Model-Based Identification of Mechanical Characteristics of *Sinosaurus* (Theropoda) Crests

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Abstract: The paired cranial crests of *Sinosaurus* (Theropoda) have been hypothesized as too weak to resist mechanical loads during combat. Finite element analysis (FEA) is used to test this hypothesis, first with geometry obtained through direct laser scanning of a well-preserved fossil of the crest, and then with two conceptual FE models of both crests analyzing the structure-deformation effects of fenestration. In the original fossil model, under direct loading on the dorsal faces of the crest, we found that the areas surrounding cavities on the crest experience shear stress that implies a high chance of material failure – the fracture of bone. In the conceptual model, a series of computational studies were conducted with varying loading directions. One simulation found that the shear stress and strain in the material around the cavity presented more deformation compared with the conceptual model without the cavities, and under this morphologically realistic scenario the loading conditions would result in local bone fractures. These model-based computational results indicate that the crest could not resist high loads, because it could not effectively decentralize the loading stress. Future investigations need to focus on more comprehensive computational experiments with more conditions, e.g. dynamical loading conditions, and direct palaeontological evidence.

Key words: Dinosauria, *Sinosaurus*, behavior, finite element analysis

1 Introduction

1.1 Finite element analysis

Finite element analysis can biomechanically test the function of unusual features in extinct vertebrates, to assess their possible utility for behavior. For example, suitability for combat has been tested for the tail clubs of ankylosaurian and sauropod dinosaurs (Arbour, 2009; Arbour and Snively, 2009; Xing et al., 2009), and the domes of pachycephalosaurs (Snively and Cox, 2008; Snively and Theodor, 2011).

Elaborate cranial ornamentation of theropod dinosaurs was diverse and widely distributed phylogenetically (such as *Oviraptor* Barsbold, 1986; *Guanlong* Xu et al., 2006). Various functional hypotheses have been advanced (Currie and Eberth, 2010); however, all are based on reasonable assumptions or analogies with modern animals, and thus far have lacked biomechanical tests. *Sinosaurus* already has been reported from four bone site (Xing, 2012; Xing et al., 2014) and one probably tracksite (Xing et al., 2009; Lockley et al., 2013) from the Lower Jurassic Lufeng Formation in the Lufeng Basin in Yunnan Province, southeastern China. Herein finite element analysis was employed on two specimens of *Sinosaurus* with distinctive crests to test functional hypotheses within a biomechanical framework.

Institutional and location abbreviations: LDM, Lufeng Dinosaurian Museum, Lufeng, Yunnan, China; ZLJ, Lufeng World Dinosaur Valley Park, Yunnan, China

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1.2 Hypotheses of crest function in *Dilophosaurus* and *Sinosauras*

Cranial ornamentations in theropods are at least distributed in abelisaurids (e.g. *Carnotaurus* Bonaparte et al., 1990), allosauroids (e.g. *Allosaurus* Madsen, 1976 and *Mapesaurus* Coria and Currie, 2006), coelophysoids (e.g. *Dilophosaurus* Welles, 1984), megalosauroids (e.g. *Monolophosaurus* Zhao & Currie 1993), oviraptorosaurs (e.g. *Oviraptor* Barsbold, 1986), and tyrannosaurids (e.g. *Guanlong* Xu et al., 2006). Within species, the ornaments were subject to ontogenetic, sexual, and individual variation (Currie and Eberth, 2010).

All species with double-hatchet crests were once assigned to Neotheropoda, including *Dilophosaurus* (Welles, 1984), "*Dilophosaurus* (= *Sinosauras* (Dong, 2003) *sinensis* (Hu, 1993) *Syntarsus* (Rowe, 1989), and *Zupaysaurus* (Arcucci and Coria, 2003). The crests of *Dilophosaurus* and *Sinosauras* are the largest and the most remarkable. They are so similar in morphology that a comparatively complete *Sinosauras* was immediately assigned to *Dilophosaurus* as a new species when it was discovered (Hu, 1993). However, based on new materials, the morphology of the crest of *Sinosauras* indicates that it possesses advanced characteristics that are more developed than in *Dilophosaurus*, such as the presence of a series of oval openings on the medial surface of the lacrimal portion of the crest, and an ovoid lacrimal pneumatic aperture near the posteroventral corner of the antorbital fossa (Xing, 2012). Recent phylogenetic analyses, based on new specimens from the Lungfeng Basin in Yunnan Province, China, show that *Sinosauras triassicus* is not the most basal dilophosaurid (Smith et al., 2007), but is more closely related to Averostra than to Coelophysidae or *Dilophosaurus wetherilli* (Rauhut, 2003; Xing, 2012; Xing et al., 2013, 2014).

There are various hypotheses of the functions of the crest of *Dilophosaurus* and *Sinosauras*. The crests of *Dilophosaurus* and *Sinosauras* are probably too thin and fragile to serve as weapons for intraspecific combat. Dong (2003) considered the crest of *Sinosauras* may have been useful to keep the abdominal wall of a carcass open while the theropod devoured it. Tykoski and Rowe (2004) considered the crests to be far too fragile to have served as offensive weapons, and were likely used for display purposes only. Gay (2005) considered the differences between various specimens of *Dilophosaurus* as due to individual variation and ontogeny alone, but not sexual dimorphism. Hone et al (2012) proposed that the cranial crests of *Dilophosaurus* were involved in mutual sexual selection, and inferred that they were most likely used for either sexual or social display. Padian and Horner (2011) pointed out that neither sexual dimorphism nor ontogenetic maturity has yet been examined statistically for these "bizarre structures" in theropods. Even the large sample of Ghost Ranch *Coelophysis* has yet to be comprehensively exploited for such studies (Padian and Horner, 2011).

2 Material and Methods

2.1 Osteology

The paired crests in *Dilophosaurus* and *Sinosauras* are formed by the nasals anteriorly, and the lacrimals posteriorly (Currie P J. personal observation). The left crest of ZLJT01 (Fig. 1) only preserves the axe-shaped posterior section, which is formed by the lacrimal. Although incomplete, it is well preserved. The partial crest is 110 mm in length, and rises to a height of 73 mm above the postorbital contact of lacrimal. The posterior part of the crest extends posterolaterally above the rim of the orbit.

The crest of LDM-L10 (Fig. 1) is 440 mm long, but the nasal extends in front of the crest along the margin of the external naris for a short distance. In dorsal view, the crests remain separate for their entire anteroposterior lengths, and diverge posteriorly. The right crest of LDM-L10 is damaged, but most of its upper margin is well preserved. The crest of LDM-L10 is pierced by several possible openings; each was probably covered by skin in the living animal. The bone can be thin (less than 4 mm) between ridges that are perpendicular to the convex dorsal margin of the crest.

2.2 Modeling approach

*Sinosauras*, as being distinct species, cannot be studied through common scientific approaches applied to the modern animals. Studying functionality of its crest, in other words, is investigating a series of mechanical responses of crest under various loads, which the results may not be observed directly, however, they can be revealed through other physical scientific approaches. *Sinosauras* crest of course has to obey the physical laws and principals, for example, the balance of energy, that govern the motions of particles and the deformation of the

![Image of cranium](image-url)  
*Fig. 1. Full cranium of *Sinosauras* (LDM-L10; left lateral), and a lateral view of the left lacrimal and its portion of the crest in *Sinosauras* (ZLJT01; right).*
material. Such understanding leads a common quantitative approach in scientific and engineering research – the computational modeling.

*Sinosauropteryx* crests are made of bony material and considered as a continuous medium; hence we adapt continuum mechanics and finite element modeling (FEM) as the analytical/mathematical foundation to study its deformation under external loads. Such analyses follow previous FE quantitative studies developed to understand bone deformations in humans and other animals (Pesce Delfino et al. 1981; Krajevic et al. 1987; Kabel et al. 1999; Fernandez et al. 2004; Rayfield et al., 2007 and references therein).

More precisely, FE modeling of the *Sinosauropteryx* crest can be divided into two major parts, the geometrical model and material model. Geometric modeling uses a finite volumetric element mesh to fill in the outer shape of the crest, reflecting its structural features and the connectivity of multiple local parts. Material modeling defines stress-strain behaviours of material (bone) under different stretch-compression situations. For more comprehensive theoretical and practical details about continuum mechanics and their application in FE modeling, the reader may refer to Holzapfel (2000), and Bonet and Wood (2008).

2.3 Geometrical modeling

Constructing a finite element model of a fossil consists of three steps: 1) Imaging/scanning, 2) geometry reconstruction, and 3) FE mesh generation. The geometrical data can be acquired by magnetic resonance imaging (MRI), computed tomography (CT) or by using a laser scanner. For bone, CT is the most common option to obtain external and internal structural images. Image segmentation is used to produce a data cloud to indirectly obtain the fossil’s shape and/or its internal structures. Then, the data cloud is processed to construct a FE model.

The crests of *Sinosauropteryx* (ZLJT01) were scanned using computed tomography (CT) to provide information on their internal structure and to derive three-dimensional models for use in volume estimates. ZLJT01 was scanned at the University of Alberta Hospital Alberta Cardiovascular and Stroke Research Centre (ABACUS) on a Siemens Somatom Sensation 64 CT scanner, with imaging resolution 0.2969 mm × 0.2969 mm × 0.6 mm. The entire set of these grey scale CT images was then loaded into a medical imaging processing software, called ITK-snap, for automatic segmentation. This segmented data cloud subsequently was used to build the FE model (Fig. 2). The mesh consists of 18343 nodes and a total 72091 linear basis elements, including 673 hexahedral elements (8 nodes) and 71418 tetrahedral elements.

The construction of the FE model of the crest of *Sinosauropteryx* (LDM-L10) requires its 3D geometric data. Because the specimen was too fragile to transport, we instead CT scanned a cast of LDM-L10 for 3D reconstruction. The machine is a Non-contact Grating-Type Structured Light 3D Scanning Systems (JiRui II, see Table 1; JiRui Xintian Technology Co., Ltd., Beijing). The high-precision 3D data of the skull of LDM-L10 were saved in IGES format for use in FE software.

The original fossil (LDM-L10) shows some taphonomic damage. An artificial correction on the full geometric model is required to ensure to capture the major geometric features of the original state as much as possible. First, the full geometric model was constructed and scaled to ensure that its height and length matched to the measurements of a full *Sinosauropteryx* crest. Second, the crest geometric curvatures followed general features observed on the LDM-L10, but with corrections on the posterior side which has been bended due to burial stresses. Third, it is almost impossible to reconstruct the crest cavities; the cavities on crest of the full geometric model followed the general features of original cavities on crest, however, for only a conceptual purpose that aims to verify the mechanical characters, rather than to reproduce the actual responses of the same crest under different loads. To examine the effects of the cavities within the preserved crest, a model of the crest was constructed without cavities.

Local structural features of the skull where the crest connects to it must be considered. The full crest model was mounted on a skull model with major cranial cavities, including nasal and antorbital fenestrae. Because we concentrated on the deformation of the crest, other regions of the skull were treated as a solid body, and their deformation was not assessed in the computational experiments. The ventral areas of the conceptual skull model were simply fixed in their spatial locations.

2.4 Material Properties and loads

The *Sinosauropteryx* crest can be treated as a homogenous isotropic linear material that is close to the properties of modern bone. In studies of modern animal bones, the values of those material constants come from material sample testing (for instance, uniaxial stretch/compression).

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Fig. 2. B, C, and D show overall views of the FE crest model. C is anterior and B and D are left (lateral) and right (lateral) view, respectively. A, the loading areas are coloured red; the blue area in E, F and G represents the spatially fixed boundaries. Red, green and blue arrows represent x, y and z directions.

However, such testing is almost impossible for dinosaur studies because fossilized bone is too brittle, and material properties were estimated using extant analogues. The crest is modelled as undergoing linear deformation under a single external loadcase, assuming that fatigue would be irrelevant given intermittent bouts of combat.

Under these assumptions, the stress-strain relation of the bony material is mathematically described as a St. Venant–Kirchhoff material model, approximating linear elastic behavior. As a starting point, the bone was assigned the Young's modulus \((E) = 10 \text{ Gpa}\), and Poisson's ratio \((\nu) = 0.4\). The choice of parameter values follows the previous study by Rayfield (2005) on an Allosaurus cranium. An assumption is made that the Sinosaurus crest possesses similar material stiffness to that of cranial bone of other large carnivorous dinosaurs. The model deformation here is a quasi-static deformation without accounting for the gravitational force; in other words, the investigation only is interested in its structural equilibrium state under different loads.

The hypothesis that the crest had a combative function implies an interaction between the bony material, i.e. crest, and the soft tissues. This typical mechanical problem can be studied using the theory of contact mechanics. However, the mechanical response, i.e. stress, of crest material highly depends on the contacted object. For example, soft tissue can be largely deformed when contacting the high stiffer crest. This could lead to smaller
stress on crest than the case of contacting the bony parts, e.g. considering the case of combat between two *Sinosaurus* individuals using their own crests. Additionally, lacking solid evidence of this combative role brings greater challenges in making assumptions of geometry of contacted objects. Furthermore, the traditional uniform pressure load in FE modelling, which acts in the perpendicular direction to the selected surface of the crest, cannot be applied for modelling the external loads that vary with geometric curvatures in a contact mechanics case.

The traction vector load is introduced here for modelling external loads on crest in the case of combating. Traction vector in this assessment refers to a vector field of uniform strength and pointing in the same direction regardless the geometric location. When applying this vector field to the selected areas of the geometric model, the resulting act pressure varies with the geometric curvature, and therefore generates a loading field approximating the loads in the contact problem.

2.5 Computational Experiments

The aim of the computational experiments is to capture a general model of crest deformation under various external loading conditions. The current sample limits the analyses from CT scans to the posterior part of *Sinosaurus* crest; therefore, the results may lack more comprehensive insight of overall structural features, especially the roles of cavities in the crest, and possibly lose useful information. To simulate mechanical behavior of the complete structure, a full crest model was built based on the *Sinosaurus* crest’s geometry and major features, including fenestrae.

A simple two-step strategy was used to study the crest based on those available samples and data. The incomplete crest ZLJ01 was modeled and its mechanical characteristics were investigated under different external loads. Based on these results, an idealized complete crest model based on LDM-L10 was built from the original data of LDM-L10, but rescaled to fit the actual length, height and width of ZLJ01. This complete model was considered as an idealized model of the actual full *Sinosaurus* crest. A series of external loads were applied to outline potential patterns of deformation.

Febio 1.4 (http://mlr.sci.utah.edu/febio-overview) was used to solve the deformation of crest model. It has been extensively used to analyze biomechanical problems, including orthopedic research on cartilage contact problems in normal human hips (Harris et al., 2011). This open-source software is developed and maintained by Musculoskeletal Research Laboratories (MRL) at the University of Utah.

3 Simulations and Results

3.1 Sample model

3.1.1 Loads and constraints

Figure 2 shows an overall view of the sample model that was built directly through CT image data. This is the posterior part of crest, for which only the dorsal area would likely have sustained the loads in combating. A directional external load (traction vector) along the Z-axis was directly applied on the dorsal contact area (Fig. 2(A)), with four levels of magnitude, 1000N, 2000N, 3000N and 4000N. This contact area was 438.82 mm²; the loading pressures were 2.2788 MPa, 4.558 MPa, 6.837 MPa and 9.115 MPa to 1000N, 2000N, 3000N and 4000N, respectively.

Figure 2(E), (F) and (G) show another set of boundary conditions, with fixed constraints, i.e. purely fixed against translation and rotation, where this portion of the crests joins the rest of the skull, and where the ascending process of the lacrimal (which supports the crest) contacts the jugal. Figure 3 shows the results corresponding to different levels of load.

3.1.2 Results

Figure 3 depicts the results from different levels of load. In general, effective stress (von Mises stress) and maximum shear strains on both the left and right sides increased proportionally with external loading. The colour distributions on both sides showed different configurations. The overall colours on the right (lateral) side show a larger area with warmer colours compared with the left (lateral) side. The warm-coloured (yellow and red) area is most prominent on the middle part of the crest model, and indicates large stress. The top region of the crest has a cooler area in stress distribution maps; however, it has a large total displacement. In the examples of 1000N, 2000N, 3000N and 4000N loading, the maximum total displacements are 0.6427 mm, 1.331 mm, 2.068 mm and 2.859 mm compared with the average displacements of 0.1193 mm, 0.2478 mm, 0.3863 mm and 0.536 mm, respectively. These are displacements of the entire structure; displacement is lower between localized regions, but strain is high. In summary, the dorsal part of crest performs like a large rigid body, with motion towards the left (lateral) side, whereas the ventral middle part of the crest provides a supporting structure resisting the entire deformation process.

In a linear context, shear strain most often causes material failure. The shear strains in four test cases exhibits a similar pattern, in which the bony part, surrounding the cavities in the crest, possessed an area with a higher magnitude of shear strain, compared with
Fig. 3. Von Mises effective stress and maximum shear strains of the crest model corresponding to 1000N (A), 2000N (B), 3000N (C) and 4000N (D) loadings. From left to right, the lacrimal and its portion for the crest are shown in lateral, medial, and medial inset views.
other regions. The maximum shear strains increased from 0.0028 to 0.01181 when raising the loading from 1000N to 4000N. Bone breaks at 0.2–0.6% strain, and failure is likely to have occurred under higher loadings.

3.2 Full scale model
3.2.1 Loads and constraints

Three loading areas had been selected, namely the anterior, middle and posterior, to perform the sensitivity analysis about the different loading scenarios. Three directional loadings, including, (1, 0, -1), (0, 0, -1) and (-1, 0, -1), had been applied on these selected areas, with magnitudes of 0.009115 GPa and 0.01823 GPa. These vectors are defined in accordance with the coordinate system used here, in that the x axis is anteroposterior, y is mediolateral and and z is dorsoventral, (Fig. 4). Applying force from (1, 0, -1) direction on the anterior area attempts to recreate the force directly on anterior part of crest. Assuming that Sinornithosaurus would lower the skull to a certain degree when loading the crest, we chose a 45° direction as the loading orientation. The vertical loading from (0, 0, -1) on the middle selected area reproduces the case of the weight load directly to the dorsal part of the skull (crest). The test loading from posterior, a force direction (-1, 0, -1), is an attempt to investigate the deformation on the posterior part of crest assuming the loading came from posterior.

The anterior, middle and posterior ventral surfaces of the model were fixed against translation and rotation movements, as in the case study of the sample model. They were considered connecting the areas of anterior nasal part, cranium and cervical area, respectively. At this stage, the modelling framework did not consider other translational or rotational movement in the dynamical process, only quasi-static cases were studied. In other words, the model gave a result when the crest holding a load applied in three different areas – anterior, middle and posterior.

3.2.2 Results

Throughout all three loading scenarios (Fig. 5), the stresses on the full crest model with cavities shows a consistent colour distribution, with higher stress concentrated on areas around the cavities. Increasing loading pressure produces a slightly higher stress represented by warmer colours; average effective stresses were 0.0177 GPa, 0.01086 GPa and 0.01838 GPa in the anterior, middle and posterior loading tests under the pressure of 0.01823 GPa. The counterexample of the full crest model (Fig. 6), however, showed a cooler colour distribution that indicates less stress than in the full crest model with cavities. The average effective stresses in same three loads reached 0.01236 GPa, 0.005705 GPa and 0.0135 GPa. In short, in all three loading tests, the stress patterns on the crest model without cavities shows less concentration of stress compared with the crest model with cavities.

The increased magnitude of loading stimulated the magnitudes of effective stress but did not fundamentally change stress patterns in either model. The model with cavities under smaller pressure (0.009115 GPa) showed a similar pattern as observed in the case of 0.01823 GPa. The peak stresses of 0.1325 GPa, 0.1039 GPa and 0.1788 GPa were reduced to 0.06702 GPa, 0.05183 GPa and 0.08881 Gpa, respectively, in the case of a directional pressure of 0.009115 GPa.

The stress is influenced by taphonomic deformation in which the dorsal part was bent towards the lateral direction. This is similar to the case of the fossil sample model. In the anterior load testing of the full crest model with cavities, the peak total displacement is 0.4292 mm and 0.872 mm, corresponding to the pressure 0.009115 GPa and 0.01823 GPa, whereas the posterior area loading bends the left posterior crest towards the left lateral direction with peak total displacement 0.6071mm and 1.2515 mm in the case of 0.009115 GPa and 0.01823 GPa, respectively. The crest in general deforms toward the sides under middle area load, with the peak displacement of 0.3582 mm (0.009115 GPa) and 0.7412 mm (0.01823 GPa). Under the same conditions, the deformations of the crest model without cavities produced similar results, with peak total displacements of 0.9935 mm, 0.7775 mm and 1.177 mm.

4 Discussion

A model-based study has been presented here to
investigate possible mechanical characteristics of the *Sinosauropteryx* crest under dorsal surface loading conditions, including different applied directions and stress magnitudes. The load testing on the model of a fossil reproduced a deformation pattern corresponding to three linearly increased vertical loads, each applied to the same limited selected area. The effective stress distributions show that the stresses were higher in regions with cavities. In general, the dorsal part of the crest deformed laterally (to the right); however, the ventral part exhibited more dorsoventral bending. Importantly, shear strain and stress are higher in this area than other regions in all cases.

Often, shearing is considered as the major factor in material failure. Higher shear strain/stress may cause a higher chance of material failure, especially in bone—a brittle material. Peak strains were high enough in the model for the bone to fail, especially under 2000–4000 N loads. The static load range of 2000–4000 N is equivalent to the mass weight of 208–408 kg which is about 0.3–0.6 of the weight of average dairy cow (700 kg). Questions thus arise of a more comprehensive role of the cavities in the bone and stress on those areas, and (most importantly) whether a more complete model would result in strains below failure levels.

The sample crest model here merely represents a partial and incomplete part of the full crest of the original. The anterior surface of the modelled crest connected to the anterior part of original crest, and restricted the movement of the material points around this region, in contrast with the totally free, moveable conditions in this study. In other words, the boundary conditions and the model were insufficient to represent the real situation from a perspective of mechanical analysis. Furthermore, the loading from a fixed direction (z axis) only applied to the initially selected dorsal areas. In a real scenario, the loading may have come from other directions. Consequently, a fixed directional load may not provide a deep insight of deformation patterns under various loading conditions.

The conceptual full crest model was built to reflect the major features of the crest geometry and structure (including cavities), and a counterexample model was constructed to give us information about what a crest does if it did not have cavities in it. Complex loads were applied to three selected areas with varying directional load (traction vectors). This objective of this
computational experiment was to reproduce a possible deformation pattern under a true scenario, or a close mathematical approximation.

The computational results from these case studies clearly show that the effective stress on the areas around cavities in the crest is higher than other regions. The results from the counterexample exhibit a different pattern, in which stresses were more evenly distributed throughout the structure. It seems that the columnar-like parts would have transmitted more energy than the remaining regions, implying higher probabilities of bone fracture within struts. A “good” structure for sustaining a high load needs to decentralize the shear stress, or reduce the local shear stress magnitude and thereby reduce the chance to meet the fatigue tolerance. However, the cavity in the crests implies an opposite effect: that the local bridging structure will sustain a higher local shear stress compared with non-cavity models, and consequently produce a higher opportunity of material failure. High stress concentration gives a clear indication that the structure suffering from shear movements – a possible fracture may be caused. Therefore, according to our modelling results, the crest was not optimized for sustaining high external loads.

Limitations to the full crest models exist. The models lack full interior and structural details of the skull, the generated stress distribution may not be valid in these areas, and the potential influence on the rest of the skull remains unknown. Furthermore, the deformations produced by the dorsal directional loads cannot reveal the stress patterns produced by mediolateral loading. Therefore, the results shown here can be considered valid under the conditions of vertical loads on dorsal regions of the crests. Furthermore, the material properties used here are each based on assumptions, and a further investigation of sensitivity to parameter values is recommended. Under linear static assumptions, deformation is expected to vary inversely with Young’s modulus, and failure load to vary directly with assumed ultimate strain.

In addition, contacting the dorsal surface of a *Sinosauropteryx* crest may not truly reflect possible applications. More precisely, the loading conditions applied in computational experiments do not consider the effect of shear stress between the soft dermis/epidermis and bone. In reality, integument covering the surface of crest also likely filled the cavities. Soft tissues can be deformed more (strain greater than 5%) and absorb more
energy than bone. Simulations of soft tissue/bone shear under impacts are amenable to methods used to examine dog vessel deformation under the shear stress of blood flow (Kamiya and Togawa 1980).

5 Conclusion

Despite existing limitations, these investigations provide insightful understanding of the crest’s structural characteristics. Results indicate that the Sinousaurus crest did not function to sustain great vertical loading on its dorsal surface. This bony structure, especially those regions around the cavities, sustained high shear strain which implies a high possibility to suffer material failure. In other words, such a structure cannot provide benefits for any activities involving direct contact of the dorsal surface. However, the crests of Sinousaurus crest may still have fulfilled some other mechanical or structural purpose.

Future research will focus on constructing a model of a full crest from fossils with internal structural details and features. A direct contact simulation with dynamical external loading conditions between the head and crest (including associated soft tissue) and similar objects can also be applied to model crest and skull deformation under different circumstances. Importantly, the shear stress on this crest structure, especially its soft tissue layer, will ideally be modelled through a fluid-solid interaction approach.

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