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AN ANALYSIS OF AN INNOVATIVE KNEE PROSTHESIS USING INTERDISCIPLINARY METHODS

Mihai Cătălin ȚENOVICI, Dragoș-Laurențiu POPA*, Daniel ILIUTA, Gabriel BUCIU, Daniela VINTILĂ, Diana PRUNOIU, Vladimir ONTICA, Dănuț Nicolae TARNIȚĂ

Abstract: *The paper first presents some methods and techniques for obtaining 3D models of bone that compose the knee joint. The components of a classic knee prosthesis were also modeled and implanted virtually on the virtual bone components. Subsequently, these metal and bone components composed a classic knee prosthesis system. Based on clinical observations, an innovative knee prosthesis was modeled to allow relative elasticity, but also sufficient rigidity, based on elastic rods on which metal spheres were placed. This prosthetic system has also been virtually implanted on the bony components of the knee joint. These two orthopedic prosthetic systems were analyzed by the finite element method to detect their behavior at load similar to human gait. The results obtained were analyzed, compared and interesting conclusions were highlighted.*

Key words: *prosthetic knee, virtual knee joint, reverse engineering, virtual analysis, prosthetic systems.*

1. INTRODUCTION

The human knee joint is one of the most complicated human joints, on the one hand, by the number of bone components (femur, tibia and patella), on the other hand, by the loads to which it is subjected, but also by the complicated spatial geometric structure. of the components involved and by the existence of many contacts between different parts [1, 2].

Being one of the most requested human joints, lately more and more people have knee diseases, which require the rehabilitation of its movements, with the help of orthotic systems or robotic structures like exoskeletons, if the disease is in a less serious stage, or even a total replacement of the human joint by using prosthesis, in the advanced case of joint destruction [3-14].

This study have as a starting point the practical need to develop an optimized model of knee prosthesis, referring in particular to the arthroplasty of the knee. We start from the data collected from the literature that highlight, on the one hand, a statistical increase in the incidence of knee pathology and a number of shortcomings found in the medical practice of existing models of knee prostheses, clinically translated into a still high rate of complications occurring in this surgical procedure [13].

Total knee replacement is a cost-effective treatment, reducing pain, increasing mobility and improving quality of life and previous studies were published on these directions [4-6]. Worldwide research is being done to improve the design and manufacture of knee prostheses, research developed in several directions: in materials, design, fixation of the implant.

The studies in this paper will be done through an interdisciplinary approach using classical and modern engineering, computational and virtual-experimental methods, similar with previous researches [13].

2. MATERIAL AND METHODS

2.1 Hardware

A 3D System Capture scanner was used to determine the external geometry of the analyzed elements and components (Figure 1).

The three-dimensional scanning, but also the primary processing of the scanned surfaces was performed with a desktop computer with the following technical characteristics: INTEL Core I3 processor with a frequency of 3.7 GHz, 8 Gb RAM memory, 466 GB hard disk, Windows 8.1 operating system on 64 bit. The sets of CT scans used and analyzed were achieved using the Toshiba Asteion CT scanner at the Craiova Emergency Hospital (Figure 2).

Fig. 1. 3D System Capture Scanner.

Fig. 2. Toshiba Asteion CT Scanner.

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

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

2.2 Software

Visual analysis of tomographic images was performed using the Syngo FastView program whose interface is shown in Figure 3.

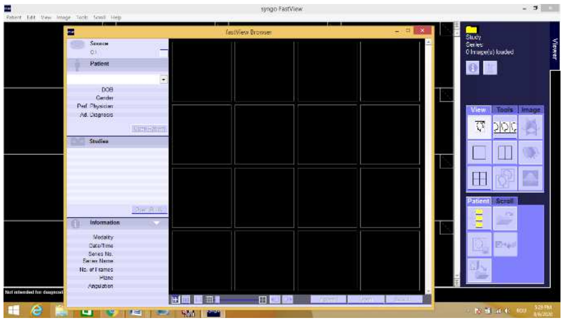

Fig. 3. Syngo FastView program interface.

A primary 3D reconstruction obtained from CT images was performed using the InVesalius program that converts the shades of gray on the images into "point cloud" geometric structures.

The analysis, processing, editing and transformation of "point cloud" structures was performed with the Geomagic program, using specific reverse engineering techniques and methods.

Transforming bone component geometries into a virtual solid was done using the SolidWorks program. Also, the different parts of the prosthetic elements were obtained. Than, the virtual model of the assembly is exported to ANSYS environment in order to perform simulations and obtain stress maps, displacements maps and deformations maps.

There are many researches based on the use of Ansys Workbench software to evaluate the stresses, displacements and deformations of human bones and joints, as well as of various orthopedic or rehabilitation robotic systems [1-4, 6-22]. ANSYS is a software package that allows to model and simulate real world phenomena [23]. It uses numerical techniques based on computational calculation to solve problems in physics, mechanics, biomechanics. The range of problems that ANSYS can solve is varied: fluid flow, heat transfer, stress analysis, kinematic analysis and more.

2.3 Methods

A number of methods were used to develop this scientific study, such as:

- CAD (Computer Aided Design) techniques and methods.
- reverse engineering methods.
- medical imaging techniques.

To analyze certain 3D models we used the finite element analysis which is based on the concept of modeling objects with complex geometry using simpler structures, or by dividing complicated models into simpler volumes for which known numerical methods can be applied. Such methods can be met in previous researches in the field of human musculoskeletal biomechanics and biomedical engineering [4, 9-17, 19 -22].

3. BONE COMPONENT MODELING OF THE INTEGER KNEE JOINT

In a first phase, a three-dimensional scan of a femoral bone component taken from the corpse was attempted. Figure 4 shows the 3D System Capture scanner during the scan operation. This operation was conducted by Geomagic for SolidWorks.

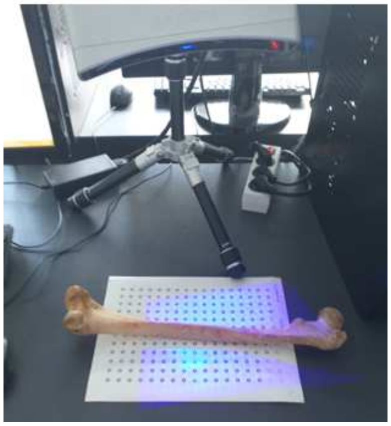

Fig. 4. Three-dimensional scanning of a femur.

Geomagic for SolidWorks scans by automatically aligning multiple successive scans. Figure 5 shows several steps of this three-dimensional scan operation.

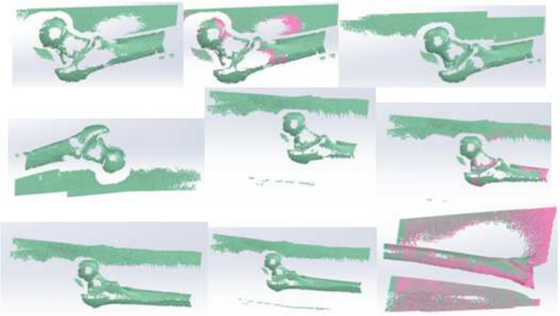

Fig. 5. Stages of the three-dimensional scanning operation.

Because this technique does not allow the determination of the internal geometry of the femur, three-dimensional scanning was abandoned, but some external surfaces were used to determine the final model.

To touch this target, the femur that was tomographed near a plastic pipe of known size were used. The presence of this pipe served to properly scale the CT images.

Using some CAD techniques included in SolidWorks, the outer and inner contours of the bone structures were drawn [1, 10, 13, 19].

A virtually engineering program, SolidWorks, was used for the virtual reconstruction of the bone components.

These contours defined the virtual solid structure of the bone components, but also the medullary canals. In these situations, Loft and Cut Loft shapes were used [1, 10, 19].

Using specific CAD methods and techniques, the complete model of the femur was obtained, which is presented in Figure 6.

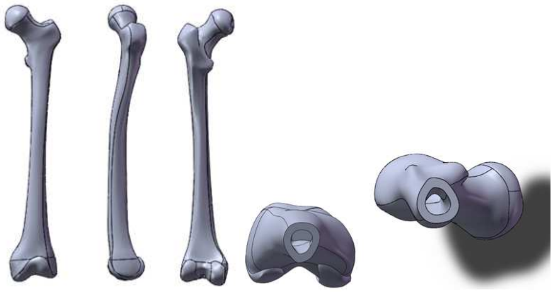

Fig. 6. Virtual model of the femur.

Also, to 3D reconstruct the knee joint, three bones were scanned CT: tibia, fibula and patella.

These CT images were loaded to the InVesalius program, which can turn into "point cloud" type some tissue structures, like bone, starting from shades of gray. Figure 7 presents the user interface of InVesalius.

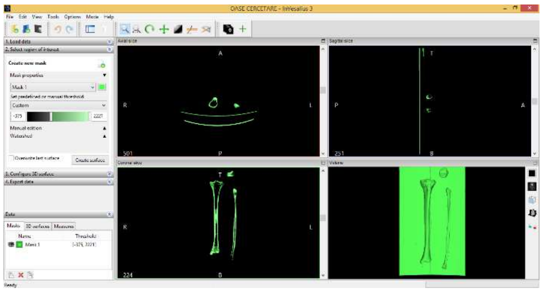

Fig. 7. InVesalius user interface for the three bone components.

The "point cloud" structure was loaded into the Geomagic program for editing, finishing and transforming into perfectly closed virtual surfaces. Figure 8 presents the user interface of the Geomagic.

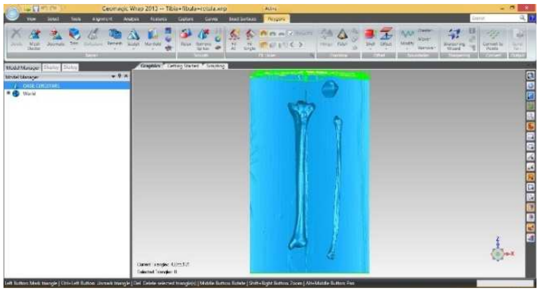

Fig. 8. Geomagic program interface.

As the support of the CT apparatus on which the three bone components were placed was also taken over, it was removed. A lasso-type selection was used, as shown in Figure 9.

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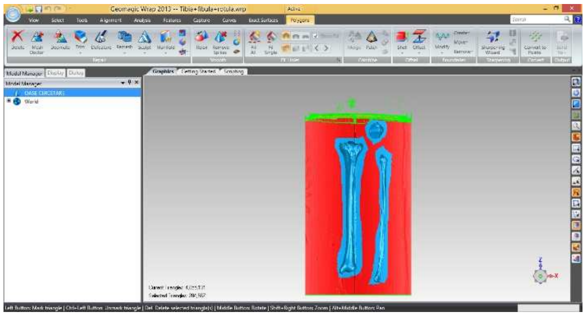


Fig. 9. Selection of surfaces to be removed (in red - selection set).

The structures that need to be removed, but also certain artifacts, being present in several layers, the removal techniques have been repeated many times. Figure 10 presents some steps of these procedures.

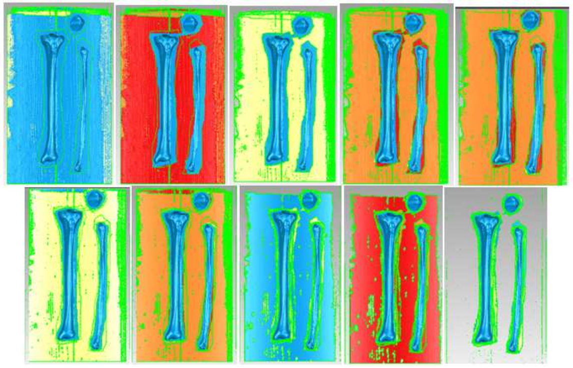


Fig. 10. Steps in the process of removing procedures.

Subsequently, several techniques and methods of Reverse Engineering were used. Also, self-intersecting surfaces and non-compliant surface elements have been removed and replaced. Figure 11 shows the final model of the three components composed of 1,078,535 elementary surfaces.

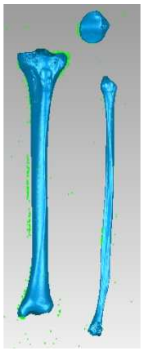


Fig. 11. Models of the three tomographic bone components.

This model will be considered as a basis for the successive definition of the three bone components. In a first phase, the fibula and patella models were eliminated (Figure 12).

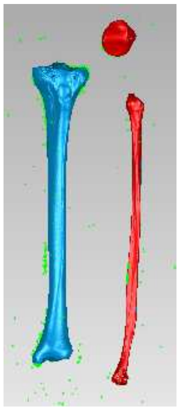


Fig. 12. Initial step of removing the fibula and patella.

Figure 13 shows the steps of removing the patella and fibula.

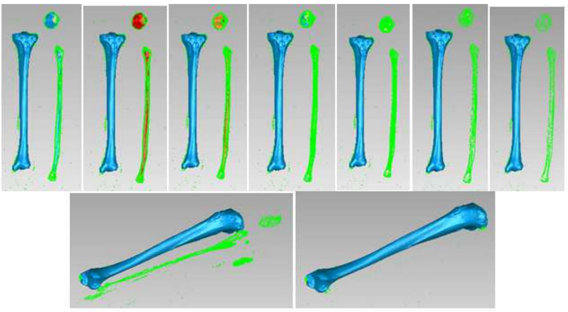


Fig. 13. Steps to remove the patella and tibia.

Next, specific Geomagic and Reverse Engineering techniques were used, and in the end, perfectly closed surfaces were obtained. In the final, the 3D structure was imported to SolidWorks where it was transformed into virtual solid. Figure 14 shows the final model of the tibia.

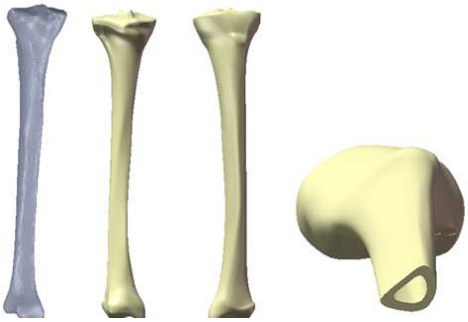


Fig. 14. The final model of the tibia.

Similar steps were taken to obtain the fibula model. Figure 15 shows the final fibula model in SolidWorks.

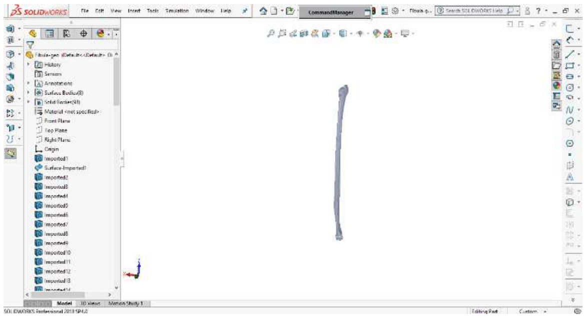


Fig. 15. The fibula model in SolidWorks.

Similarly, the virtual patella was obtained. This model was imported into SolidWorks and automatically converted into solid (Figure 16).

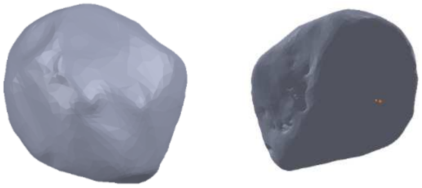


Fig. 16. Patella model in SolidWorks.

These bone components were imported into the SolidWorks assembly module named Assembly. The anatomical positions were taken into account and, based on them, the movement constraints were defined. The result of these operations is presented in Figure 17.

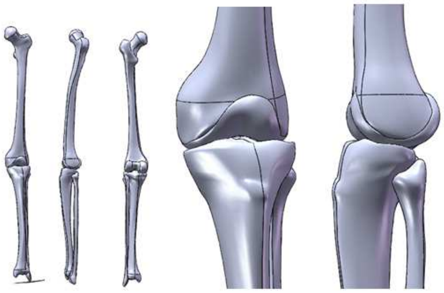


Fig. 17. The virtual model of the integer knee joint.

4. CLASSICALLY PROSTHETIC KNEE JOINT MODEL

Using CAD techniques and methods, virtual models of prosthetic components were created. When necessary, the 3D scanner was also used. Also, bone models were prepared to be able to mount the prosthesis, as it happens during the surgical procedure.

In the final stage, in the Assembly module, the virtual model of the human knee was obtained as presented in Figure 18.

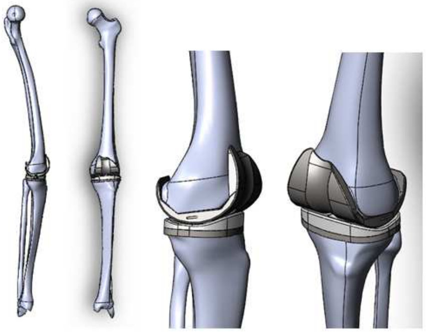


Fig. 18. The virtual model of the prosthetic knee.

5. MODELING AN INNOVATIVE METAL BALL PROSTHESIS FOR THE KNEE JOINT

Analyzing the disadvantages of current knee prostheses, but especially the problems that occur at the bone-metal contact interface, we imagined a prosthesis that has some elasticity consisting of two main components, namely, the femoral component and the tibial component. The femoral component is shown in Figure 19.

This component can also be transformed into a revision femoral component with the possibility of adding some additional pins, as shown in Figure 20.

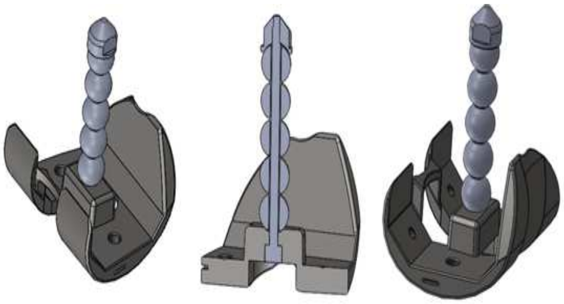


Fig. 19. The assembly of the femoral component of the innovative prosthesis with metal spheres (spatial views and sections).

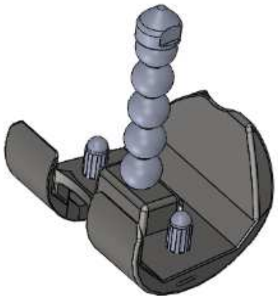


Fig. 20. Femoral compnent with added pins.

The tibial component of the innovative knee prosthesis consists of several elements that are fixed in the main body, as shown in Figure 21.

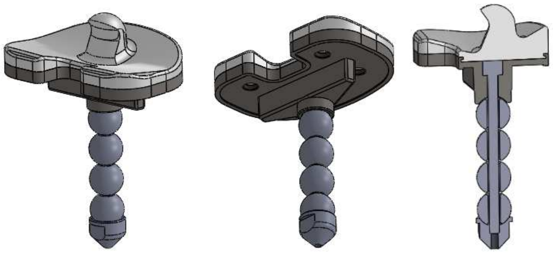


Fig. 21. Tibial component of the innovative knee prosthesis (views and section).

In order to obtain a virtual orthopedic assembly containing an innovative prosthesis with metal spheres, the bone components were prepared taking into account the known surgical protocols.

The two virtual prosthetic components, as well as the bone components were assembled in SolidWorks and the virtual model of the orthopedic system with innovative knee prosthesis was obtained, as presented in Figure 22.

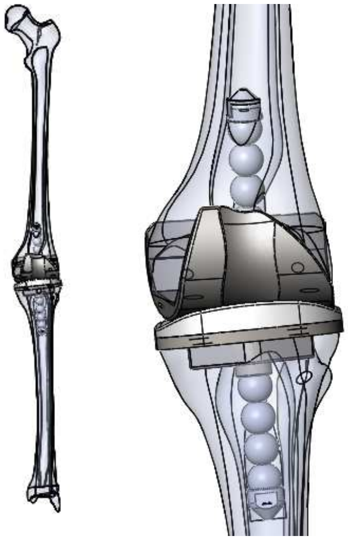


Fig. 22. The final model of the orthopedic system with an innovative prosthesis with metal spheres (two views with a degree of transparency).

6. SIMULATION OF CLASSIC PROSTHETIC KNEE JOINT BEHAVIOR AT NORMAL WALKING LOADING

The final model of the knee prosthetic joint was exported to the Ansys Workbench program, where the model was analyzed using finite element method. Figure 23 shows the model of the classic prosthetic knee joint.

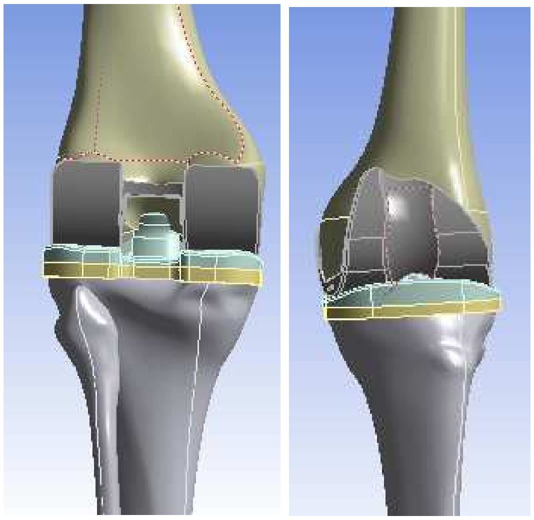


Fig. 23. The final model of the orthopedic system with classic prosthesis in Ansys Workbench.

Ansys Workbench stores materials and their mechanical properties in a library named Engineering Data, as shown in Table 1.

Table 1

Materials used to simulate the prosthetic knee.

Component	**Material**	**Density (kg/m3)**	**Young Modulus (Pa)**	**Poisson Ratio**
Femur	Bone	1400	1 E+10	0.3
Tibia	Bone	1400	1 E+10	0.3
Fibula	Bone	1400	1 E+10	0.3
The femoral component of the prosthesis	Titanium Alloy	4620	9.6 E+10	0.36
Polyethylene tibial component	Polythene	950	1.1 E+9	0.42
Tibial metal component	Stainless steel	7750	1.93 E+11	0.31

A loading system similar to normal human gait was used. The force acting on the two femoral components has been determined in various studies.

The geometry of the analyzed system was divided into tetrahedral finite elements. 169,698 items were obtained. This finite element structure of the analyzed system is shown in Figure 24.

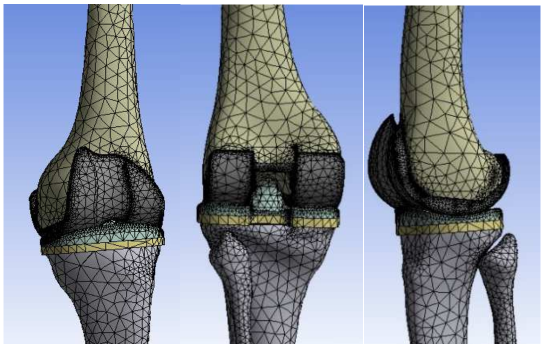
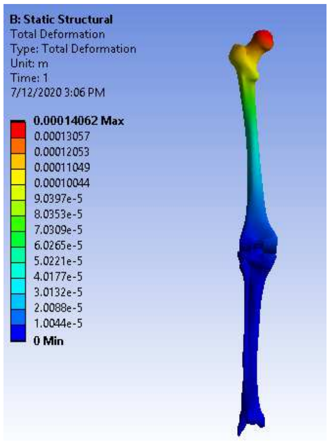


Fig. 24. The finite element structure of the analyzed system.

After running the finite element method simulation, result maps were obtained. Figure 25 shows the displacement map.



B: Static Structural
Total Deformation
Type: Total Deformation
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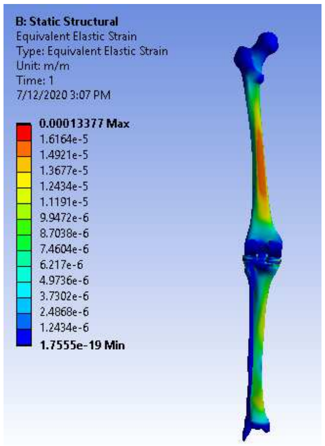
Fig. 25. Displacement map.

A map of the equivalent elastic strain as shown in Figure 26 was also obtained.



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Equivalent Elastic Strain
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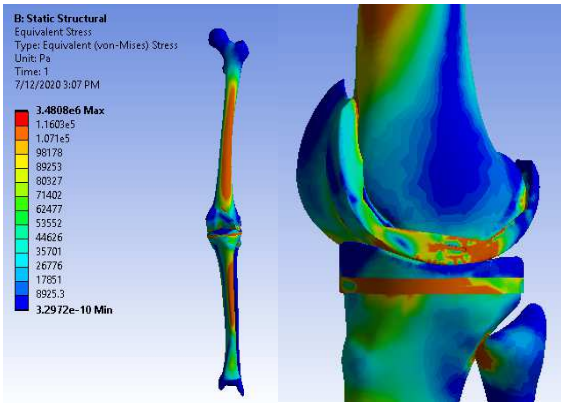
Fig. 26. Strain map.

Figure 27 shows the map of equivalent stress obtained by von Mises criteria.



B: Static Structural
Equivalent Stress
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Fig. 27. Stress maps.

7. SIMULATION OF THE PROSTHETIC KNEE BEHAVIOR WITH THE INNOVATIVE METAL BALL PROSTHESIS AT NORMAL WALKING LOAD

The virtual model of the knee prosthesis with innovative metal ball prosthesis was imported to the Ansys Workbench program, where it was analyzed using finite element method. Figure 28 shows the user interface of this program with the model of the prosthetic knee.

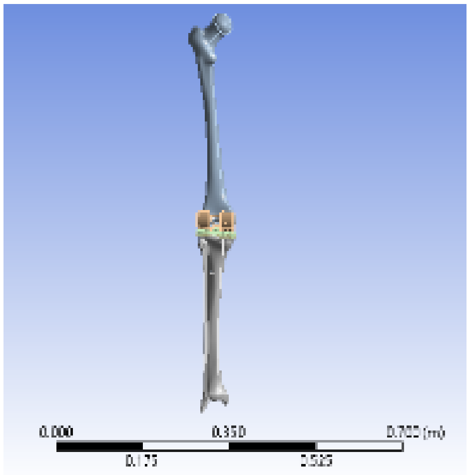


Fig. 28. Ansys Workbench user interface with prosthetic joint.

The materials presented in Table 2 were used in this simulation.

Table 2

Materials used to simulate the prosthetic knee.

Component	**Material**	**Density (kg/m3)**	**Young Modulus (Pa)**	**Poisson Ratio**
Femur	Bone	1400	1 E+10	0.3
Tibia	Bone	1400	1 E+10	0.3
Fibula	Bone	1400	1 E+10	0.3
The femoral component of the prosthesis	Titanium Alloy	4620	9.6 E+10	0.36
Polyethylene tibial component	Polythene	950	1.1 E+9	0.42
Tibial metal component	Stainless steel	7750	1.93 E+11	0.31
Tibial component shaft	Stainless steel	7750	1.93 E+11	0.31
Axis femoral component	Stainless steel	7750	1.93 E+11	0.31
Metal sphere	Stainless steel	7750	1.93 E+11	0.31
Tibial component shaft end	Stainless steel	7750	1.93 E+11	0.31
Femur component shaft end	Stainless steel	7750	1.93 E+11	0.31

A loading system similar to normal human gait was used. The force acting on the two bone components has been determined in various studies and has been thought to act for one second. The geometry of the analyzed system was divided into 72,453 tetrahedral finite elements. This finite element structure of the analyzed system is shown in Figure 29. After running the simulation, displacement maps was obtained (Fig. 30).

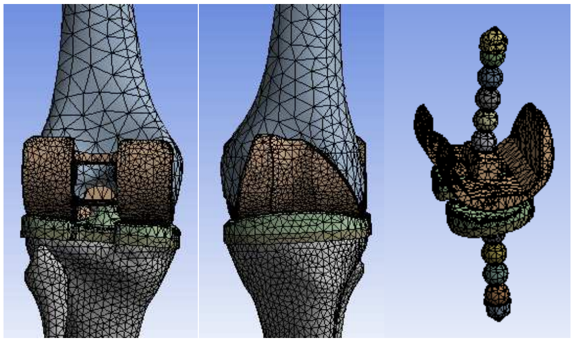
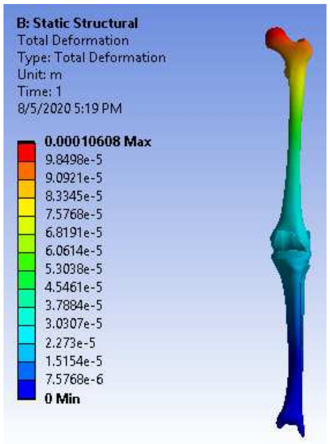


Fig. 29. The finite element structure of the system.



B: Static Structural
Total Deformation
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Fig. 30. Displacement map.

A map of the equivalent elastic strain as shown in Figure 31 was also obtained.

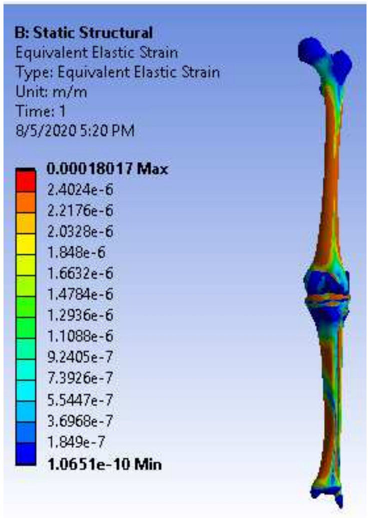

Fig. 31. Strain map.

Figure 32 shows the map of equivalent stress obtained by von Mises criteria.

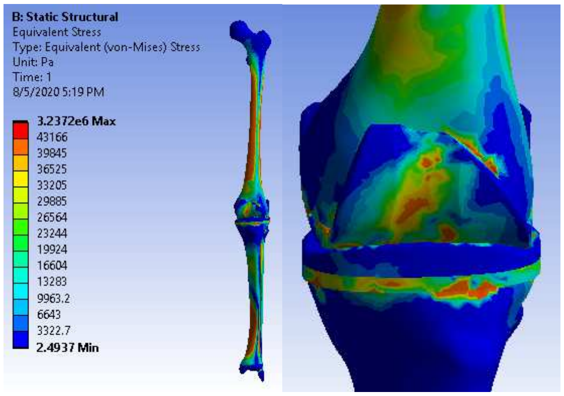

Fig. 32. Stress maps.

8. DISCUSSIONS, CONCLUSIONS AND CONTRIBUTIONS

Analyzing the methods, techniques, models and results obtained the following observations were considered important:

- The bone components, but also the components of the knee prostheses are parameterized, so that they can be modified in size or shape;
- These models can be adapted to different normal or pathological situations and can be tested virtually;
- By attaching prosthesis models to virtual bone components such as the femur or tibia, various simulations can be performed in the virtual environment.

Analyzing the maximum values of the simulations, the comparative diagrams in figures 33, 34 and 35 were obtained.

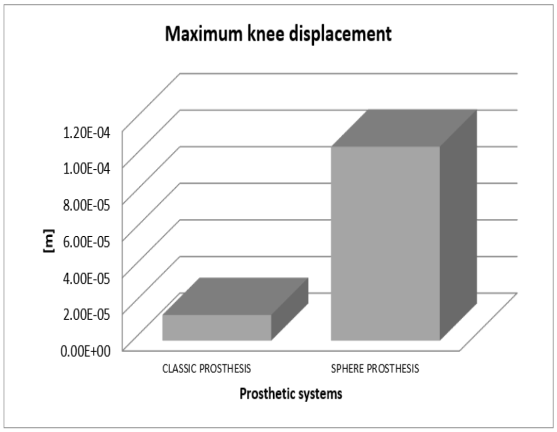

Fig. 33. Comparative diagram of maximum displacements.

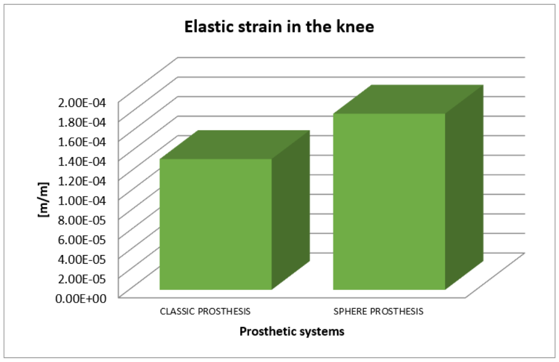

Fig. 34. Comparative diagram of maximum elastic strains.

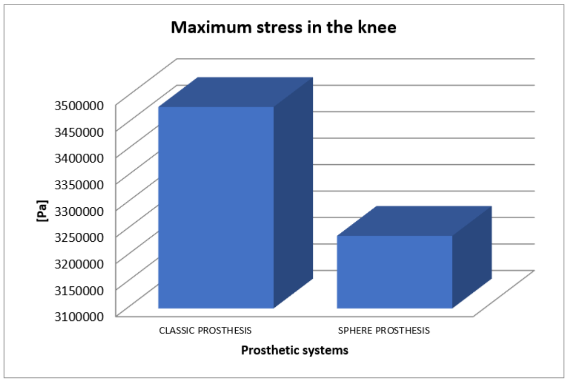

Fig. 35. Comparative diagram of maximum stress.

The aim and objectives of this study started from the practical necessity of developing an optimized model of knee prosthesis, referring in particular to the prosthesis of the knee, starting from the data collected from the literature that highlight, on the one hand, a statistical increase in the incidence of knee joint pathology and, on the other hand, a number of shortcomings found in the medical practice of existing models of knee prostheses, clinically translated into a still high rate of complications occurring in this surgical procedure.

Globally, important studies are being done to improve the design and manufacture of knee prostheses, research developed in several directions: in terms of constituent materials, design and modeling, how to fix the implant.

The objectives of this study are to achieve the model of the human knee integer and prosthetic, the behavior of the normal knee using the finite element method. A parameterized environment was used in which the prosthesis elements were modeled using both the direct measurement method and the three-dimensional scan.

Biomechanical studies have shown that polyethylene stresses are directly proportional to polyethylene wear. The vast majority of studies attempting to determine the effect of erosion of prosthetic components on contact pressure have been performed either in vitro using pressure-sensitive films or quasi-static mathematical models.

The research in this study was conducted through an interdisciplinary approach using classical and modern engineering methods, computational and virtual-experimental. Using advanced modeling techniques, the model of an innovative prosthesis was obtained using metal spheres placed on rods, which provide increased elasticity, but also a convenient stability at the level of prosthesis-bone component contact.

Using the finite element method, two orthopedic assemblies were analyzed:

- a model of the classic prosthetic knee joint without varus-valgus degrees;
- a model of the prosthetic joint of the knee with an innovative prosthesis with metal spheres without varus-valgus degrees.

Analyzing the presented comparative diagrams obtained from the finite element analyzes, the following conclusions were drawn:

- the highest maximum displacements were obtained in the case of the prosthesis with an innovative prosthesis with metal spheres, and this finding shows that this model is the most elastic;
- for the prosthetic cases the biggest deformations were obtained in the situation of the innovative prosthesis with metal spheres;
- it was also found that between the prosthetic knee system, the model with an innovative prosthesis with metal spheres is the one in which the stresses are the lowest;
- the maximum value of the stress in the system with classic prosthesis without varus-valgus degrees was $3.48 \cdot 10^6$ Pa.

The results obtained in this paper could be very useful for designing, prototyping or analyzing the kinematic behavior for different types of orthopedic implants or robotic structures used in medical recovery and rehabilitation of human upper limb or lower limb [15-16, 24-29], as well as to analyze the human movements stability [30, 31].

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O ANALIZA A UNEI PROTEZE DE GENUNCHI INOVATIVE UTILIZAND METODE INTERDISCIPLINARE

Rezumat: Lucrarea prezintă mai întâi câteva metode și tehnici de obținere a modelelor 3D ale componentelor osoase care alcătuiesc articulația genunchiului. Componentele unei proteze clasice de genunchi au fost, de asemenea, modelate și implantate virtual pe componentele osoase virtuale. Ulterior, aceste componente metalice și osoase au compus un sistem clasic de proteză de genunchi. Pe baza observațiilor clinice, a fost modelată o proteză inovatoare de genunchi care să permită o relativă elasticitate, dar și o rigiditate suficientă, pe baza unor tije elastice pe care au fost așezate sfere metalice. Acest sistem protetic a fost, practic implantat pe componentele osoase ale articulației genunchiului. Aceste două sisteme protetice ortopedice au fost analizate prin metoda elementelor finite pentru a le detecta comportamentul la sarcină similar cu mersul uman. Rezultatele obținute au fost analizate, comparate și au fost evidențiate concluzii interesante.

Mihai Cătălin ȚENOVICI, PhD Student, University of Medicine and Pharmacy of Craiova, Anatomy Department, mihai.tenovici@yahoo.com, Office Phone 0040351 443 500, Petru Rares street, no.2, Craiova, Romania.

Dragoș-Laurențiu POPA*, PhD, Associate Professor, **Corresponding author**, University of Craiova, Faculty of Mechanics, Automotive, Transportation and Industrial Engineering Deprtment, popadragoslaurentiu@yahoo.com, Office Phone +40251543739, Calea Bucuresti, 107, Craiova, Romania.

Daniel ILIUTA, PhD Student, PhD Student, University of Medicine and Pharmacy of Craiova, Anatomy Department, iliutadaniel94@yahoo.com, Office Phone 0040351 443 500, Petru Rares street, no.2, Craiova, Romania.

Gabriel BUCIU, PhD, Lecturer, Titu Maiorescu University, Faculty of Health Care, buciugabriel@yahoo.com, Office Phone 0040253221116, Ecaterina Teodoroiu Av., no. 100, Târgu Jiu, Romania.

Daniela VINTILĂ, PhD, Professor, University of Craiova, Faculty of Mechanics, Applied Mechanics Department, vintila_dnl@yahoo.com, Office Phone 0040251543739, Calea Bucuresti, no. 107, Craiova, Romania.

Diana PRUNOIU, PhD student, University of Craiova, Faculty of Mechanics, Calea Bucuresti street,107, Craiova, Romania, Phone: +40 251 543 739

Vladimir ONTICA, PhD Student, PhD Student, University of Medicine and Pharmacy of Craiova, vladontica@gmail.com, Office Phone 0040351 443 500, Petru Rares str,.2, Craiova, Romania.

Dănuț Nicolae TARNIȚĂ, PhD, Professor, University of Medicine and Pharmacy of Craiova, dan_tarnita@yahoo.com, Phone 0040351 443 500, Petru Rares street, no.2, Craiova, Romania.