# Modeling of a Virtual Open Platform for Human Cranium Simulation

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**Abstract.** To prevent, detect and treat trauma brain injuries (TBI) one must understand them and know how they occur. With the integration of biomechanical and clinical theories, as well as research cases, a new era of cooperation must be initiated. For that reason, our proposal of developing a virtual platform based on the BioCAD protocol through computed tomography (CT) software, computer aided design (CAD) software and finite element method (FEM) analysis software, represents a joined effort in that direction. Results obtained with the resultant model were in line with maxillary expansion results from the literature, thus validating it. This model must be adaptable to the user and/or patient, leading to an innovative tool for research, prevention and treatment of TBI.

**Keywords:** BioCAD · Brain · Finite element method · Simulation · Trauma

## 1 Introduction

The human head is one of the most critical area of the human body, so with severe trauma to the head comes a possible death situation or long-term disability [1]. From an anatomical point of view, the scalp, skull, sub-arachnoidal space and dura matter are natural protections for the brain but they cannot withstand the dynamical loading conditions of today's accidents [2]. The current methods to analyze the kind of injury sustained by the head in a trauma situation are mostly based on translational acceleration [3]. Since there are other parameters that cause injuries, such as rotational acceleration, the need to improve current test procedures is required [4]. As a result, our proposal to improve the approach to the classification of TBI is based on an interdisciplinary work group comprising engineers and a neurosurgeon with the objective of developing a virtual open platform to study these events. With this work group concept, problems that once were studied separately can be analyzed together allowing for faster and solid advances on TBI problems, such as, subdural haematoma (SDH), diffuse axonal injury (DAI) and strain rate on the cerebral tissue [5, 6]. Consequently, an extensive study to the anatomy of the human head was conducted, so that it could be correctly represented even if some simplifications had to be made. The development of this virtual platform, or computational model, leans on the premise that it must simulate TBI situations and for that, it is constructed using the BioCAD protocol with a specific patient modeling (SPM) method [7]. This protocol comprises a

V.G. Duffy (Ed.): DHM 2015, Part II, LNCS 9185, pp. 358–366, 2015.
DOI: 10.1007/978-3-319-21070-4_36

series of sequentially coordinated tasks in different softwares. It starts with the loading of a computerized tomography (CT) scan in a medical image processing software, then the resulting file is imported to a computer aided design (CAD) software and in the end a finite element method (FEM) analysis software is used. This proposed computational model is in the development stage an assessment was made to the stress distribution through the geometry, so that it could be verified if the behavior was consistent with other validated studies in the literature.

In the end, this virtual platform has to be adaptive to the user and/or patient, in order to simulate TBI close to reality. This will lead to an important tool for the study, treatment and prevention of TBI, which will be publicly available.

## 2 Materials and Methods

Since the main objective of this study is to develop a TBI platform, the head anatomy was studied. It was important that the geometry to obtain would not be too simplified nor too detailed, in order to reproduce coherent results in the simulations. Therefore, it was made a choice to use a compromised solution. An analysis to the basic structures of the human head was conducted with an outward to inward direction. First, appears the scalp with a thickness varying from 5 to 7 mm, followed by the skull and the meninges. The membranes that compose the meninges are the dura mater, arachnoid and the pia mater, having cerebrospinal fluid (CSF) in the subdural and subarachnoid space. This fluid creates a disconnection between them and has an important role in absorbing shock to the head, according to the scientific community [8].

Next, in our analysis, came the brain structure divided, by the invaginations, in three parts, which are the cerebrum, cerebellum and the brain stem (Fig. 1) [8].

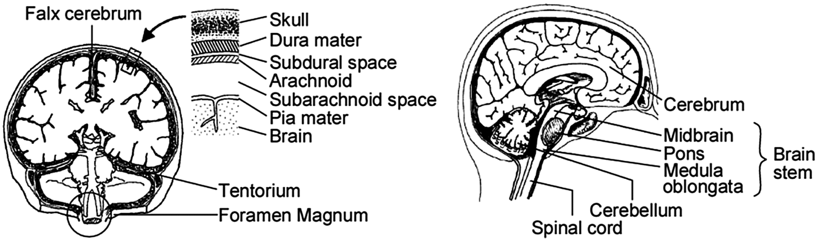

**Fig. 1.** Image portraying cutting planes of the human head [8]

Once understood the basic head anatomy, the next step was to study the types of injuries that could occur. In light of this, the head injuries are classified as open and closed. Open injuries relate to skull fracture but can also be linked to damage to the soft intracranial tissue, while in the presence of a skull fracture. Closed injuries do not have a skull fracture but have trauma inflicted to the intracranial contents. The most challenging injury to understand and replicate is the closed injury [8].

Nonetheless there were more structures and specific injuries to describe, an extensive anatomical analysis, as well as physiopathological, will be postponed since our model only contemplates, in this phase, bony structures.

Generally, the study of TBI has taken two separate approaches to the problem, the bioengineers view and the medical view. The bioengineers view leans specially on the input variables that cause the injuries, usually being those the linear acceleration, strain and strain rate in the brain tissue [6]. In the other hand, the medical view consists in the study of the consequences of the trauma, such as, diffuse axonal injury (DAI) and/or brain edema (BE) [9]. Despite of this, advances in the TBI research area have been achieved regarding, for example, head impact situations with or without helmets, skull fracture and the behavior of the human brain under impact conditions, as well as other studies [3, 4, 10, 11].

What is proposed with our study is a third approach by joining the previous two approaches, consequently, reinforcing the potential for research. This integration led to an interdisciplinary team formed by engineers and a neurosurgeon. In addition to this integration, there has been an objective of creating a computational model based on a SPM method with the ability to be adjusted to different purposes or situations. This means that this model will result into a virtual platform with the most important anatomical characteristics of the human head. For this to be possible, the model development followed a protocol called BioCAD. The BioCAD protocol was developed in the Division of Three-Dimensional Technologies (DT3D) in the Center for Information Technology – Renato Archer (CTI), Campinas, São Paulo, Brazil [12]. It comprehends a sequence of tasks executed in various softwares, starting with the loading of CT scans into the InVesalius® software, also developed in CTI [13]. This operation had the purpose of processing these CT images, suppressing imperfections and soft tissues, generating a stereo lithography (STL) mesh of the bony structures (Fig. 2a). The CT scan equipment used to acquire the images was a GE LightSpeed16 with a threshold parameter of −1024 to 3071, gap between slices of 1.25 mm, an image size of 512 × 512 pixels, a kVp of 120, a detection tilt of 0° and 16 channels.

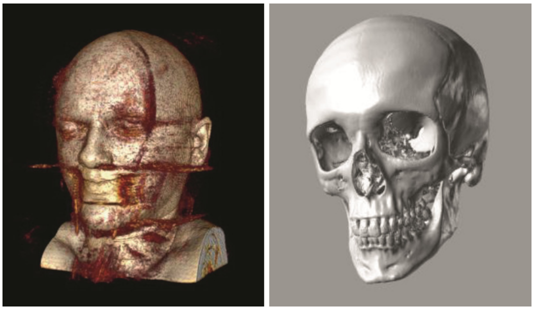

**Fig. 2.** In the lef, a CT scan loaded into the InVesalius® software and, in the right, a STL mesh generated in the same software and loaded into Rhinoceros® CAD software.

Next, the STL mesh file was imported into the CAD software Rhinoceros® because of the ability of this tool to combine surface modeling with complex geometries, as are the ones present in the human head (Fig. 2b).

With this STL mesh as a modeling guide, a geometry can be created having an anatomical accuracy in line with what is necessary for this specific case. In other words, this particular condition allows for the preservation of the skull anatomy and, at the same time, adjusts the detail depending of the area that needs to be represented and the importance to achieve a correct simulation. As mentioned above, all of these conditions depend on an accurate anatomical study of the human head.

Once the geometric model was created, it was imported to the FEM simulation software Hypermesh®. A mesh was created and optimized, in order to simulate the intended situation (Fig. 3) [14].

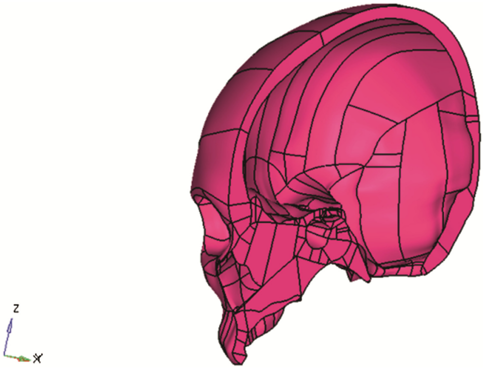

**Fig. 3.** Image of the geometry loaded into Hypermesh®

## 3 Discussion

One of BioCAD advantages is the fact that it is able to maintain the anatomical coherence of the models. This capability differs from other models found in the literature.

Models with a lack of detail, as seen in Fig. 4(a), for example, lead to incomplete results or difficulty to simulate due to a very rough mesh detail. On the other hand, the models with excess of detail can impose difficulties with a high need of processing power and a difficulty in presenting a correct solution. This excess of detailing, in the whole model, also makes impossible to have local detail adjustment. Example of such a model can be seen in Fig. 4(b). Differing from this first two examples, are models which resemble themselves to crash-test dummies heads. These models, due to their shape, have a different energy distribution on its geometry than a human head, leading to incorrect results. It can be observed in Fig. 4(c), an example of that kind of model.

During the development of the model, problems with the anatomy of the human head have been raised. For example, the bone inside the eye socket, that comprehends parts of the ethmoid, sphenoid, lacrimal and maxillary bones, was not totally represented by the CT scan due to its low thickness (Fig. 5a). Another problem, also because of low thickness and the anatomical geometries, was the generation of the 3D mesh that had, as an example, collapsed elements (Fig. 5b).

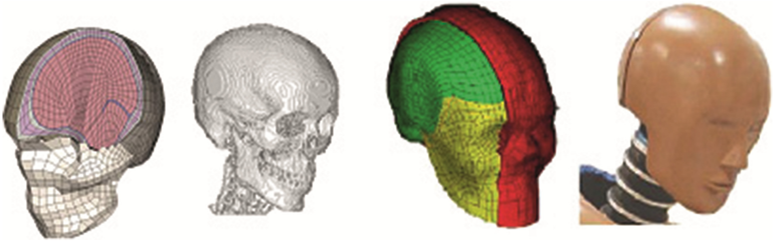

**Fig. 4.** Model (a) has little geometrical detail, model (b) has an excess of detail and a model (c) has an anatomy resembling the head of a crash-test dummy (d) [17–20].

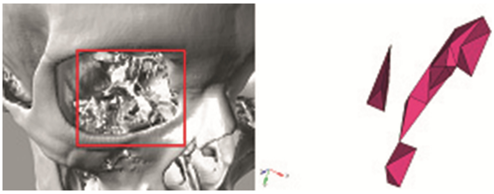

**Fig. 5.** In the left, a poor geometry representation and, in the right, collapsed 3D elements

A refinement, using the tools available in Hypermesh® software, was performed to the 2D surface mesh in order to eliminate imperfections in the elements and generate a 3D mesh close to simulation stage. Nonetheless, it was still necessary to perform a refinement to the 3D mesh.

Aside from these development obstacles, there is a constant evaluation of the work strategy due to the challenge of modeling complex anatomical geometries.

## 4 Simulation and Results

The current state of development of the computational model represents the skull structure with the cortical interior and exterior bone (Fig. 3).

The geometry exported for the simulation had half of the skull because it saves computer processing power and time, maintaining the ability of achieving similar results which do not threaten the validity of the model. This geometry was exported in the IGES (.igs) format from Rhinoceros® to Hypermesh®. Inside Hypermesh®, it was generated a 2D triangular surface mesh with an element size of 3.5 mm. From this 2D mesh was generated a 3D tetrahedral mesh with linear elements that was used in the simulation (Fig. 6).

A material for the cortical bone was created as linear isotropic with a Young's Modulus of 13700 MPa, a Poisson Coefficient of 0.35 and a Density of 2e-6 kg/mm$^3$. All of these are average values found in publications, regarding the cortical bone [15, 16]. For these initial simulations the bone was considered solid, meaning that the space between the exterior and interior cortical bone is filled with pyramidal elements.

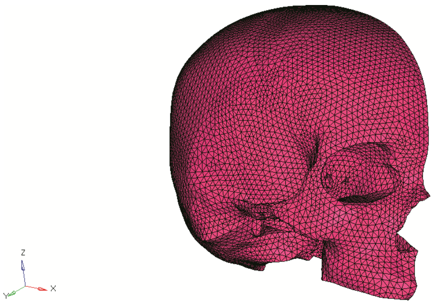

**Fig. 6.** Final 3D mesh

Since it was intended to verify if the model behavior was correct, the situation to simulate was a maxillary expansion. To emulate the stress distribution characteristic to this process, a pressure of 1 MPa was applied to a small area in the maxilla near the midsagital suture, as can be seen in Fig. 7. This pressure was applied normal to the surface. In Fig. 8, with blue color triangles, it can be seen the fixed support located in the foramen magnum.

This pressure value did not represent any real value obtained in this kind of procedures because, as mentioned earlier, the only aim is to observe the stress distribution in the geometry. Given that in such procedures there is a maxillary separation in the midsagital suture and that it was being used half of the skull, the sagital surfaces near the

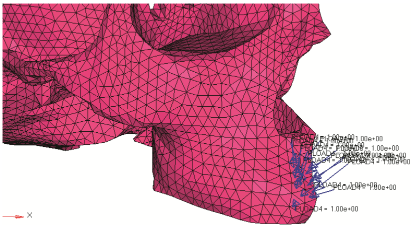

**Fig. 7.** Representation of the pressure application

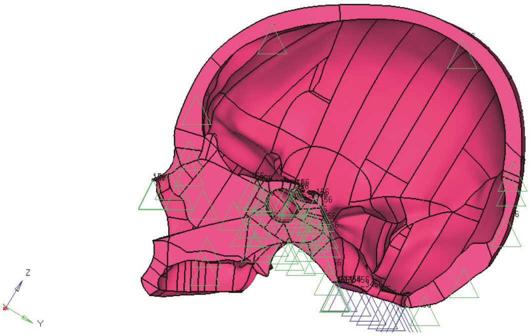

**Fig. 8.** Image showing the constraint present in the foramen magnum (Color figure online)

midsagital suture were free of constraints and the remaining sagital surfaces were given restrictions, in order to simulate symmetry. To accomplish this, these surfaces did not have translational movement in the x axis and rotational movement in the y and z axis, as can be observed in Fig. 8 in green color triangles.

Once all the considerations where in place the simulation was configured as linear static and the situation was replicated. The results were shown in a color map format regarding the absolute maximum principal stress, so that one could be able to compare its behavior with studies presented in the literature (Figs. 9 and 10).

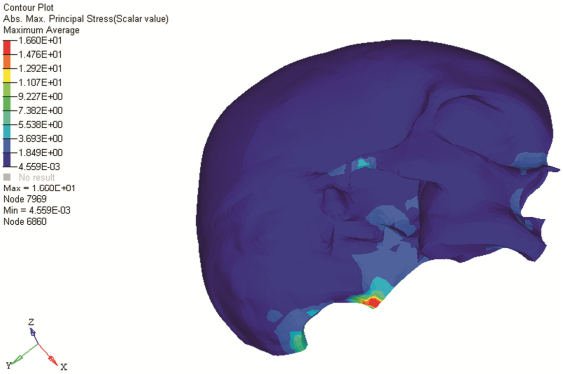

**Fig. 9.** Outer stress distribution map

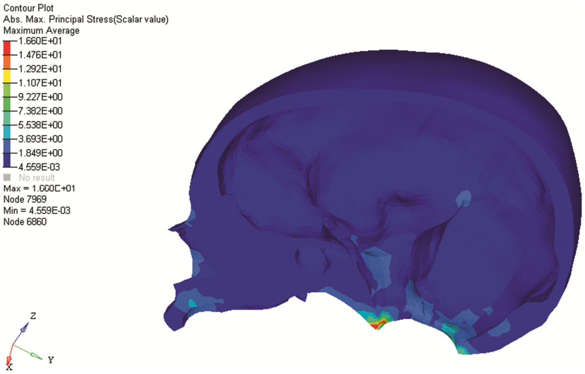

**Fig. 10.** Inner stress distribution map

The stress distribution is in line with what is referred in the literature, that is to say that there is an occurrence of stress in the skull base, in the sphenoid bone and in the zygomatic arch [21]. Furthermore, a propagation of stress takes place near the eye socket and in the palatal bone [22]. These patterns of stress dispersion are all in accordance with what is already confirmed.

## 5 Conclusion

Our model behaved as expected in the simulation of a maxillary expansion. The fact that it was possible to validate our model in this simulation strengthens the premise that models with poor anatomical representation, with excess of detail, rough or too refined meshing produce less accurate results. Nonetheless, that more simulations are to be made and that the model needs further development, the possibility of achieving breakthrough results has been reinforced. The application of the BioCAD protocol plays a very important role in the modeling as well as in the simulation, for example, due to its ability to create the conditions to reproduce anatomical geometries and to refine the mesh in specific areas of interest to the project. Although, it is important to refer that these tests do not have a clinical purpose but the objective of confirming that the model has achieved a state that is closer to the intended virtual platform.

As future works, steps must be taken to model the brain, simulate the model with a brain geometry inside and validate the results. When finished, this virtual platform will be an important advance in the study, prevention and treatment of TBI because of its qualities but also because it is intended to be made available publically.

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