Original Paper

Contributions to the Study on the Effects of Incorrect Implantation of Knee Prostheses Depending on the Degree of Varus / Valgus

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ABSTRACT: Introduction. The human knee is one of the most complex human joints, by the number of components, by the stresses to which it is subjected, by the complicated spatial geometry of the components and by the existence of multiple contacts between different components. Material and Method. A series of modern devices and equipment that were used for the three-dimensional reconstruction of the components of the analyzed systems. Results. Also, the elements of a knee prosthesis were modeled in a parameterized virtual environment and six orthopedic systems were compared. These systems have been studied using the finite element method using loads specific to normal human gait. Discussion. The results obtained consisting of maps of displacements, deformations and stresses were stored, analyzed and compared. Conclusions. Finally, important conclusions were highlighted.

KEYWORDS: *Degree of varus / valgus, finite element method, CAD methods, knee prosthesis.*

Introduction

From a biomechanical point of view, the human knee joint is a complicated structure, both by the number of components that come into direct contact, but also by the complex geometry of the components.

Also, the knee component includes both rigid and elastic structures, which leads to complicated analyzes when the studies are performed using the finite element method [1-3].

Osteoarthritis of the knee, one of the major chronic diseases commonly encountered in middle-aged and elderly people, affects a very large number of people. Due to the sharp increase in osteoarthritis cases by 2030 in the US, the total number of total hip arthroplasties will increase by 572,000 (approximately 174%), while total knee arthroplasties will increase by 3.48 million procedures (about 673% between 2005 and 2030 the number of hip revision procedures in the US will be double by 2026, while the number of knee revisions has already doubled by 2015. The situation is similar in Europe and in our country [4,5,6,8].

From our previous studies we used the virtual model of the knee joint and the virtual model of the knee prosthesis. Starting from the normal situation the aim of the study was to determine the effects of incorrect implantation of the knee joint depending on the degree of varus / valgus.

Virtual studies have brought to medical practice some valuable information because is better to see those negative effects in virtual mode in order to improve surgical skills and to observe long term modifications.

The virtual analysis allows us to imagine any possible scenario and in order to do that we had to start from the normal situation which means from the virtual model of the normal knee joint and the virtual model of the prosthetic knee implanted correctly [22].

After having the correct form we were able to make the incorrect implantation of the knee prosthesis in valgus-degree 2 and 4 and varus degree 2 and 4.

With all the models generated in virtual mode in Ansys program we were able to obtain the biomechanical behavior.

The correct anatomical alignment of the prosthesis elements and the bone components of the tibia and femur is the most important factor that determines the functioning of the prosthetic knee joint. If there are significant changes in alignment, additional tension may occur in the prosthetic knee joint that may lead to the damage of the bone components-tibia and femur, but also to the loss of the prosthesis or lead to other pathologies of the knee joint. Thus, additional forces can be induced to cause an incorrect loading of this important joint [9].

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Material and Method

A series of modern devices and equipment were used for the three-dimensional reconstruction of the components of the analyzed systems, because our study was performed only in virtual mode.

The bone components: femur, tibia and patella, are part of the collection of the human anatomy department within U.M.F. of Craiova and were subjected to three-dimensional scanning and computer tomography.

The 3D System Capture scanner was used for a preliminary assessment of the geometry of the bone components, but its use was only for external surfaces.

The analyzed tomography sets were obtained with the Toshiba Asteion CT scanner installed at the Craiova Emergency Hospital.

Three-dimensional reconstruction, finite element analysis, but also the use of certain visualization, reverse engineering or three-dimensional scanning programs were performed on a Lenovo laptop computer with 2.6GHz processor, 16GB RAM with a Windows operating system on 64 bit.

In some situations, when the analysis of several researchers required the expertise of another researchers, at the same time, a Legamaster Smart Board device with Optoma video projector was used.

A series of state-of-the-art computer programs were also used to generate the three-dimensional geometric structures of the analyzed and studied components [10-12].

Virtual analysis of tomographic images was performed using the program Syngo FastView.

The primary conversion of tomographic images in to three-dimensional geometries was obtained with the InVesalius program, a specialized program for medical research.

The conversion, processing and analysis of the geometry of the virtual bone components was done with the Geomagic program which specializes in 3D scanning and reverse engineering.

The transformation into virtual solid of the geometries of the bone components was made using the SolidWorks program. The different components of the prosthesis elements were generated in the same program.

Finite element analyzes were performed using the Ansys Workbench program which allowed the introduction of conditions, constraints and loads specific to human gait applied on different orthopedic systems and assemblies.

In carrying out this study, several methods were used, some classic, others innovative, such as:

- medical imaging methods.
- reverse engineering and three-dimensional scanning methods.
- CAD (Computer Aided Design) methods.
- finite element analysis method (FEM).

Initially, in order to determine the correct geometry of the knee joint, in a virtual environment, reverse engineering methods were applied.

In order to obtain the bone geometries, we started from the analysis of several tomographic images that were taken and analyzed with the InVesalius program. Subsequently, the Geomagic program was used, which corrected and improved the obtained geometry, and, finally, the model was finalized in the SolidWorks program, where the knee joint was transformed into virtual solids.

These were loaded into the Assembly module, where the movement constraints were defined and the virtual model of the knee joint was obtained. [13,14-20].

Results

Using high-performance numerical calculation methods and a high-capacity personal computer, high-fidelity virtual models of the vicious knee prosthesis were obtained as follow:

Virtual models of the incorrectly prosthetic knee at 2 and 4 degrees of inclination in the valgus and 2 and 4 degrees in the varus, respectively (Figure 1 a, b, c and d).

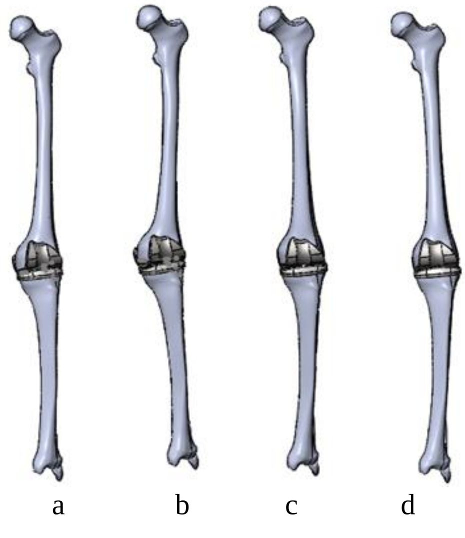

Figure 1. Valgus-varus type malposition.
a) valgus 2º; b) valgus 4º; c) varus 2º; d) varus 4º.

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To obtain the biomechanical behavior of the normal knee articulation, the virtual model was uploaded to Ansys.

Subsequently, the finite element structure consisting of tetrahedral volumes was obtained, as shown in Figure 2.

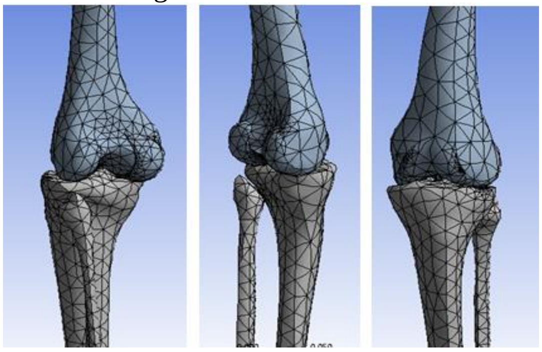


Figure 2. Finite element structure of the integer knee joint.

Then, a force-loading system characteristic of normal human gait was used [21-25].

This system of forces was similar used in [26-28]. After running the applications, the maps of displacements, stresses and strains are shown in Figure 3.

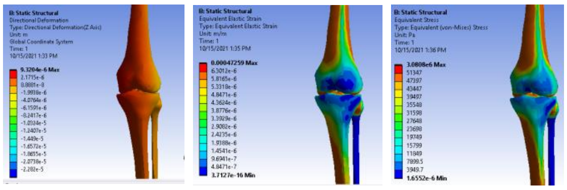
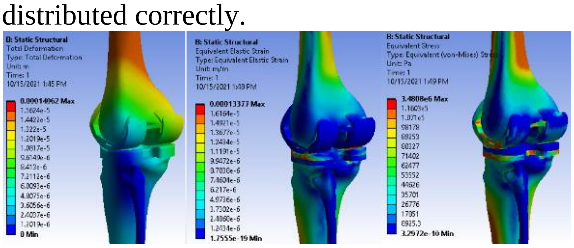


Figure 3. Result maps
a. Displacements. b. Strains. c. Stresses.

Also, the orthopedic system of the prosthetic knee joint and anatomically aligned correctly was studied. The model was divided into tetrahedral finite elements.

The same system of forces characteristic of human gait was used. After running the applications, the maps of displacements, stresses and strains are shown in Figure 4.

When knee prosthetic is aligned correctly, the equivalent elastic strain is distributed correctly and there is no red zone neither on bone and neither on prosthetic. Weight was distributed correctly.



a b c

Figure 4. Result maps.
a. Displacements. b. Strains. c. Stresses.

To study the behavior of the incorrectly prosthetic knee with 2 degrees valgus, the virtual model was imported in Ansys. The model was divided into tetrahedral finite elements.

The same force system was used in this orthopedic system. For the components of this system, the physical and mechanical properties are similar. After running the applications, the maps of displacements, stresses and strains are shown in Figure 5.

For 2 degrees valgus we observe that the equivalent elastic strain goes to lateral side of the diaphysis, and then goes to the lateral condyle and lateral side of the prosthetic components sustain more weight.

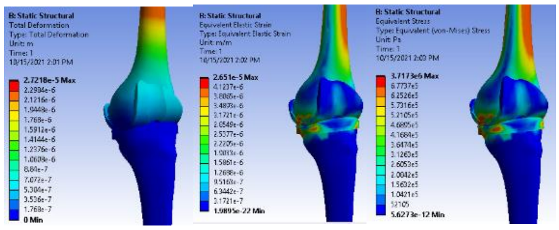


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Figure 5. Result maps
a. Displacements. b. Strains. c. Stresses.

The incorrectly prosthetic knee with 4 degrees valgus was also imported into Ansys. The model was divided into tetrahedral finite elements, as shown in Figure 6.

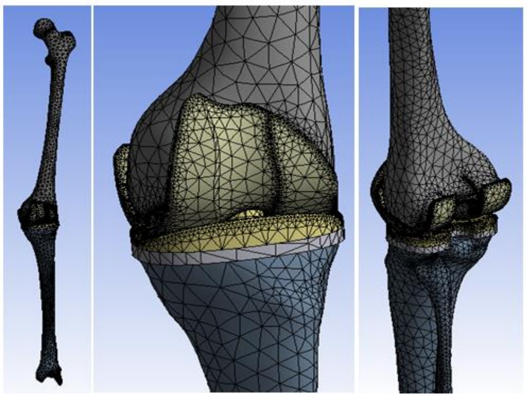
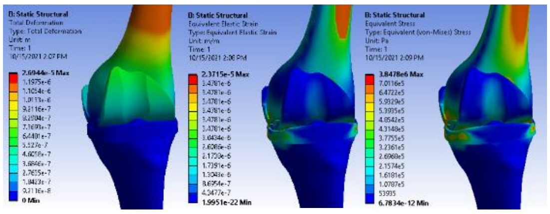


Figure 6. Finite element structure of the prosthetic knee joint.

To obtain the simulation of mechanical behavior, this system was loaded with a system of forces corresponding to human gait. For the components of this system, the physical and mechanical properties are similar. After running the applications, the maps of displacements, stresses and strains are shown in Figure 7.

For 4 degrees valgus we see much more pressure on the side of the tibial prosthetic component and the polyethylene insert, which in time will deteriorate prosthetic components.



a b c

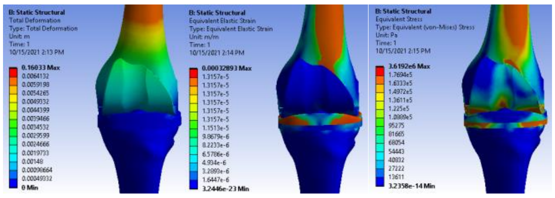
Figure 7. Result maps.
a. Displacements. b. Strains. c. Stresses.

To study the behavior of the prosthetic joint of the incorrectly prosthetic knee with 2 degrees varus, the virtual model was imported in Ansys.

The model was divided into tetrahedral finite elements.

And in this case, the same system of forces similar to human gait was used. For the components of this system, the physical and mechanical properties are similar. After running the applications, the maps of displacements, stresses and strains are shown in Figure 8.

For 2 degrees varus the equivalent elastic strain goes from the middle of diaphysis to the medial side. More weight will be distributed to the medial side of the prosthetic components.



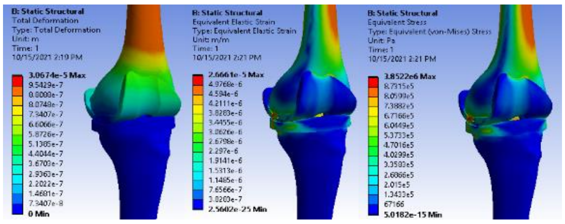
a b c

Figure 8. Result maps
a. Displacements. b. Strains. c. Stresses.

To study the behavior of the prosthetic joint of the incorrectly prosthetic knee with 4 degrees varus, the virtual model was exported to Ansys Workbench. The model was divided into tetrahedral finite elements.

To obtain the simulation of mechanical behavior, this system was loaded with a system of forces corresponding to human gait. For the components of this system, the physical and mechanical properties are similar to the cases analyzed above. After running the applications, the maps of displacements, stresses and strains are shown in Figure 9.

For 4 degrees varus will change to much mechanical axis and put more pressure on medial side of the prosthetic components, which will lead to the deterioration of polyethylene insert or deterioration of all prosthetic components.



a b c

Figure 9. Result maps
a. Displacements. b. Strains. c. Stresses.

Discussion

Analyzing the results obtained after the simulations performed in Ansys using the finite element method, three comparative diagrams were obtained [29-33].

Figure 10 shows the comparative diagram of elastic deformation for the six situations analyzed.

It is observed that the maximum deformation is obtained in the case of the normal knee, and, for this reason, it can be said that this system has maximum elasticity.

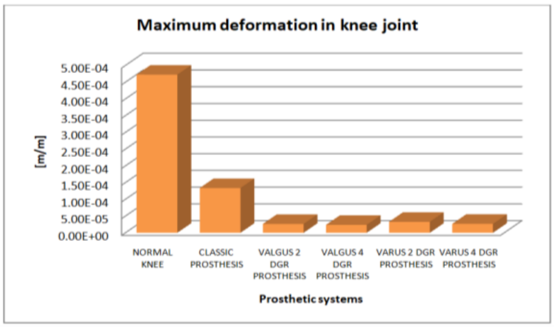


Figure 10. Comparative diagram of elastic deformation.

Figure 10 shows the comparative diagram of the maximum displacements obtained based on data from the simulations performed on the six orthopedic systems analyzed.

Maximum displacement in the knee joint appears in the case of varus 4 degrees, which proves that in this situation, the joint has the greatest instability-Figure 11.

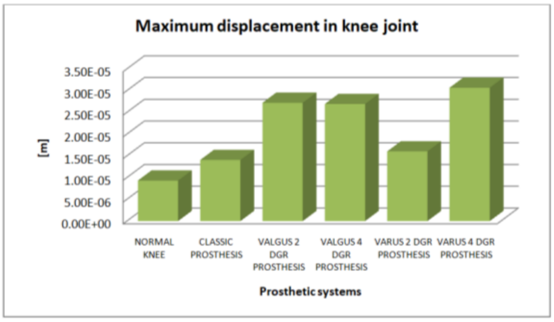


Figure 11. Comparative diagram of maximum displacements.

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Also, the values of the maximum stresses obtained in the analyzed systems were analyzed and compared.

Figure 12 shows the comparative diagram of these values.

It is observed that maximum stress in the prosthetic knee is obtained in case of incorrect implantation of varus 4 degrees, which can lead to rapid deterioration of bone components.

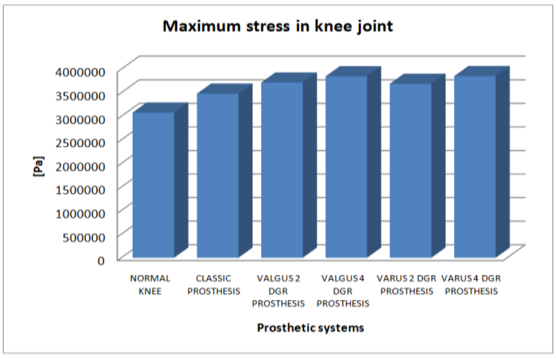

Figure 12. Comparative diagram of maximum stress.

The methods of three-dimensional reconstruction of bone components, coupled with reverse engineering methods and CAD techniques allow obtaining virtual models of bones and joints with great accuracy [10,11-18].

These virtual models can be subjected to axial compression, torsion, bending, etc. tests.

The results obtained providing valuable data for the realization of new orthopedic implants that meet the requirements of medical practice [6,8,9,11].

The results obtained in this paper agree with clinical observations, in the sense that deviations from the correct alignment of knee prostheses lead to premature degradation of the prosthetic assembly or premature wear, which causes the patient suffering and involves new surgery with prostheses revisions, which are much more expensive and also much more disabling for the patient, because they involve a greater loss of bone capital, followed by the impossibility of further interventions.

Conclusions

From the analysis of the data and values obtained through the obtained simulations, but also of the comparative diagrams by applying the finite element analysis method, the following conclusions were highlighted:

- the elastic deformations obtained in the cases of the intact knee are the largest compared to the situations in which the knee is prosthetic;

- the values obtained for displacements were minimum in the case of the intact knee and maximum in the case of the prosthetic knee with varus of 4 degrees;

- the results obtained for stress were minimal in the case of the intact knee and maximum in the case of the prosthetic knee with valgus of 4 degrees.

- research is needed in order to create an instrument for implanting prostheses that would allow the orthopedic surgeon to achieve a correct positioning of the knee prosthesis.

Conflict of interests

None to declare.

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