


# COMPUTATIONAL MODELING OF ADAPTATIVE HIP GUIDE FOR PERIACETABULAR OSTEOTOMY SURGERY

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***Abstract.*** *Arthrosis is a progressive and irreversible condition where there is loss of joint cartilage causing pain and, in some cases, deformity, especially in joints with weight, such as the hip joint. From the social and economic point, the impacts are enormous, since the arthrosis reduces the quality of life of the affected patients and their treatment involves procedures with great cost. In this context, the study of three-dimensional modeling is the key to the development of methodologies to help in the prevention and correction of joint pathologies. In this work, a computational modeling of the adaptive hip guide was developed. First, a guide was created from the 3D (three dimensional) model of the patient's hip bone. Meshmixer specific tools were used and a bone surface negative was created with the shape and dimensions of the guide. This guide has complex and irrgular geometry. To reduce computational cost a new geometry was created in Abaqus for finite element analisys. To simulate the surgeon's eccentric hammering during the periacetabular osteotomy, rotations were imposed on the cutting chisel which generated different stress distributions, with maximum values up to 225,5 MPa and minimum values close to 0 MPa. With the preliminary computational 3D modeling complete, it is be possible to perform finite elements analisys of the surgical procedure and determine the maximun rotation angle of the chisel that the guide supports.*

***Keywords:*** *Periacetabular osteotomy, surgical guide, computational modeling, 3D printing, finite element analysis.*

# 1 INTRODUCTION

Osteoarthritis is a degenerative joint disease resulting from intense or traumatic stress. One of the most affected joints is the hip joint which can be anatomically defined as the junction connecting the pelvis (hip bone) with the femur (thigh bone), allowing the motions of the lower limbs as shown in Figure 1 (Hebert et al., 2016).

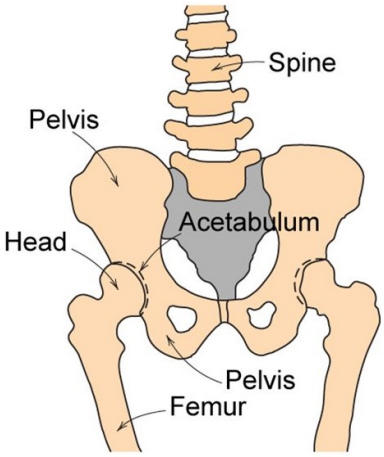



**Figure 1: Schematic diagram of a human hip. Adapted from Callister (2007)**

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In osteoarthritis the wear of the flexible protective tissue between the acetabulum and the femoral head occurs, causing pain and deformity, impairing the locomotion of the individuals. Osteoarthritis has a great social and economic impact since it reduces the quality of life of the individuals affected and its prevention demands procedures with very high cost.

In Brazil, between 2008 and 2015, more than 90,000 total hip arthroplasties were performed by the Unified Health System (SUS), with a cost of R$ 405.166.392,50 (de Castro Ferreira et al., 2017).

For the prevention and correction of the arthrosis, the surgical procedure of periacetabular osteotomy is performed. This procedure is destructive, cutting the pelvis in order to leave the acetabulum free for the correction of the acetabulum-head the femur contact. Surgical chisels penetrate the pelvis in predetermined directions and angles Ganz et al. (1988). Figure 2 shows the surgical planning of the periacetabular osteotomy procedure.

The periacetabular osteotomy is a very difficult procedure. The region of interest contains large amounts of cartilage, muscles and nerves, and the surgeon cuts the pelvis with little precision.

In this scenario, to improve the accuracy of this surgery, it becomes interesting to use a surgical guide that contain the cavities for the insertion of the chisels. The figure 3 shows a conceptual representation of the guide in modeling compound, adapted to a plastic model of the bone, in reduced scale, and markings of planes where penetration of surgical chisels should occur.

The Finite Element Method has been used to analyze stresses from the surgical procedure of periacetabular osteotomy. Zou et al. (2013) developed a finite element model to optimize the

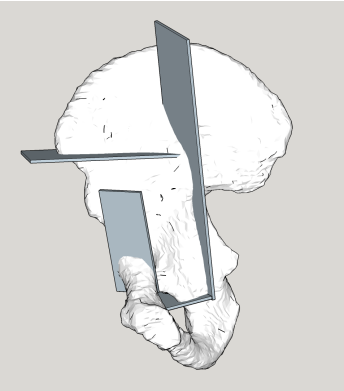


**Figure 2: Three-dimensional representation of surgical planning of periacetabular osteotomy.**



**Figure 3: Conceptual representation of the guide prototype in modeling compound.**

position of acetabular fixation during periacetabular osteotomy surgery. Chegini et al. (2009) determined the distribution of tensions to a hip after correction using this same methodology.

The goal of this work is to propose a 3D computational model of a guide based on the patient's hip bone and perform a finite element analysis of the periacetabular osteotomy surgery in order to evaluate its behavior while the surgeon hammers the chisel through the guide.

## 2 MATERIAL AND METHODS

In computational biomechanics it is possible to generate 3D models of bone structures from various protocols for converting tomographic images to simplified meshes. After applying filters and masks one obtain editable 3D models with which analysis and mechanical projects are developed in order to contribute to the improvement of corrective and preventive procedures.

After the pelvis model was obtained through a protocol well described in previous work (Fabiane G. Silva, 2016), the *Meshmixer* software was used to work with the triangle mesh (.STL) to design the adaptive surgical guide that fits the bone. Surgical chisels with simple rectangular geometry have also been designed to perform guide cuts through boolean subtraction operations.

Finally, the geometric model of the guide was exported to the Finite Element code *Abaqus* for study. However, a preliminary analysis were established where all parameters of the simula-

tion could be well oriented such as assembly, boundary conditions, surface interactions and load application, which included the simplification of the geometry of the parts. These procedures are detailed next.

## 2.1 Design of surgical guide on Meshmixer

*Meshmixer* is a free program of *Autodesk* intended to create 3D objects, working with 3D meshes and manipulating them easily. It contains different tools that allow the generation from simple geometries to the more complex ones.

The mesh of the patient's pelvis was imported into the *Meshmixer* as shown in Figure 4. With the selection tool (paint) the region of interest was highlighted and then smoothed so that its edges had a more anatomical shape. The offset tool was used so that the negative surface of the pelvis was created. This negative gave rise to a preliminary guide shown in Figure 5.



**Figure 4: Triangular mesh (.stl) of the pelvis imported to the Meshmixer.**

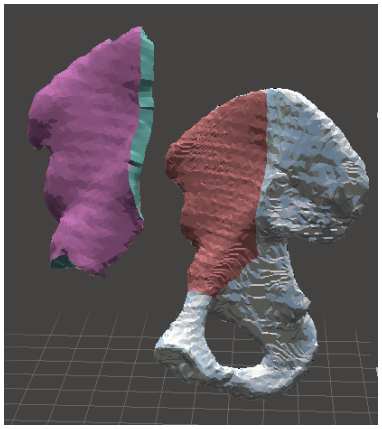
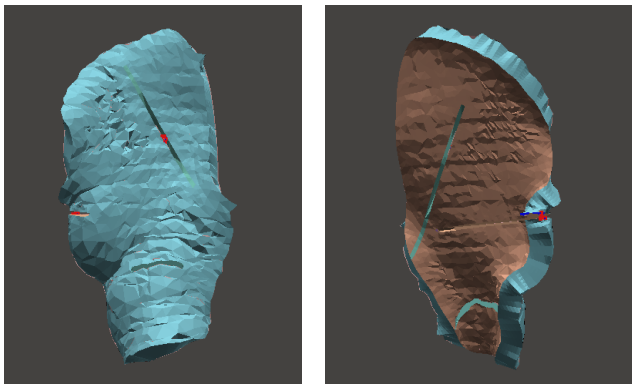


**Figure 5: Region of interest of the selected pelvis and three-dimensional guide model in the *Meshmixer*.**

The designed chisels were positioned at the correct angles and with the boolean subtraction the guideways were generated as shown in Figure 6.

## 2.2 Preliminary finite element model

Surgical guides are intended to help the surgeon to make the cuts and perforations in the correct locations. As the chisel passes through guide cavities, damage to nerves, cartilage and bone parts can be avoided.



(a) Front view of perforated guide. (b) Back view of perforated guide.

**Figure 6: Geometric model of surgical guide generated in the *Meshmixer***

The designed surgical guide has complex and irregular geometry. In order to reduce the computational cost and verify if all stages of the simulation are well elaborated, new geometric parts were created in *Abaqus* itself for a pre-analysis. The simplified model for the guide has a thickness of 10 mm.

For this surgical use, the idea is to have a specific printing protocol in order to obtain 3D printed guide in ABS polymer. In this work, the ABS filament used to print this prototype is from *Ultimaker*. Its properties are shown in the Table 1.

**Table 1: Properties for printed ABS: density, Young's modulus, Poisson's coefficient and tensile stress at break. Adapted from Datasheet Ultimaker 3D and Cantrell et al. (2017)**

| $\rho(kg/mm^3)$ | $E(MPa)$ | $\upsilon$ | $\sigma(MPa)$ |
|---|---|---|---|
| $1,0988^{-6}$ | $1681,5$ | $0,37$ | $33,9$ |

A similar geometry to the guide was constructed to represent the hip bone to be operated. The properties of the hip bone are represented in Table 2.

**Table 2: Properties for hip bone: density, Young's modulus, Poisson's coefficient. Adapted from Dalstra et al. (1993).**

| $\rho(kg/mm^3)$ | $E(MPa)$ | $\upsilon$ |
|---|---|---|
| $3,53^{-4}$ | 24500 | $0,40$ |

Cutting chisels can be made according to the need and type of surgery. The chisels for hip arthroplasties are usually rectangular, with a constant cross section, and made of martensitic stainless steel. Its properties are shown in Table 3.

The chisel geometry was constructed using the Abaqus geometric modeling tools, based on real chisel measurements of one available at the Department of Anatomy of the Federal University of Juiz de Fora. The chisel has 150 mm in length, 19 mm in width and 2 mm in thickness. The cutting tip of the chisel has 1 mm in thickness.

**Table 3: Properties for stainless steel 420: density, Young's modulus, Poisson's coefficient. Adapted from Callister (2007) and AKSteelCorporation (2007).**

| $\rho(kg/mm^3)$ | $E(MPa)$ | $\upsilon$ |
|---|---|---|
| $7,74^{-6}$ | 200000 | $0,28$ |

Screws with a diameter of 4 mm are used for fastening the guide on the hip bone. To model the screws, the *'Tie Constrain'* tool was used to glue previously defined surfaces. Three circumferences were constructed on the rear surface of the guide at the positions of the screws and these were attached to the circumferences constructed on the front surface of the hip bone geometry.

The three parts (chisel, hip bone and guide) received tetrahedral mesh elements, with 3438, 21833 and 17648 elements, respectively. The elements were of the type C3D10: A 10 node quadratic tethaedron. The mesh in the contact regions between the chisel and the guide cavity, between the chisel and the hip bone was refined. Figures 7, 8 and 9 show the finite element meshes of the guide, hip bone and the chisel. The material properties adopted are those indicated in the Tables 1, 2 and 3 for ABS, hip bone and steel, respectively.

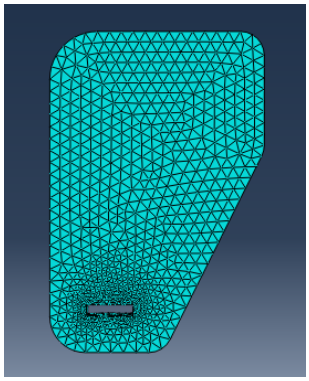


**Figure 7: Finite element mesh of the guide with tetrahedral elements and mesh refinement regions.**

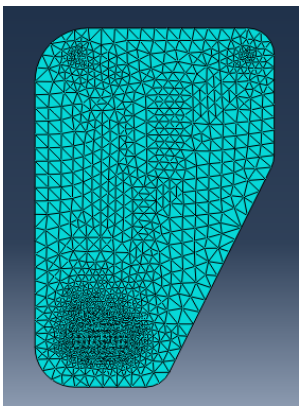


**Figure 8: Finite element mesh of the hip bone with tetrahedral elements and regions of mesh refinement.**

The finite element analysis performed has two steps. In the first step, the bone was fixed in its borders where all the 6 DoF (degrees of freedom) were restricted.The guide was fastened

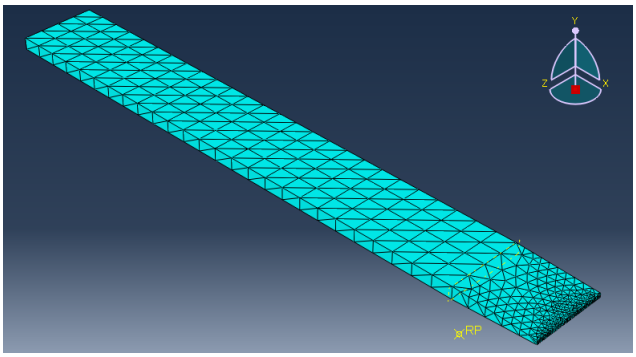



**Figure 9: Finite element mesh of the chisel with tetrahedral elements and regions of mesh refinement.**

to the bone by the three screws. For the chisel, only the displacement in the $Z$-axis was free where a displacement of -10 mm was imposed. This moviment is done by the surgeon to engage the chisel in the guide before the hammering starts. Then, the second step simulates the chisel displacement and rotation in relation to a reference point in the guide. This movement simulated the eccentric penetration of the chisel in the hip bone.

The contact between the chisel and the guide was defined by *'Frictionless contact'*, simulating a low coefficient of friction between the chisel and the guide. The contact with normal behavior was set up as *'Hard contact'* in order to avoid the penetration of one another. The same conditions are used to define the contact between the chisel and the bone.

By preliminary simulation, it was determined that the displacement in the $Z$-axis of -10.012 mm gave a stress of 119 MPa, sufficient to cut a bone. İplikçioğlu and Akça (2002) showed that stresses between 100 MPa and 130 MPa are necessary to fracture the bone. Different rotations were simulated to ascertain the maximum possible rotation angle of the chisel without fracturing the guide.

When the hammer is not perfect, that is, the hammer is eccentric, a displacement of the chisel is generated. For the calculation of the displacement (eccentricity) we used basic trigonometry. The Figure 10 shows the triangle formed by the chisel structure and the imposition of rotation $\theta$. The Equation 1 was used to calculate the displacement (eccentricity) of the chisel.

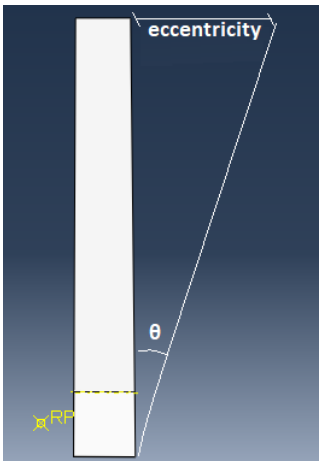



**Figure 10: 2D schematic diagram of the chisel geometry and the $\theta$ angle.**

$$Displacement = \tan(\theta) * 150 \quad (1)$$

# 3 RESULTS

The finite element analysis were done with the commercial code *Abaqus*. In order to simulate the cuts and perforations during the periacetabular osteotomy, rotations were imposed on the cutting chisel which generated different stress distribution in the guide. As 3D printed components in ABS polymer normaly presents brittle behavior (Kurauchi and Ohta, 1984), the *Tresca* stress (maximum shear stress) was compared to its tensile stress (see Table 1). Table 4 presents the *Tresca* stress values for each rotation angle imposed to the chisel and the displacement caused in the chisel by the imposed rotation.

**Table 4: *Tresca* stress values for each rotation angle imposed to the chisel and the displacement caused in the chisel by the imposed rotation.**

| Rotation (degree) | Displacement (mm) | *Tresca* stress (MPa) |
|---|---|---|
| 5 | 13,12297769 | 225,5 |
| 4,5 | 11,80496679 | 180,5 |
| 4 | 10,48876503 | 134,0 |
| 3,5 | 9,174168613 | 85,39 |
| 3 | 7,860974732 | 26,64 |
| 2,5 | 6,548981437 | 11,31 |
| 2 | 5,237987512 | 9,52 |
| 1,5 | 3,927792353 | 7,6 |
| 1 | 2,618195842 | 5,55 |
| 0,5 | 1,308998227 | 3,5 |
| 0 | 0 | 0 |

According to Tab.4, when the surgeon hammers the chisel in a centric way, the resulting stress in the guide is zero, showing good cavity design. Figure 11 shows the increasing behavior of *Tresca* stress as the eccentricity of the hammer is increased. Significant stress variation occurs after 3 degrees of rotation.

The maximum rotation that can be imposed to the chisel during surgery is 3 degrees, that is, an eccentricity of up to 7.86 mm can be applied. Figure 12 shows the *Tresca* stress distribution in the surgical guidewire and also in the screw region. It can be seen that the corner region of the cavity becomes a stress concentrator due to the more intense contact with the surface of the chisel.

For rotations greater than 3 degrees, the maximum stresses occur in the bolted joints. Figure 13 shows the *Tresca* stress distribution for 5 degrees. It can be seen that the maximum stress occured in the guide cavity, and is higher than the ABS tensile strees at break (33,9 MPa). For

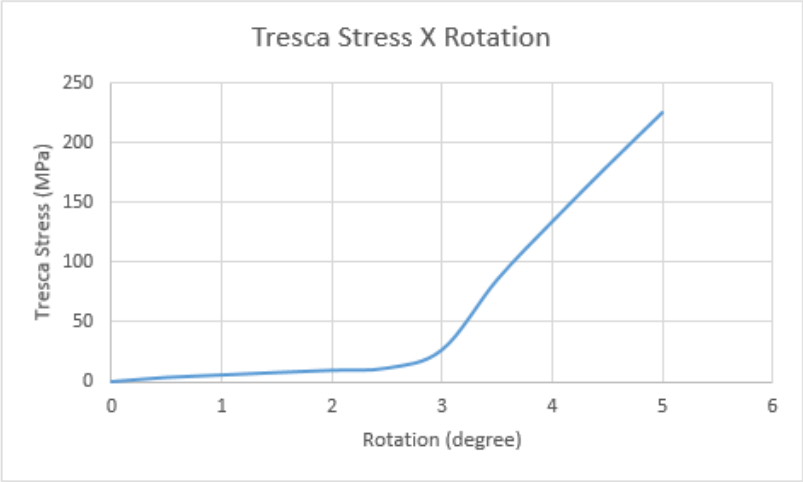



**Figure 11: Behavior of *Tresca* stress according to the different rotations imposed on the chisel.**

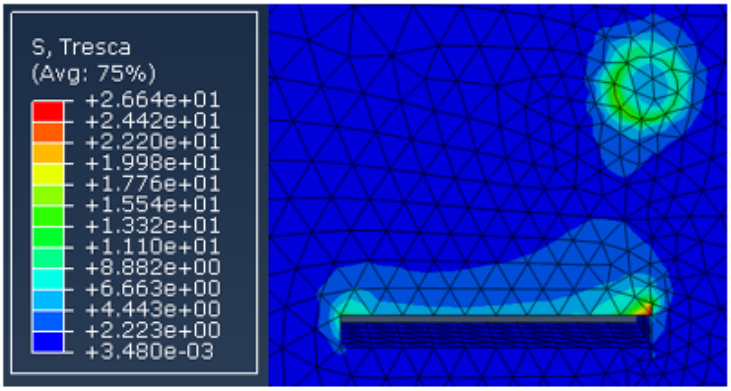



**Figure 12: Distribution of *Tresca* stress for a rotation of 3 degrees.**

the maximum rotation angle simulated for the chisel (5 degrees), the maximun *Tresca* stress in the guide was 225,5 MPa (see Figure 13).

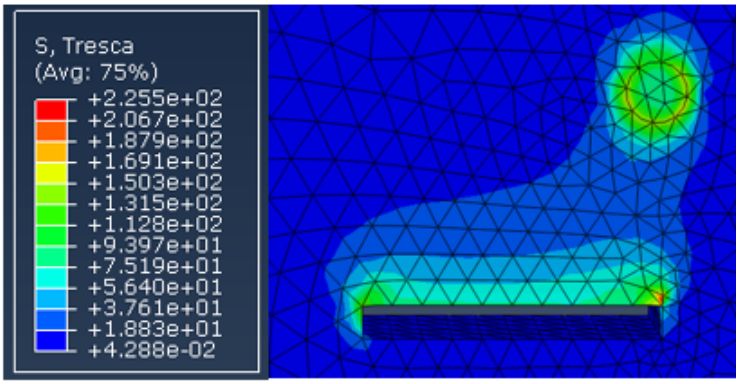



**Figure 13: Distribution of *Tresca* stress for a rotation of 5 degrees.**

# 4 CONCLUSION

According to the results presented, the *Meshmixer* is a powerfull tool for the development of computational models, where the guide was created from the 3D model of the patient's hip bone, with an anatomical shape and adaptable to the hip. The procedure of the intersection of the chisel mesh faces with the pelvic mesh was successful, generating the penetration cavities of the chisel in the positions and angulations ideal for the surgical procedure.

As expected, the higher the eccentricity which the surgeon hammers the chisel, the higher the chisel rotation (imposed to the chisel and transmited to the guide by the contact between them), the higher the *Tresca* stress distribution in the guide.

It was observed that very low rotation angle leads to low contact between the chisel and the guide cavity surface. This behavior can be seen for rotations of 0 degree until 3 degrees, where there was no hard contact between the chisel and the guide.

The maximum rotation applied to the chisel (5 degrees) resulted in *Tresca* stress in the guide up to 225,5 MPa, which corresponds to six times of 3D printed ABS polymer tensile strength. By the finite element analysis performed, the maximum rotation of the chisel acceptable by the guide is 3 degrees, corresponding to a maximum eccentricity of 7,86 mm. For this rotation the generated *Tresca* stress is lower than the tensile stress at break of the printed ABS.

The guide 3D printed ABS guide showed to be efficient in its function to guide the chisel during the periacetabular osteotomy surgery, allowing the surgeon to perform his task more safely and precise.

For future works, it is needed to simulate the computational model of the guide with the complex and irregular geometry generated by *Meshmixer*.

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