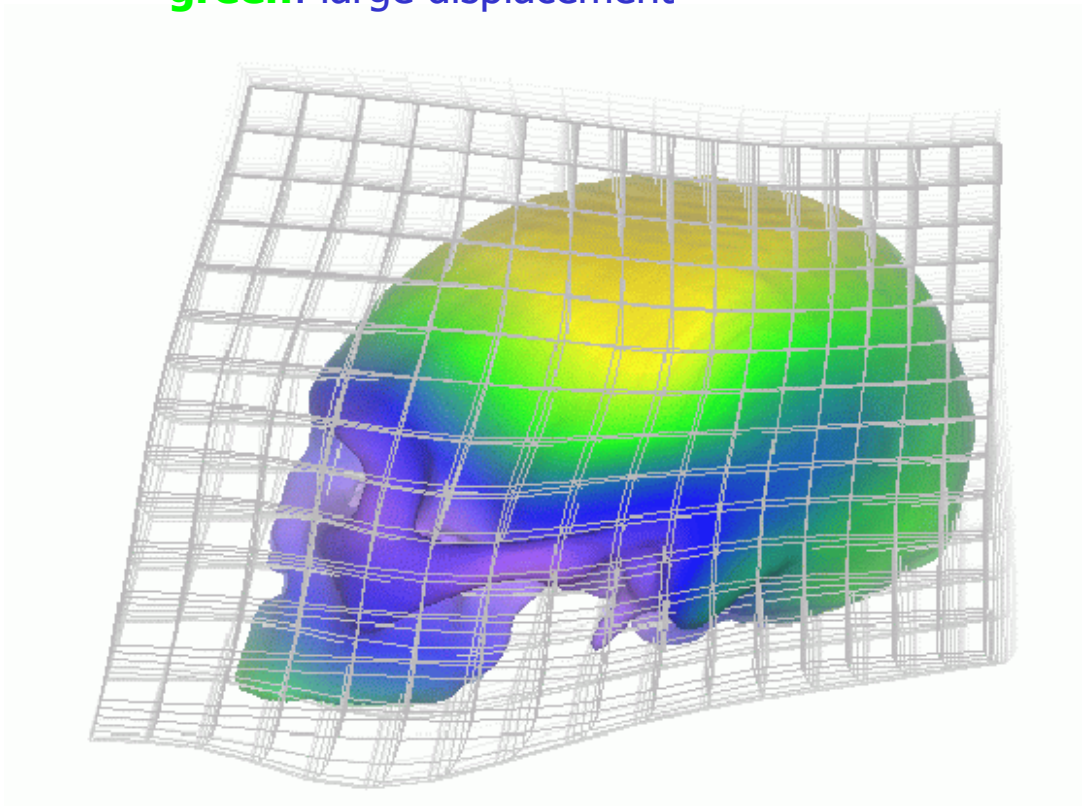
Excerpt of 2mn. The full movie is available at:

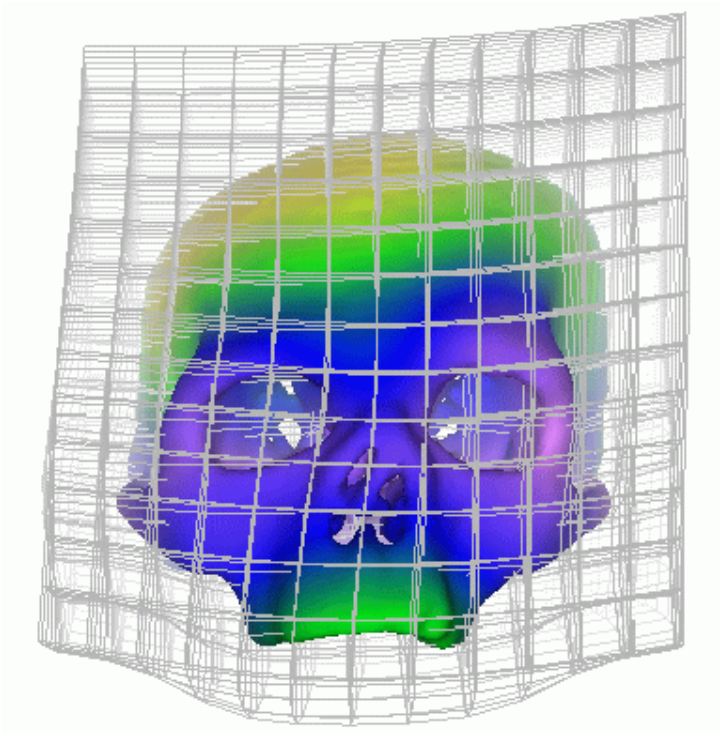
http://www.inria.fr/multimedia/Videotheque/0-Fiches-Videos/451-fra.html

Step 6: Quantitative Analysis

Visualization of the displacement intensity:

- **violet**: small displacement
- **green**: large displacement



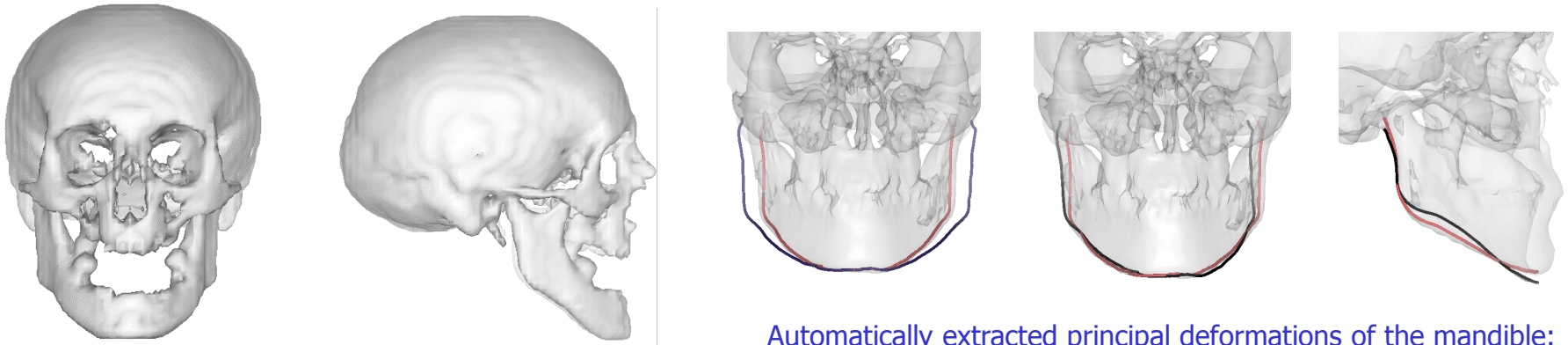


At the moment, we did not perform any further analysis, as a decomposition into a basis of principal deformations [Ponce de León & Zollikofer, *Nature* - 2001].

Other Applications (1)

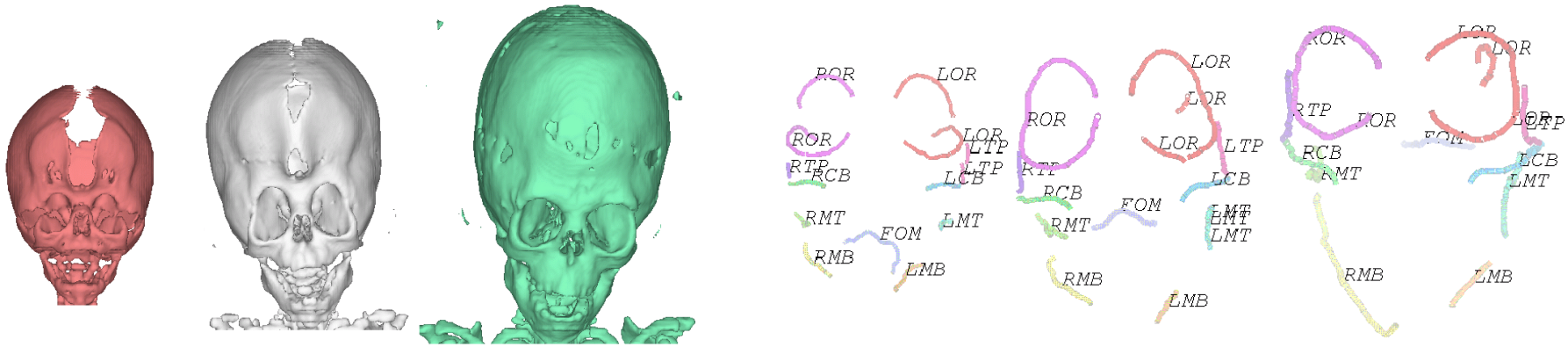
Morphometric Study of the Skull Shape

- Skull with a **mandibular hypolasia** [Subsol, Thirion & Ayache, *Medical Image Analysis* - 1998]:



Automatically extracted principal deformations of the mandible: breadth, twist and curvature.

- Study of the **skull growth** [Subsol, *Ph.D. Thesis* - 1995]:

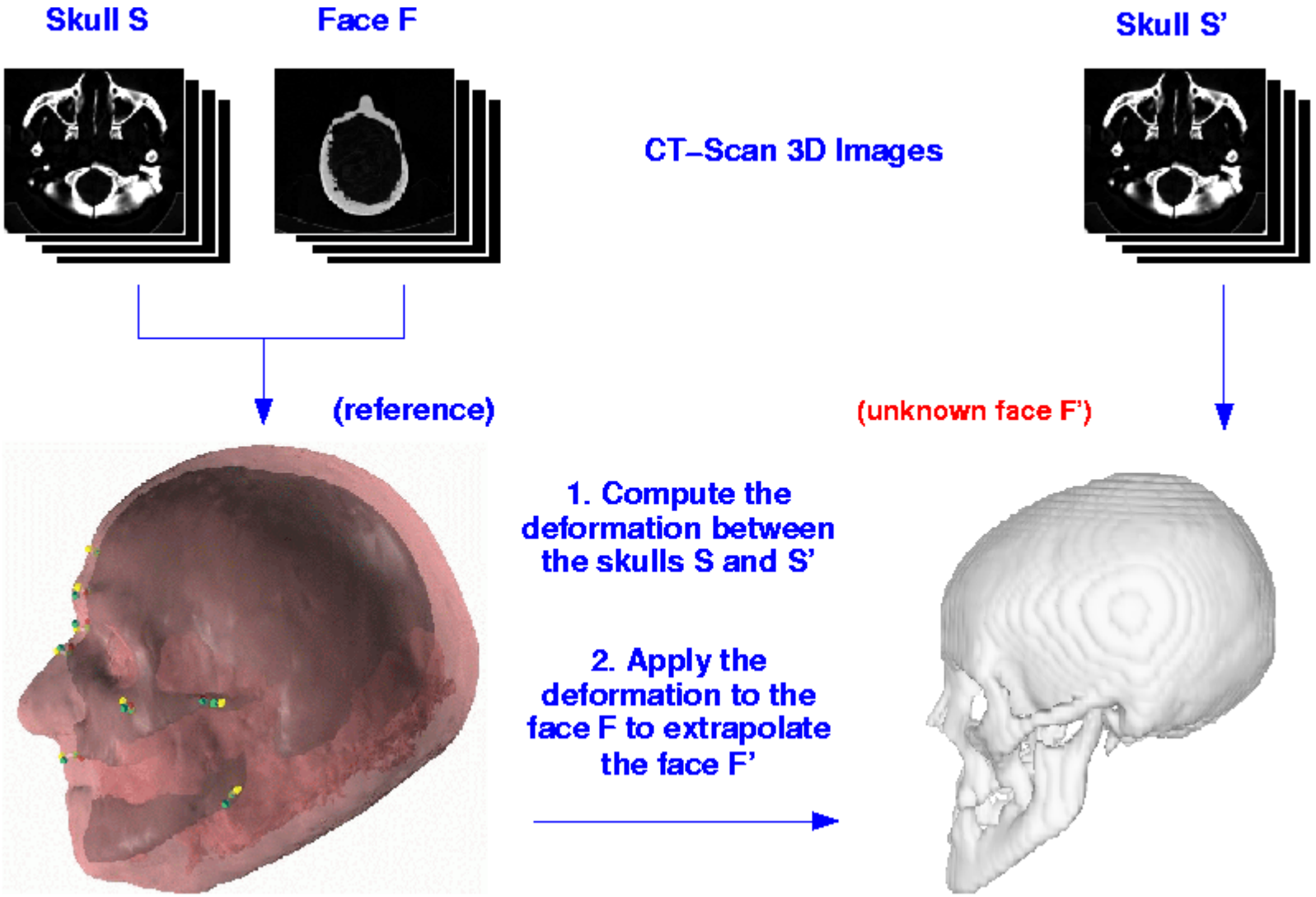


Extraction and identification of some homologous crest lines.

Other Applications (2)

Facial Reconstruction - Methodology

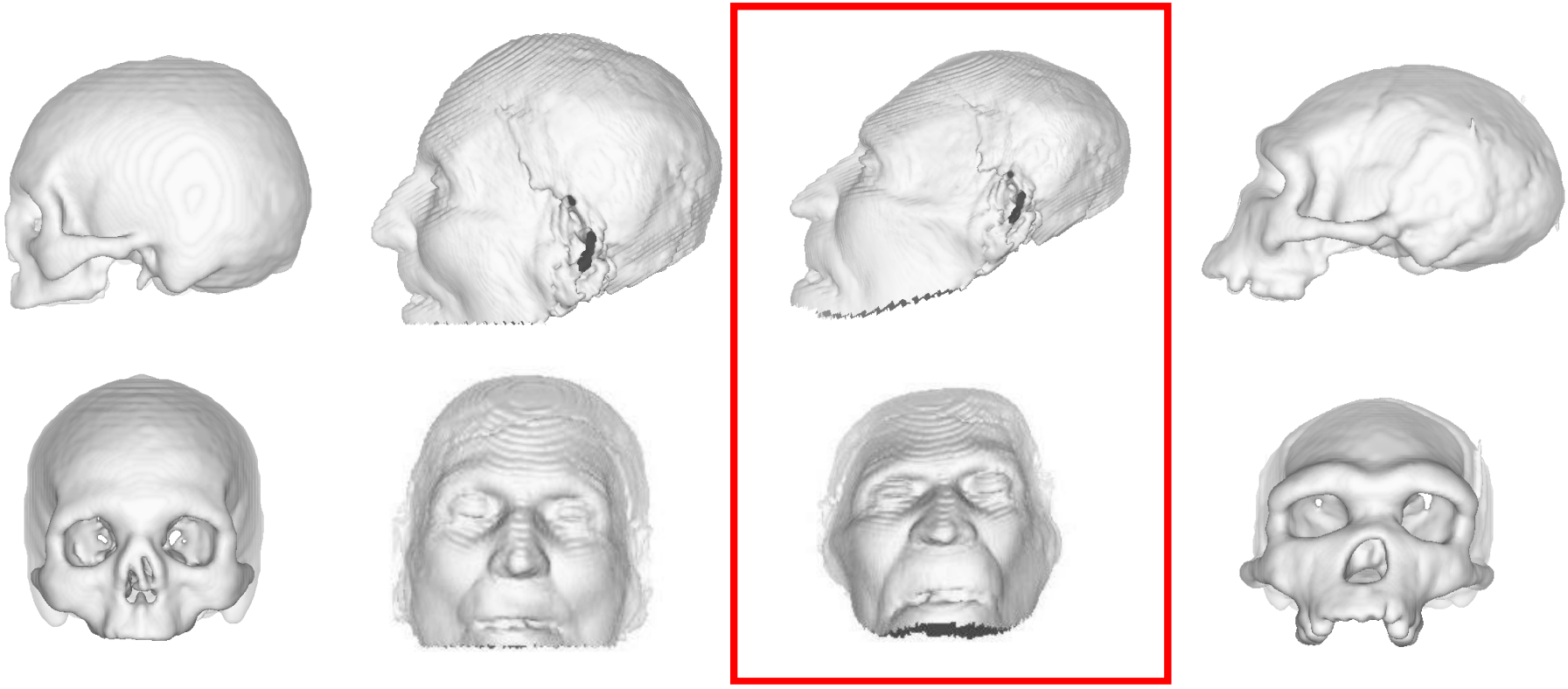
(in collaboration with G. Quatrehomme (University of Nice, France)



Methodology described in [Quatrehomme, Cotin, Subsol, Delingette, Garidel, Grevin, Fidrich, Bailet & Ollier, *Journal of Forensic Sciences* - 1997].

Other Applications (2)

Facial Reconstruction - Preliminary Results



Modern Man

Man of Tautavel?

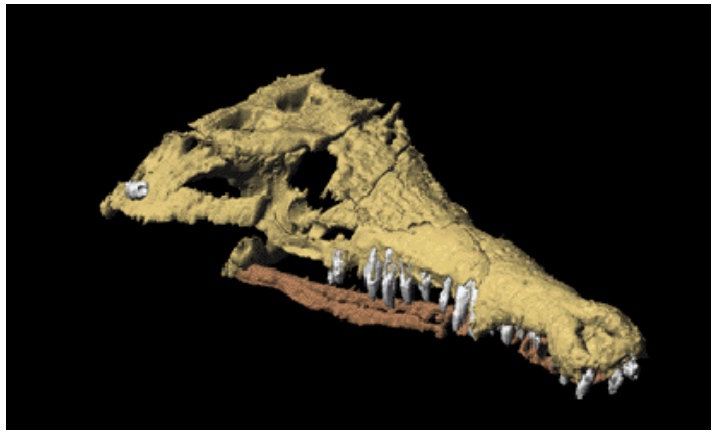
Conclusion and Future Work (1)

1. Assessment of the preliminary results:

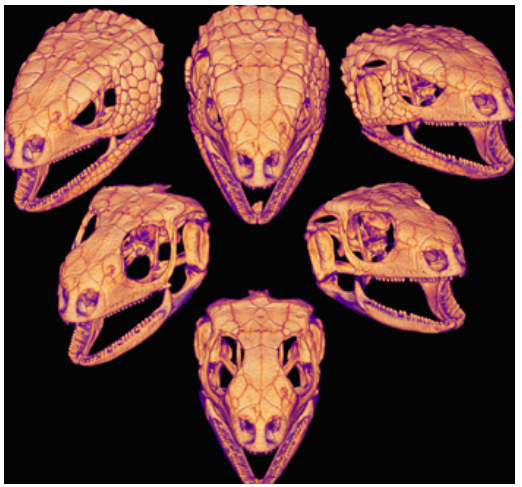
- Preliminary results must be carefully analyzed and compared to current established results.
- Requires a close collaboration between physicians, anatomists, computer scientists morphometricians and paleontologists.

2. Development and improvements…

- Improve all the steps of the scheme, especially the morphometric analysi.
- Apply this automatic scheme on other anatomical structures: e.g. pelvis [Marchal, *Journal of Human Evolution* - 2000], or animal fossil bones:



Paleocene alligator specimen [Zollikofer, *Web site*].

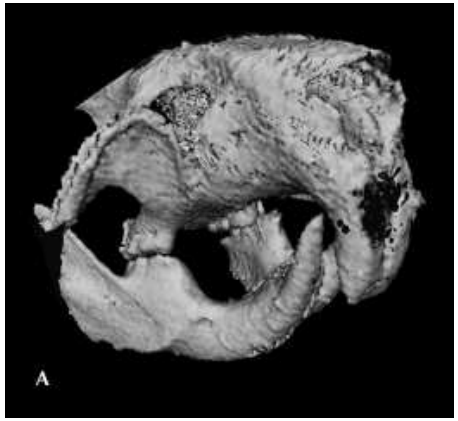


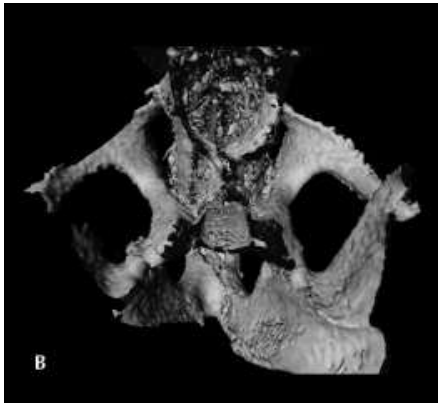
Gerrhosaurus [Univ. of Texas, Chris Bell, *Web site*].

Conclusion and Future Work (2)

2. ...Development and improvements

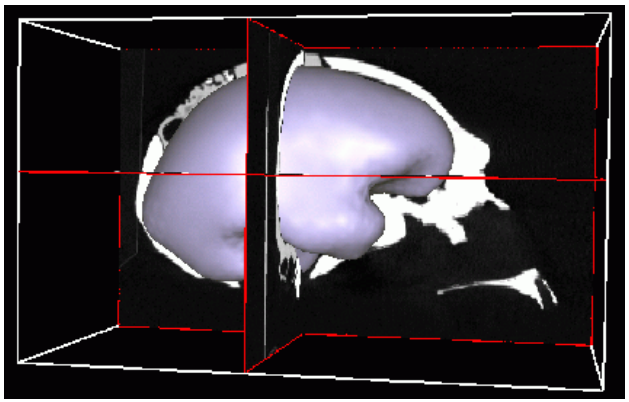
- Use new modalities as laser scanning or Magnetic Resonance Imaging [Steiger, *Computers & Geosciences* - 2001]:





Vertebrate skulls are put into silicon oil, degassed and imaged with high resolution 3D-MRI [Bruker Medical, Web site].

- Use other 3D image processing tools. For example,3D deformable model based segmentation to extract and analyze the endocranium [Montagnat & Delingette, *Signal Processing* - 1998] :



Computed volume = 1169 cm^3

Actual volume = 1150 cm^3

Conclusion and Future Work (3)

3. Create a worldwide research community on "3D Imaging and Paleontology"

- Set-up an international database of 3D images of fossils accessible by Internet.
- Create a regular (yearly?) international and multidisciplinary workshop on this topic.