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Cranial Biomechanical Simulation

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Abstract

In order to improve the understanding, detection and prevention of traumatic brain injury (TBI), a step forward must be taken in the research. A pursue of biomechanical and clinical theories in separate, must give place to a joined effort. Therefore, it is proposed the development of a virtual platform using BioCAD protocol, surface modeling software and finite element method (FEM) analysis software, in order to achieve a model that can be adapted to the needs of the user or patient. This will result in an innovative and most needed tool, so that research and prevention of TBI enter a new level.

1. Introduction

With an increasing number of people affected by TBI, it is estimated that 10 million people are affected annually, according to the World Health Organization [1]. The research made in this area has been growing over the years but there is still a lot of controversy regarding the choice of pathways to the future. Studies of exterior forces applied to the head have been made using linear and angular accelerations, in order to evaluate its effects in the brain. Results, such as the diffuse axonal injuries and strain rate through the brain mass, have been analyzed and discussed [2]. Being those, undoubtedly, great breakthroughs on TBI investigation, there is still a need to look at the problem from another point of view or even improve the method in which the analysis is made.

Our approach to TBI investigation is to create a virtual open platform which can recreate and simulate situations that can lead to trauma. By virtual open platform, we intend it to be a human head modeling and simulation tool using FEM with imposed physical constraints, so that the natural movements can be assured. Subsequently, the validation stage appears, so that the platform results are subjected to comparison with results that are already corroborated.

2. Materials and methods

There are two courses of action that have been taken by the community of scientists that investigate TBI. The first one is the physics approach taken by bioengineers, meaning that the authors give special attention to the input variables causing the TBI. In general, those are the linear acceleration, angular acceleration, strain and strain rate in the brain [2].

The second one is an almost exclusively clinical approach to the problem by studying diffuse axonal injury (DAI) [3] and/or brain edema (BE) [4], for example.

What we propose is a third course of action that differs by joining the two mentioned approaches. To accomplish this, an interdisciplinary team that includes a neurosurgeon was brought together, so that the whole analysis remains homogeneous. The creation of an open

platform from a specific patient modeling method (SPM) has been the approach taken from the beginning [5]. However, the aim is to transform it into a general platform with results that can be applied worldwide.

For this model, the SPM follows a protocol called BioCAD. It is a sequence of tasks that comprises imaging software called InVesalius® 3.0, developed in the Division of Three-Dimensional Technologies, in the Centre for Information Technology Renato Archer, (DT3D/CTI), with computer-aided design (CAD) tools and finite element analysis (FEA) software.

The BioCAD protocol starts with the patient computed tomography (CT) scans loaded into InVesalius® 3.0 (figure 1), with posterior cleaning for imperfections as well as soft tissues. Succeeding these operations is the generation of a stereo lithography (STL) mesh.
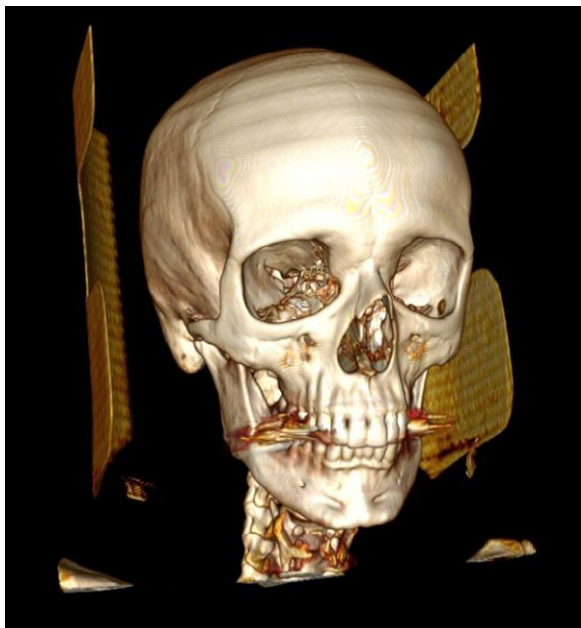

Fig. 2 – STL mesh loaded into CAD software.

3. Discussion

The concept of BioCAD contrasts with the models found in the literature, which lack detail and thus moving to incomplete results or difficulties to simulate. For example, this could be because of a very rough mesh detail (figure 3).

Fig. 1 – DICOM file loaded into InVesalius® 3.0.

After being exported to CAD software Rhinocerus® 4.0, which has the ability to combine surface modelling with complex geometries, this STL mesh has a role of guidance so that one can model a skull with maximum accuracy (figure 2). The level of accuracy goes only to the point necessary to have optimum results with the appropriate detail, regarding the purpose of the project and an anatomical study of the human cranium. This opens the possibility of adjusting the model depending on the level of refinement the user wants on an exact part of the cranium. Once the modeling is optimized and the mesh created, it is initiated the FEA mesh optimization and posterior result discussion [6].
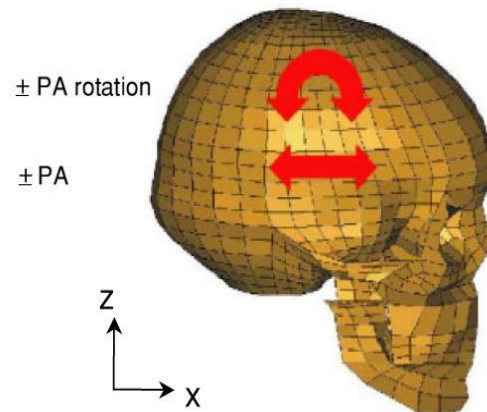

Fig. 3 – A cranium model with rough meshing [7].

As another example, is the case of a voxel based model which has an excess of detail that can lead to difficulties, on the solution process and with a very high

need for computing power. The lack of mesh control, in order to have more detailed areas, is also a problem because the whole model will have to be detailed (figure 4).
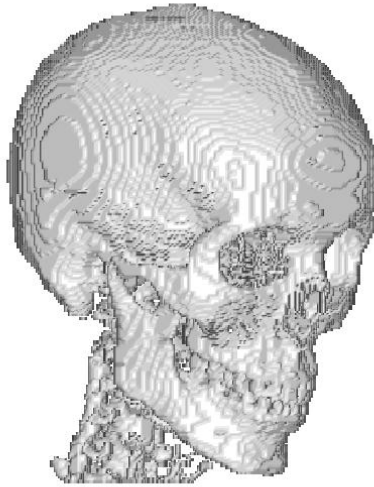

Fig. 4 – Voxel model with an excess of detail [8].

Other example is the poor representation of the human head anatomy, similar to the crash-test dummies, which lead to a different energy propagation upon an external force application (figure 5).
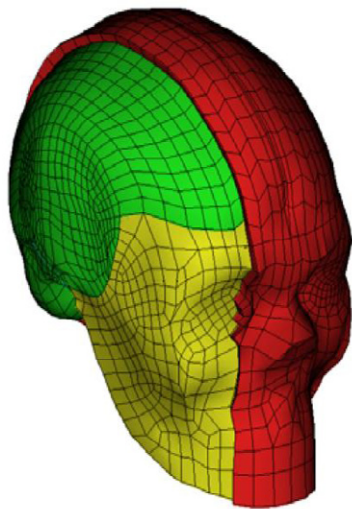

Fig. 5 – A model with an anatomy resembling the head of a crash-test dummy [9].

So far, in the development of the platform, there has been a difficulty in overcoming some anatomical problems, such as, some areas of the cranium on the CT scan that were not perfectly represented resulting in a flawed area in the STL mesh. The case of the ethmoid bone is an example of it (figure 6).
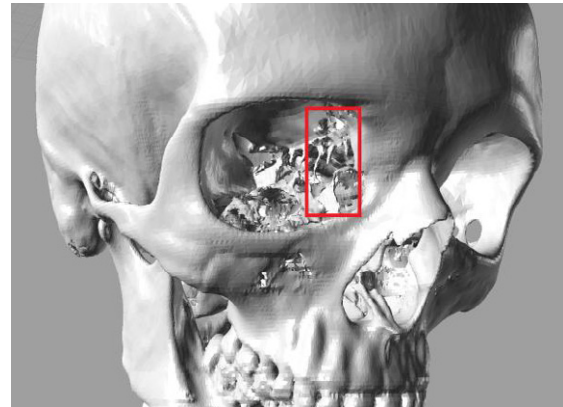

Fig. 6 – InVesalius® 3.0 STL mesh flawed ethmoid bone.

Another difficulty is realizing what protuberances or anchorage points need to be modeled to make sure that all important muscles to the head movement are correctly simulated. This challenging aspect is going to be discussed with specialists in anatomy and biomechanics, since they are more acquainted with this area.

4. Simulation

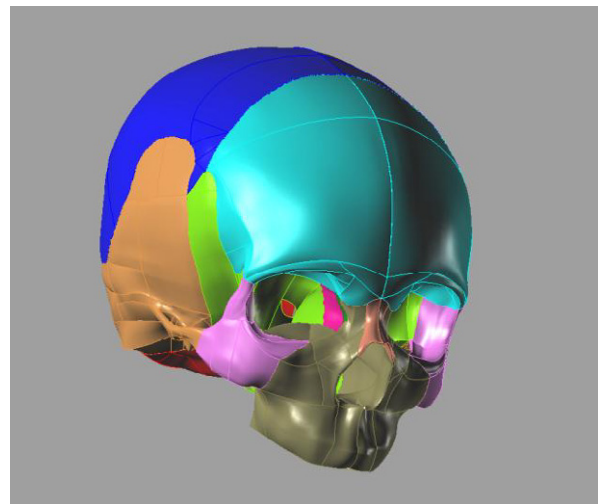The actual development state of the model represents the human head exterior cortical bone (figure 7).

Fig. 7 – Virtual platform model.

As a result, in order to learn if the model behaves as intended when in a simulation, an archive in the ACIS (.sat) format was exported, from Rhinocerus® 4.0 to Ansys® 14.0. Since Ansys® 14.0 did not have in its library, a material with the properties of cortical bone, it

was defined a cortical bone material with a Young's Modulus of 13700 MPa and a Poisson Coefficient of 0.35. These are the average values found in biomechanical publications for the cortical bone [10]. It was, also, assumed that the whole geometry material was a cortical bone with a thickness of 2 mm [9].

Once the material was created the generation of a model mesh was required to proceed to the simulation phase (figure 8). This mesh was generated in the automatic mode of the software because of the early state phase of simulations. Nonetheless, with the model complete the mesh will be refined.
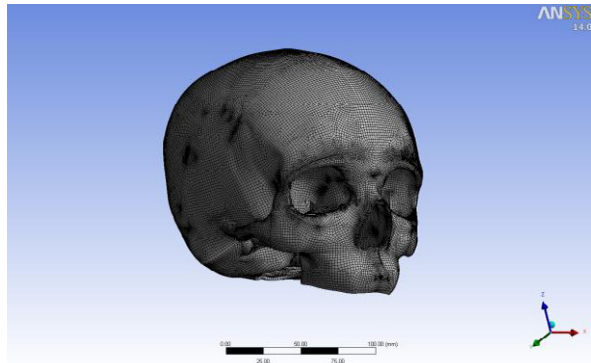

Fig. 8 – Mesh of the model generated in Ansys® 14.0 software.

In order to obtain a simulation that would create a possible situation of a head TBI with an easy interpretation, a fixed support and a force where defined. The intended situation was an impact to the malar bone near the eye socket. As can be seen in figure 9 and 10, the fixed support was located in the foramen magnum and the force has been applied to a small surface near the eye socket.
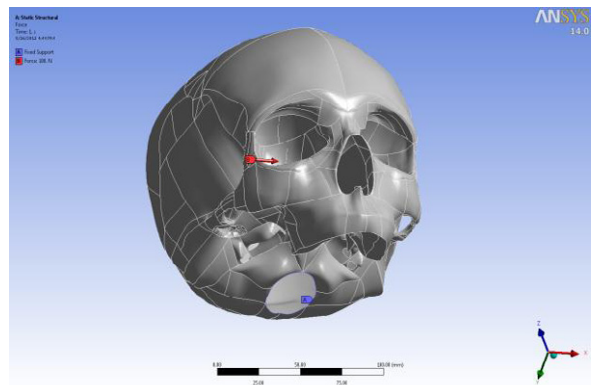

Fig. 9 – Definition of a fixed support and a force in the model.
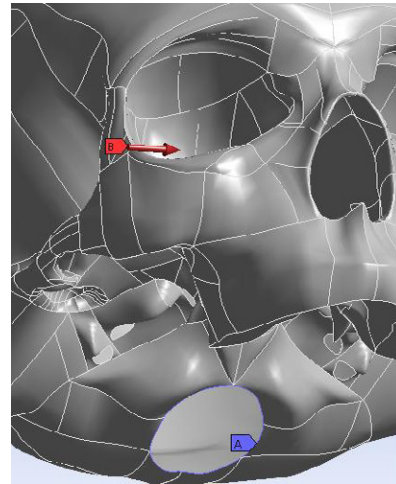

Fig. 10 – Detailed image of the force definition point and the fixed support.

With all the considerations in place, the situation was simulated. The results were introduced in the format of a colour map concerning to the maximum stress analysis in the model, so that a behavior acknowledgement of the geometry would be made (figure 11). The numerical results are presented in figure 12 to present a better visualization.
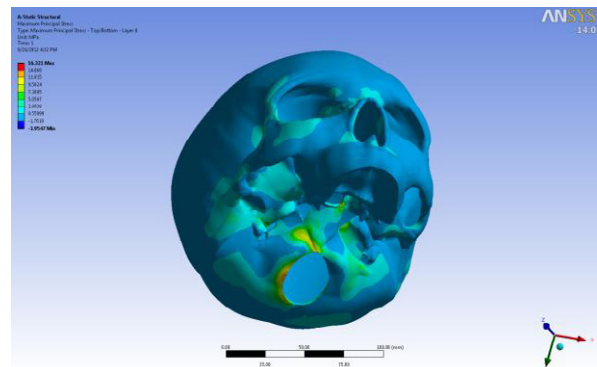

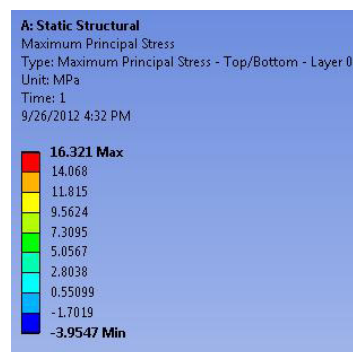Fig. 11 – Colour map of the maximum stress analysis.

Fig. 12 – Maximum stress analysis simulation results.

5. Conclusions

A model with a poor representation of the human head anatomy detailed in excess and with a rough meshing, outcomes in less accurate results. With our virtual platform we propose a model that is constructed based on a real human cranium, with true anatomical design and with better possibilities of obtaining close to real results.

It has been demonstrated with the simulation, using simplification hypotheses and constraints that the model behaved as expected. Nonetheless, tests using a different software will be done to create a comparison basis between results, since the validation is obtained experimentally. Still, it is important to highlight that these tests do not have a clinical purpose but the aim of verifying that a base of work to a more evolved model has been achieved.

With the project development and the BioCAD possibility of adjusting the mesh detail after the level of importance in a certain area of the head, we improve the chances of obtaining breakthrough results.

The next steps to be taken, so that the project conclusion is reached, are the complete modeling of the cranium interior and brain, the model simulation and results validation. When built, this platform will prove to be a relevant advance in the area of TBI research and even on its prevention.

References

[1] Hyder, A., Wunderlich, C., Puvanachandra, P., Gururaj, G., Kobusingye, O., 2007. The impact of traumatic brain injuries: A global perspective. In NeuroRehabilitation Journal. IOS Press.

[2] King, A., Yang, K., Zhang, L., Hardy, W., 2003. Is head injury caused by linear or angular acceleration?. in IRCOBI Conference – Lisbon (Portugal).

[3] Onaya, M., 2002. Neuropathological investigation of cerebral white matter lesions caused by closed injury.

[4] Marmaru, A., 2003. Pathophysiology of traumatic brain edema: current concepts. in Acta Neurochir. Springer-Verlag.

[5] Castellano-Smith, A., Hartkens, T., Schnabel, J., Hose, D., Liu, H., Hall, W., Truwit, C., Hawkes, D., Hill, D., 2001. Constructing patiente specific models for correcting intraoperative brain deformation. in MICCAI2001. Springer-Verlag.

[6] Noritomi, P., Xavier, T., Silva, J., 2012. A comparison between BioCAD and some know methods for finite elemento model generation. in: Bártolo, P., et al., ed. 2012. Innovative developmens in virtual and physical prototyping. Leiden: CRC Press/Balkema, pp. 685-690.

[7] Kleiven, S., 2006. Evaluation of head injury criteria using a finite element model validated against experiments on localized brain motion, intracerebral acceleration, and intracranial pressure. in IJCrash 2006. Woodhead Publishing Ltd.

[8] Watanabe, D., Yuge, K., Nishimoto, T., Murakami, S., Takao, H., 2008. Head impact analysis related to the mechanism of diffuse axonal injury. in "High-Tech Research Center" Project for Private Universities – MEXT, Japan.

[9] Ghajari, M., Deck, C., Galvanetto, U., Ianucci, L., Willinger, R., 2009. Development of numerical models for the investigation of motorcyclists accidents. in 7th European LS-DYNA Conference. DYNAmore Gmbh.

[10] Akca, K., Cehreli, M., 2006. Biomechanical consequences of progressive marginal bone loss around oral implants: a finite element stress analysis. in International Federation for Medical and Biological Engineering. Springer.