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Methodology based on Genetic Algorithms and Finite Elements to obtain the 3D Surgical Planning for the Periacetabular Osteotomy procedure in treatment of hip dysplasia

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Abstract. Developmental dysplasia of the hip is characterized by a condition of joint instability in which the head femoral artery presents an abnormal relationship with the acetabulum, which may be accompanied or not a partial (subluxation) or complete dislocation (dislocation) of the femoral head. The treatment of hip dysplasia in adults aims to prolong the longevity of the joint by performing the periacetabular osteotomy. In patients without early diagnosis and treatment and in treated young adults inappropriately or incorrectly, surgical interventions such as osteotomies are performed to prevent coxarthrosis and other pathologies that can develop secondary to dysplasia. Periacetabular osteotomy aims to change the biomechanics pathological condition of the hip, causing a reorientation of the acetabulum and consequent improvement of joint stability. In view of the complexity presented, both by the curve of learning and the performance of the surgical procedure, it is interesting to use of tools and computational models in order to assist the surgeon in his achievement and, consequently, in the improvement of results. The present work seeks study the application of a genetic algorithm in conjunction with simulations via the method of finite elements using the ABAQUS®software, in a geometric model obtained through of a computed tomography in a real patient, aiming to optimize the surgical planning based on maximizing the resulting force obtained as a function of contact pressures and contact area in the acetabular cartilage. A comparison is made with the results obtained from the surgical planning developed according to radiographic parameters, from which it is verified that the proposed methodology results in an optimal configuration for the fragment, which translates into improved joint stability. The values of rotation angles in the x, y and z directions are shown.

Keywords: Developmental dysplasia of the hip; Periacetabular Osteotomy; Abaqus®; Optimization; Genetic Algorithm.

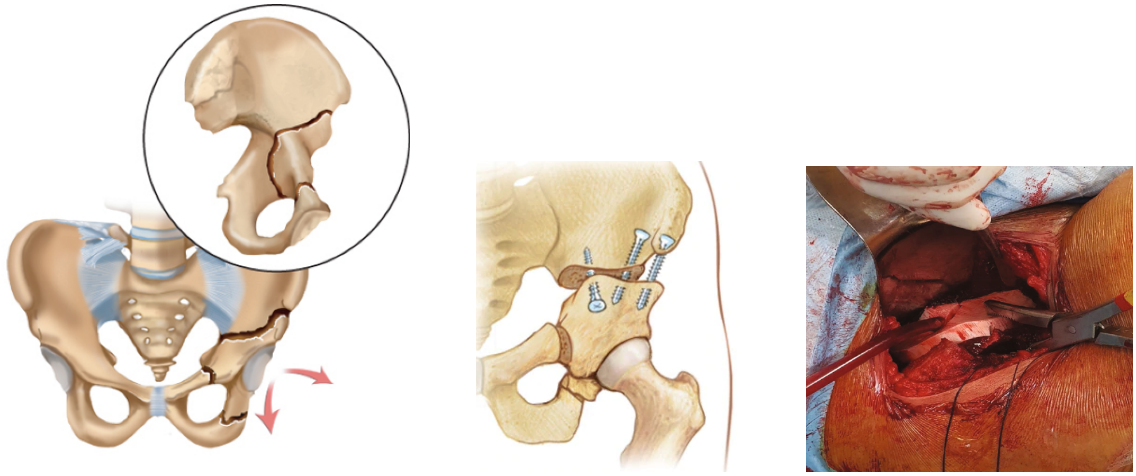
1 Introduction

Pathological deformities of the hip leading to mechanical failure in the joints constitute a large portion of the challenges being studied in the field of orthopedics. Oftentimes, these morphological, congenital or acquired alterations cause physical limitations, discomfort and intense pain to the affected patient. However, if identified and treated previously, such problems can be reversed, improving the quality of life of these patients [1, 2].

Developmental dysplasia of the hip is considered the most common cause of osteoarthritis of the hip [3], and is characterized by loss of lateral and anterior coverage of the femoral head by the acetabulum, which increases the contact pressure on the joint while performing usual activities [4].

The treatment of hip dysplasia in adults aims to prolong joint longevity by performing a periacetabular osteotomy. Diagnosis, when performed early, can be relatively simple, safe and promote generally effective treatment [5]. Early treatment provides levels of approximately 96% good results [6]. However, late diagnosis and lack of immediate intervention can lead to early osteoarthritis in the young adult [7, 8]. Half of the cases of DDH diagnosed and treated late will show some degree of degeneration of the hip joint between 16 and 31 years [9]. The DDQ is, therefore, a factor established risk for early coxarthrosis (before 50 years of age) [10].

Periacetabular osteotomy (OPA) aims to restore the alignment of the hip joint, and consequently the normal relationship between the femoral head and the acetabulum (increasing the coverage of the first and distributing the contact pressure on the cartilage surface), resulting in an improvement in gait, in addition to a reduction in pain. It is called a preservative because, unlike the ATQ, there is no replacement of the joint by any prosthetic component [4, 11, 12].



(a) Location of pelvic osteotomies by chisels [opa].

(b) Screws fix the hip joint after repositioning [pao].

(c) Execution of Periacetabular Osteotomy in a Patient with DDH, with the aid of prototyped guides [15].

Figure 1. Periacetabular Osteotomy.

In this procedure (considered destructive), the cuts in the pelvis, as shown in Fig. 1 (a), are performed with the aid of surgical chisels in order to leave the acetabulum free for correction and smoothing of the contact between the femoral head and the acetabular fragment. The cuts penetrate the pelvis in the established directions and angulations by Ganz et al. [16] and the repositioning of the acetabulum occurs according to parameters clinical trials, in an attempt to restore the anatomy and, mainly, the normal function of the hip movement. The fragment is fixed by screws (Fig. 1 (b)) and the bone consolidation [17].

The OPA is widely recognized for its technical complexity (Fig. 1 (c)), as the region of interest is difficult to access, containing a large amount of cartilage, and nerves, which can cause potential complications [18–20]. It must be considered that, in Brazil, due to the small number of surgeons orthopedists who perform OPA regularly, there is extreme difficulty in accessing of patients to the required treatment [15]. The few professionals in the market who master these techniques come making every effort to create specific instruments and methodologies and protocols systems that support and facilitate the training and proficiency of new specialists [21, 22].

Computer-assisted surgical planning has been shown to be an effective tool in performing periacetabular osteotomy, ensuring greater surgical accuracy and precision [23]. Numerous researchers in the field have applied finite element analysis tools for biomechanical validation of surgical planning, in order to verify the best position of the acetabular fragment according to the variation of clinical and anatomical parameters [4, 11, 12, 24].

Surgical planning based on the Finite Element Method (FEM) modifies the paradigm of surgical planning for orthopedic patients as it aims not only to surgical correction based on radiographic parameters, as shown in recent studies [15], but by focusing decision-making on biomechanical variables (pressure of contact, area of contact, tensions and deformations in the cartilage, damage and wear of the cartilage), correlated with a higher probability of good clinical and increased longevity of operated joints. The optimization process based on genetic algorithms has been successfully used in other areas of knowledge, but with few applications identified so far in the area of orthopedic surgery, among which there were no studies related to periacetabular osteotomy [25–28].

The genetic algorithm consists of an evolutionary algorithm that is based on techniques based on Darwin's evolutionary theory, adopting concepts such as mutation, heredity, natural selection and crossing-over. According to this theory, beings undergo mutations over the course of their generations, so that the fittest, considered the best, outlive the others. Inspired by these concepts of the evolutionary process, by adapting them to other problems, we can achieve an efficient scan in search spaces, with the objective of achieving results closer to the best possible solution [29].

Escaping the manual scope of optimization, and considering that there were no studies related to the implementation of genetic algorithms in the optimization of variables necessary in the surgical planning of hip-sparing surgeries, it is interesting to study this approach in order to help the surgeon in the preoperative decisions of periacetabular osteotomy surgery, in order to find the best scenario that presents the optimal configuration for the acetabular fragment (in terms of x, y and z rotation angles) that guarantees joint stability, as well as contact and area pressures satisfactory contact information in the interface.

This paper seeks a possible approach aimed at optimizing the angular orientation of the acetabulum, adopted by the surgeon when performing the surgery, through the application of a Genetic Algorithm in conjunction with simulations using the ABAQUS®finite element software, based on maximizing force. resultant contact area in the contact area of the acetabular cartilage (as a function of the contact pressure exerted and the contact area) of a computational geometric model obtained through computed tomography of a real patient in the preoperative period.

The objective is also to compare the results found with those obtained in a study carried out considering the same case [15], in which the surgical planning was developed based on medical experience and on radiographic parameters of the hip via the literature.

2 Materials and Methods

Details of computational modeling and implementation are presented in this section. To assess the applicability of the genetic algorithm (GA) coupled to finite element simulations via ABAQUS®, for surgical planning of the pericatabular osteotomy, a case study was considered, described in the following subsections. This way, it was necessary to develop and execute several procedures, divided into steps according to the flowchart represented in Fig. 2.

2.1 Construction of the Geometric Model

When using computational tools in the surgical planning of periacetabular osteotomy, the surgeon can come to work with geometric models based on the anatomy of the patient's hip. One way to obtain this model is through a computed tomography of the pelvis and femur, which, with the help of the InVesalius 3.0 software, can be converted into a format usable in three-dimensional modeling programs such as CAD (Computer-assisted design).

The geometric model used in the present work was obtained from a recent study [15], where a female patient (28 years old, dentist, white, Brazilian) came to the consultation reporting right inguinal pain for a year. and trochanteric discomfort over prolonged periods and was evaluated and diagnosed with right hip dysplasia.

The resulting computed tomography images were imported into the InVersalius 3.0 software in DICOM electronic format (Digital Imaging and Communications in Medicine) and converted to STL format. However, when generating the faceted image that simulates the original object, the Inversalius software ends up for generating files that have an extremely large number of points, which makes it necessary to treat and smooth the mesh, which specifically in this work, took place through the Meshmixer software. The final step in the construction of the geometric model consisted of preserving the refined features of only the areas of interest for the simulation, eliminating and simplifying considerably the remaining areas of the objects, in order to make the simulation less computationally expensive.

2.2 Computational Modeling via ABAQUS®

At this stage, we seek to adapt the geometric model built to carry out a simulation using finite elements in the ABAQUS®software. In this way, it will be possible to assess the impact that the reorientation of the acetabular fragment generates on the contact between the acetabular cavity and the femoral head when analyzing quantities such as pressure and contact area.

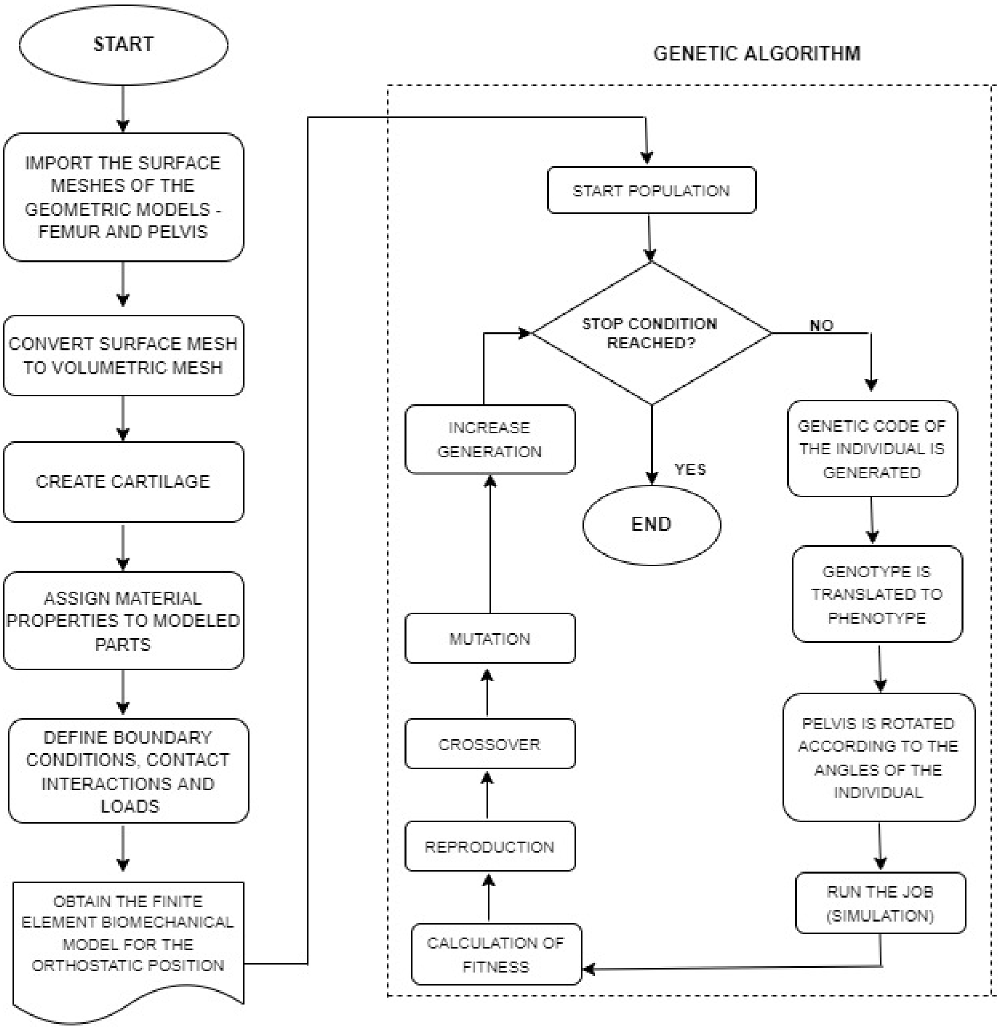


Figure 2. Flowchart of procedures performed

Adaptation of the characteristics of the geometric model when importing to the ABAQUS®

The images obtained in the format (.stl) consist of surface meshes, and to assign characteristics to the materials it is necessary to modify the surface mesh to a volumetric mesh (solid model). This procedure is carried out using tools in the ABAQUS®software. Then, three-dimensional models that define the geometry of the femur and pelvis are obtained.

In the free space between the acetabulum and the femoral head of the models, a 0.5 mm thick pelvic cartilage was created (Fig. 3 (a)), sufficient to fill the soft tissue region, since the DICOM image conversion was not able to capture the real cartilage of the patient's hip. This is considered a limitation of the model, as it reveals that the image segmentation step was not sufficiently precise, generating little space for cartilage construction.

With the intention of avoiding unwanted penetrations during the optimization when rotating the pelvis, in addition to creating cartilage via offset, a small negative displacement of the femur object in the X and Z axes was performed, in the opposite direction to the displacement that will be imposed in the simulation.

A reference point was created at the centroid coordinates of the femoral head. The position of each coordinate was calculated using tools native to ABAQUS based on the object's own mass properties, resulting in by 105.75 mm on the X axis, -208.02 mm on the Y axis and 161.74 mm on the Z axis.

Material Properties

The properties of each material were defined according to Lippert [30] and Zou et al. [11]. It is worth mentioning that the materials referring to the femur, the pelvis and its cartilage were defined as homogeneous - having the same properties throughout its extension, isotropic - with egalitarian properties in all directions and with linearly elastic behavior, so that its deformation varies in a different way. linear to the applied voltage. For the bones of the femur and pelvis, Modulus of Elasticity (E) = 17 GPA and Poisson's ratio (ν) = 0.3 were adopted.

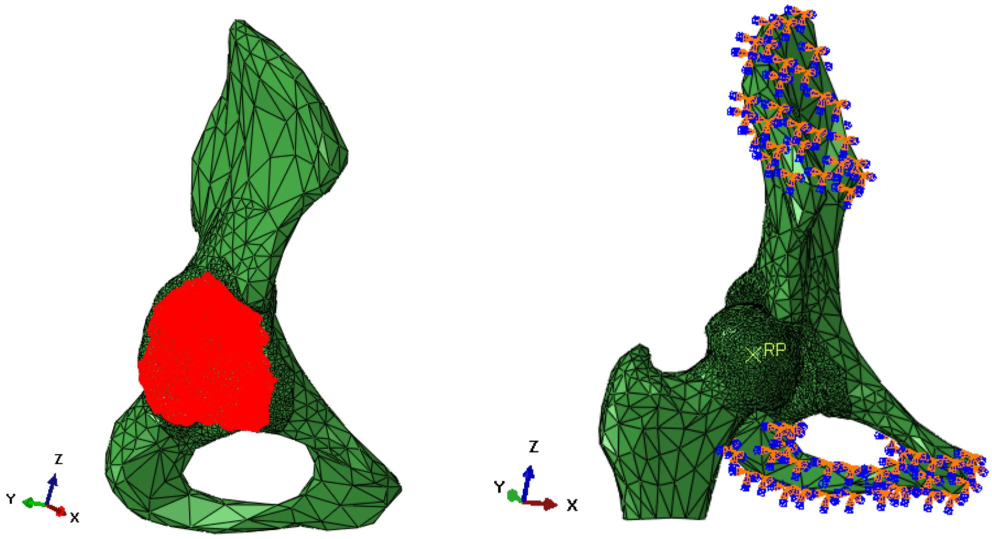
For cartilage, E = 15 GPa and ν = 0.45 were assumed.

Contact Surfaces and Interactions

Two surfaces were defined for the total model, one representing the femoral head and another related to the cartilage generated by the offset in the acetabular cavity. OK emphasize that the surfaces were determined through manual selection, with emphasis on for the cartilage, where the unitary selection of each point of interest present was performed. The determination of the contact itself was formulated based on the option surface to surface, with the surface of the femoral head assigned as the master and that of the cartilage as an apprentice (slave). Such attribution avoids the overlapping of the parties involved when performing the simulation, as if one surface were able to see the other. Properties were defined for the interactions that allowed them to simulate a low coefficient of friction between their parts in terms of local tangential directions (frictionless) and to consider only the resistance in relation to normal penetration. (hard contact).

Boundary Conditions (BCs) and restrictions

The pelvis model was set in the regions that fix the local model to the rest of the body, that is, in the osteotomies planes, as seen in Fig. 3 (b). As for the model of the femur, the nodes belonging to the surface of its head were coupled to the point referring to the centroid of the same, previously defined, through a kinematic coupling constraint. This way the femur will move together with the reference point, whose movement has been constrained in the Y-axis direction and maintained free in the X and Z axes. For the movement of the femur itself, a displacement of 1.1 mm was stipulated in the X direction and 3.3 mm in the Z direction. According to constraint reference to coupling kinematic of the same in relation to the centroid, the imposition of the movement was made in the reference point.



(a) Offset of the inner surface of the acetabulum for cartilage creation

(b) Boundary conditions and restrictions applied to the pelvis and femur.

Figure 3. Model.

Steps

A step called "Contact" was created with the purpose of performing the analysis of the problem for a period of 1 s. A maximum number of increments equal to to 100 with initial size of 0.1 s, with subsequent increase defined automatically. Due to the geometrically nonlinear characteristic of every contact problem, the option of geometric nonlinearity has been activated. As in previous works [11] the simulations were performed considering the orthostatic position of the hip joint, where the individual is standing.

2.3 Implementation of Genetic Algorithm

The algorithm was developed using the Python programming language, which facilitated its integration with the ABAQUS®software. Establishing a parallel with the concept of optimization, the characteristics of the problem presented and the simulation of interest, we sought to carry out a series of analytical tests that corresponded to the contact established between the femoral head and the patient's acetabulum, under different angulations. It is then necessary to use some strategy that makes it possible to intelligently choose these angles, aiming to get better results.

The optimization strategy followed by the AG will take into account previous results. res in order to promote an "evolution" of subsequent results. You must then adapt the that will determine an individual present in the population, which will influence the populations of future generations. To represent an individual, a class called "Individual" was implemented. Such a class will have as main fields:

- A *index* attribute taking a numeric value, which will act as a shape identification of the individual before others. (Ex: Individual 3 has the same index to 3);
- Three attributes (x angle, y angle, z angle) responsible for storing the values of angles at which the acetabulum will be rotated;
- A *fitness value* attribute to store the individual's fitness value.

Considering that the main objective of performing the periacetabular osteotomy is to reduce the patient's pain in the hip region when moving, the interest is to analyze the quantities referring to contact pressure and contact area resulting from the simulation in finite elements. .

Something that was observed when performing tests involving the GA for the problem was that, when we rotated the pelvis at different angulations, the simulation was affected in the following ways:

- The simulation ran in its entirety, returning success;
- The simulation returned successfully, but the contact between the femur and the acetabulum did not occur;
- The simulation did not run in its entirety and returned an error.

Such points presented themselves as a challenge in determining the way of evaluating the results, since individuals with simulations that returned error could negatively influence the performance of the genetic, in the possibility of favoring an individual based on a "false" result, and individuals who returned successfully but did not establish contact were more numerous than those who did.

The strategy adopted was based on causing a displacement in the femur that would most likely cause an error in the simulation, but would allow contact and analysis of the results obtained up to the point at which the simulation was aborted. In order for this analysis to be fair and not to favor an individual who continued further in his simulation, or even completed it, given the extreme difficulty of predicting which angulations would result in error or success in the simulation, we chose to normalize the point of analysis of the simulations obtained.

The results of the simulations in ABAQUS®are divided into increments, which makes it possible to verify their values during the simulation. Thus, the increment in which the maximum contact pressure in the acetabulum reached a limiting value was verified, in order to perform the analysis of the results only in the increment in question. The limiting value was adopted based on preliminary studies [31] , verifying that the value of 13.5 MPa was consistent with valid individuals.

In the analysis itself, it was decided to relate the two quantities as follows when determining the objective function to be maximized:

$$F_i = p_i * a_i \tag{1}$$

where,

- i the first increment of the simulation to reach or exceed the limiting value adopted (13.5 MPa);
- F_i the resultant force obtained based on the contact pressures and the contact area at all points of the acetabulum in the increment i;
- p_i the average contact pressures at each point on the acetabulum surface in the increment i;
- a_i the sum of the contact areas at each point on the acetabulum surface in the increment i.

The optimization aimed to identify the individual with the highest value in the calculation of F. Following the reasoning of the calculation of Eq. 1, we have that the individual considers better off would be the one who needed to exert greater force to reach to the limiting value, since a good contact is obtained by the load that meets with greater distribution. As a result, individuals who were unable to reach the limiting would be considered unsuitable for solution and disregarded. Then the optimization revolved around identifying the individual with the highest value in the calculation of F. The implementation of the techniques used was strongly based on Arora's (2019) reasoning. The initialization of the first population was done randomly, with the help of from the random library, having individuals having genetic material represented by binary encoding. Thus, another 3 attributes of the "Individual" class were necessary in order to store the content of the genes for use in genetic procedures, such as mutations and recombinations. The final scope of the class is in Fig. 4.

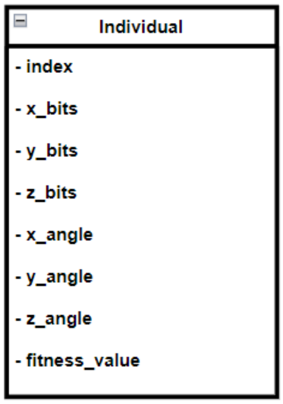


Figure 4. Individual class representing the individual of each population and its attributes

Together with the orthopedic surgeon responsible for the surgery of the patient whose computer model was based, the angulation limits in the x, y and z planes were obtained Tab. 1.

Table 1. Intervals to be adopted by the angles of each individual generated.

Axis	Inferior Limit	Superior Limit
x	0	20
y	-35	0
z	0	15

A summary of the strategies adopted can be found in Tab. 2.

Table 2. Parameters used in the Genetic Algorithm.

Parameter	Value/Description
Genotype Encoding	Binary (Bit String)
Probability of recombination	100%
Chance of mutation occurring	30%
Parent Selection	Tournament
Formation of the new population	Parental (Elitism)
Individuals by population	20
Number of generations	22

3 Results and Discussion

Following the parameters in Tab. (2), the performed attempt was completed in an average time of 39.5 hours, performing 460 simulations. The Tables (3) and (4) present the results obtained by the trial, in comparison with the model without undergoing any rotation and the model whose pelvis was rotated based on the angles used in the planning via medical experience:

When analyzing the results of the 3 table, it is noticeable that the values of X and Z had a considerable approximation regarding the angles used in planning via medical experience, showing a percentage difference in absolute values of 13.6% and 18.96%, respectively, in relation to the latter. it is verified, however, that for angle Y, the percentage difference is 42%. It appears that, although the objective function result is better for the model configuration via AG (as can be seen in Tab. 4), the Y angle would reflect in a better scenario if the modeling not only considered the orthostatic position of the patient, but also the angular amplitudes of flexion.

Table 3. Comparação entre os ângulos do planejamento e dos resultados pelo AG (em graus)

Model	X angle	Y angle	Z angle
No rotation (dysplastic hip)	0	0	0
Surgical planning (radiographic parameters)	14.88	8.93	-28.38
AG Parental replacement	12.31	5.18	-33.76

In this context, even with computational optimization, it is essential that the results are evaluated by the responsible surgeon, being interesting, in these cases, to offer not only the best result obtained, but a range of possible angles that result in a good area of contact between the surfaces.

The table 4 contains the values assumed by the function used and its variables for each case. When using AG with parental replacement, the results were satisfactory according to the objective function adopted. As expected, the model whose pelvis did not undergo any rotation (which translates into the dysplastic hip model) presents the worst result with respect to the F value. The model that used the angles based on the planning by the orthopedist indicates an improvement when compared to the fitness value obtained by the original position of the pelvis, which demonstrates the ability of the chosen function to indicate considerable improvements in the contact area regarding the reorientation of the acetabulum.

In the column referring to the values of p, the considerably small value obtained by the models is noticeable. This was due to the fact that the average of the contact pressures was calculated taking into account all points on the surface, so that not all points were subjected to a pressure, having a null result. This resulted in an extremely small average due to the number of points on the surface. This feature, however, did not impact, in practice, the calculation of the F value, since all individuals had the same number of points on the surface in question. Consequently, this also did not impact the calculation, and subsequent comparison, of the fitness value between individuals.

Table 4. Comparison of the values obtained in the Eq. 1 with the results by the AG

Model	p (contact pressure)	a (contact area)	F (force contact)
No rotation (dysplastic hip)	0.049693008395	19.3174531162	0.959942359873
Surgical Planning	0.127345098832	29.6218593121	3.77219860169
AG Parental replacement	0.163768445583	49.1064937413	8.04209414805

4 Conclusions

Through the analysis of the numerical values obtained by the analyzed biomechanical quantities, and their visualization in the graphical interface of ABAQUS, it is concluded that an optimization of the surgical planning of the surgery, combining the use of AG with simulations using the FEM, besides being possible, it allows a feedback as to the biomechanical quality that the change in the reorientation of the acetabular fragment will cause for the patient who will be submitted to the procedure.

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