Tension analysis in a knee prosthesis model under different loading conditions using the finite element method

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Abstract. Given the fundamental importance that collaborative and interdisciplinary developments have for scientific knowledge, this work brings an approach focused on the stress distribution presented by a knee prosthesis prototype, to assess the impact of the prosthesis geometry in the intervention regions. Quantitative analysis was performed using the Finite Element Method. 3D digital models of the prosthesis were made, based on the catalogs of commercial prostheses, and of the bones, based on radiographic images and anatomy literature. Subsequently, the bone models were segmented, seeking to approximate the model geometry to the intervention performed in the real case, based on the procedure described by the American Academy of Orthopedic Surgeons. In this model, a numerical simulation was performed, considering the uniform weight distribution and different positions that occurred during a gait, that is, the way human walk. From these results, it is possible to observe that, despite the great variability of geometries involved, there are concentrations of stresses at specific points of intervention to support and fix the prosthesis to the bones. Thus, to reduce impacts on bones, these points must have geometries that reduce these stress concentrations.

Keywords: arthroplasty, stress analysis, numerical simulation, finite elements, biomechanics.

1 Introduction

According to the report of the United Nations - UN [1], by 2050, one in six people in the world will be over 65 years old. As age advances, it is common to have clinical symptoms such as those approached by Moore and Dalley [2], which deal with the wear and tear of the knee joints that is part of the aging process, in addition to mentioning the injuries that are common, as it is a joint that has mobility and acts in support of weight. In more severe cases, surgical treatment and placement of a prosthesis, that is, an artificial structure to replace damaged tissues, are required.

For this intervention to be successful, the prosthesis needs to have a good response and its mechanical behavior is an important aspect of the procedure. Therefore, this work brings an approach focused on the stress distribution presented by a prototype knee-prosthesis and bone components involved in the intervention, when subjected to different conditions of static loads. These static conditions aim to approximate the dynamic phenomenon of gait, in which loads and positions vary over time, based on their discretization in four loading conditions in which the demands are considered more severe.

The objective of this work is to obtain, through computer simulation, the stress distributions in the knee-prosthesis system and the values of the active stresses, to evaluate the system's behavior in a dynamic request.

2 Methods

2.1 3D modeling

The prosthesis-knee system was modeled considering the characteristics seen as the most common. For that, anatomy books, radiographic images, prosthetic catalogs, and other academic works that deal with themes related to the one covered in this work were consulted. Every modeling step was done using the SolidWorks® software. In Figure 1, bone components can still be seen without cutting.

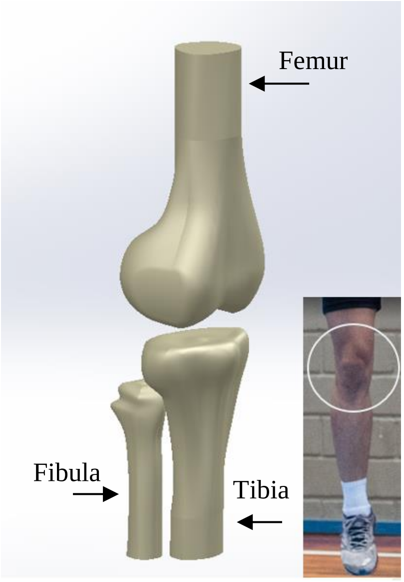


Figure 1. Bone components of the model.

The bone model was based on the right knee. The modeled prosthesis was made seeking to adapt to the bone components used, considering a total knee arthroplasty, without the use of rods. In Figure 2, the assembly of the model used can be seen. The prosthesis components are already fixed in the places where the cuts were made in the bony parts of the model.

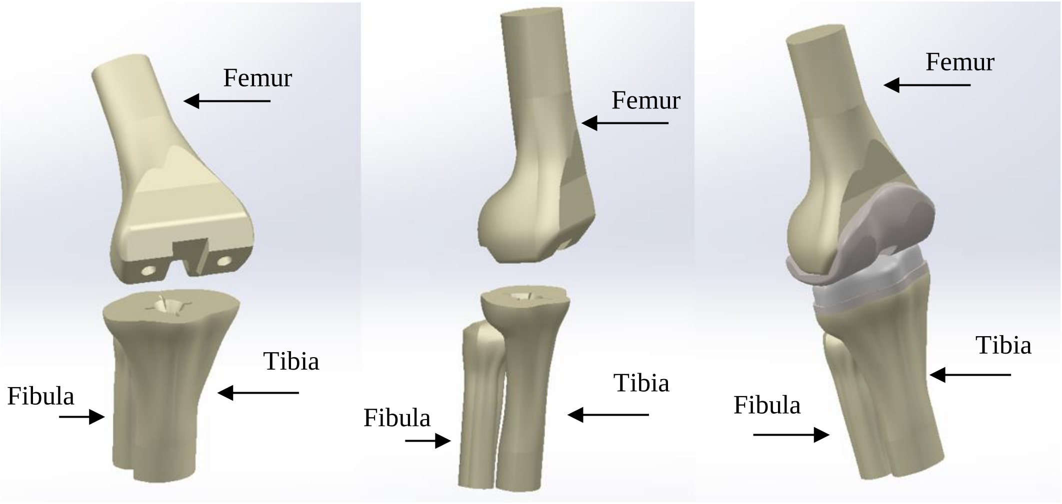


Figure 2. Bone component cuts and model assembly.

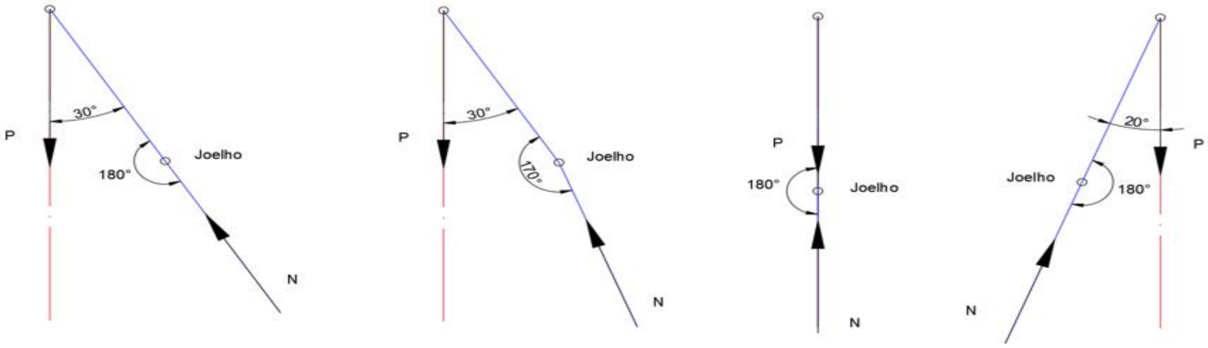
For the bone cuts and perforations necessary for fixing the prosthesis, the procedure described by the

American Academy of Orthopedic Surgeons - AAOS [3] was followed. They were made considering geometries similar to those used in the real procedure but aiming to adapt to the prosthesis model used.

2.2 Problem modeling

The march consists of two phases, namely: the support phase and the swing phase. In the swing phase there is no contact of the foot with the ground. Therefore, stages of the support phase were adopted, which is when the foot has contact with the ground and is subject to the reactions caused by this support. These reactions put a strain on the knee region and other supporting structures of the body. The stages of the support phase are: initial contact, acceptance of weight, medium support, terminal support, and pre-balance. The latter was not considered because, when it occurs, the leg is already under the action of the muscles that perform knee flexion and support the weight of the leg, starting the swing phase. In Figure 3, the stages of the support phase considered in the study can be seen.

Initial contact Weight acceptance Medium support Terminal support



Initial contact Weight acceptance Medium support Terminal support

Figure 3. Marching stages and force diagrams of the stages of the support phase (Adapted from Moura) [4].

For bone models, real surface characteristics, such as porosity, callus and viscosity, were disregarded. Only a few furrows were made, as in the fibular support point on the tibia. The segments made do not consider the wear and superficial finishing states resulting from the cutting process used in the actual procedure. The bones are composed of cortical bone and trabecular bone. In the model, only the cortical component, which is the outer layer, was considered, as it is more resistant and has greater participation in structural support. In addition, bones have great variability in terms of mechanical properties, complex to be faithfully represented and, therefore, they were considered isotropic.

In commercial prostheses, different materials and geometries are used. In this model, for metallic components, only the Cobalt-Chromium-Molybdenum alloy was considered, which is widely used in prostheses, as it has good mechanical properties and low rejection by the body. There is also the polyethylene component, which is the interface responsible for the movement of the prosthesis. In the interfaces of the prosthesis with the bones, it is common to apply a bone cement, which has the role of fixing these components, allowing greater stability.

For the boundary limits of the problem, it was considered that all knee movement occurs in the same plane, that is, the flexion and extension occur only in the direction related to the movement of walking, parallel to the sagittal plane. Possible atypical rotations and slips (different from the slip that occurs at the interface responsible for the movement) that may occur during gait were disregarded. The other organic components that surround the structure were also disregarded, such as cartilage, ligaments, fat, skin and the patella, which, despite being a bone, has no structural role in the analysis carried out. The efforts made by muscles and tendons, and the support of the other foot are points that influence the distribution of weight. For the force acting on the model, an 80 kgf person was considered; gravitational acceleration as 9.81 m/s²; a safety factor - F.S. of 1.25 was adopted to address the uncertainties involved; and, in the initial contact stage, an impact factor of 1.2, according to Norton [5]. Thus, the total weight used is 981 N.

2.3 Computational numerical simulation using the finite element method

For the computational numerical simulation, the complexity of the model geometry is an aspect of great relevance. For this reason, a mesh was generated with refinement at the points where it is estimated that there is a higher concentration of stresses and where there are requests on the bone-prosthesis interfaces. As it is a geometry with solid behavior, and considering the existence of stresses in several directions, a mesh with 1st order Tetrahedral Solid elements was used. The mesh used for the simulation is shown in Figure 4.

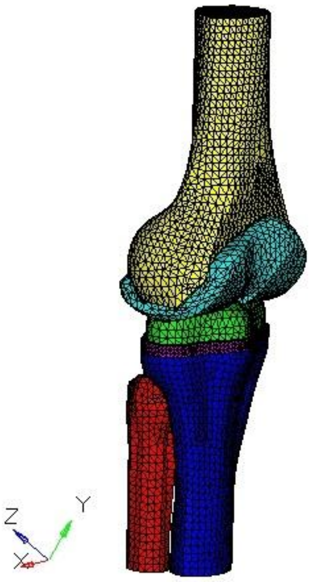


Figure 4. Mesh used in the simulation.

In addition to the geometric and mesh aspects, the properties of the materials involved in the study are fundamental for obtaining the behaviors presented in each component when submitted to loading requests. Table 1 shows the properties considered for the materials of the knee-prosthesis model.

Table 1. Properties of the materials used in the simulation (Adapted from Fouda *apud* Fernandes; Completo *apud* Fernandes; and Mergulhão) [6] [7].

Material	Modulus of elasticity (E) - GPa	Flow Limit (σ) - MPa	Poisson's ratio (ν)
Co-Cr-Mo (ASTM F75)	248	450	0.3
Polyethylene	1	22	0.3
Cortical bone	17	90	0.3

The model does not have the extension of the bones of the tibia and femur, as the focus of the study is the knee joint. However, due to the efforts considered, it is important that the action of the forces is close to the configuration of the real case. For this reason, rigid elements were used, representing non-modeled extensions. A Tie-type contact, similar to a glued surface, was used, as well as what happens with the use of bone cement.

3 Results and discussions

All the geometric characteristics of the model were, as estimated, aspects responsible for making the simulated model more complex and difficult to solve. In this way, simplifications are an important tool, but, of course, keeping as close to the real configuration as possible. With the considerations made in modeling the problem and the others described about the simulation, the calculation model was executed without success in the first attempts. It was necessary to evaluate the contact surfaces in more detail. That done, the model converged and the simulation was successful. From this simulation, the stress distribution graphs presented below were obtained. In Figure 5, the graph for the set can be seen in the weight acceptance stage. In Figure 6, the results of the sections of isolated bone components are presented.

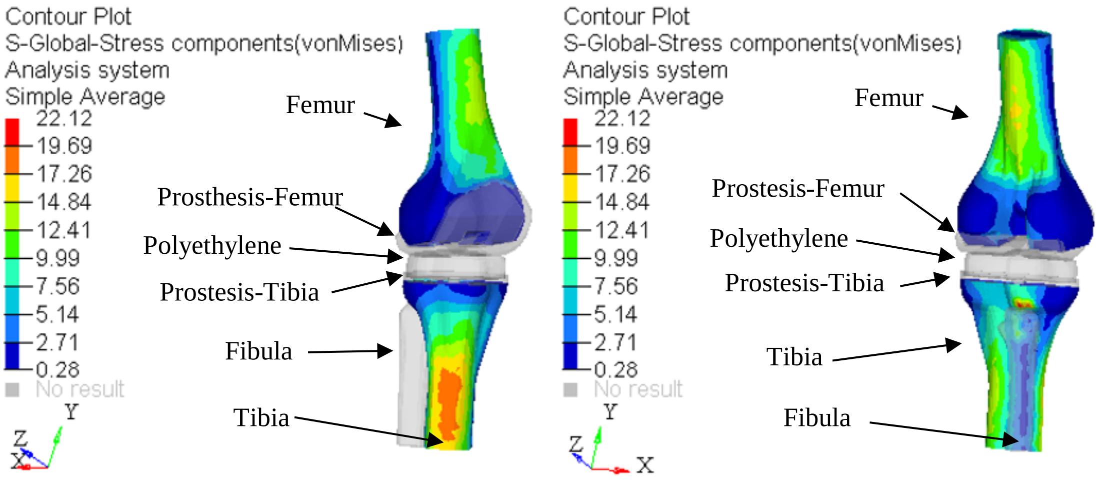


Figure 5. Stress distribution [MPa] in the set during weight acceptance.

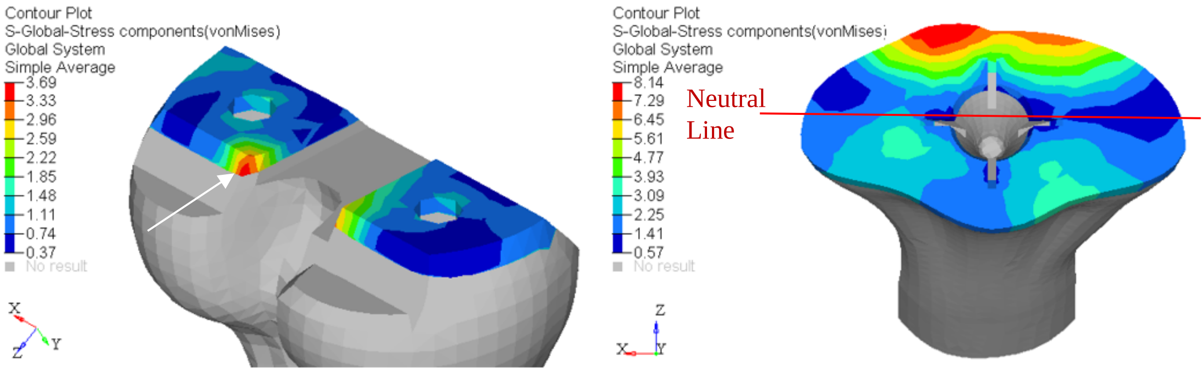


Figure 6. Stress distribution [MPa] in the bone component sections for the weight acceptance stage.

In this case, there were higher values of tension in the bone extensions, caused by the section reductions and bending moments that occur. There are also stress concentrations, which can be seen at specific points in the sections. In the case of the tibia, it is possible to perceive how the sustaining support made by the fibula, in the posterior part, contributes to the reduction of the tensions occurred, in comparison with the anterior face of the tibia.

For the analysis, it is very important to assess the stress distribution in the sections made by the intervention necessary for the placement of the prosthesis. In Figure 7, the results presented by the femur on the face of the sections, in the medium support stage, can be seen.

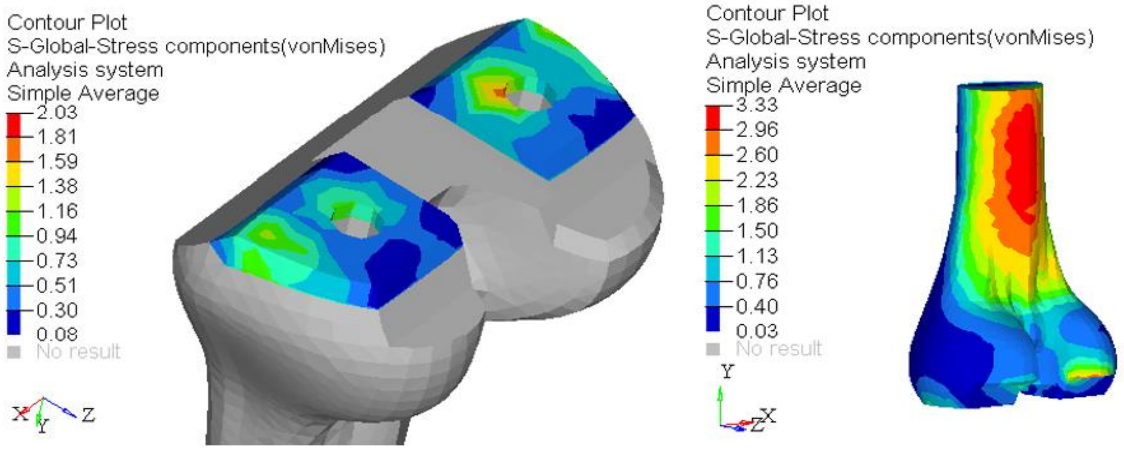


Figure 7. Stress distribution [MPa] in the sections for the medium support step.

In the tibia section, the stress concentrations at specific points, caused by the compression efforts in the central region of the bones, are caused by the localized application of the efforts in that region, in the medium support stage. As can be seen in Figure 8.

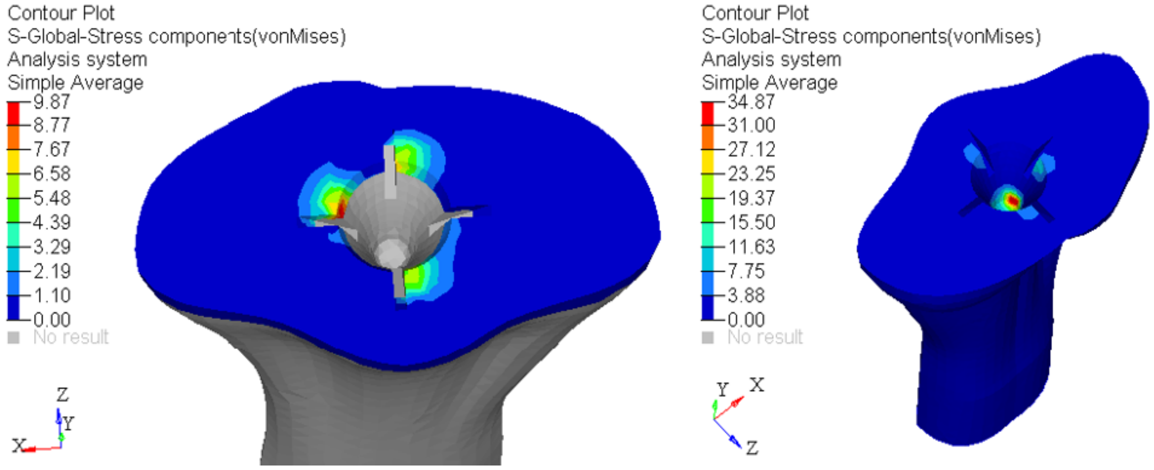


Figure 8. Stress distribution [MPa] in the tibia in the medium support step.

For the medium support stage, the entire body weight is applied to a single knee. The efforts are predominantly compressive, as there is no inclination in the application of the efforts and the knee joint is vertically aligned. This configuration of the extended leg and the linear behavior adopted for this analysis, allow the comparison with the results presented in the work of Fernandes [6], who dealt with the configuration of the extended leg, with asymmetric load and comparing geometry and material. In the case of the configuration of the prosthesis model 1 and the material of the metallic parts being the Cobalt-Chromium, which are parameters similar to those used in this work, the values of tension obtained have a close order of magnitude. The greatest variations were caused by the concentration of tension and differences in the other parameters of the analyzes.

4 Conclusions

The analysis made it possible to locate the regions in which there is a concentration of tensions. This is important information, as it demonstrates which geometries must be worked on so that the impacts of the intervention on the bones are less intense. This reduces the expenditure of time used in the design and testing stages of prototypes, reinforcing aspects of computational numerical methods in terms of cost reduction and repetitions common in physical experiments. It allows the experiments to be more directed to specific points elucidated through computer simulation.

The considerations made to isolate the knee-prosthesis system from the other structures, allow an analysis focused on the structural aspects of the set, being more appropriate to the proposed scope. Some characteristics disregarded for the analysis, such as the presence of other tissues existing around the bones and prosthesis or the viscosity existing in the mobile interface, can be treated more adequately in studies focusing on organic structures, which are carried out by researchers in the relevant areas to that kind of approach.

Every study developed and described in this work, is based on engineering aspects for stress distribution. It is interesting that more research is done in a complementary way, involving other areas related to the theme, such as physiotherapy, physical education and orthopedics, for example. Mainly research that seeks to evaluate the points of intervention in which stress concentrations were highlighted. In addition, the direct involvement of people who have undergone knee arthroplasty, which has already been studied for the purpose of postoperative treatment, can be used with support material for other analyzes similar to the one treated in this text, aiming to take advantage of this information from the prosthesis conception and design steps.

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