3D retrodeformation of paleoanthropological fossils based on biomechanical simulation

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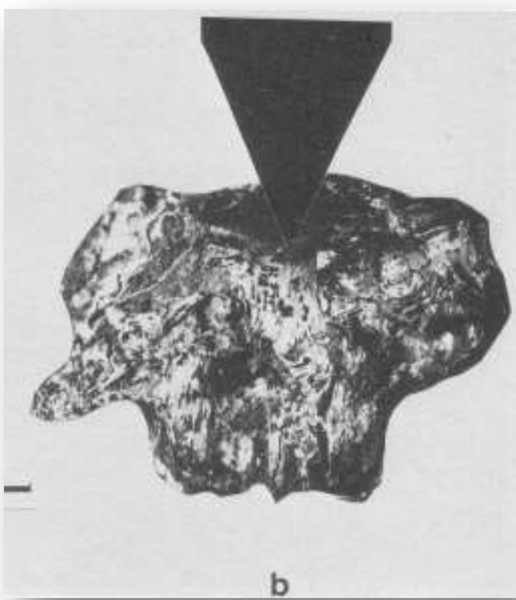
Plastic deformation

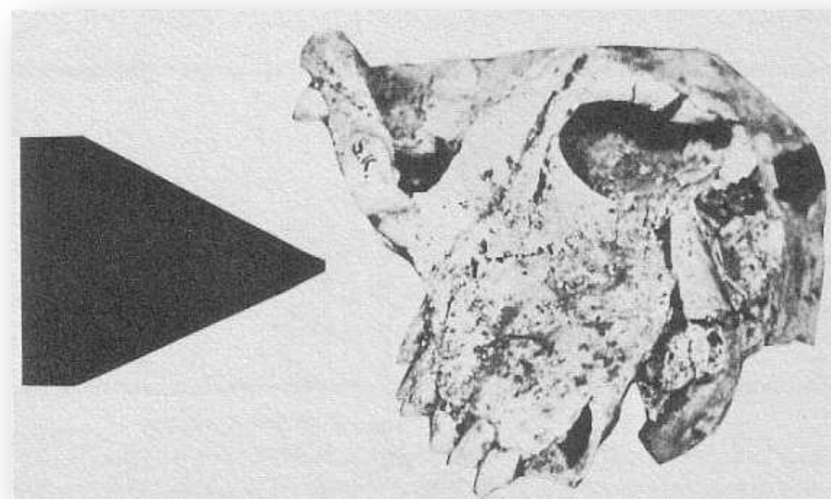
Arago XXI (~400,000 BC)

Yunxian II (~780,000 BC)

Toumaï (~7 Myears BC)



Brain. "Some Compressional Effects on Bones Preserved in Cave Breccia". The Hunters or the Hunted?, 1981.

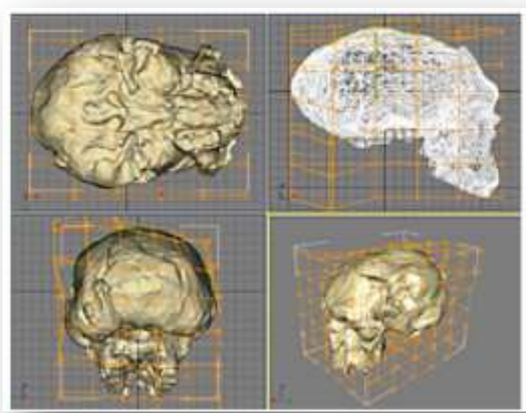


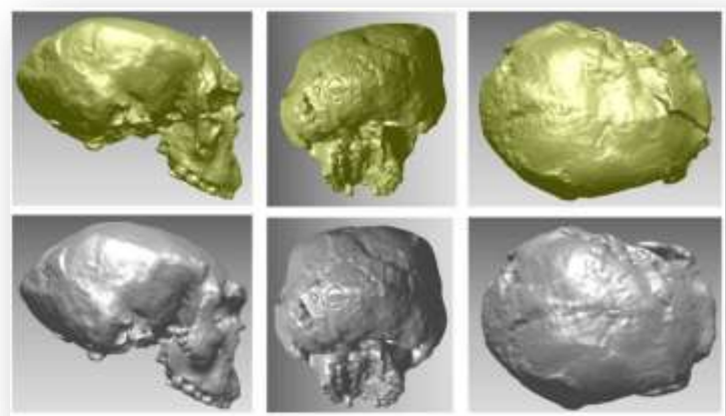
→ How to compute a plastic retrodeformation?

Expert-based methods

Benazzi et al. "Individual Tooth Macrowear Pattern Guides the Reconstruction of Sts 52 (Australopithecus africanus)". AJPA, 2013.

1. Reposition landmarks based on hypotheses proposed by experts and compute a 3D deformation (Geometric Morphometrics tools).
2. Define interactively a global transformation (FFD, TPS, Geomagic, RapidForm…).

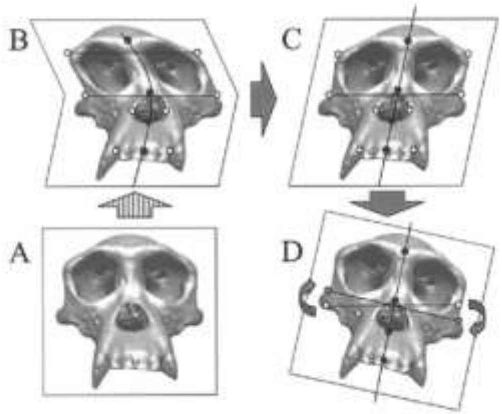




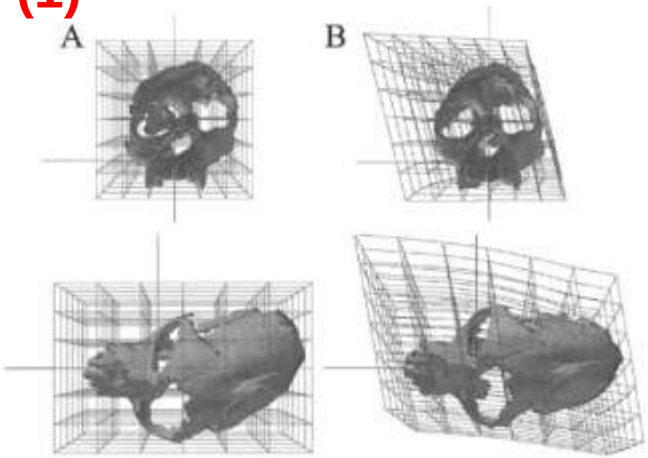
Vialet et al. "Homo erectus from the Yunxian and Nankin Chinese sites: Anthropological insights using 3D virtual imaging techniques". Palevol, 2010.

→ Based on expert knowledge. Reproducibility and objectivity?

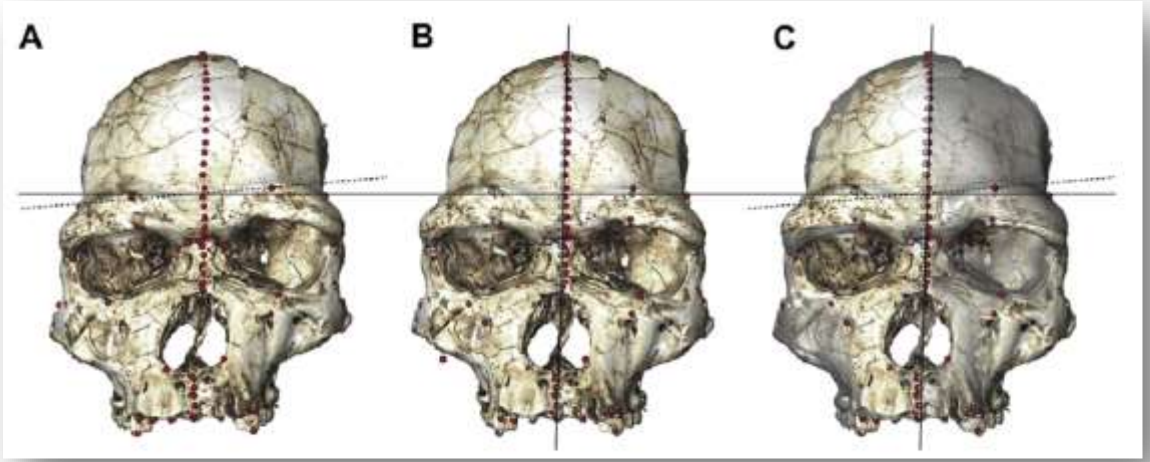
Exploiting the symmetry (1)



Ogihara et al. "Computerized Restoration of Nonhomogeneous Deformation of a Fossil Cranium Based on Bilateral Symmetry". AJPA, 2006.



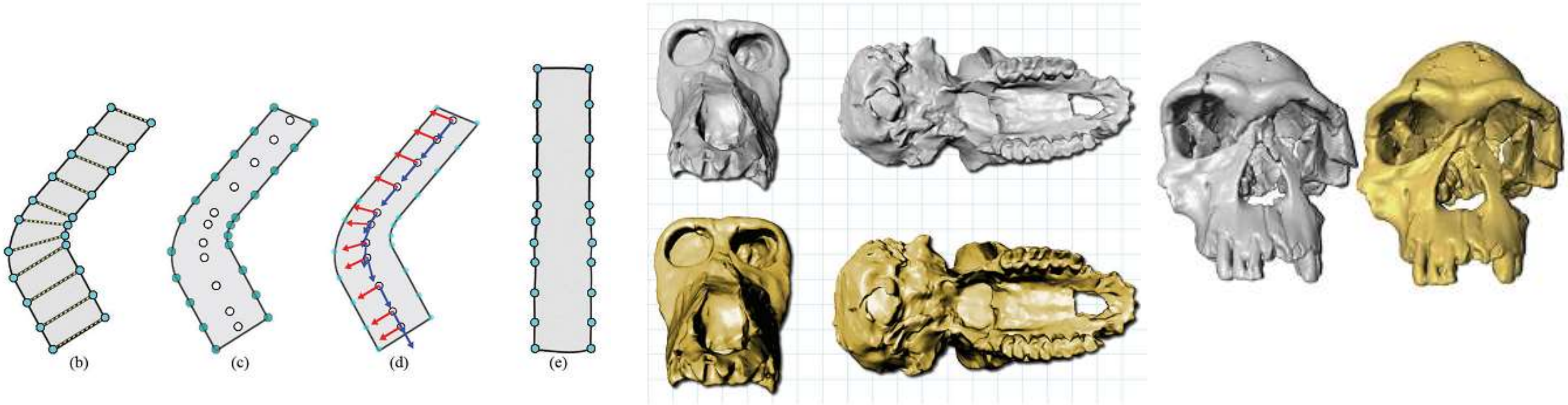
1. Reposition the landmarks which should be on mid-sagittal plane in a common plane.
2. Reposition pairs of landmarks in order that they are perpendicular to the plane.
3. Compute a 3D deformation (TPS) based on these repositioned landmarks.



Gunz et al. "Principles for the virtual reconstruction of hominin crania". JHE,2009.

1. Define midline landmarks.
2. Define bilateral landmarks..
3. Compute a 3D deformation (TPS) between the original (= distorted) and symmetrized (= undistorted) landmarks.

Exploiting the symmetry (2)

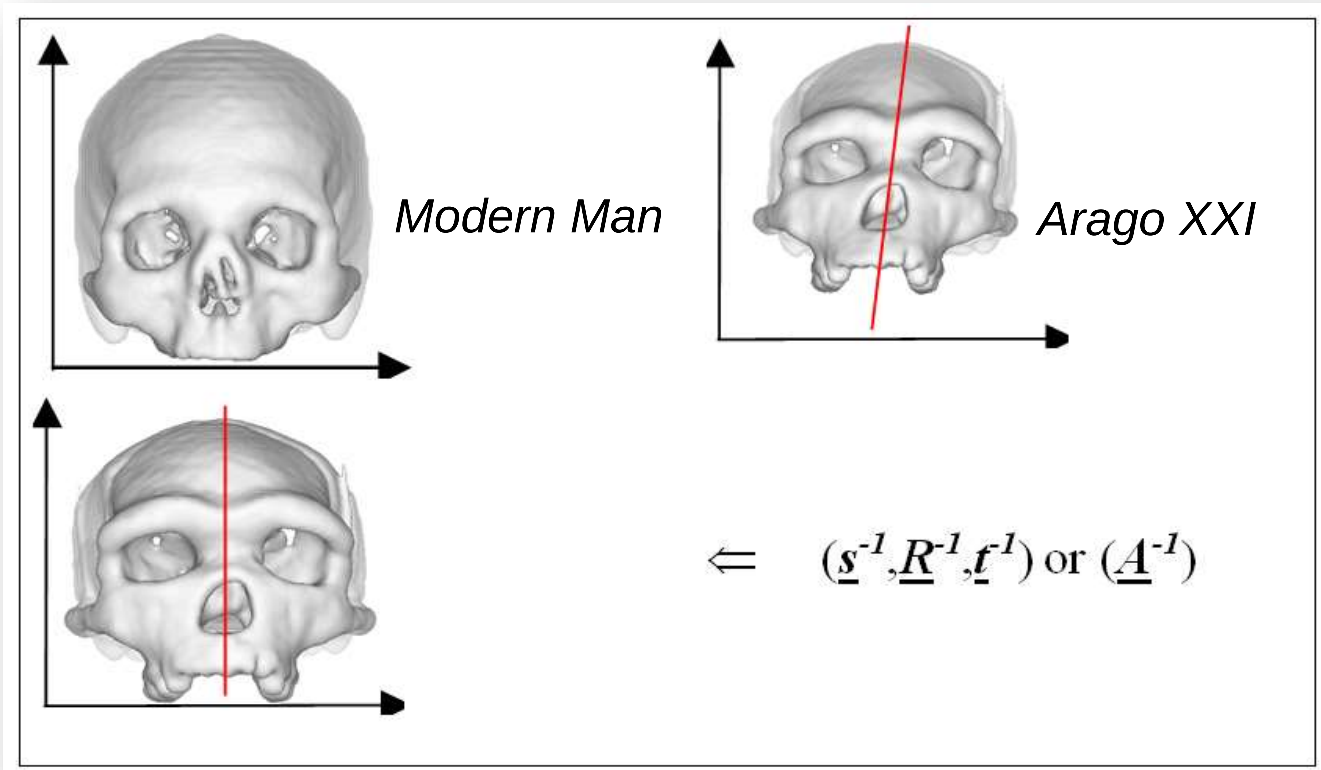


Ghosh et al. "Closed-form Bending of Local Symmetries" . Eurographics Symp., 2010.

1. Compute the centroid and a local frame based on corresponding landmarks.
2. Compute the minimal stretch deformation in order to make each frame orthogonal.
3. Rotate the frames in order to obtain a (symmetry) plane.
4. Extrapolate the deformation to the whole space.

→ Based on the strong assumption that it exists a (strict) symmetry.

Comparison with a reference model

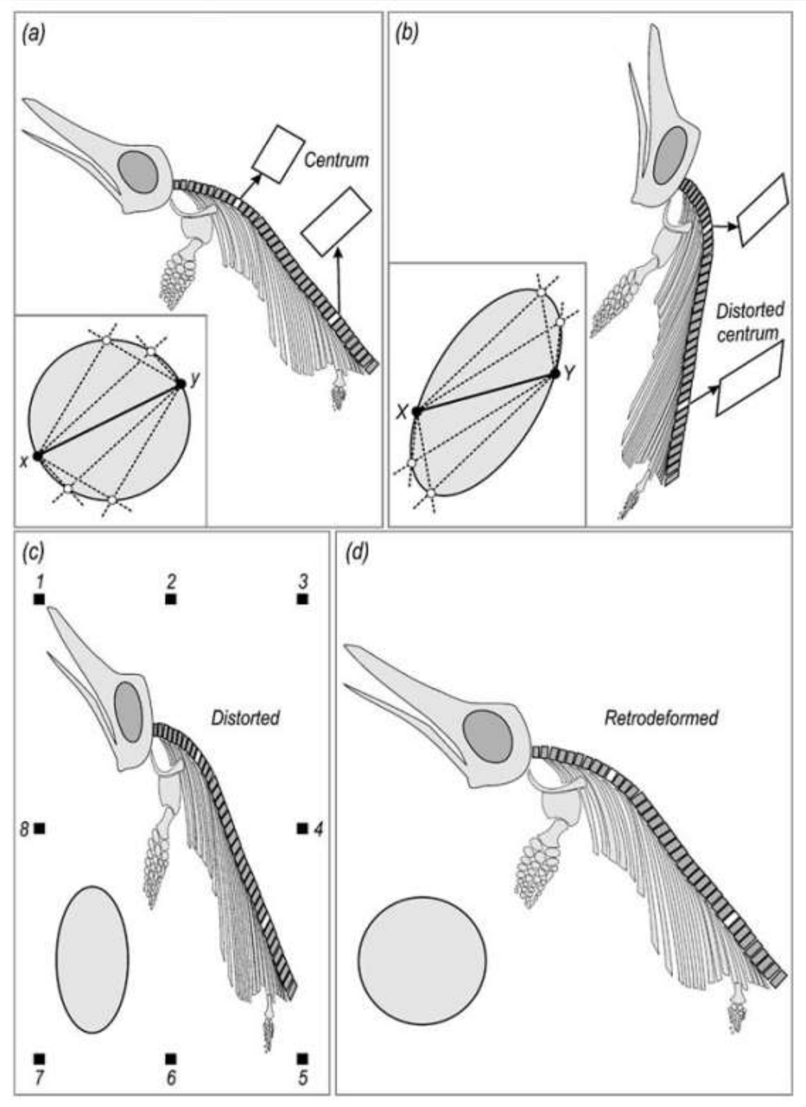


Subsol et al. "3D Image Processing for the Study of the Evolution of the Shape of the Human Skull: Presentation of the Tools and Preliminary Results". XIVth UISPP, 2001.

1. Choose a reference model ("normal" or average)
2. Find automatically pairs of 3D landmarks with a registration algorithm.
3. Define a class of admissible transformations for the retrodeformation..
   Hypothesis: linear transformations (also called "affine")
   = position + orientation + different scalings + shearing
4. Compute a 3D admissible transformation which aligns at best pairs of landmarks.

→ Only a simplistic deformation?

Strain-based methods



Shah & Srivastava. “Strain estimation from distorted vertebrate fossils: application of the Wellman method”. Geological Magazine, 2006. *

1. Build a parallelogram by drawing parallel lines to sides of the anatomical structures.
2. Put all these parallelograms in a reference frame defined by a common diagonal.
3. In the case of distorted structures, we get a strain ellipse
4. Compute the deformation which transforms the ellipse into a circle.

→ How to generalize in 3D?

→ Limited class of deformations (shear).

→ But get the direction of the constraint.

Simulation of the retro-deformation

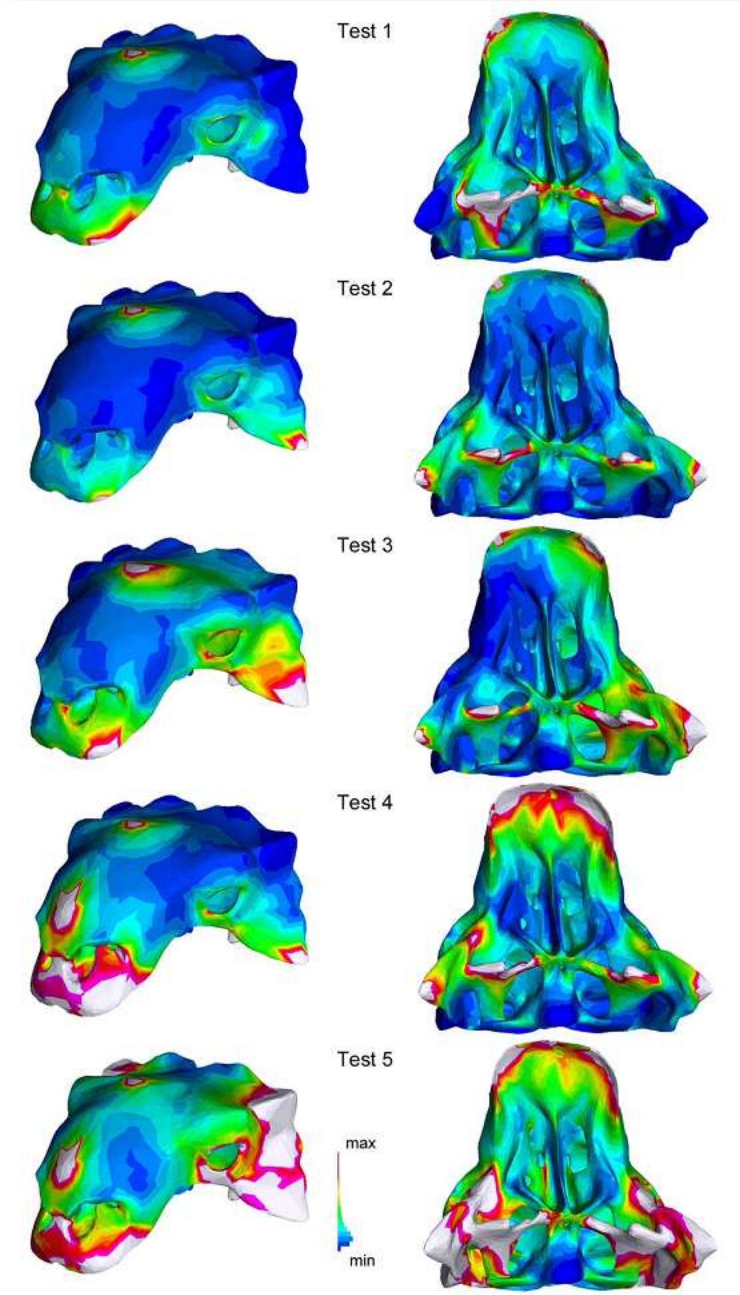


Table 2. Summary of force and constraint parameters in five finite element tests simulating taphonomic deformation of AMNH 5405 and INBR 21004.

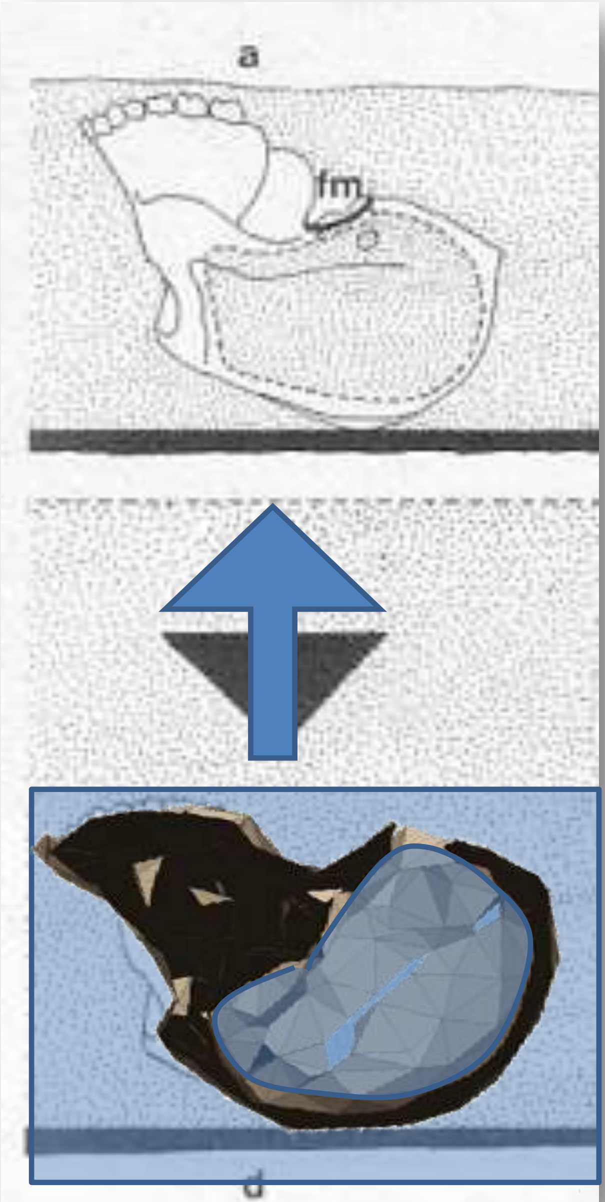
	Constraint Location	Force Location and Direction
Test 1	On the rostiolateral edges of the premaxilla, and on the medial end of each quadrate head.	On the dorsal surface at the midline between the orbits, ventrally directed.
Test 2	On the rostrolateral edges of the premaxilla, on the medial end of each quadrate head, and on the ventrolateral tip of the quadratojugal horns.	On the dorsal surface at the midline between the orbits, ventrally directed.
Test 3	As for Test 2.	On the dorsal surface at the midline between the orbits, ventrolaterally directed.
Test 4	As for Test 2.	On the dorsal surface at the midline between the orbits, and at the midline near the rostral end of the maxilla, ventrally directed.
Test 5	As for Test 2.	On the dorsal surface at the midline between the orbits, at the midline near the rostral end of the maxilla, and at the distal tip of each squamosal horn, ventrally directed.

Arbour & Currie. "Analyzing Taphonomic Deformation of Ankylosaur Skulls Using Retrodeformation and Finite Element Analysis". PLOS One, 2012.

1. Build a biomechanical model of the fossil structure (homogeneous, linear elasticity).
2. Locate some constraints and apply a force (5 tests)
3. Visualize the strain (e.g. the quantity of deformation)

→ Only used to see which parts are most likely to be deformed and not to see the resulted retrodeformed fossil.

Proposed methodology



"Some Compressional Effects on Bones Preserved in Cave Breccia". Brain, 1981 (The Hunters or the Hunted?)

1. 3D modeling of the fossil (geometry + mechanics);
2. 3D modeling of the environment (geometry + mechanics);
3. Apply a retrodeformation constraint on the environment;
4. Simulate biomechanically the deformation of the virtual environment and of the virtual fossil;
5. Analyze the result according to anatomical or in-situ observations;
6. Find the "optimal" retrodeformation which results in an "optimal" retrodeformed fossil..

(some preliminary tests have been done with a "fossilization simulator")

Subsol et al. "A 3D biomechanical simulation of a fossilization process of a bony structure - New perspectives for the retrodeformation of paleo-anthropological fossils". AAPA 2012.

Application to STS 52 (1)

Australopithecus africanus specimen found by Robinson in Sterkfontein in 1949 (~ 2.5 My).

- Sts52a = partial lower face somewhat compressed laterally;
- Sts52b = slightly distorted mandible.

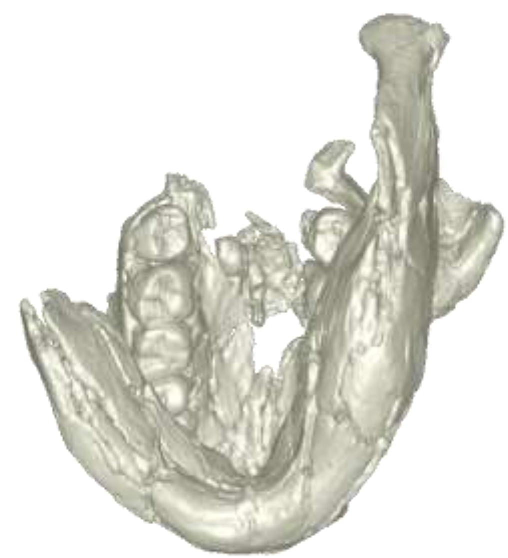
No in-situ observation on the discovery?

Schwartz & Tattersall. "The Human Fossil Record, Vol. 4", 2005.

CT-Scan of the original skull:

- 398 slices of 1024 × 1024 pixels
- 0.1270 × 0.1270 × 0.2992 mm

→ Find the retrodeformation to apply on the lower face to fit with the mandible.



Application to STS 52 (2)

1. 3D modeling of the fossil (geometry + mechanics):

- Extraction of the 3D mesh of the lower face (and of the mandible);
- Decimation of the 3D mesh;

- Volume meshing by hexaedron elements (with a resolution of 2 mm);
- Homogeneous, isotropic, compressible material (Poisson's ratio=0);
- Linear elasticity: Young's modulus = 150.

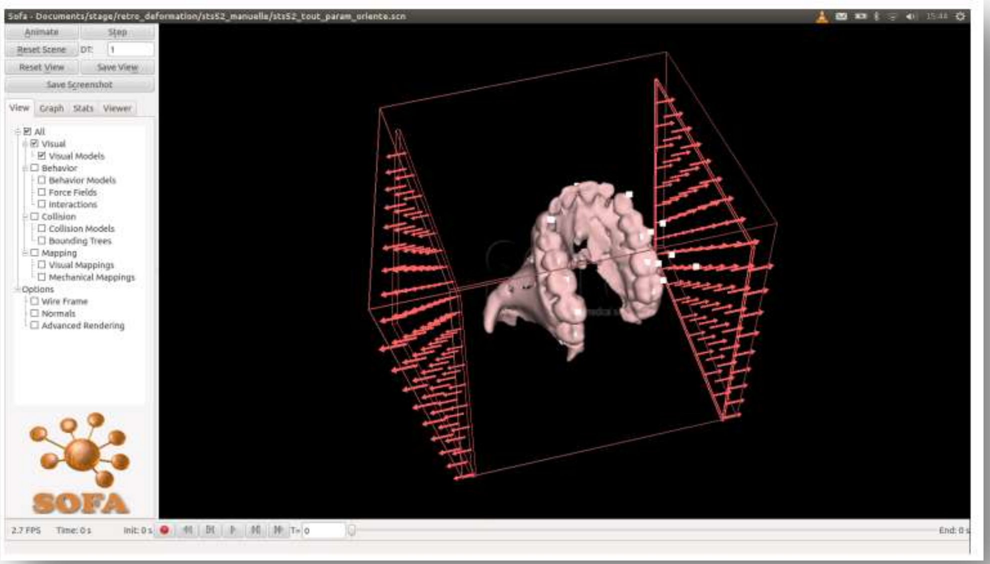
2. 3D modeling of the environment (geometry + mechanics):

- 3D bounding box around the fossil;

- Young's modulus = 5 (/30 w.r.t. fossil).

3. Apply a retrodeformation constraint on the environment:

- Retrodeformation applied in opposition on the 2 sides of the box;
- Parameterized by a direction given by 2 angles.



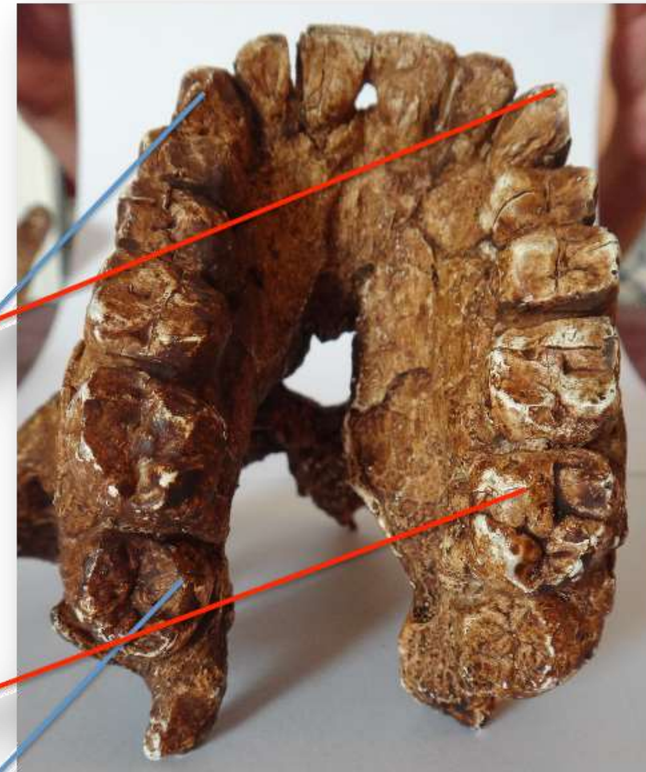
4. Simulate biomechanically the deformation of the virtual environment and fossil:

- Finite Element Method;
- Open-source SOFA framework for real-time medical simulation (*http://www.sofa-framework.org*);
- Wait for the static equilibrium;
- Computation time = ~10 s.

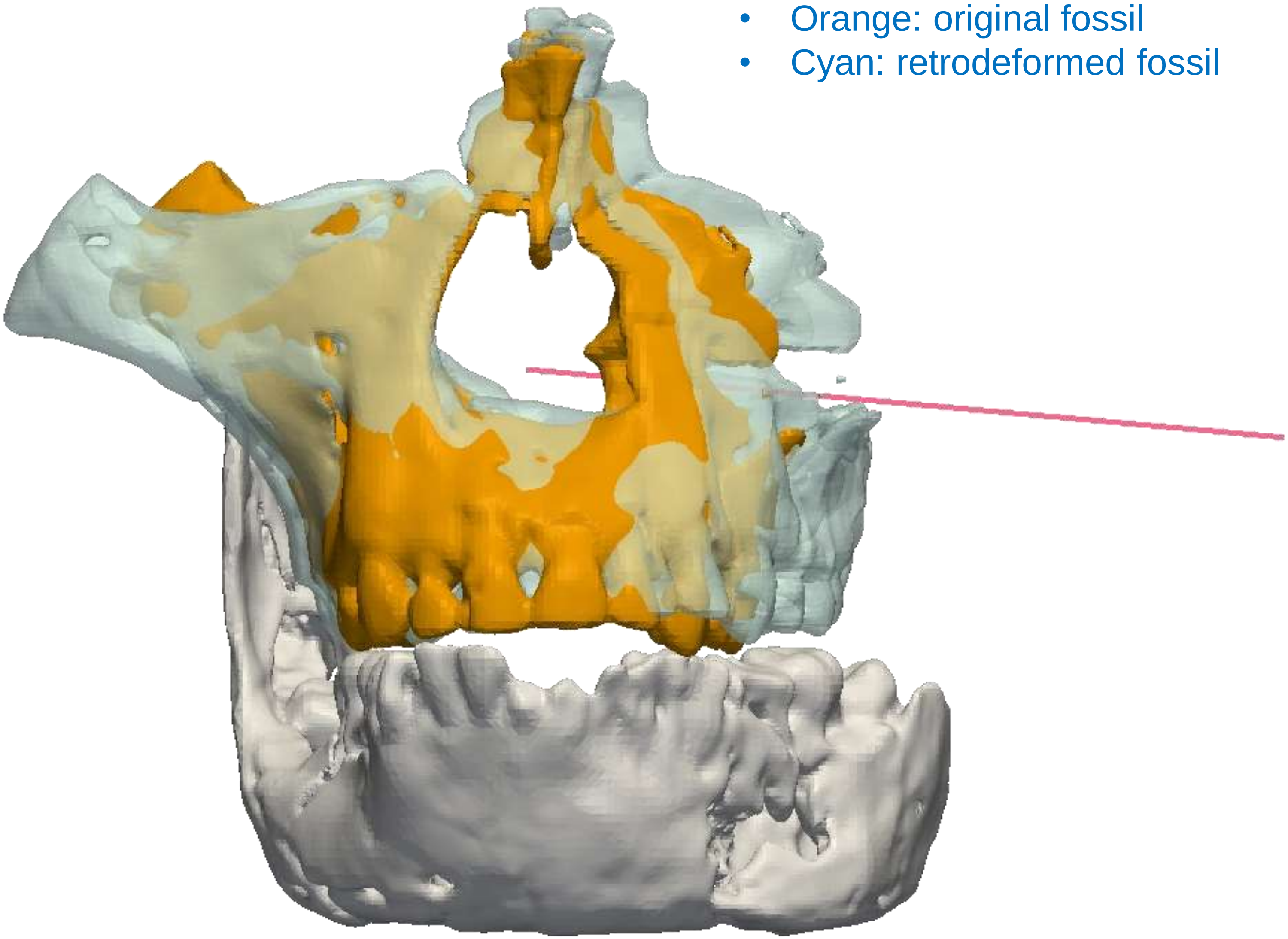
Application to STS 52 (3)

5. Analyze the result according to anatomical or in-situ observations:
   - Based on occlusion characterized by the distance between corresponding points defined by José Braga.

6. Find the "optimal" retrodeformation which results in an "optimal" retrodeformed fossil:
   - Multiscale dichotomy method;
   - Precision up to 1°.
   - Computation time: 2 h.



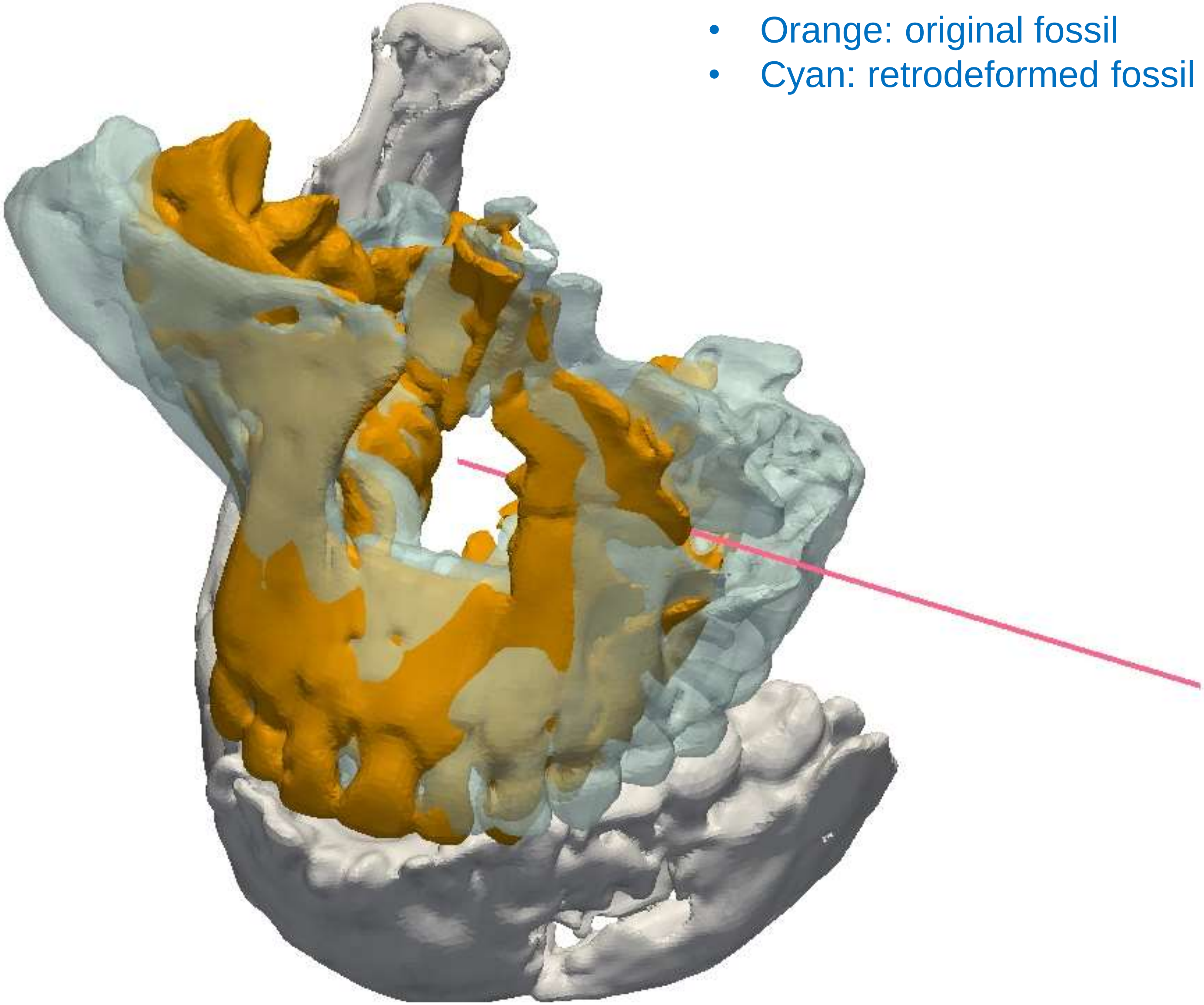
Some results



- Orange: original fossil
- Cyan: retrodeformed fossil

→ We can see a big “opening” of the face with a slight (counterclockwise) rotation.

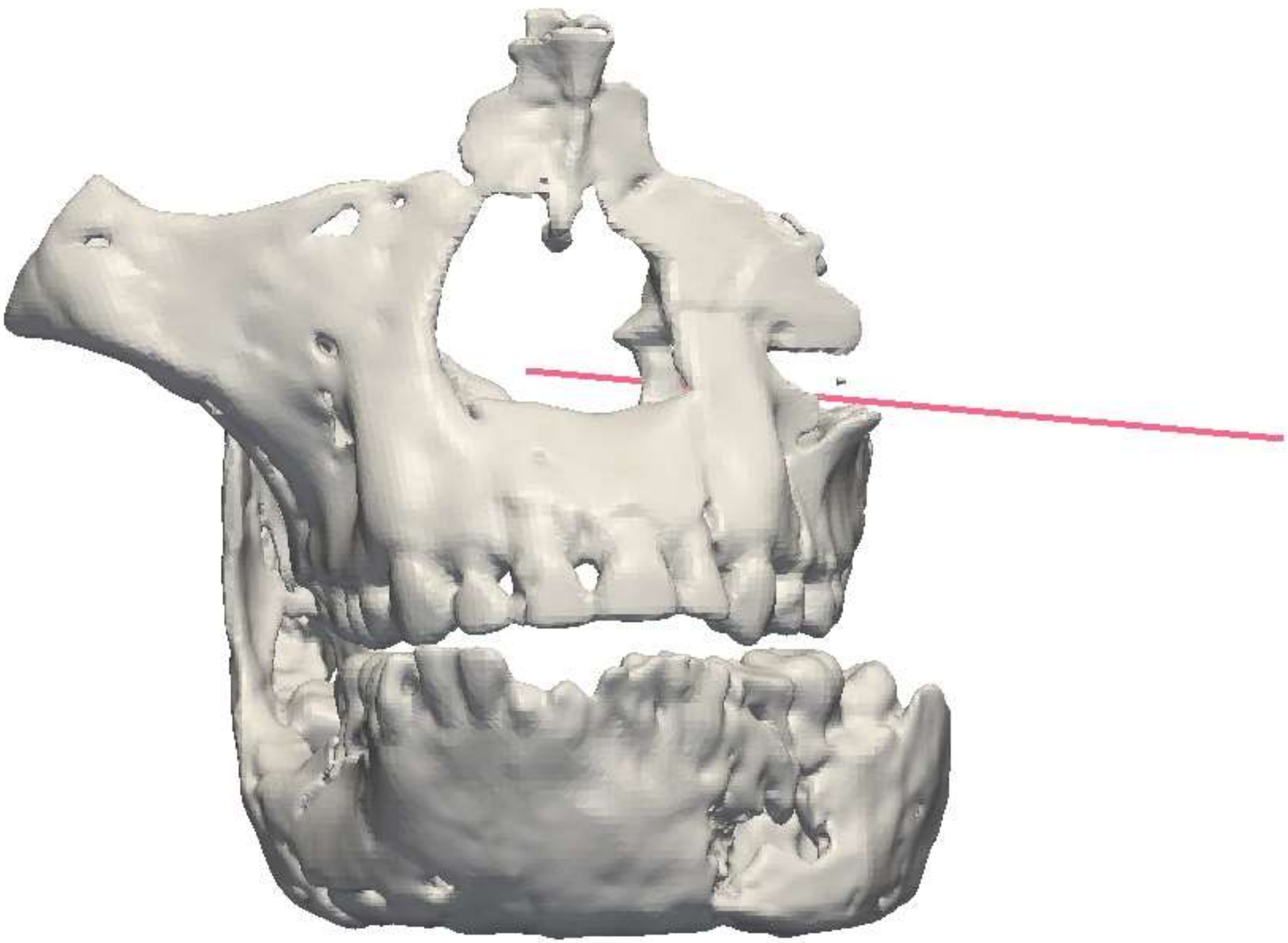
Some results



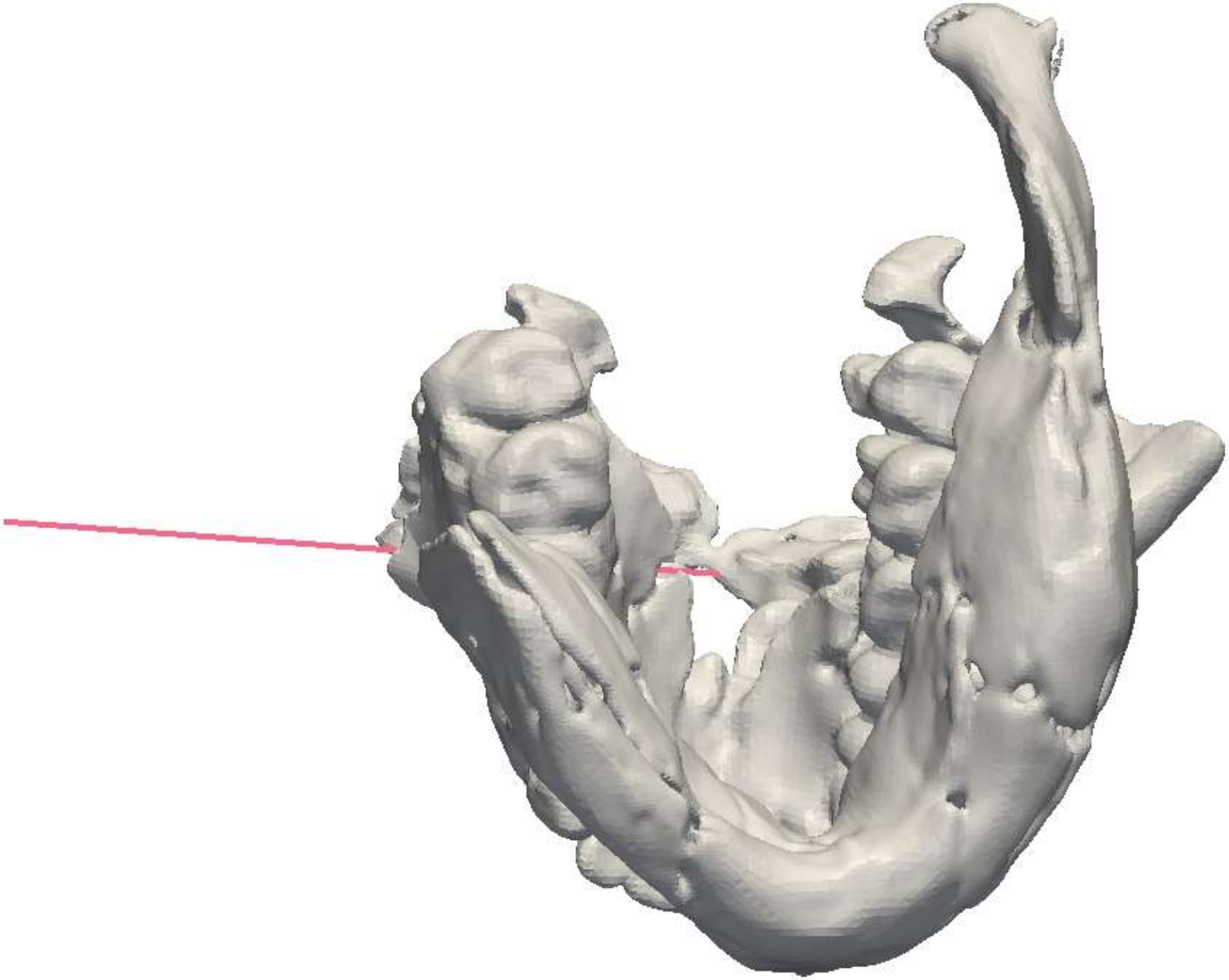
- Orange: original fossil
- Cyan: retrodeformed fossil

→ The retrodeformation constraint is lateral but not perpendicular to the side of the face.

Some results

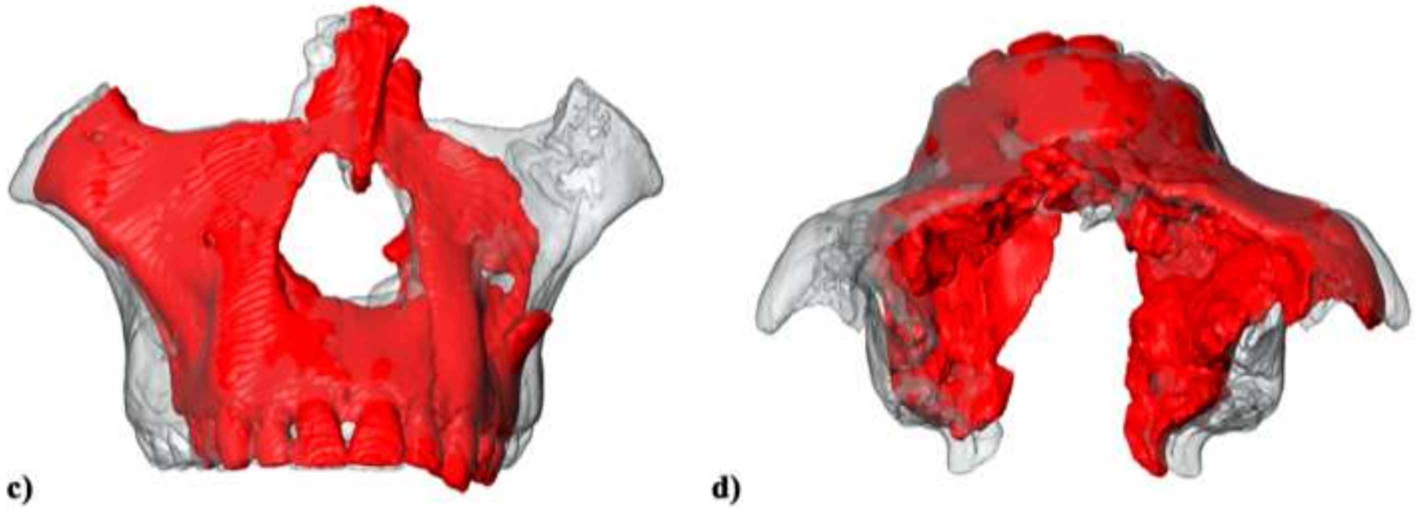


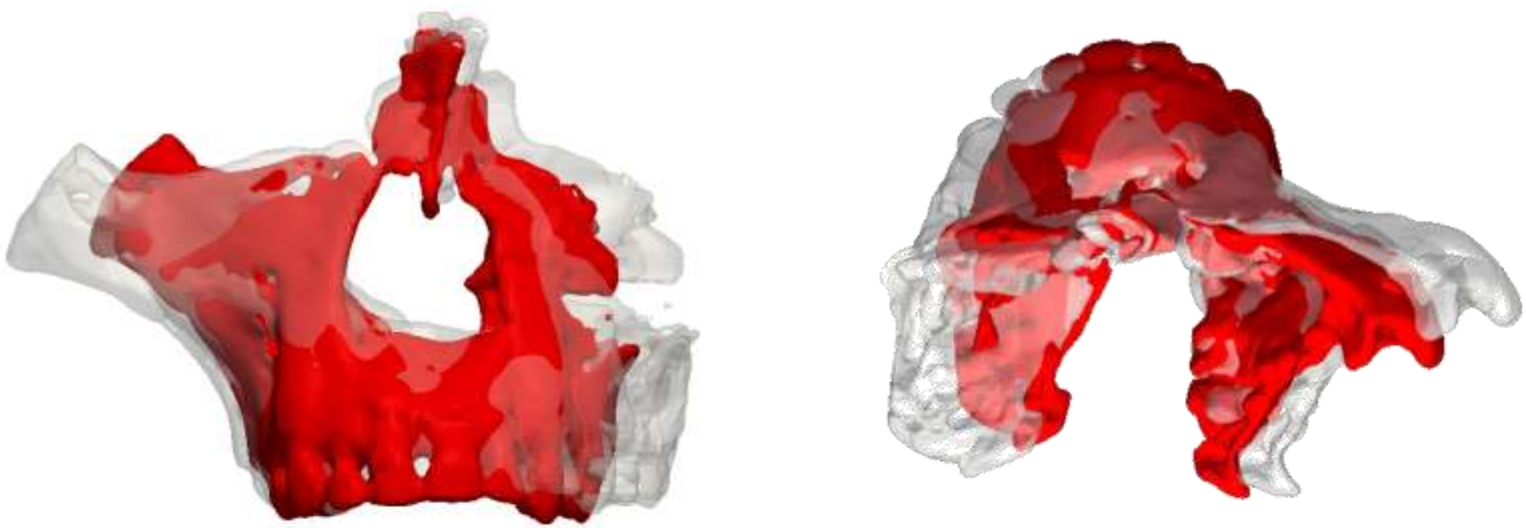
Some results



Comparison of results

Benazzi et al. "Individual Tooth Macrowear Pattern Guides the Reconstruction of Sts 52 (Australopithecus africanus)". AJPA, 2013.



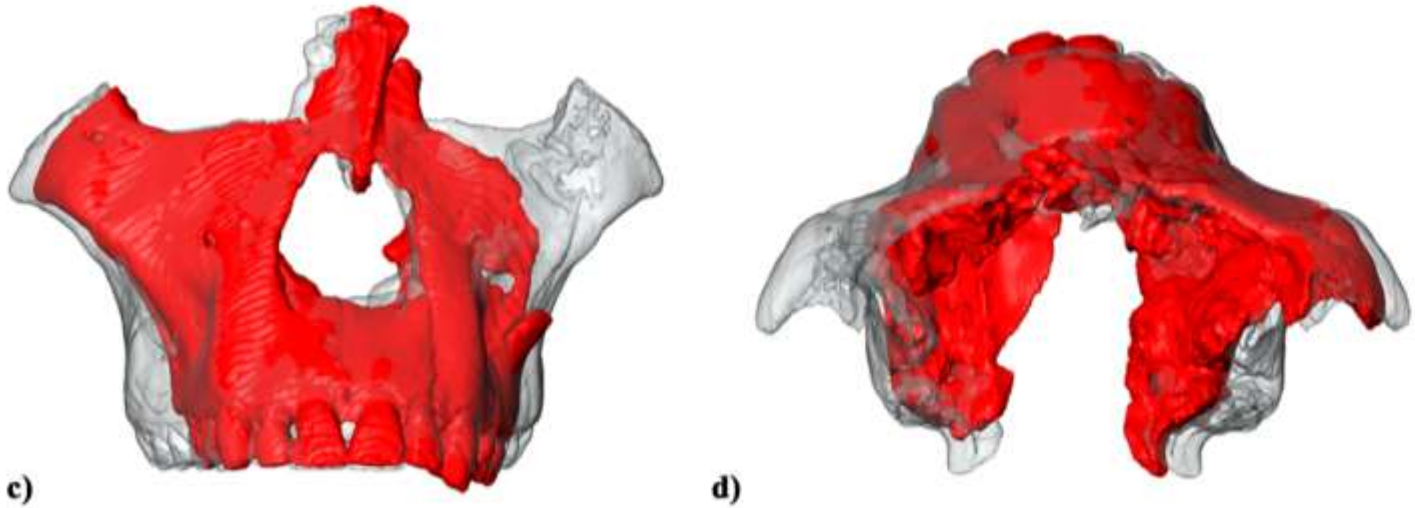


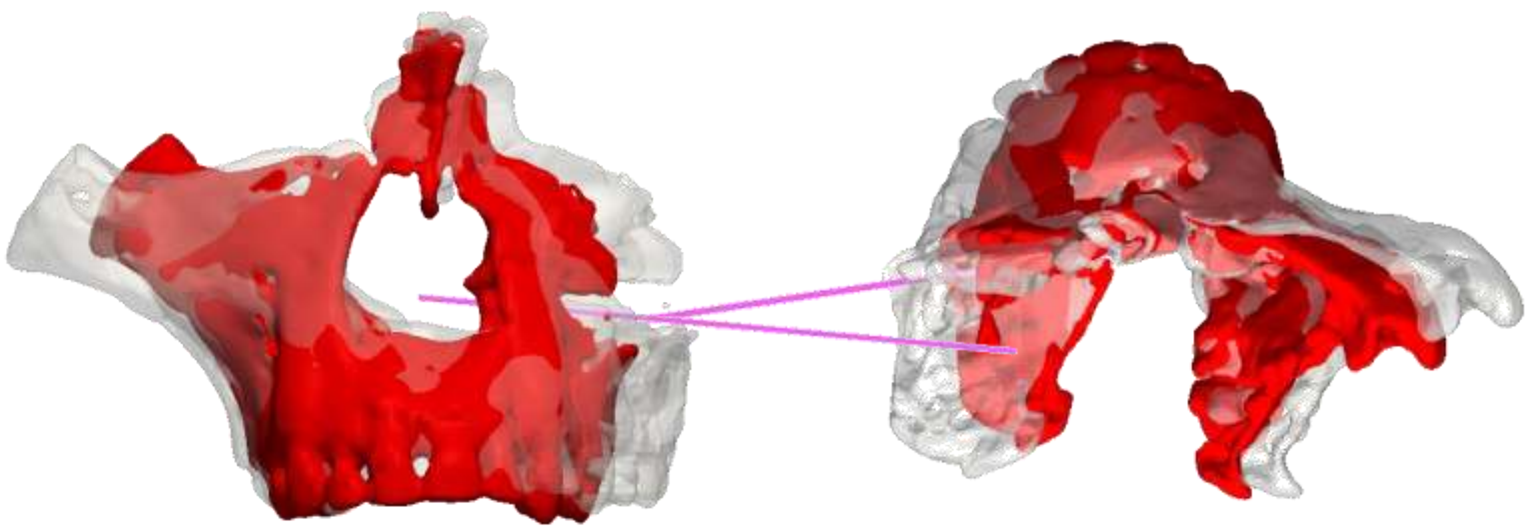
→ Same tendency. Maybe too large in our case…

- Red: original fossil
- Grey: retrodeformed fossil

Comparison of results

Benazzi et al. "Individual Tooth Macrowear Pattern Guides the Reconstruction of Sts 52 (Australopithecus africanus)". AJPA, 2013.





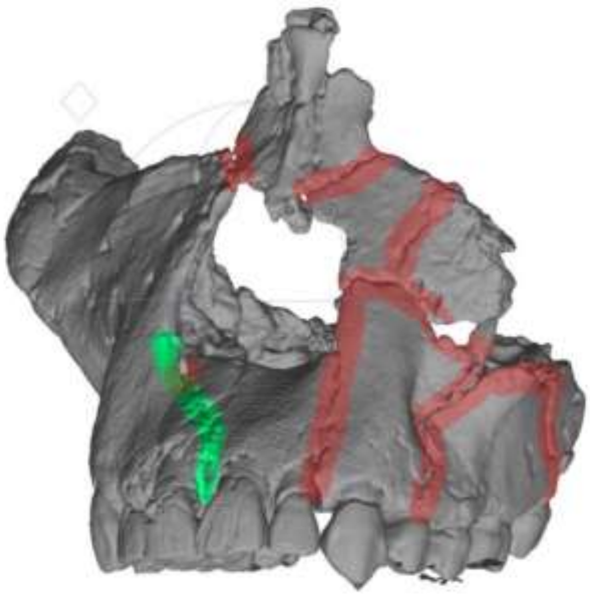
→ Same tendency. Maybe too large in our case…
but we get the direction…

- Red: original fossil
- Grey: retrodeformed fossil

Future work

- Define a better correspondence criterion (e.g. occlusion line);
- Observe more detailed anatomical features (e.g. fracture planes);
- Perform an optimization on the magnitude or on the elasticity parameters;
- Compute sequentially several retrodeformations;
- Model brittle deformation by defining different parts with different physical parameters;
- Compare with in-situ observations (e.g. by using 3D scan of the excavation sites).

Thank you for your attention!



G. Subsol et al. "3D Digitization of the Excavation Site of a Fossil Hominid (StW 573 / "Little Foot", Sterkfontein, South Africa". Paleoanthropology Society, April 2011.