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**The Mechanical Function of the Postorbital Bar in *Eulemur fulvus*
Analyzed Using Finite Element Analysis**

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Senior Thesis

Dr. David Strait

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INTRODUCTION

This study examines the functional anatomy of the primate postorbital bar. Postorbital bars are “bony arches that encompass the lateral aspect of the eye and form part of a circular orbit,” (Heesy 2005). They are formed by the dorsal part of the frontal bone and the ventral part of the zygomatic. Postorbital bars are not unique to primates. In fact, historically, they have evolved many times in many different mammalian species. However, they are found in all primates and, thus, are considered a defining characteristic of the family. Nevertheless, while their importance is undeniable, their reason for evolving and their functional role is highly debated among scholars.

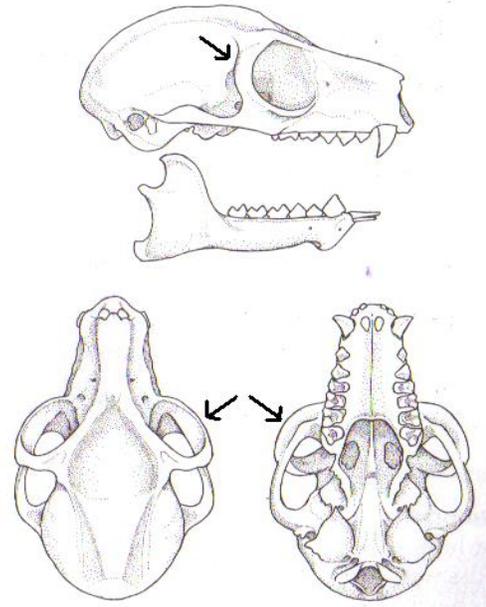


Figure 1. This image depicts a postorbital bar in the skull of a lemur (Lawlor, 115).

There are many different theories as to the origin of the postorbital bar in primates. Some can be easily disregarded while others bear more weight. However, there seem to be three basic hypotheses that are most seriously considered by experts in the field.

The first was put forth by Prince (1953, 1956) and Simons (1962). It suggests that the postorbital bar serves to protect against external trauma by shielding the orbit from things like lateral blows, bites, etc. While this may be true to some extent, Cartmill (1970) argues that, considering the thickness of the bar, it would not defend very well against something like a tooth puncture. Therefore, this hypothesis can be rejected.

The second popular hypothesis states that unilateral bite force without a postorbital bar present would severely increase torsional loading on the skull (Greaves 1985). This would then

be “transmitted to the facial skull and probably cause the face to bend and, to some extent, twist up against its moorings,” (Rosenberg, 1986). The inference here is that the bar serves to reduce some of this torsion and subsequent twisting by stabilizing the skull. However, Greaves’ helices of tension and compression are not accurate portrayals of those in primates and anthropoid strains don’t support torsional loading (Hylander and Ross 1996).

Finally, the third hypothesis from Cartmill (1970,1972,1980) states that increasing orbital convergence shifts the anterior temporalis laterally, thereby distorting the lateral orbital wall. This distortion would then presumably disrupt oculomotor precision unless stabilized by the postorbital bar. While it may be the best prediction thus far, the problem with this is that it does not account for the evolution of bars in other non-primate mammals that lack orbital convergence.

The reason it is so hard to prove why exactly the postorbital bar evolved is because we still have not proved what exactly the postorbital bar does. What function does it serve? Why is its presence essential? It has been long suggested and agreed upon that postorbital bars function to stiffen the lateral orbit, thereby decreasing deformation and disruption to oculomotor precision. However, there is very little proof on the actual mechanical function and significance of the postorbital bar, as it has never been experimentally tested directly.

FOCUS OF THIS STUDY

The point of this research is to test the actual mechanical function of the postorbital bar. In doing so, we hope to determine the extent to which the postorbital bar serves to absorb the stresses caused by mastication in *Eulemur fulvus*, a prosimian primate that in several critical respects resembles the earliest primates known from the Eocene epoch, approximately 50 million

years ago. Like early primates, this species possesses a postorbital bar but lacks a bony plate that seals the orbit posteriorly, as in the more derived anthropoid primates (including monkeys, apes and humans). The null hypothesis is that the postorbital bar is functionally neutral insofar as it has no effect on stress and strain distributions in the skull.

We will test this hypothesis by using finite element analysis. (FEA). FEA is a standard engineering technique used to examine how objects of complex geometry respond to loads. In FEA, the object of interest (in our case, a skull) is modeled virtually as a mesh of many small elements, each of simple geometry, that are joined at nodes. The mesh, representing a virtual model of the original object, is assigned material properties (i.e., it is given the stiffness of bone), forces and constraints are applied (in this case, simulating a bite on the molar teeth), and resulting stresses and strains are calculated. Hypothesis testing is made possible by creating two skull models, one with the postorbital bar and one without, then applying equivalent muscle forces to each and comparing the results. The two models are exactly identical, except for the postorbital bar. Therefore, any differences we find can be completely attributed to this and only this.

METHODOLOGY

Terminology:

Before describing the methods, some terms need to be defined. *Stress* is equal to the force being applied to an object divided by the area over which it is applied (including cross-sectional areas). *Strain* is a dimensionless measure of deformation, expressed most simply as the change in length of an object divided by the objects original length. When forces are applied to an object, stresses are generated within the object, and the object deforms. Thus, stress causes

strain. There are many types of stresses and strains that may be expressed simultaneously at any given point on an object. The simplest types of stress and strain are tensile and compressive. The maximal tensile strain experienced by a point on an object is called *maximum principal strain*, and the maximum compressive strain at the point is called *minimum principal strain*. A more complicated type of strain is called *von Mises strain*, which refers to distortional strain associated with the loss of geometric similarity after loading.

Additional terms pertain to the material properties of substances. The *elastic modulus* (also known as *Young's modulus*) describes the axial stiffness of an object in simple tension or compression, and is calculated as the slope of the linear portion of the stress-strain curve for a substance. As the elastic modulus increases, the object becomes stiffer. *Poisson's ratio* describes the lateral stiffness of an object. For example, if a cube of rubber is compressed between two flat plates, Poisson's ratio describes the degree to which the sides of the cube bulge out.

Model creation:

The basic idea behind our methodology was a geometry-based approach. Essentially, we began with a stack of 1302 sequentially numbered two-dimensional images. These images were in the form of bitmap slices derived from computed tomography scans of a *Eulemur fulvus* skull. Next, we turned these into a “water-tight” three-dimensional surface model, meaning we created a 3D hollow frame of the images covered in a stretched “material” of interlocking triangles. Finally, we took this hollow model and filled it in with tetrahedral “bricks” so it became a solid finite element model, which can be constrained and loaded with forces.

We began this process in the Mimics computer program. Here, we rendered the 2D image stacks as volumes and then edited the surface model manually. This included filling small

holes, removing digital “noise”, smoothing and reducing triangles, re-meshing, and segmenting the mandible for easier access when applying forces later on. We used techniques like thresholding and region re-growing to eliminate the thinner bone and floating particles from poor scanning.

Next we brought our model, as an STL file, into Geomagic, a digital shape sampling and processing software, where we were able to edit and clean the polygon surface model. In this step, the model was refined, decimated, and aligned until there were no intersecting triangles or other errors remaining.

Then, it was brought back into Mimics once again as an STL where a volume mesh was now created. The parameters we used for this were a maximum edge length of 2.5 and a shape quality threshold of 10.0. It is also important to control for edge length and use edge ratio (max/min) (A) for the shape measure. Once the mesh was complete, we discarded all cavities but the actual skull and exported as a Nastran file into Strand 7.

Strand 7 is a state of the art Finite Element Analysis (FEA) program. It is used for solid meshing and FEA. Here, we applied a test force of -2.5N along the Y-axis on the left (working) first molar. A constraint/restraint was assigned at the TMJ in each the X, Y, and Z directions. We then selected elements for each of the muscle attachment areas we were working with: the left and right masseter, medial pterygoid, and temporalis. Next, a

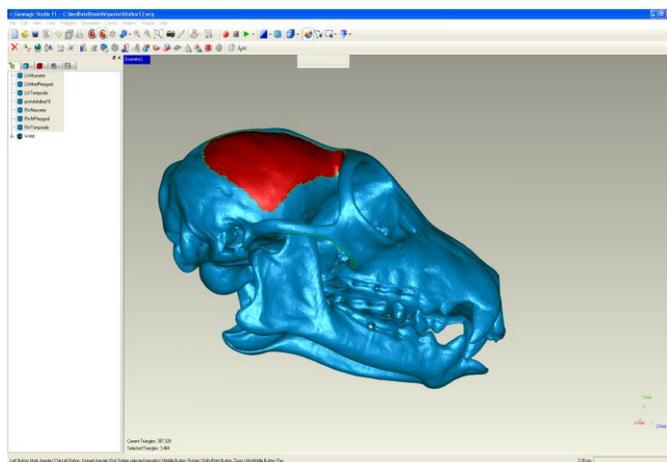


Figure 2. This image depicts the selection of muscle group plates in the Geomagic program.

group was created for each separate attachment area. For each group brick properties were defined as cortical bone with a Modulus value of 17.3 Gigapascals, Poisson's ratio of 0.28, and a plate membrane thickness of 1.0×10^{-5} m.

After checking that our model solved, it was brought back to Geomagics as an STL again. Muscle attachment area plates were selected, turned into individual objects, and renamed and saved as STLs accordingly. They were then all imported back into Strand yet again and “zipped” together so that the plates were actually attached to the model and shared nodes with

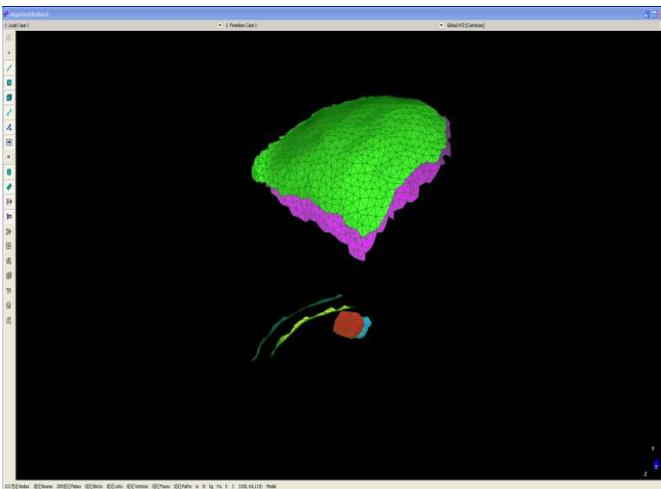


Figure 3. The image above depicts the muscle group plates alone, with no skull bricks present in the Strand7 program.

the bricks. The same Young's Modulus and Poisson's Ratio values were assigned to each set of plates and used for the bricks, as well as the material property and plate membrane thickness. At this point, any unused plates and all bricks were deleted so that only the muscle attachment area plates remained.

Each was assigned a number to be used in Boneload to assign muscle forces.

BoneLoad works via an excel spreadsheet in which you enter all your force and focal coordinate data for each muscle group from Strand. After we compiled this, BoneLoad was run using a tangential traction loading method. When complete, these loaded muscle attachment areas plates were then imported back into Strand7 one last time onto our original FE model (with the bricks still intact and the previous plates all deleted). These were once again “zipped” together and then solved linear statically. Below is a graph of all the forces plugged into BoneLoad, and the resultant vectors it produced for both models.

Group #	Muscle	Input Force	Applied Force Mag	Vector Force Mag Without Bar	Vector Force Mag With Bar
All muscle forces measured in Newtons (N)					
1	WMasseter	40.8	40.8	31.81955515	30.50516428
2	WMedPtery	19.2	19.2	19.05559248	19.01145377
3	Wtemporalis	60.9	60.9	56.96154734	56.8274099
4	Bmasseter	20.4	20.4	8.68109665	16.42494335
5	BMedPtery	9.6	9.6	9.549641388	9.520150028
6	Btemporalis	30.45	30.45	28.70913848	28.32154188

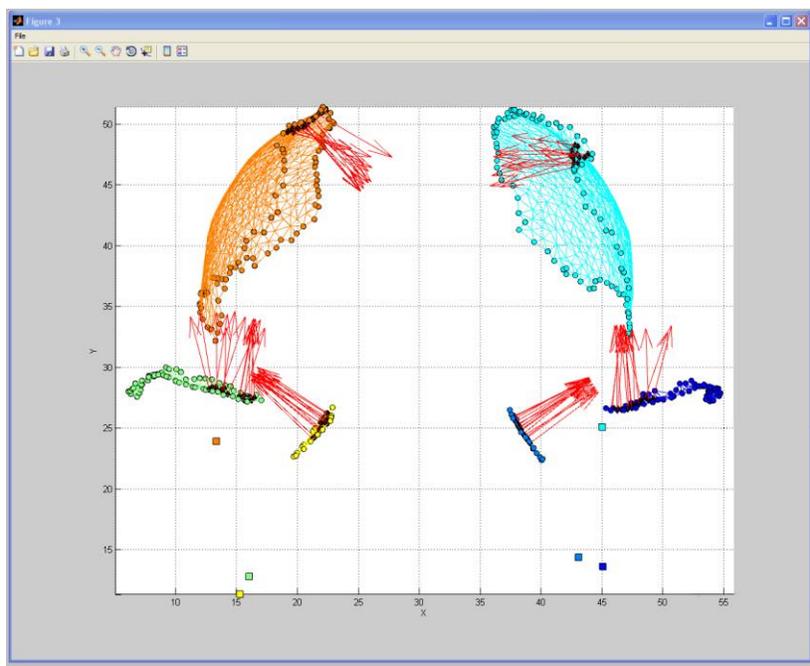


Figure 4. This is an image of the resultant vectors produced in Boneload for each muscle group.

RESULTS & DISCUSSION

Results of FEA can be depicted visually as color maps illustrating the magnitudes of stress and strain at each element in the model. Below are several figures that depict the three different strains discussed above on the surface of the two models in various views. Figure 1 shows A) minimum principal/compressive strain, B) maximum principal/tensile strain, and C) von Mises strain on a *Eulemur fulvus* skull with the postorbital bar intact. Figure 2 shows A) minimum principal/compressive strain, B) maximum principal/tensile strain, and C) von Mises strain on a *Eulemur fulvus* skull without the postorbital bar present.

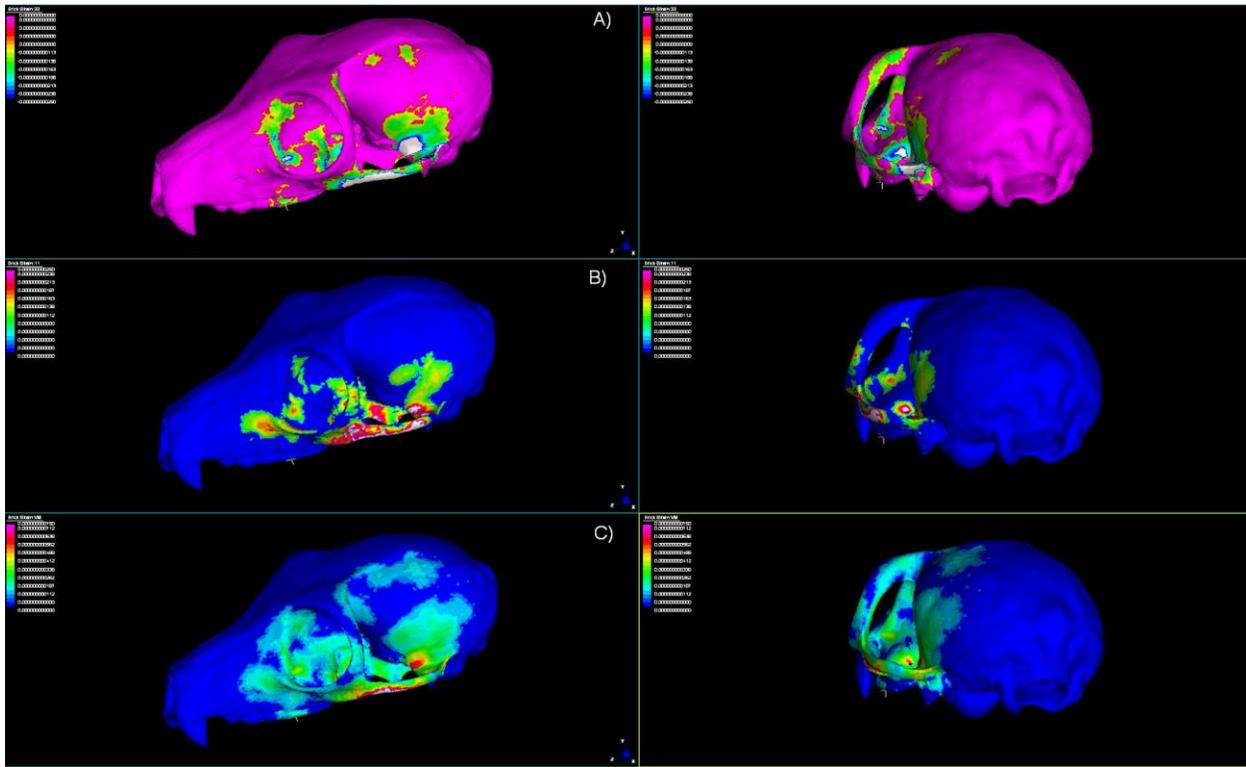


Figure 5. The above shows A) minimum principal/compressive strain, B) maximum principal/tensile strain, and C) von Mises strain on a *Eulemur fulvus* skull with the postorbital bar intact.

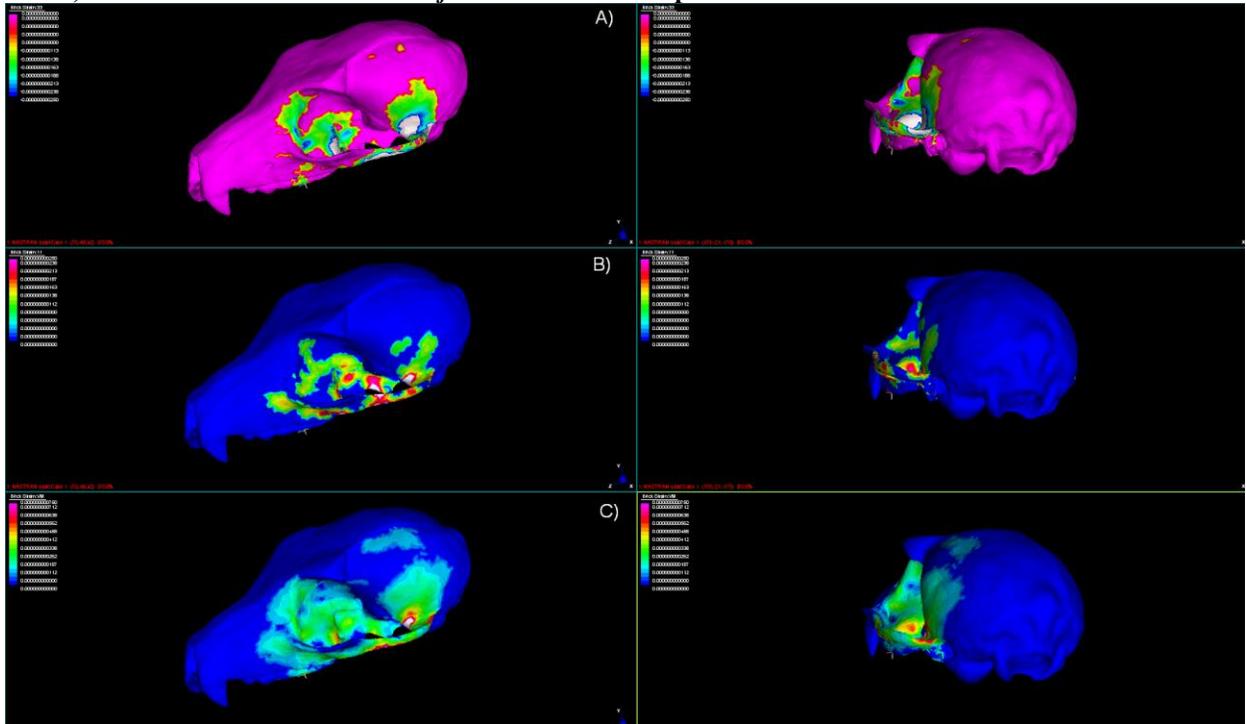


Figure 6. The above shows A) minimum principal/compressive strain, B) maximum principal/tensile strain, and C) von Mises strain on a *Eulemur fulvus* skull without the postorbital bar present.

According to our findings, the model with the postorbital bar present showed high strain on the zygomatic arch and low strain on the orbital walls. On the contrary, the model without the postorbital bar had low strain on the zygomatic arch, but high strain on the zygomatic root and the medial wall of the orbit.

The implications of this finding are profound. The wall of the orbit is particularly thin bone and high strain could severely deform or damage it. It goes without saying, that this would presumably affect vision. Lemurs, like all primates rely greatly on sight in order to survive, therefore they evolved a postorbital bar. The function of this bar is to transfer the strain caused by masticatory muscles forces from the wall of orbit and the root of the zygomatic throughout the entire zygomatic arch, a much thicker (and therefore sturdier) bone.

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