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A CAD-CAE MODELLING OF THE BIOMECHANICS OF THE BIPLANAR MEDIAL OPENING WEDGE HIGH TIBIAL OSTEOTOMY

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Abstract: Biplanar Medial Opening wedge high tibial osteotomy (BMOWHTO) is a surgical procedure often used to eliminate the effects of knee osteoarthritis. The geometric planning of this operation is a very important step for the success of the intervention and rapid postoperative recovery. In this article the optimization of ones of the geometric parameters which characterize this geometric planning have approached. The research methods used are: computer-aided design (CAD) for 3D modelling of the tibia, the CAE method for performing numerical analyses and Taguchi method for analysis of the results. The results obtained can be a good guide for orthopaedic doctors.

Key words: *Biplanar Medial Opening Wedge High Tibial Osteotomy; Correction Angle; Osteotomy cutting point; Angle between OWHTO Planes; FEM analysis; CORA point*

1. INTRODUCTION

Knee osteoarthritis (hereinafter KOA) is unfortunately an increasingly common disease in both men and women, especially after the age of 40 [1], [2]. The diseases appear due to the wearing of the articular cartilage in the medial compartment of the knee, effect causing pain and from a biomechanical point of view an axial deviation of the entire lower limb. These deviations lead to an incorrect loading of the knee which continues the wear of the cartilage, which was already damaged anyway, accelerating the disease [3]. One of the most efficient surgical methods for managing this disease is the Opening wedge high tibial osteotomy (hereinafter OWHTO) [4]. Although this method is generally free of complications, for a successful operation and a quick recovery, it is important to respect specific elements that will help to avoid some inconveniences such as: lateral hinge microfractures or stability loss of the articulation of the knee [5]. One of these is optimal geometric planning. The main purpose of this paper is to model the biomechanics of this surgery. The objectives of the research are to develop a 3D model of the OWHTO in a biplanar version, which is less approached in the specialized literature, to carry out finite element analysis (hereinafter FEM) to study the loading state occurring in the knee during the intervention and finally to optimize the geometric planning of the OWHTO using specific design of the experiment methods.

2. MATERIALS AND METHODS

The aims and objectives defined at the end of the previous chapter will be achieved by computer aided research methods such as Computer Aided Design (hereinafter CAD) modelling for the development of graphic models of the OWHTO and the effective simulation of the operations, Computer Aided Engineering (hereinafter CAE) approach for performing analyses by the FEM and finally DOE method for the optimization of the geometrical planning of the surgery using Taguchi method.

2.1 CAD Modelling of the Biplanar OWHTO

The 3D modelling method by CAD means of operations applied to the bone system is a new procedure that offers genuine advantages such as: specific evaluation of the situation on a customized 3D model, analysis of the compatibility with possible implants and transplants required, but also the possibility of learning and practicing the operating steps by simulating the operation on a virtual model.

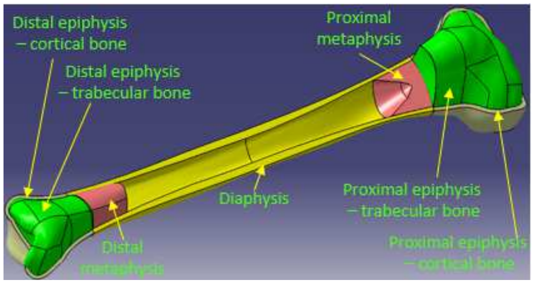


Fig. 1. Section in human tibia 3D model [4]

For the CAD modelling of the biplanar OWHTO, we start from the 3D model of the tibia made by part of the authors of paper [4]. The important aspect of this 3D model is that the model is conceived as a set of entities, thus taking into account the actual bone and geometric structure of the tibia. As can be seen in Figure 1, this resulted in a number of seven entities with different shapes and mechanical characteristics: proximal epiphysis with cortical bone, proximal epiphysis with trabecular bone, distal metaphysis with spongious bone, diaphysis with only cortical bone, proximal epiphysis with cortical bone, proximal epiphysis with trabecular bone and proximal metaphysis with spongious bone. The software Catia V5R20 was used for modelling of tibia bone.

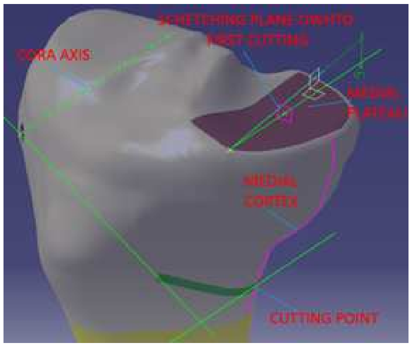


Fig. 2. 3D modelling of the OWHTO - first cutting

Modelling the entity set in this way is important both for respecting the anatomical reality of the bone and especially for further FEM approaches, offering the possibility to introduce different mechanical characteristics for each of the entities in the analysis.

The CAD modelling of the OWHTO has been done in a generalized and parameterized way in order to perform future CAE studies and to have the possibility to simulate as many customized situations as possible.

For the development of the modelling, the geometrical planning and the necessary steps for the real operation were taken into account.

A sagittal plane (Figure 2) of the tibial plateau was defined in which the 7° inclination of this plateau with respect to the horizontal plane was highlighted by a line. A plane perpendicular to this line was then constructed halfway along the anterior posterior distance of the tibial plateau, which will be the sketching plane of the first cut of the OWHTO. The intersection between this plane and the medial cortex of the knee is a curve on which will stand an important geometric planning parameter called Cutting Point Position.

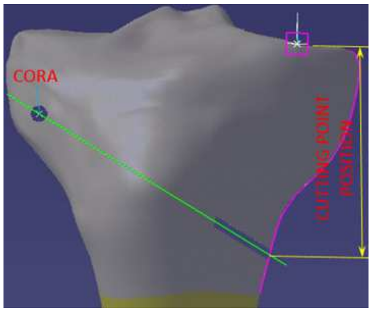


Fig. 3. CORA and Cutting Point Position

This point is positioned at the medial plateau of the knee (Figure 3).

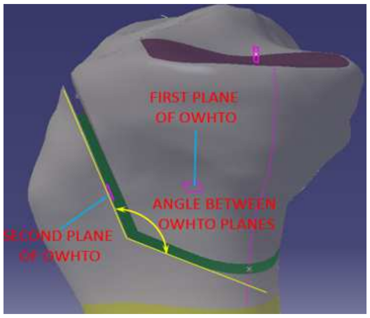


Fig. 4. 3D modelling of the second cutting

Another important point used for determining the OWHTO cutting plane is the Centre of Rotation of Angulation axis (CORA hereinafter) which is the hinge around it will be achieve the open wedge osteotomy. CORA is positioned relative to the lateral tibial plateau and lateral cortex of the tibia [4]. The OWHTO plane is made from the posterior side but not completely but up to the intersection of the CORA with the anterior part of the tibia.

For the second cut, a new plane was established to control the angular position between the two osteotomy planes (Figure 4).

The last step of the modelling is creating the osteotomy wedge controlled by the Correction Angle parameter (Figure 5).

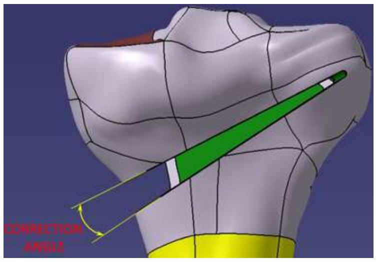


Fig. 5. Correction angle - posterior views

The study will continue in the next subchapter with an FEM study aimed at optimizing the geometrical and dimensional parameters of the OWHTO.

2.2 FEM Analysis of biplanar OWHTO

The aim of the FEM analyses is to study the behaviour of the bone structure in the CORA area during and immediately after the osteotomy wedge. The possibility of micro fissures in this area may have negative consequences on the success of the operation.

The input variables considered are those mentioned above, i.e. Cutting Point Position, Correction Angle and Angle between OWHTO planes.

Table 1

Input Variables-Influence Factors

Variables	**Unit**	**Level 1**	**Level 2**	**Level 3**
Cutting Point Position	[mm]	30	40	50
Correction Angle	[^{o}]	6	10	14
Angle between OWHTO Planes	[^{o}]	105	110	115

As can be observed in Table 1 for the three input variables we used three level of variations. The values chosen are in accordance with those existing in surgical practice [4], [6]. Output variables or Response Functions will be Equivalent von Mises Stress and Maximum Principal Stress. The FEM analysis was performed using the ANSYS program by successively going through the well-known stages.

The geometric model used is the one presented in the previous paragraph and is imported into ANSYS from Catia V5R20.

The mechanical characteristics used are distinct for each tibia structural entity as follows: proximal metaphysis with spongious bone with Young's modulus 1 GPa, proximal epiphysis trabecular bone with Young's modulus 5 GPa and proximal epiphysis—cortical bone with Young's modulus 17 GPa. For all entities Poisson's ratio was 0.33.

The model has been discretized using tetrahedral elements with 4 nodes. For increasing the precision of the mesh, we chosen 1,5 mm for maximum edge length and 2.4 × 10–3 mm for minimum edge length.

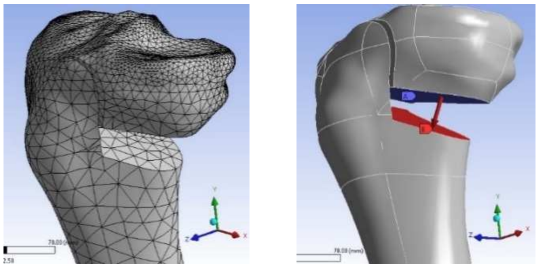

a. b.

Fig. 6. Meshing the models (a) and application of forces and constraints (b).

Forces and constraints are applied on both sides of the osteotomy wedge and values are taken from the literature, as following: 75 N for the 6^{o} Correction Angle, 150 N for the 10^{o} Correction Angle and 250 N for the 14^{o} Correction Angle.

After running the numerical simulations, the von Mises stresses and the maximum principal stresses were obtained.

3. RESULTS. OPTIMIZATION OF BIPLANAR OWHTO GEOMETRICAL PLANNING

An important objective of the geometric planning optimization is to find the best combination of the parameter levels presented in the previous paragraph in order to obtain the lowest values for the output variables.

For this, in order to determine the combinations of parameters and levels of variation Taguchi methodology was used and this was done automatically using MiniTab 18 software package.

The Taguchi L9 (3^3) orthogonal matrix was selected. Table 2 shows this matrix in which 9 combinations of the 3 levels of influence factors analysed will be examined.

Table 2

The Taguchi orthogonal array L9 (3^3) for the input variables

	Cutting Point Position [mm]	**Correction Angle [degree]**	**Angle between OWHTO Planes [degree]**
1	30	6	105
2	30	10	110
3	30	14	115
4	40	6	110
5	40	10	115
6	40	14	105
7	50	6	115
8	50	10	105
9	50	14	110

For the combinations in the table 2 the numerical analyses will be run and the equivalent Von Mises voltages and respective maximum principal voltages will result in each of the nine cases.

The Taguchi method allows to minimize the number of combinations of variables with relatively many levels of variation under the conditions of obtaining consistent results regarding the effect of influencing factors on the response functions.

The method also allows a reliable design of the tests by determining the signal-to-noise ratio, which in fact highlights the ratio between sign factor which is the response function or the output variable and disturbing factories (noises) which are uncontrollable in most cases.

Depending on the experimental objectives, three formulas of the Signal-to-noise ratio (hereinafter SNR) can be selected: "Nominal is the best", "Smaller is better" and "Larger is better".

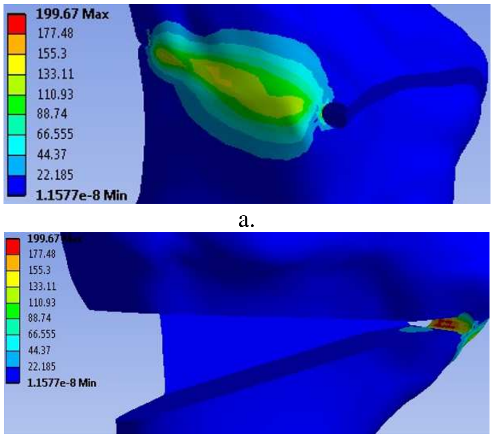
Table 3

The results for the Output variables

	Equivalent von Mises Stress [MPa]	**Maximum Principal Stress [MPa]**	**SNRA1**	**SNRA2**
1	75.955	89.288	-42.3286	-43.6559
2	130.746	152.334	-46.5922	-47.6244
3	213.605	240.557	-37.1013	-38.5202
4	71.625	84.335	-42.0057	-43.4637
5	125.975	149.000	-46.0063	-47.3337
6	199.670	232.640	-37.4545	-38.7876
7	74.598	86.973	-43.3768	-44.7913
8	147.516	173.607	-46.9447	-48.3276
9	222.452	260.842	-42.3286	-43.6559

Obviously, in our research we choose "Smaller is better" because we want the resulting tensions to be as low as possible in the CORA area. The higher the signal-to-noise ratio, the better.

The results are presented in Table 3 where SNRA1 is the Signal-to-noise ratio for Equivalent von Mises Stress and SNRA2 is the Signal-to-noise ratio for Maximum Principal Stress.



a.

b.

Fig. 7 Equivalent von Mises stress, in the outer side (a.) and in the inner side (b.) of CORA

Analysing the results in the table we can observe lower values for both Equivalent von Mises Stress and for Maximum Principal Stress in the case of the Cutting Point Position at 40 mm from the tibial plateau and for the SNRA the highest values (i.e. those where the stresses are the lowest) are found for combinations 3, 4 and 6.

In figures 7 and 8 is shown the distributions of the equivalent stress and maximum stress for combination number 6 (40 mm, 14^o and 105^o), both on the inner and on the outter surface of the tibia bone.

The equivalent von Mises stress on the outer wall of the tibia (Figure 7) is around 110 MPa and inside the CORA the values are higher, reaching a maximum of 199 MPa.

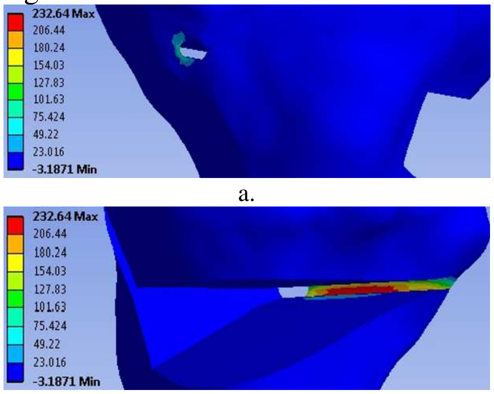


Fig. 8 Maximum principal stress, in the outer side (a.) and in the inner side (b.) of CORA).

The main stress is maximum inside the CORA hole (Figure 8) and has very low values on its outer surface.

After performing the Taguchi analysis taking in account the condition "Smaller is better" for our two response functions the results are shown in tables 4 and 5 and in figures 9 and 10.

Table 4 shows the mean response values of the SNRA analysing the effect of the influencing factors on the response function Equivalent von Mises stress. The highest SNRA values (hence the lowest equivalent stresses) are for Cutting Point Position at the 40 mm, for Correction Angle at the 6^o and for the Angle between OWHTO Planes at the third level - 115^o.

Table 4

Response table for signal to noise ratio (SNR) for the Equivalent von Mises stress

Level	Cutting Point Position	Correction Angle	Angle between OWHTO Planes
1	-42.18	**-37.39**	-42.33
2	**-41.70**	-42.57	-42.12
3	-42.59	-46.51	**-42.02**
Delta	0.89	9.13	0.31
Rank	**2**	**1**	**3**

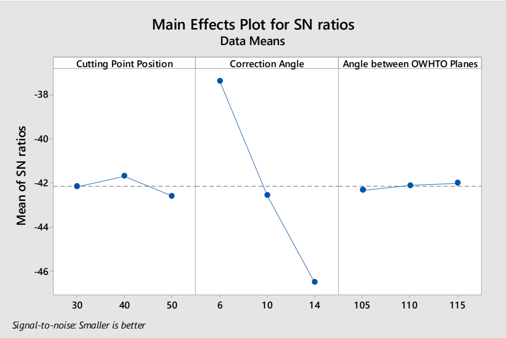


Fig. 9. The main effects plot for the Equivalent von Mises stress

Delta measures the magnitude of the impact of that factor and the rank determines the order of the factors. In this case the Correction Angle factor clearly has the greatest influence on the von Mises equivalent stress, followed by Cutting Point Position but with a Delta 10 times smaller than this while Angle between OWHTO Planes has the least influence with a Delta 30 times smaller than the most important parameter.

Figure 9 captures in a suggestive graphical way the above considerations.

Table 5

Response table for signal to noise ratio (SNR) for the Maximum principal stress

Level	Cutting Point Position	Correction Angle	Angle between OWHTO Planes
1	-43.43	**-38.77**	-43.71
2	**-43.11**	-43.97	-43.50
3	-43.97	-47.76	**-43.29**
Delta	0.86	8.99	0.42
Rank	**2**	**1**	**3**

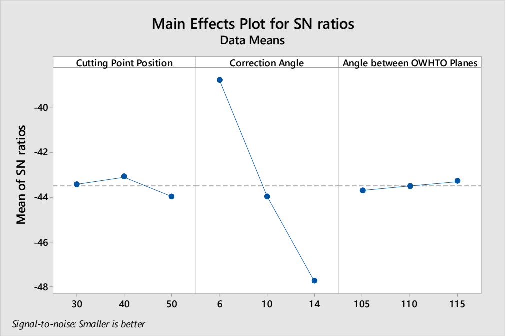


Fig. 10. The main effects plot for Maximum principal stress

The Taguchi analysis was also performed for the second response function - maximum principal stress. It is noted that the influences of the input magnitudes remain unchanged.

4. CONCLUSION

The main purpose of this article was to model from a biomechanical point of view one of the most common surgeries in orthopaedic practice. CAD modelling of biplanar OWHTO performed in a parameterized way is an important contribution allowing the development of custom CAD models. The FEM analysis and especially the analysis using Taguchi methodology highlights the combinations of geometric parameters of the surgery leading to minimal stress states and obviously to avoid the appearance of micro fractures in the CORA. The values obtained can be a guide for surgeons.

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MODELAREA CAD-CAE A BIOMECANICII OSTEOTOMIEI BIPLANARE MEDIALE DE TIBIE CU DESCHIDERE DE PANĂ

Rezumat: Osteotomia tibială medială biplanară de deschidere este o procedură chirurgicală adesea folosită pentru a elimina efectele osteoartritei genunchiului. Planificarea geometrică a acestei operații este un pas foarte important pentru succesul intervenției și recuperarea rapidă postoperatorie. În acest articol s-a abordat optimizarea unora dintre parametrii geometrici care caracterizează această planificare. Metodele de cercetare utilizate sunt: proiectarea asistată de computer (CAD) pentru modelarea 3D a tibiei, metoda CAE pentru efectuarea de analize numerice și metoda Taguchi pentru analiza rezultatelor. Rezultatele obținute pot fi un bun ghid pentru medicii ortopezi.

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