XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Preliminary model for evaluation of surgical guide in the periacetabular osteotomy procedure through finite element evaluation, optimization in Genetic Algorithms and topological optimization

Gustavo S. de O. Marques[1], Marcus V. de S. Ferraz[2], Flávia de S. Bastos[3], Bruno G. S. e Souza[4]

[1]*Departamento de Engenharia de Produção e Mecânica, Universidade Federal de Juiz de Fora*
Campus UFJF - Faculdade de Engenharia - Sala 4268, 36100-040, Juiz de Fora - MG, Brazil
gustavomarques.sdo@gmail.com
[2]*Departamento de computacao e mecânica, Centro Federal de Educação Tecnológica de Minas Gerais*
R. José Péres, 558 - Centro, 36700-000, Leopoldina - MG, Brazil
marcusferraz@cefetmg.br
[3]*Programa de Pós-Graduação em Modelagem Computacional, Universidade Federal de Juiz de Fora*
Campus Universitario - Bairro: Martelos, 36036-330, Juiz de Fora, Brazil
flavia.bastos@ufjf.edu.br
[4]*Programa de Pós-Graduação em Saúde Coletiva, Universidade Federal de Juiz de Fora*
Av. Eugenio do Nascimento s/n° - Bairro: Dom Bosco, 36038-330, Juiz de Fora, Brazil
bruno.schroder@medicina.ufjf.br

Abstract. It consists of a preliminary model to evaluate the surgical guide, a tool used in the periacetabular osteotomy procedure, a highly complex surgery used in the correction of hip dysplasia. A code ("script") capable of generating static, simplified and two-dimensional models in finite elements in the software "ABAQUS", optimizing parameters using Genetic Algorithms and performing topological optimization, was developed to evaluate the guide. The parameters evaluated in the Genetic Algorithm are height of the guide, radius of the screw used to fix the guide in the bone, distance of the screw in relation to the chisel, clearance between guide and chisel, and inclination of the chisel. The topological optimization consists in changing the modulus of elasticity in regions that present the lowest stress values. Through the results obtained, it was possible to minimize the maximum stress in the guide, obtain better theoretical parameters for the procedure, and obtain a guide that fits better to the bone. The results obtained through this preliminary study are good indications for the construction of an optimal guide of great utility in the surgical procedure, in addition to serving as a basis for more complex studies.

Keywords: Surgical guide, Periacetabular osteotomy, Finite Element Method, Genetic Algorithm, Topological optimization

1 Introduction

The present work is a continuation of the work of Marques et al. [1], which consists in creating a script to generate a finite element model and apply a Genetic Algorithm as a preliminary assessment of a surgical guide used in the periacetabular osteotomy procedure. This work proposes the implementation of a structural optimization in addition to what was previously applied (Marques [2]).

According to Dezateux and Rosendahl [3], osteoarthritis is a degenerative disease that affects synovial joints and promotes fibrillation zones and cracking in the articular cartilages. Studies indicate that there is a direct relationship between dysplasia with osteoarthritis, so that hip dysplasia promotes osteoarthritis of the hip.

Ganz [4] proposed the Bernese-Ganz periacetabular osteotomy, a surgical procedure of high complexity performed in order to correct hip dysplasia and prevent osteoarthritis. It is performed by making cuts in the bone that target a better contact between the acetabulum and femur, by releasing the acetabulum and allowing the correction of its angulation and position. After correction, screws are fixed to the acetabulum in order to maintain stability, restore hip anatomy and relieve the patient from pain (Ferreira [5]).

In order to help the orthopedist in the periacetabular osteotomy procedure, a surgical guide that contains the regions to perform the cuts in the bone, was developed by Souza [6] (Souza and Bastos [7]). The guide is specific for each procedure and patient, is composed of ABS polymeric material, made from tomography images through the additive manufacturing process (3D printing), and it is fixed to the bone with screws.

The Finite Element Method (FEM), is a mathematical model capable of reaching approximate solutions to problems by subdividing the problem regions into simpler geometries. These subdivisions, called finite elements, are connected by points called nodes, or nodal points and the set of nodes and elements form the mesh of finite elements, which can be two-dimensional or three-dimensional and can assume different shapes.

Genetic Algorithms are parameter optimization algorithms based on the principles of natural selection and natural genetics. They are mainly inspired by the evolutionary theory of Charles Darwin, who believes that the fittest has greater chances of survival and greater probability to transmit its information (genetic material) to the following generations, perpetuating similar characteristics.

According to ARORA [8], the Genetic Algorithm consists in generating a random initial population (first generation), which is done only once, evaluate the adaptability of each individual through the fitness function, select the fittest individuals, submit them to the crossover to generate a new population, and perform the mutation. The cycle is performed until it reaches a pre-established number of generations, or verify a convergence in the results (Garcia [9]).

The topological optimization, or structural optimization, is a type of optimization that consists of removing unnecessary material, without compromising its function and integrity. In a recent work, Liang and Xia [10] proposed a method that consists in change the modulus of elasticity (Young modulus) of the element to a very small value, which solves the mesh-related problem in methods that consists in removing the elements.

The maximum value of Von Mises Stress of the part mesh (σ^{vm}_{max}) is used to determine if the Young modulus of the element will change. To change the value, is compared the maximum stress to the stress value element (σ^{vm}_{e}) multiplied by the removal ratio (c_{rr}), according to the eq. 1. To return to normal, is compared the maximum stress to the stress value of an adjacent element ($\tilde{\sigma}^{vm}_{e}$) multiplied by the inclusion ratio (c_{ir}), according to the eq. 2.

$$\sigma^{vm}_{e} < c_{rr} \cdot \sigma^{vm}_{max} \rightarrow \text{element removal} \tag{1}$$

$$\tilde{\sigma}^{vm}_{e} > c_{ir} \cdot \sigma^{vm}_{max} \rightarrow \text{element addition} \tag{2}$$

2 Methodology

The finite element model is a simplified bi-dimensional and static representation of the periacetabular osteotomy procedure, containing the cutting chisel (tool used to cut the bone), hip bone, surgical guide and screw used to fix the guide in the bone, and was developed in the software *ABAQUS*. To simulate the screws, the regions of bone and guide were tied. The boundary conditions are to fix the bone, and for the contact between the parts.

The material properties attributed to the cutting chisel are specified by Steel [11] and Askeland and Phulé [12], for the hip bone are those specified by Dalstra et al. [13], and Íplikçioglu and Akça [14], and for the surgical guide are specified by Silva [15]. The model Young modulus (E), Poisson's coefficient (υ), maximum Von Mises stress to fracture (σ_{lim}), and others parameters are in Table 1, the assembly is in and Fig. 1.

Table 1. Finite element model parameters

Part	Lenght/Diameter (mm)	Height (mm)	E (*MPa*)	υ	σ_{lim} (*MPa*)
Chisel	150	19.0	200000	0.28	-
Bone	69	10	24500	0.40	$100 \leq \sigma \leq 130$
Guide	50	10	1681.5	0.37	30
Screw	4	-	-	-	-

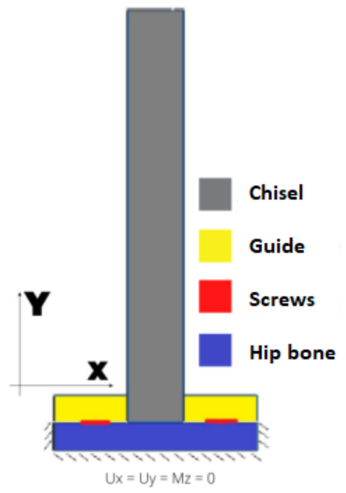

Figure 1. Finite element model

The model consists of applying force distributed at the tip of the chisel, in order to generate stress in the guide. The force is obtained by evaluating the stress to fracture the bone, and the chisel tip region is equivalent to the contact area of the surgical hammer used in the procedure.

The mesh convergence method consists in verifying the vertical displacement in a specific node in each part by reducing the space between each node by 10% per iteration, if the percentage difference is bellow 1% after two iterations, the mesh converges. After the convergence, the chisel has 217 nodes and 360 elements; the bone has 216 nodes and 350 elements; and the guide has 252 nodes and 408 elements.

The script was designed in Python using the commands present in SIMULIA [16] to generate the finite element model, and allow it's parameterization, to run in the software *ABAQUS*. In the same script, will be implemented an parameter optimization based in the Genetic Algorithm theory, and a topological optimization.

In the Genetic Algorithm, the genes (parameters) are binary numbers, the output is the maximum Von Mises stress in the guide elements, and the fitness individuals have a small output value. The parent selection method is tournament with a single-point method crossover, the probability of the occurrence of mutation is 10%, and the elitism is not applied. The number of generations is 25 which 20 individuals each. All these concepts are well presented in ARORA [8].

There genes are, the guide height (gene 0), radius of the screw used to fix the guide in the bone (gene 1), distance of the screw in relation to the chisel (gene 2), clearance between guide and chisel (gene 3), and inclination of the chisel (gene 4). The gene 0 intends to develop a smaller guide; the genes 1 and 2 were selected in order to verify a better positioning and type of screw; the gene 3 is to verify if it is better a larger cavity; the gene 4 is to verify the effect of an inclination, that implies a cut in the guide to adjust to the inclination. The genes precision, and minimum and maximum value are in Table 2.

Table 2. Genes parameters

Gene	Description	Min. value	Max. value	Precision
0	Guide height	6.0	12.0	0.2
1	Screw radius	1.0	3.0	0.2
2	Screw distance	-2.0	2.0	0.5
3	Guide clearance	0.0	0.25	0.05
4	Chisel inclination	0.0	1.2	0.2

The topological optimization removal ratio and increment ratio for the elements are respectively 0.05 and 0.8, the young modulus factor are 0.001, and there are five iterations. It is applied when the Genetic Algorithm finishes and it selects the individual with highest fitness in the last generation. Only the surgical guide is affected by the optimization.

3 Results

In the Table 3, is compared the individual with the lowest value of fitness in the first generation, and the individual with the highest fitness value in the last generation.

Table 3. Genetic Algorithm results

Case	Gene 0	Gene 1	Gene 2	Gene 3	Gene 4	Max. stress
Worst	9.48	1.0	-0.86	0.25	1.2	33.717
Best	8.71	3.0	0.29	0.04	0.0	17.17

After five iterations of topological optimization in the best model, 32 elements Young modulus changed, and the maximum Von Mises stress percentage difference was 0,21%. The elements changed are in the Fig. 2.

Figure 2. Topological optimization results

4 Conclusion

After the parameter optimization, the maximum Von Mises stress reduced 49%, and was indicated the optimal parameters of height of the guide, radius of the screw, distance between screw and chisel, gap between chisel and guide, and inclination of the chisel.

For the topological optimization results, it was possible to generate a guide that takes up less space, which helps a lot the orthopedist, and which a percentage difference of 0.21% in the maximum Von Mises stress.

These results from this preliminary study are a good indication that the guide resists the efforts, and it is a good example of how you can unite various concepts and methodologies and apply them to solve problems in the most diverse areas of knowledge.

For future works, the pretense is to generate a more complex finite element model, three-dimensional and which more sophisticated geometries, and evaluate other parameters in the Genetic Algorithm.

Acknowledgements. The authors would like to thank the Universidade Federal de Juiz de Fora for granting scientific initiation grants that enabled the development of this work and the continuity of this study.

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