Three-dimensional finite element analysis of the dural folds and the human skull under head acceleration

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Abstract
Bone and collagen fiber architecture adapt to external mechanical loads. In humans, due to the low insertion of the temporal muscle, mastication does not lead to a physiological loading of the calvaria. Forces applied to the skull by the dural folds can lead to compressive stresses in the calvaria. To investigate the relationship between mechanical loads and form in the skull and its membranes, in a finite element three-dimensional model of the human skull, loads due to head acceleration in daily activities are applied to the falx cerebri and the tentorium cerebelli. The dural folds are modeled as membranes. The stress paths in the dural folds correlate with anatomical fiber direction. Head accelerations of 9 g lead to compressive stress in the calvaria. Finite element analysis of the falx cerebri and the tentorium cerebelli can be used to study the influence of mechanical stresses on the ossification of the dural folds and their impact on calvarial growth. This study presents an example of functional loading of bone by fibrous membranes and describes a possible mechanism by which Wolff's law works on the bone of the calvaria creating evolutionarily beneficial lightweight constructions.

1 | INTRODUCTION

The skull vault or calvaria are the skull bones enclosing and protecting the brain. There has been an ongoing debate concerning the low or absent compressive stresses in the calvaria from masticatory loading. By Wolff's law, it is expected that bone which is not loaded by compression is resorbed. In contrast, the bone of the calvaria is maintained. Different explanations include the idea that the bone mass is not dependent on mechanical loading (Rawlinson, 2017) or proposed mechanisms for loading of the calvaria through surface pressure applied to the dural folds from head accelerations (Witzel & Hofmann, 1993).

The dura mater is the outermost of the three membranes surrounding the brain and the spinal cord. It consists of two layers. The outer layer, the endocranium, is identical with the peristemeum of the skull. The inner layer, the meningeal layer, consists of dense connective tissue and is internally covered by flattened cells. The dura mater consists of about 80 concentric laminas (Reina, López-García, Dittmann, & de Andrés, 1996). The two layers are separated by the dural venous sinuses. From these, the meningeal layer extends into the cranial cavity and forms four main dural folds, also known as dural reflections (Rea, 2015):

- The largest one is named the falx cerebri and attaches anteriorly at the crista galli and follows the longitudinal fissure. Superiorly it is attached to the frontal, parietal, and occipital bones and forms the superior
sagittal sinus. Inferiorly it forms the inferior sagittal sinus and divides the two hemispheres of the cerebrum with its concave and free border following the corpus callosum.

- Posteriorly, the falx cerebri passes into the tentorium cerebelli which separates the occipital lobe from the cerebellum. It is attached to the internal occipital protuberance, the mastoid process and the petrosal part of the temporal bone, and the anterior and posterior clinoid process. Its internal border is concave and free.
- The falx cerebelli divides the two hemispheres of the cerebellum. It is attached superiorly to the tentorium cerebelli and posteriorly to the occipital bone, containing the occipital sinus.
- The diaphragma sellae spans the sella turcica with the hypophysis.

The mechanical role of falx cerebri and tentorium cerebelli has widely been recognized in injury biomechanics and crash tests (Hernandez et al., 2019) mostly focusing on their influence on the brain (Ho, Zhou, Li, & Kleiven, 2017). However, less is known about the loading of the dural folds by activities of daily life and sports and about the functional loading applied by the dural reflections to the skull. This study focuses on the function of the falx cerebri and the tentorium cerebelli due to the assumed minor influence of the falx cerebri and the diaphragma sellae because of their relatively small surface.

Knowledge of stress magnitude and orientation inside the dura mater and in the skull bone is important to investigate the relationship between function and form. From an evolutionary perspective, it is beneficial to fulfill the need of strength with minimal material input to minimize metabolic cost and energy needed for movement. From an evolutionary perspective, it is beneficial to fulfill the need of strength with minimal material input to minimize metabolic cost and energy needed for movement—a concept known as lightweight construction (Witzel, Mannhardt, Gößling, De Micheli, & Preuschoft, 2011). In bone, modeling and remodeling leads to the removal of unloaded bone tissue (Wolff, 1892). This mechanism can be regarded as a form-function unit: a certain function results in an optimized form. By that, Wolff's law is similar to the method of topology optimization, a mathematical method to find the best material distribution for outer loads and constraints within a given design space. The mechanical stimulus is a function of time and stress amplitude. The resulting functional loading is calculated as physiological superposition of the extreme values of the principal stresses of all load cases (Carter, Orr, & Fyhrie, 1989). In contrast to the strong relationship between bone density and mechanical stresses in the appendicular skeleton, the skull bone is more preserved. Osteoporosis is rare in the skull (Warriner et al., 2011) and while bone mass decreases in general during space flight, skull bone density does not, and even may increase as was observed in postflight measurements of crewmembers of the International Space Station after month-long stay in space (Iwase, Nishimura, & Mano, 2012) and in mice after 15 days in space (Zhang, Cory, Bhattacharya, Sah, & Hargens, 2013). The same effect has been reported after 17 weeks of bed rest of normal male volunteers (Leblanc, Schneider, Evans, Engelbreton, & Krebs, 1990).

A similar form-function unit can be found in connective tissue: collagen fibers are oriented in the direction of the highest tensile stresses (Carter & Beaupre, 2001). A characteristic macroscopically visible fiber architecture has been found in the falx cerebri and the tentorium cerebelli. One fiber tract arises from the crista galli moving arched backward with some fibers leaving the tract and reinforcing the superior sagittal sinus. A second fiber tract arises from the frontal crest and can be followed across the tentorium to the transverse occipital sulcus. It is crossed by fibers descending from the posterior part of the superior sagittal sinus fanning out over the tentorium. Fibers begin at the foramen magnum and end at the sella turcica (Bluntschli, 1925; Witzig, 1940). While the dural folds normally consist of collagen fibers, usually partial intercranial ossifications are rarely found. They can be associated with pathologies, but also occur in isolation (Granger, Kim, Kollias, & Rajnauth, 2017). Ossifications of the falx cerebri are more common than ossifications of the tentorium cerebelli (Tubbs et al., 2012). In cats, ossifications of the falx cerebri do not significantly change the stress in the skull, but ossifications of the tentorium cerebelli are associated with localized increase in stress in the temporal and parietal bone (Selles de Lucas et al., 2018).

Especially the falx cerebri and the tentorium cerebelli play an important role in the development and functional loading of the cranium. Dural folds determine the suture sites and their absence is accompanied by a lack of suture formation in place (Smith & Töndury, 1978). Bite forces and muscles of mastication cause mechanical stresses in the craniofacial skeleton (OHiggins et al., 2012; Prado et al., 2016) and the skull base (Kim et al., 2012). In humans, due to the low insertion of the temporal muscle, mastication does not lead to a physiological loading of the calvaria, but head accelerations induce compressive stresses to the calvaria (Lipphaus & Witzel, 2019): the inertia of the brain leads to surface pressure on the dural folds transferred into the skull at the attachment sites. A previous finite element analysis displayed the functional loading of the calvaria using a model of the falx cerebri only (Witzel, 2011; Witzel & Hofmann, 1993). As mentioned above, the application of general mechanobiological rules to the cranium is more complex than to the appendicular skeleton. This study attempts to understand the mechanobiology of the calvaria better by considering forces other than masticatory forces, in particular surface pressure on the dural folds.
generated by head accelerations, as a possible origin of stresses in the calvaria as a stimulus to maintain bone according to Wolff’s law. The aim of this study was therefore to create a three-dimensional model of the dural folds to test two hypotheses:

1. Stress paths in the dural folds correlate with the anatomical fiber orientation.
2. Surface pressure to the dural folds translates into functional compressive loading of the skull.

2 | METHODS

All calculations were performed using ANSYS Mechanical 19. The finite element model of the human skull used in this work was generated in a previous study (Boryor et al., 2007) based on CT scans of a dry skull from a 35-year-old European male provided by the anatomical department of the University Ulm, Germany. The model consists of 1,223,478 tetrahedral elements. Linear elastic material properties with a Young’s modulus of 17,000 MPa for cortical bone and 300 MPa for spongy bone and a Poisson’s ratio of 0.3 were defined. Bearings were applied to the occipital condyles. Figure 1 shows the model of the human skull.

As the original model only contained bones and teeth, the falx cerebri and the tentorium cerebelli had to be reconstructed as shown in Figure 2. Coordinates of the attachment sites were selected in the skull model and used as landmarks for the modeling of the membranous dural folds. Their three-dimensional structures were derived from routine CT data of a patient after fall on the ward provided by Di Muzio, Royal Melbourne Hospital, Australia. Cranial sutures and muscles were not included in the model nor was the brain explicitly modeled.

Shell 281 membrane elements, eight-node structural shell elements allowing the calculation of tensile or compressive, but not bending stresses, were used for modeling of the dural folds. The nonlinear analysis was performed using the Newton–Raphson method. Thermal expansion of $-100 \times 10^{-6}$ K with an expansion coefficient of seven $10^{-4}$ was applied in order to achieve the necessary preload. The thermal stresses were subtracted from the results at the end of the analysis. To stabilize the analysis, a damping of 0.001 was used. The application of the force was performed with an end time of 200 s and time steps between $10^{-6}$ and 1 s. The dura mater was assigned a Young’s modulus of 31.5 MPa (Kleiven & von Holst, 2002) and a thickness of 0.5 mm (Bashkatov et al., 2003). Nether brain nor muscle forces were included in the present model.

Common head accelerations during daily activities like sneezing, sitting down, standing up, and coughing range from 1.9 to 3.5 g. Accelerations up to 10.1 g are reported for plopping in a chair (Allen et al., 1994). Measurements using linear accelerometers and an angular rate sensor inside the mouth of the subject (Funk, Cormier, Bain, Guzman, & Bonugli, 2009) revealed values between 3.9 and 6.4 g for jumping and 3.8 g for head shaking (Funk et al., 2011). During sports like collegiate football values rise up to a median impact of 17.5 g (Rowson, Brolinson, Goforth, Dietter, & Duma, 2009). Due to the inertia of the brain, head accelerations lead to surface pressure on the dural folds. Four load cases were defined based on an acceleration of 9 g and a brain mass of 1.3 kg (Harvey & Krebs, 1990): perpendicular on the falx cerebri in right and left directions, on the tentorium cerebelli in the anterior–posterior direction directed toward the occipital bone and on the tentorium in the caudal direction. This load cases correspond to head movement to the right and left, upward, and forward.

The reaction forces at the attachment sites of the membrane model were translated to the corresponding nodes in the skull model and principal stresses calculated.

Dissections of an anonymous body donor were performed at the Department of Anatomy, Ruhr University Bochum, Germany. The dural folds were removed from the skull at the attachment sites. The falx cerebri was embedded in 2.5% agar, 0.9% NaCl and 30% sucrose and
for 15 min in isopentan flash-freezed. Sagittal slices with a section thickness of 30 μm were prepared using a microtome (Micron HM 500 OM) at an object temperature of −21°C. Samples were stained with Aldehydfuchsin-Goldner and the fiber orientation visually evaluated with ×5.8 magnification.

3 | RESULTS

The applied surface pressure leads to tensile stress in the membrane model. Figure 3 displays the tensile stress vectors due to the different load cases. Surface pressure applied to the falx cerebri in left or right direction show mirrored results. Therefore, a separate presentation of both load cases was not presented. Lateral head accelerations account for tensile stress paths beginning at the crista galli. These stress paths diverge posteriorly in the tentorium cerebelli. Other stress trajectories start at the superior sagittal sinus and build arches which can be followed backward on the falx cerebri. Inertia forces in caudal and occipital direction lead primary to tension in the tentorium. In the caudal load case the trajectories radiate backward in the falx cerebri and in the occipital load case forward. In the tentorium, caudal inertia forces cause first principal stresses directed in the lateral direction while the trajectories arch rostrally for loading in the direction of the occipital bone. Both stress paths end at the sella turcica.

Figure 4 shows a summary of the fiber orientations in the falx cerebri as found in the dissection (Gaida, 2008). This matches the fiber architecture described in literature. Most fibers in the sagittal line form arches, beginning at the crista galli and the superior sagittal sinus. Posteriorly they are crossed by fibers radiating from the transition of the falx cerebri into the tentorium cerebelli. The inner edge of the falx cerebri is reinforced by a strengthened fiber tract.

Application of the reaction forces of the membrane model as forces at the attachment sites of the dural folds in the skull model cumulatively affects compressive stresses. Head acceleration of 9 g leads to

FIGURE 2  Finite element membranous shell model of falx cerebri and tentorium in (a) lateral, (b) posterior, (c) cranial, and (d) isometric view. Major attachment sites are labeled
compressive stress of $-0.5 \text{ MPa}$ and strains of 20 $\mu$e in the calvaria. The attachment of the tentorium cerebelli at the skull base also contributes to the functional loading of the cranial base. Figure 5 shows the third principal stresses after physiological superposition of the four load cases.
The aim of the present study was to compare stress paths in the dural folds with anatomical collagen fiber orientation and to test if head acceleration translates into functional loading of the calvaria using a three-dimensional model of the dural folds and the human skull.

Regarding hypothesis 1, that stress paths in the dural folds correlate with the anatomical fiber orientations, a high agreement between the tensile stress trajectories in the falx cerebri and the tentorium cerebelli with the fiber orientation found in the human dural folds was noted. The interaction of functional adaption of skull bone, muscles, and connective tissue constitutes altogether a form-function unit by which the skull can fulfill its duties concerning biting and brain protection at minimum weight.

Hypothesis 2 states that surface pressure to the dural folds translates into functional loading of the skull. The analysis supports this hypothesis by finding compressive stresses in the finite element model after the application of forces due to loading of the dural folds. Head accelerations can provide functional compressive loading of the calvaria supporting mechanobiological form-function unit theories. In evolution, the balance between the necessary strength and mass is optimized as in lightweight structures (Demes, 1985; Witzel & Preuschoft, 2005). On the other hand, in ontogeny bone metabolism in the skull seems to be less dependent on mechanical stimulation and more preserved in general. This agrees well with the findings of relatively low stresses in the calvaria. The stresses and strains in the calvaria reported here are distinctly lower than stresses of 1 to 20 MPa and strains of 50 to 1,500 με normally expected in bone (Frost, 2003). This could explain why increased bone density in the skull can be observed after space flight in adults. Negative feedback systems regulate the release of parathyroid hormone to stabilize the serum calcium concentration (Mundy & Guise, 1999). Low or absent mechanical loading leads to bone resorption according to Wolff's law. This results in increased calcium serum level. Serum parathyroid hormone, which regulates serum calcium level by releasing calcium stored in bone, is therefore decreased (Iwamoto, Takeda, & Sato, 2005). While in highly mechanoadaptive bones, resorption predominates, the inhibition of bone resorption by the decrease in parathyroid hormone could hypothetically explain the increase in bone density in a more metabolically dependent and less mechanosensitive skull. This could be a possible explanation for the low mechanical loads calculated in the calvaria. Further investigations in differences in mechanobiology of the skull and the appendicular skeleton are therefore of high interest to develop treatments for diseases causing low bone density like osteoporosis.

A point of uncertainty is the reconstruction of the dural folds. As the skull model has been generated using CT scans of a dry skull, dimensions, and attachment sites of the falx cerebri and the tentorium cerebelli had to be reconstructed later. Morphological accuracy can be improved by generating the model of the skull and the model of the dural folds by MRI data of one person (Glaister, Carass, Pham, Butman, & Prince, 2017).

The ultrastructure of the dura mater is far more complex than we are able to represent in our model with multiple laminas and some fibers orientated in various directions (Reina et al., 1996). In this study, the dura mater was reduced to one layer and only the major fiber tracts were investigated. A possible biomechanical explanation for the complex fiber architecture could be the

**FIGURE 5** Compressive loading of the skull after superposition of third principal stress of four load cases in (a) oblique view and (b) top view. Surface pressure applied to the dural folds due to head accelerations leads to compressive loading of the calvaria. Tensile stresses in the dural folds are shown in (c) for superposition of all load cases.
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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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