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THREE-DIMENSIONAL RE-EVALUATION OF THE DEFORMATION REMOVAL TECHNIQUE BASED ON "JIGSAW PUZZLING"

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ABSTRACT

Retrodeformation is the process of removing distortions in fossils caused by tectonic or overburden stresses. These methods are very important for paleontologists because they can be used to estimate true fossil shapes necessary for studies in systematics, phylogenetics, and functional morphology. Deformation may be brittle, breaking the specimen apart but leaving the original shape of the broken pieces unaltered, or plastic, altering the original shape without breakage. The effects of plastic deformation are often overlooked in fossils with extensive brittle deformation. Anthropological studies dealing with brittlely-deformed bones tend to rely on simple "jigsaw puzzle" reconstruction, in which fractured pieces are manually or digitally placed back together. These methods assume that most of the deformation is brittle, and that the original fossil shape can be restored without plastic retrodeformation. We tested the validity of jigsaw puzzle reconstruction by using three-dimensional (3-D) computational techniques. More specifically, we examined if plastically deformed skull pieces can be arranged to form a 'symmetrical skull' that morphologically differs from the true skull under a digitally controlled environment. A cranium of a Woolly Monkey (*Lagothrix lagotricha*) was digitized using a 3-D laser scanner. We virtually fragmented and then plastically deformed this skull to create skull pieces with known plastic deformation. We found that these pieces fit well onto the true skull and an incorrect skull shape equally well, suggesting that "jigsaw puzzle" methods can lead to inaccurate specimen reconstruction that superficially appears 'correct'. We conclude the plastic deformation must be removed before "jigsaw puzzle" fossil reconstruction.

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INTRODUCTION

There are two primary categories of fossil deformation, brittle and plastic. Brittle deformation may be described as structural cracking without shape change of the individual broken pieces, whereas plastic deformation is described as shape change without breakage. Plastic deformation alters the true shape of a fossil, the shape of the body part during life.

Fossil deformation is the result of many different forces and processes. Overburden stress and resulting porosity loss are the primary processes that cause fossil deformation. As fossils are initially buried the weight of the overlying sediments linearly compacts the fossil from above. Depending on numerous associated factors, including confining pressure and strain rate, this can cause the fossil to break and/or warp. All fossils undergo these forms of diagenetic deformation, implying that the true fossil shape is rarely, if ever, preserved.

Secondary causes of fossil deformation include tectonic stresses and sediment cracking. Tectonic stresses from large- and small-scale plate motion can be a major source of both brittle and ductile deformation. Tectonic deformation is usually nonlinear and very complicated (Davis and Reynolds 1996). Because of this it is very difficult to predict and correct for tectonic deformation. Likewise sediment cracking/expansion is a poorly understood process that involves the invasion and expansion of sedimentary matrix material into weak areas of a fossil, such as sutures (White 2003). This process can greatly alter the shape of a fossil.

It is important to consider the effects of deformation in almost all paleontological studies. Many false conclusions may be drawn if a plastically deformed fossil is thought to retain its true shape. Functional morphology relies on fossil shape to hypothesize motion capabilities and lifestyle of extinct organisms. Systematic and phylogenetic studies use fossil shape when recognizing a taxon and coding its characters in the process of tree building. Using plastically deformed fossils for either type of study carries great inherent risk and adds enormous amounts of error to all results. Because of this, numerous methods have been created for removing both brittle and plastic deformation. Such methods have been called retrodeformation (Hughes and Jell 1992).

Plastic deformation is difficult to remove and retrodeformation can only be attempted digitally (Zollikofer and de León 2005, Zollikofer et al. 2005) or optically (Lake 1943, Hills and Thomas 1944). Almost all plastic retrodeformation methods require that the original fossil shape was symmetrical. These methods use the re-acquisition of symmetry as the basis for the transformations applied to the fossil. The geometric average method involves identifying symmetrical landmark pairs and equalizing their distance to an established sagittal plane (Ogihahra et al. 2006). The minimum stretch method calculates the minimum amount of stretch necessary that a fossil would have to undergo to re-attain its symmetry and deforms the fossil according to this calculation (Zollikofer and de León 2005). It is not our purpose to examine the methods for plastic retrodeformation.

Brittle retrodeformation is generally accomplished using a method we refer to as "puzzle piecing." The method consists of taking the broken pieces of a fossil and piecing them back together in their presumed original shape, much like constructing a model airplane. This can be done both physically, with the actual fossil fragments or fragments of a cast, or digitally, using digitized representations (Zollikofer et al. 1995, 2005). We believed that this method would yield unreliable and unrepeatable results, which could lead to inaccurate studies of the fossils in question. Therefore, we tested this method of reconstruction in a completely controlled environment by piecing together digitally deformed pieces of an extant specimen using both the original specimen and an alteration of the original specimen as reconstruction templates. We wanted to know if 1) puzzle piecing only results in the true skull shape; and 2) the fact that deformed skull pieces could be arranged into a symmetrical 'skull' justifies the assumption that plastic deformation from overburden compaction does not cause additional significant losses of shape data.

MATERIAL AND METHODS

We digitized a skull of an extant species; split the specimen into several different configurations; linearly shortened each splitting configuration from several different angles; reconstructed the distorted pieces on both the original skull and a deformed version of the original skull; and measured the fit and symmetry of the resulting reconstructions. Each step is explained below.

We digitized the skull of a Woolly Monkey (*Lagothrix lagotricha*), which had a principal component axis length of 10 cm, with a Minolta Noncontact 3-D Digitizer Vivid 910. Next, using Rapidform 2004 3-D Visualization and Manipulation software, we split the skull into four different

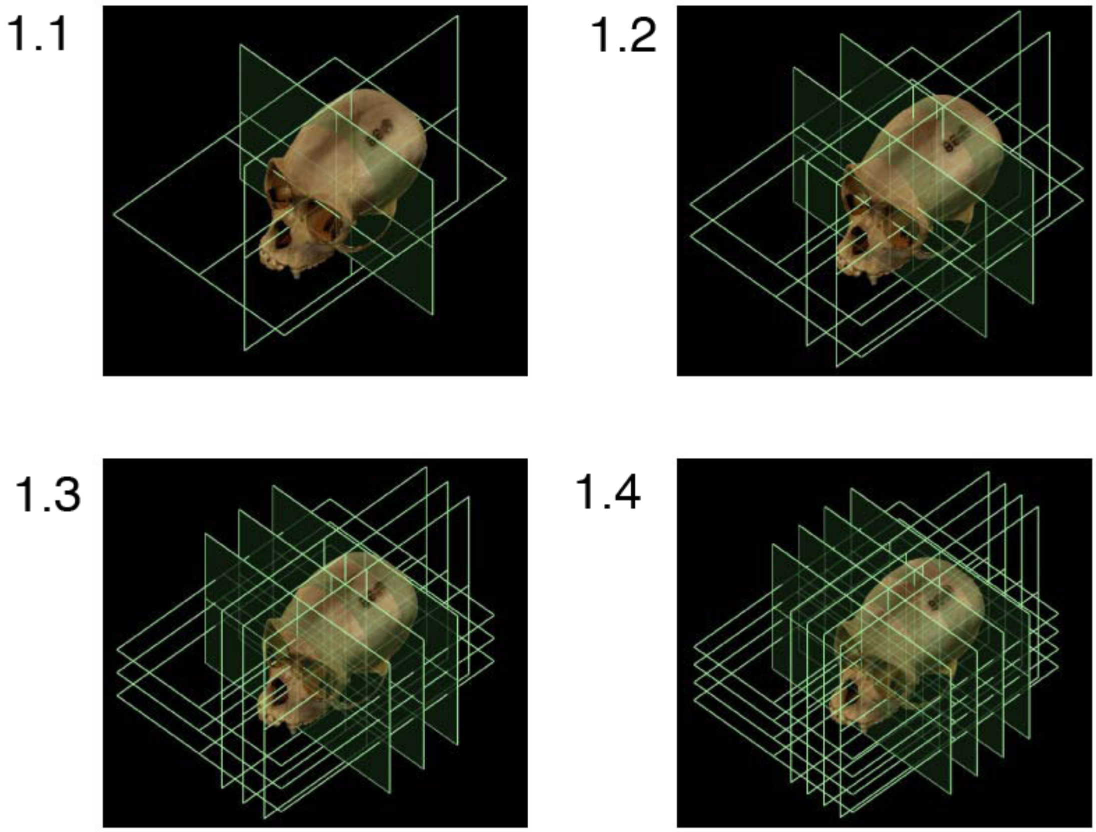

Figure 1. 1. The first splitting scheme, split in halves on the principal axes, resulting in 8 pieces. **2.** The second splitting scheme, split into thirds on the principal axes, resulting in 27 pieces. **3.** The third splitting scheme, split into fourths on the principal axes resulting in 67 pieces. **4.** The fourth splitting scheme, split into fourths on the principal axes resulting in 96 pieces.

configurations. The splitting regimes were dictated by the construction of an artificial 3-D Cartesian coordinate plane within the skull with its center at the center of volume of the skull. The Y-axis connected the top and the bottom of the skull, the Z-axis connected the dorsal and the ventral portions, and the X-axis connected the two sides of the skull. The first splitting group divided the skull into halves on each of these axes with an end result of eight pieces. The second group split the skull into thirds on the axes resulting in 27 pieces. The third and fourth groups split the skull into fourths and fifths respectively, yielding 61 and 95 pieces (Figure 1). These splittings divided the space into 64 and 125 cells, respectively, but some of these cells did not contain bones, and thus the piece count is less than these numbers.

Each splitting group was then linearly compacted to 70% of its original length from 10 different angles. This compaction ratio is within the standard range for overburden stress deformation. The first five deformation angles were confined to the positive X-Y plane. The first angle was 15 degrees oblique to the X-axis, the second 30 degrees, the third 45 degrees, the fourth 60 degrees, and the fifth 70 degrees oblique to the X-axis (Figure 2.1). The last five followed the same spacing configuration as the first but were confined to the positive Z-Y plane (Figure 2.2).

The next step was reconstructing the skull with the deformed pieces. To do this we used two template skulls, the original skull and one deformed template. The deformed template skull is the original Woolly Monkey skull but compacted to 85% of its original width along the previously mentioned X-axis. The skull remained symmetrical but was no longer the true shape. The pieces from each deformation trial were fit onto both template skulls using automated surface recognition and registration techniques.

To measure the relative fit of our reconstructions, we calculated the average distance between

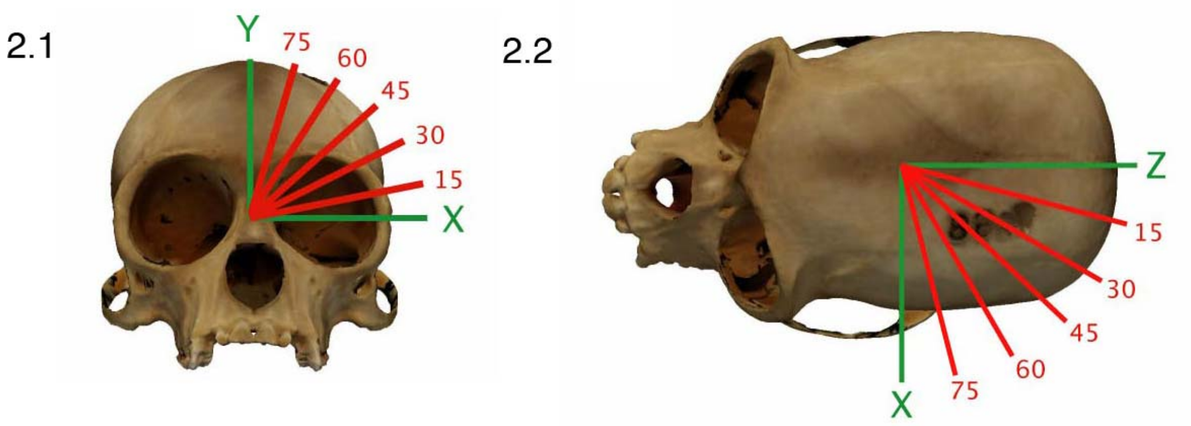

Figure 2. 1. The five angles of deformation and their relative positions to the major axes for the first five trials. **2.** The five angles of deformation and their relative positions to the major axes for the second five trials.

the reconstruction and the template. The template and reconstruction were aligned in Rapidform 2004, which then calculated the average distance between the two models by measuring the distance from each vertex of one object to the nearest surface of the other. We used this average distance as the score of fit. To test the symmetry, a mirror image of each skull reconstruction was made and aligned with the original, and then the average distance between the two skulls was calculated by Rapidform 2004 as in the previous case. This average distance was used as the symmetry score. In both cases, the distance found for each vertex was coded in color and plotted on the skull surface as a color distance map to show regional variation in the distance.

RESULTS

The average distance calculations showed that there was very little difference between the fit of the deformed pieces on the original skull template versus the deformed skull template. There was less variation in the average distance scores between trials when fitting on the original skull template than on the deformed skull template (Figure 3). Overall the closest fit reconstructions, those with the smallest calculated average distances, were completed using the deformed skull template. Specifically the best-fit scores were produced by the X-15 and Z-75 trials, fitting on the deformed template (Figure 4, Figure 5). The differences in the symmetry scores were similarly ubiquitous. There was no discernable difference in the results of the symmetry scores between the original skull template and the deformed skull template trials. There was more unpredictable variation within the trials fitting on the deformed skull template (Figure 6).

The fit score demonstrated that the greater the number of pieces a specimen is split into, the better the fit. The best-fit reconstructions were accomplished using the deformed template on the 95 pieces trials. However, it is noteworthy that even the poorest score of fit that we found using only eight pieces was less than 1% of the maximum dimension of the skull (Figure 3, Figure 6). The same is true for the symmetry score: even the worst score was less than 1% of the skull length (Figure 3, Figure 6).

The color map plots revealed the areas that showed the worst fits. These areas were generally confined to the bone surrounding the major fenestra and holes in the skull including the orbit, the foramen magnum, the nasal cavity, and the zygomatic arch (Figure 7). These areas were also the areas of least symmetry.

DISCUSSION

The results showed that there was no immediate discernable difference in the average distance and symmetry score data collected for the true shape template and deformed template trials. Also, our results show that these reconstructions would typically show small asymmetry when deviation is averaged over the skull. This strongly indicates that it would be just as easy and convincing to reconstruct the deformed pieces from this experiment into an incorrect shape as it would be to reconstruct them into the true one. As per the questions that we raised earlier, we conclude that: 1) puzzle piecing does not necessarily result in the true skull shape; and 2) the fact that deformed skull

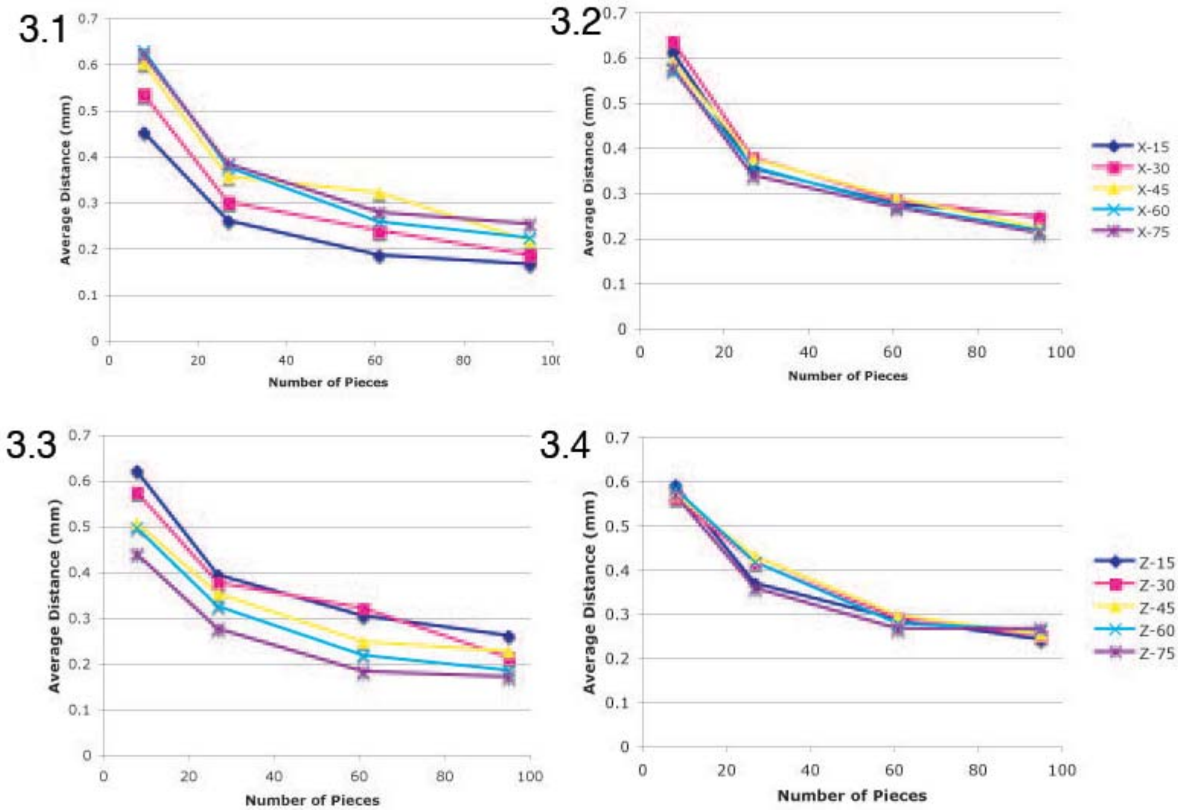

Figure 3. 1. Average distance between skull reconstructions and the deformed template for deformation trials on the X-Y plane plotted against the number of pieces in each reconstruction. **2.** Average distance between skull reconstruction and the undeformed template for deformation trials on the X-Y plane plotted against the number of pieces in each reconstruction. **3.** Average distance between skull reconstructions and the deformed template for deformation trials on the X-Z plane plotted against the number of pieces in each reconstruction. **4.** Average distance between skull reconstruction and the undeformed template for deformation trials on the X-Z plane plotted against the number of pieces in each reconstruction.

pieces could be arranged into symmetrical 'skull' does not justify the assumption that plastic deformation from overburden compaction is absent. We argue that retrodeformation methods that use brittle "puzzle piece" reconstruction requires cautious examination of its assumptions. Most importantly, removal of plastic deformation is of vital importance, given that plastically deformed pieces showed improved fit onto an incorrect template.

The considerable variation in the average distance calculations and symmetry scores for the deformed template reconstructions seems to be directly related to the relation of the deformation scheme and the shape of the template skull. In general, deformation schemes that resembled straight X-axis or skull width compression most closely fit the template skull. As stated earlier, the template skull was compressed to 85% of it original width along the established X-axis. By identifying the areas of the specimens that showed the least fit we hope to provide other scientists an idea of where to look to see if and to what extent their fossil is deformed.

This study is merely a preliminary foray into testing "puzzle piece" retrodeformation methods for correcting plastic deformation. More studies need to be done that can statistically test these methods. Several procedures in the methods used in this study need to be addressed. The reconstruction methods allowed for piece overlap, two pieces occupying the same place. This obviously could not happen in an actual physical reconstruction. In the best-fit trials these overlaps hardly happened, but in the other trials the overlaps should be either

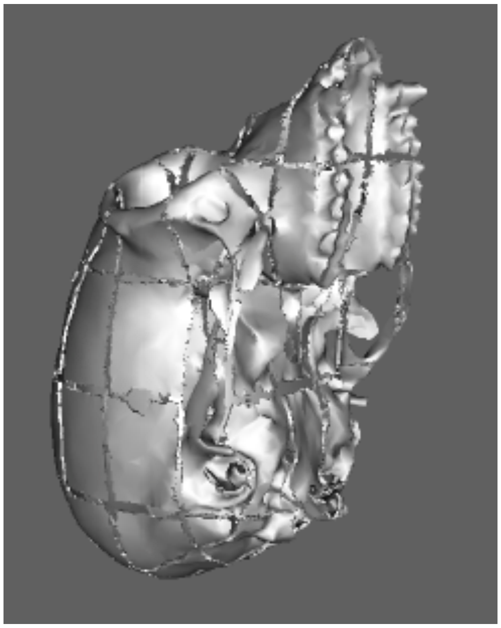

Figure 4. The reconstruction of the wooley monkey skull deformed from 15 degrees off the X-axis and split into 96 pieces. It was fit on the deformed template.

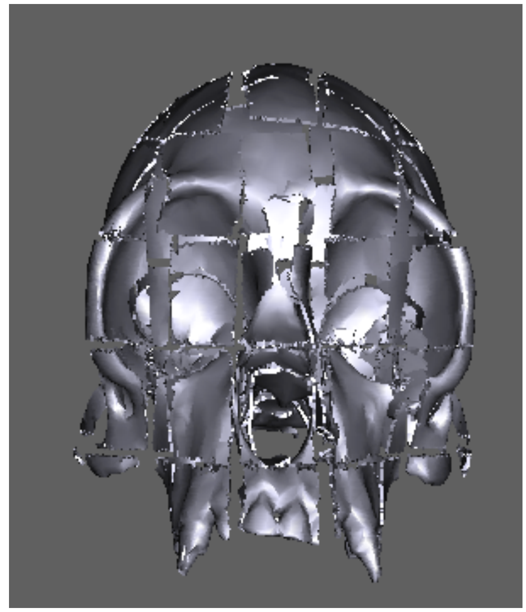

Figure 5. The reconstruction of the wooley monkey skull deformed from 75 degrees off the Z-axis and split into 96 pieces. It was fit on the deformed template.

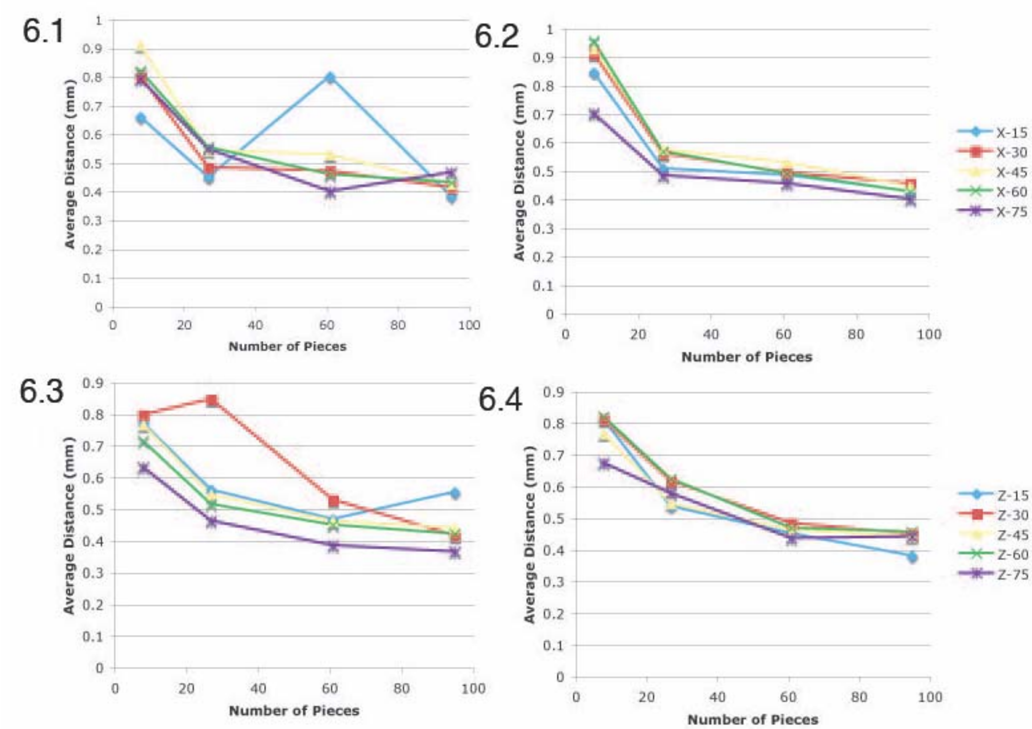

Figure 6. 1. Average distance between mirrored skull reconstructions originally fit on the deformed template for deformation trials on the X-Y plane plotted against the number of pieces in each reconstruction. **2.** Average distance between mirrored skull reconstructions originally fit on the undeformed template for deformation trials on the X-Y plane plotted against the number of pieces in each reconstruction. **3.** Average distance between mirrored skull reconstructions originally fit on the deformed template for deformation trials on the X-Z plane plotted against the number of pieces in each reconstruction. **4.** Average distance between mirrored skull reconstructions originally fit on the undeformed template for deformation trials on the X-Z plane plotted against the number of pieces in each reconstruction.

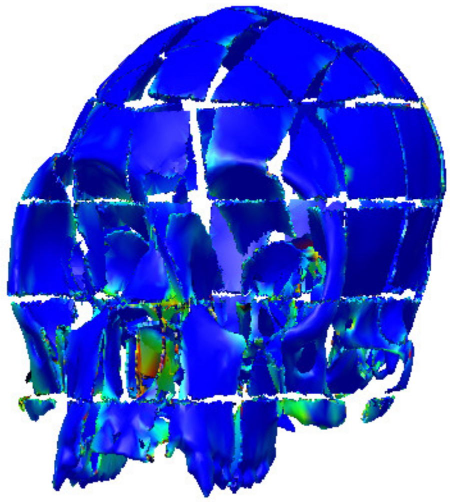

Figure 7. The color map plot of average distance calculations between the reconstruction trial in Figure 5 and the deformed template. Blue represents good fits while red represents bad fits.

eliminated or carefully measured to assure more accurate and meaningful results. Another issue that needs to be addressed is the computerized fitting procedure. The computer measures the distance from each vertex of the piece models to the closest surface of the template model. Such a measurement compiles a huge amount of data that has a standard deviation that is often larger than the average distance measurement itself. We propose to conduct a new experiment that performs reconstructions by minimizing the root mean square distance between a series of pre-established landmarks on the specimen in question. We also wish to use a splitting scheme that more closely resembles those found in the natural world. It is possible that the splitting scheme greatly impacts the outcome of such a trial.

Even given the possible improvements listed above, our study represents the first controlled and quantitative examination of the puzzle piecing method of retrodeformation that is being widely used without being tested. However elaborated the model may become, the fact remains that even eight-piece division, which is the simplest model that gave the poorest symmetry score, resulted in a rather symmetrical model with an average asymmetry of less than 1% of the maximum dimension of the skull. This strongly indicates that the puzzle piecing method cannot be validated using symmetry scores. We conclude that independent criteria, such as the knowledge of approximate skull shape as in one published case, are necessary.

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