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A SPLINES BASED METHOD FOR MODELING THE HUMAN HEAD FOR USE IN FINITE ELEMENTS ANALYSIS

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Abstract. *This paper proposes a sequential methodology for modeling the human head, based on medical images, for use in finite element software. Through this methodology an easy model to construct is obtain, computationally slight, without presence of discontinuities and representative of the different structures present in the human head, which makes it feasible for high performance simulations.*

Keywords: *Biomechanics, 3D Modeling, Splines, Craniofacial Reconstruction, Finite Elements.*

1. INTRODUCTION

The analysis of the human head by finite element (FE) has demonstrated great utility in the forensic, medical and biomechanical areas. Also, it is a support tool in the investigation for car accidents, study of cranioencephalic injury mechanisms, development of technologies for its prevention, maxillo facial and cranial reconstruction, and in the selection of the most indicated postoperative treatments (Motherway, 2009; Koch, 1996;). The difficult to obtain a good quality 3D CAD model is one of the main disadvantages in this analysis. A 3D CAD model of the human head is considered of good quality when it presents fidelity with the different anatomical forms and does not show flaws, discontinuities or interference inside and between the anatomical elements that compose it, allowing a discretization without errors, plausible to be analyzed by FE. Due to the complexity of anatomical surfaces, manual modeling lacks a standard technique and methodology. This would cause disagreements between results of a head modeling is performed by different engineers using different techniques (loft, splines, etc.). Therefore, in this manuscript it is proposed the study of a sequential methodology that explains the steps for the implementation of a 3D CAD model of the human head by the use of splines. The methodology allows obtaining good quality and customizable models for FE analysis, and it can provides a technical reference for computational modeling of the human head, since it proposes a standardization of the process, reducing the disagreements indicated above.

2. PROPOSED METHOD

It consists in 8 sequential steps (Fig. 1), where the first 5 are used to model the solids in CAD format. The last 3 steps are focused on FE simulation, so they will not be covered in detail. The method consists of importing medical images from a 3D CAD software. The imported medical image as a “box of pixels” serves as a reference for the design of 3D splines, which in turn allow the generation of solid bodies such as skull, intracranial structures (brain, arachnoid, cerebrospinal fluid, etc.) and extracranial structures (muscles, etc.). The obtained system is simulated by FE to validate the methodology.

At step 1, the medical images are obtained. They come from computerized tomography (CT) or magnetic resonance imaging (MRI) taken from the patient. The medical images come as a file containing a set of 2D photos, where each photo corresponds to a slice of the patient's investigated anatomy. The set of photos should be opened in a medical imaging software such as InVesalius® or 3D Slicer® (Fig. 2).

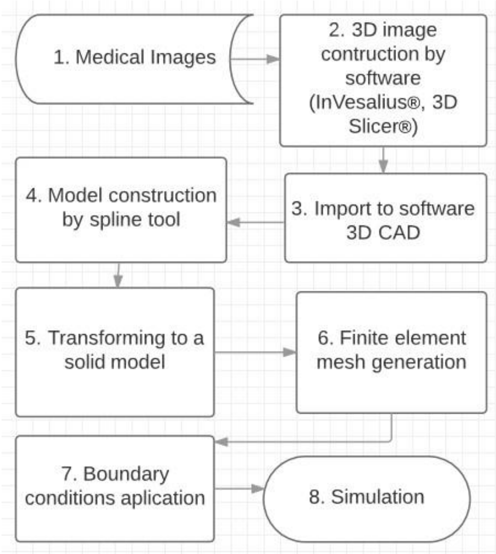

Figure 1. Procedure to obtain and use the adaptive model.

These softwares build a 3D image from a set of 2D images (Amorim et al, 2011; Pieper, et al 2004) as explained at step 2.

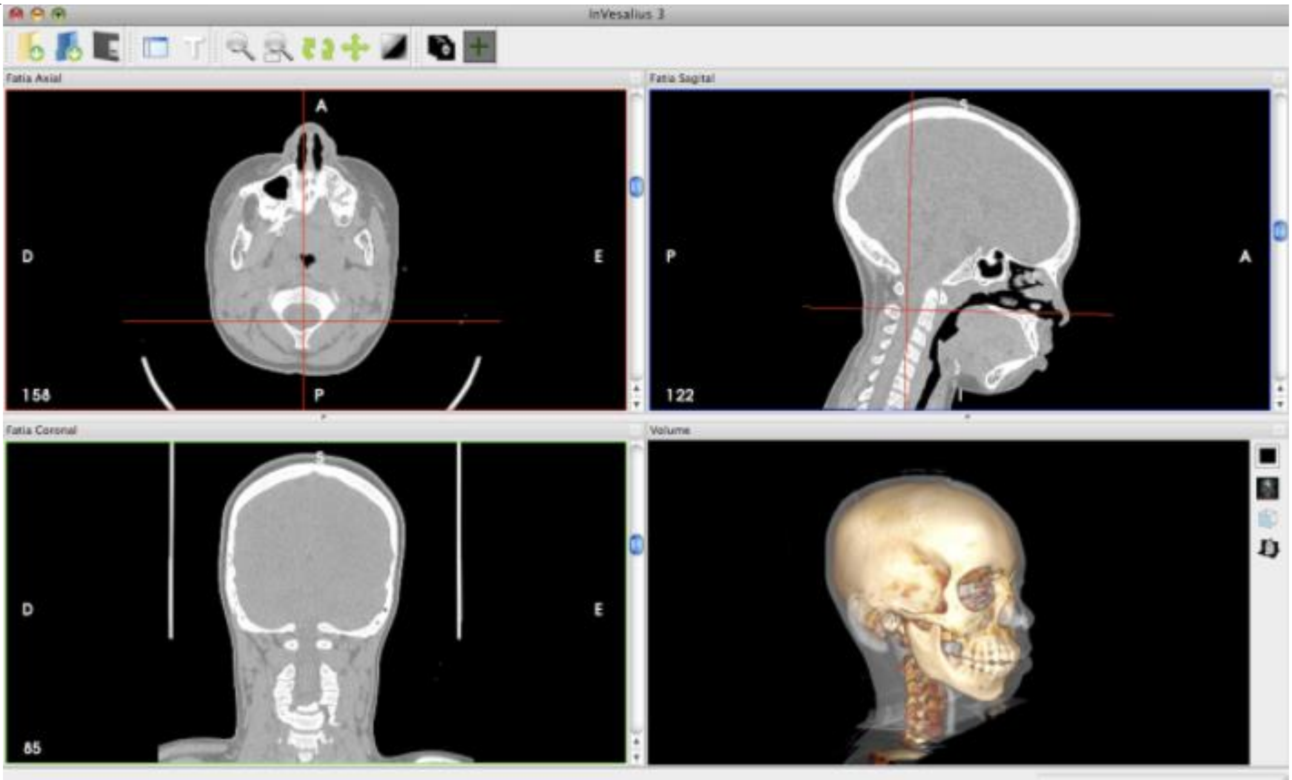

Figure. 2. A 3D image reconstructed form a set of 2D images, using InVesalius® software.

When viewing the constructed 3D image, only a "box of pixels" can be seen as the product of the 2D image junction (Moraes and Miamoto, 2015).

In step 3, the 3D image is saved in the "STL" format (StereoLithography) in the same medical image reconstruction software. The "STL" format makes the file compatible for importing from CAD software. In this work, the file was imported from Solidworks® software (Fig. 2a), but nothing else prevents the use of other CAD or FE software (AutoCad®, Algor®, Solid Edge®, Ansys®, etc.). It is recommended that the selected file corresponds to the skull, because of its anatomical complexity. Although the open file in Solidworks® can be manipulated as a solid, this is not enough to allow FE analysis, as there are interferences between solids (bodies) and discontinuities (voids), which necessitate a next step.

At step 4, the imported skull in "STL" format serves as a geometric reference to elaborate, above it, splines as edge lines. In order for the splines to circumvent exactly that region of the model, planes must first be created that divide the solid in the form of parallels and meridians, as shown in Fig. 2b. In each of these planes the splines must be elaborated, faithfully following the anatomical contour of the solid that intercepts the planes.

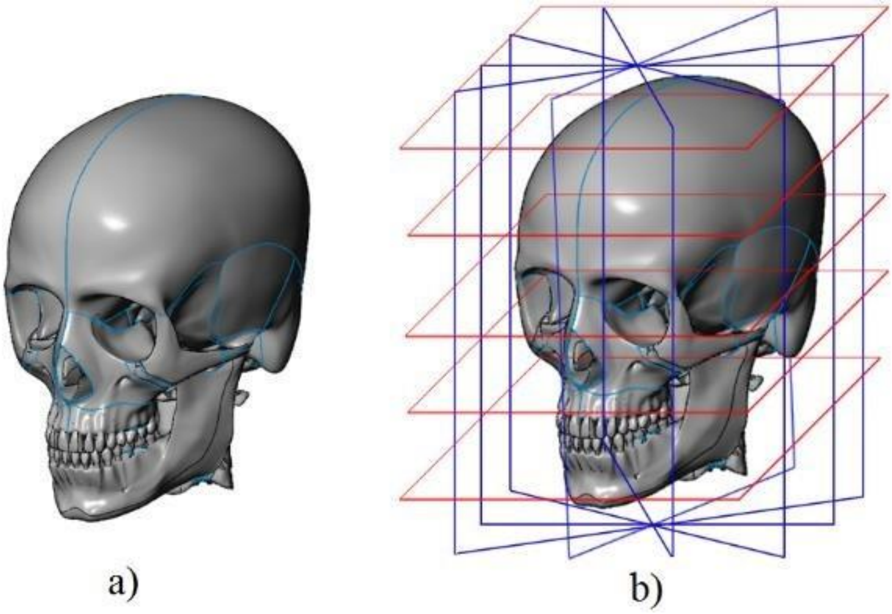

Figure 2. a) Imported medical skull image for Solidworks® program; b) Inclusion of planes in the form of parallels and meridians.

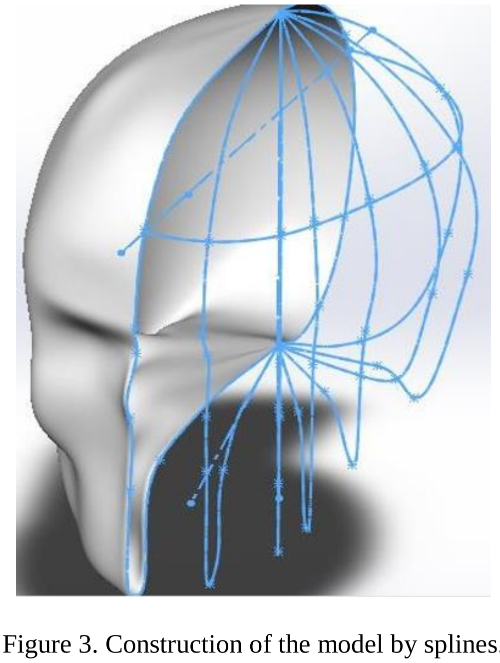

Figure 3. Construction of the model by splines.

Once all the splines are drawn through the planes, an arrangement of splines is obtained which, by use of the surface generation tools of Solidworks® 2013 (limiting surface), forms a surface (Fig. 3) without discontinuities and geometrically similar to the imported skull. In the cranium, a surface was generated from 9 vertical planes (meridians) and 5 planes. Oriented horizontally (parallel). For simplification it is recommended to generate the surface of only one side of the skull, since Solidworks® offers the "mirror" tool (Fig. 4) that promotes a mirrored duplicate of the model, allows joining both shells together to form a solid (SLDPRT format) lightweight, undamaged, homogeneous, and similar in geometry to the original imported model. This gives the first massive skull model.

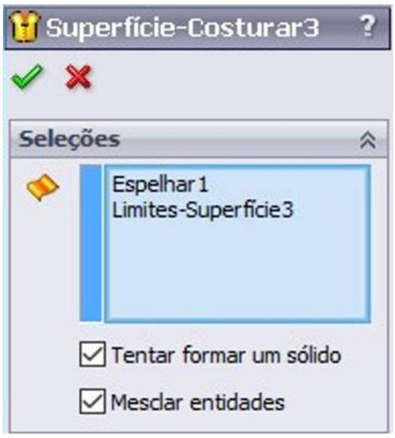

Figure 4. Solidworks® tool for mirroring bark, joining bark and turning bark to solid.

Based on this first solid, the intracranial structures (brain, arachnoid, brain fluid, etc.) and extracranial structures (muscles, skin, etc.) are elaborated in the same way. In adjacent anatomical elements (skin and skull, skull and membrane, membrane and liquid, etc.) the arrangement of the splines that form them must have congruence between them (Fig 5).

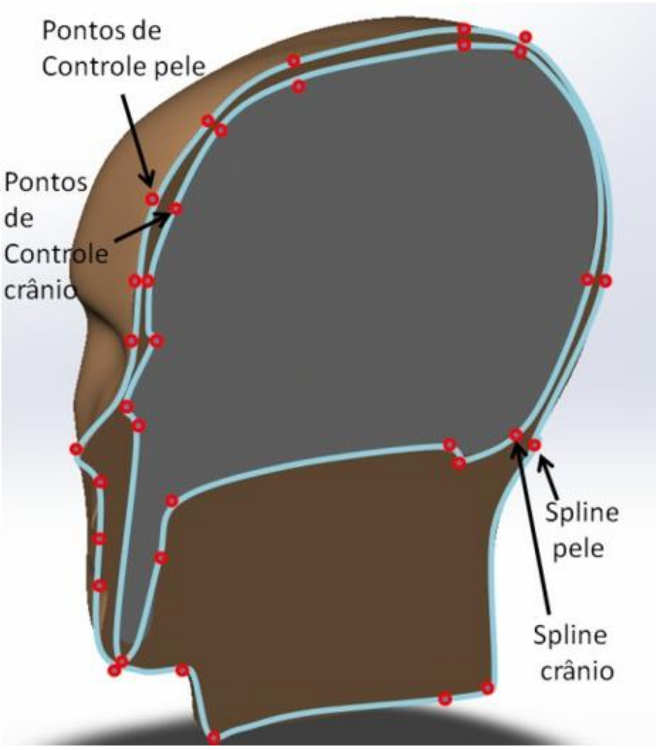

Figure 5. Congruent arrangement of splines between adjacent anatomical structures. ("Pontos de controle pele" as control point of skin, "Pontos de controle crânio" as control point of skull, "Spline pele" as skin spline,"Spline crânio" as skull spline.

Since these new pieces are a complete solid and made from a single skull, it is possible to obtain Boolean operations with their cavities and anatomical thicknesses, as shown in Figure 6. Boolean operations are based on the addition, subtraction and intersection of solids. All the depleted parts must be assembled, in order to conceive the model of human head formed by:

- Skull: obtained by the subtraction of the solid skull model with the brain structure;
- Skin: obtained by subtracting the model of the skin (massive) with the skull;
- Brain: obtained from the shape of the cranial cavity, reduced in one scale.
- Cerebrospinal fluid: remains between a solid of dimensions of the cranial cavity, minus a solid the size of the brain;
- Membranes (arachnoidand meninges): its construction process should be similar to that adopted in the

cerebrospinal fluid, but considering different thicknesses.

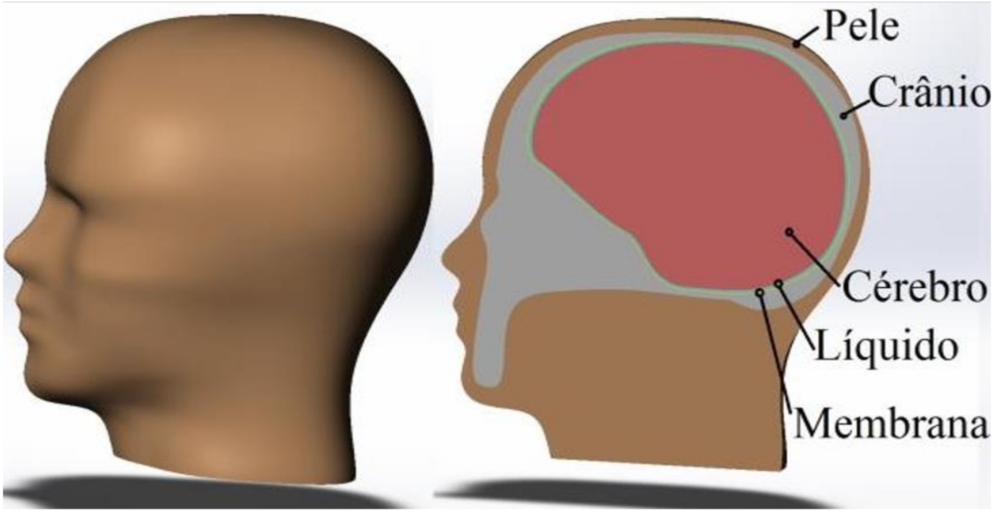

Figure 6. Model of the human head, by assembling the pieces with their respective cavities and anatomical thicknesses ("Pele" as skin, "Crânio" as skull, "Cérebro" as brain, "Líquido" as liquid," Membrana" as membrane.

Up to this point, the proposed methodology has a plausible model to be analyzed by FE. To do this, the template must be imported from the FE software. In step 6, the mesh generation process can be performed automatically by the chosen EF software, or manually, to ensure a mesh refinement in regions of interest.

The mesh of the model obtained in SolidWorks® Simulation is shown in Figure 7.

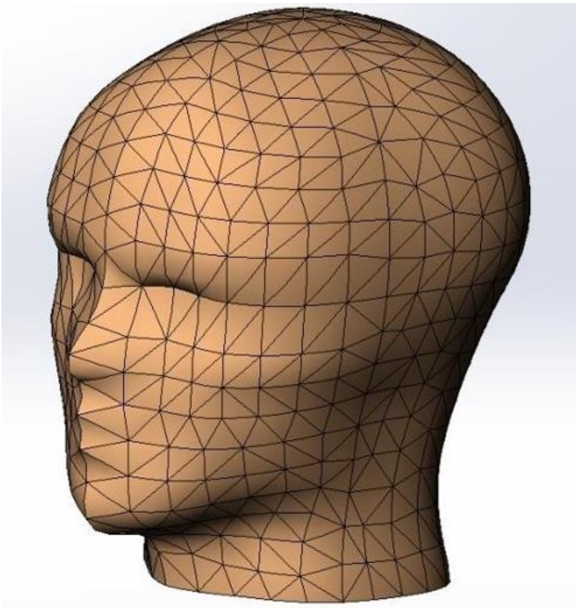

Figure 7. Discretized model as finite elements.

Solids obtained from splines have smooth and simple surfaces, with missing edges or more complex geometries that can cause singularities in the generation of mesh. The construction of the adjacent anatomical elements by use of splines with arrangement is congruent (Fig 5) allows to form geometries with congruent surfaces, which facilitates the process of mesh generation. The proposed methodology was also applied to other commercial software, generating successful meshes.

In step 7, the boundary conditions are applied to the discretized system. The boundary conditions correspond to the initial values of the problem (forces, type of supports, contacts, movement restrictions, etc.) that allow equating the variables of the mathematical modeling of the problem. The boundary conditions must be specified by the user of the FE software as well as the materials and mechanical characteristics. Finally, step 8 consists of the simulation of the model, using the boundary conditions and the finite element method.

The proposed methodology has already proved to be effective. A simulation of the effects produced in the human head by the impact of a soccer ball was presented by a medical team and engineers from the Federal University of Santa

Catarina, Pontifícia University Catholic of Chile and the University of Tarapacá (Ponce *et al*, 2014) (Fig. 8). This impact results in bruising and abnormalities in the spinal cord and may cause changes in the area of the disc and in the external region of the vertebra. Repetition of Impact can cause chronic injury, according to reference.

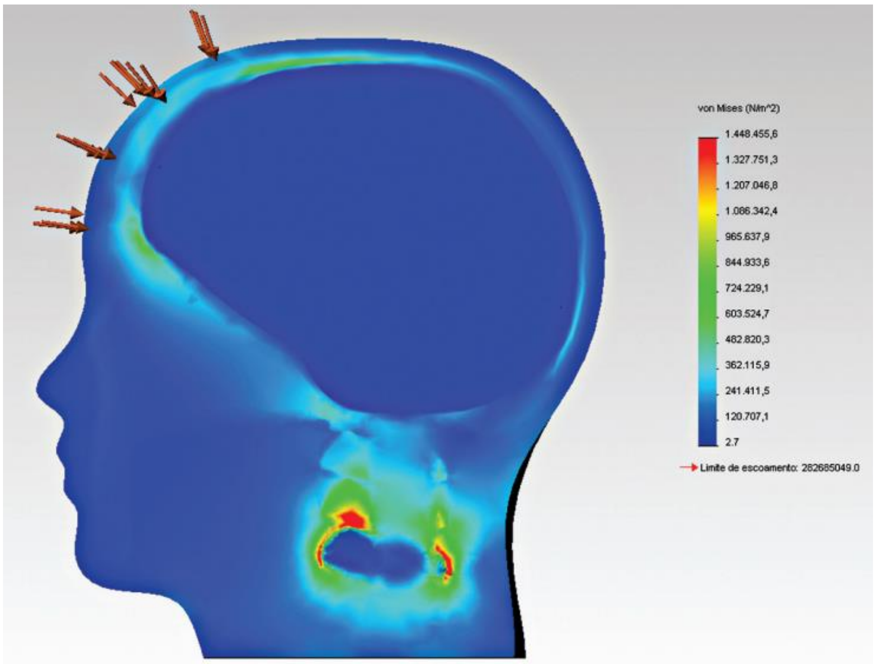

Figure 8. Simulation of the contusions in the skull and in the vertebrae by impact of soccer ball in the forehead (Ponce *et al*, 2014).

Figure 8, obtained from (Ponce *et al*, 2014), simulates a stroke of a ball in the upper part of the head. This image makes it very explicit how this simulation can bring meaningful and not intuitive results, greatly aiding medicine. As the Figure 9, shows another kind of impact.

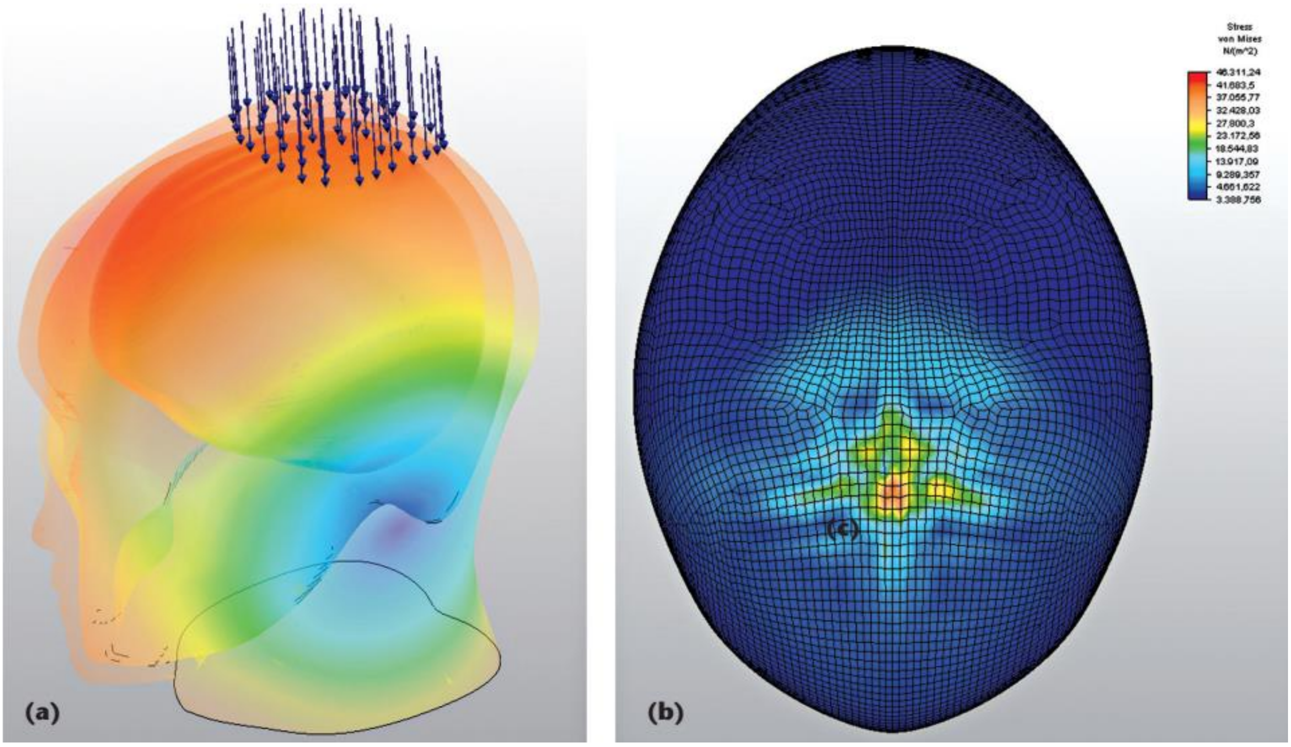

Figure 9. Simulation for a stroke in the upper part of the human head (Ponce *et al*, 2014).

Additionally, when compared the proposed technic whith other methods for generate solids, for example, those that use loft technics (a solid generated from a main structure made from contours of successive slices oriented in parallel form), as the used by (Ponce and Ponce, 2011), the solid obtained has a more rough and coarse surface (Fig. 10).

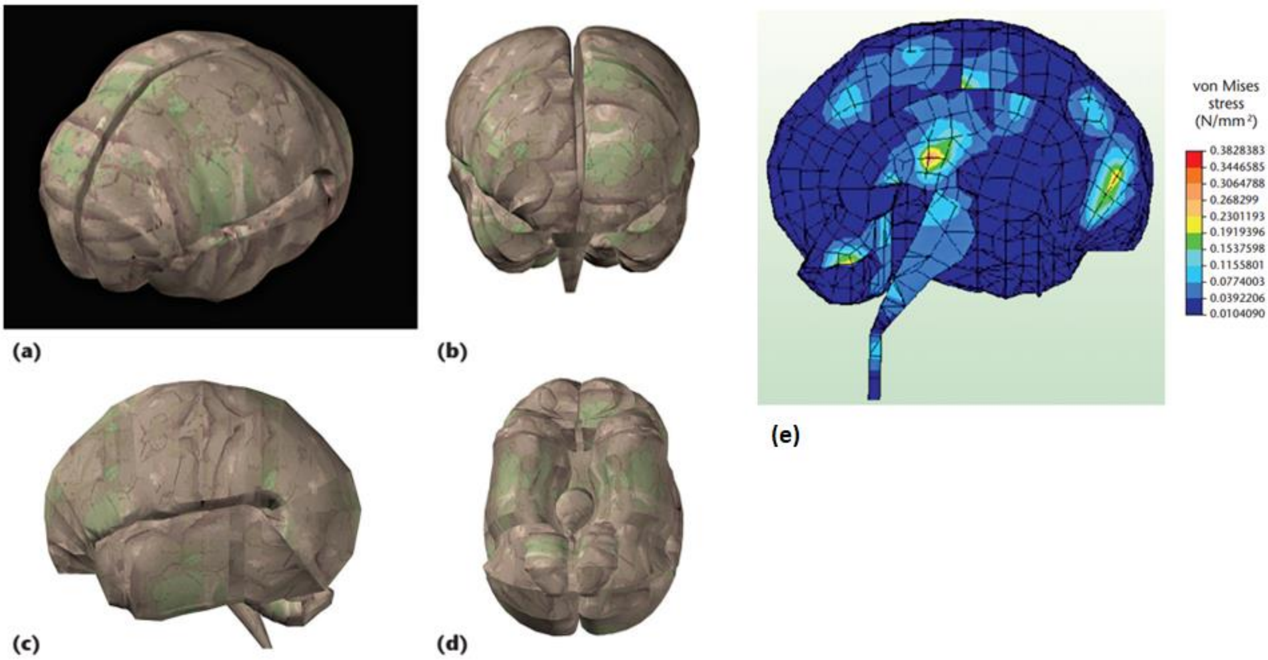

Figure 10. 3D views of the brain model obtain by loft technic: (a) isometric, (b) posterior, (c) lateral, and (d) bottom. The view (e) is the result of FE simulation. Obtained from (Ponce and Ponce, 2011).

3. CONCLUSION

The proposed method has already been used for modeling and simulation of strike in the human head (Ponce *et al*, 2014) demonstrating its effectiveness. Currently, there are customized models for modeling the human head (Li *et al* 2016), but these models are child specific which limits their customization. The geometry of these models is determined in the fabrication of the mesh, which requires sophisticated mathematical techniques (Li et al, 2016). In contrast, the proposed model is based on a simple methodology to reproduce. Also, the proposed method based on splines, shows better results that those based on loft technics. All of these characteristics allows an easy geometric customization that can be done in any 3D CAD software, to be applied in any FE software.

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

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