A virtual approach to orthopedic systems based on implants and prostheses

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Abstract. In the parameterized virtual environments almost all the joints in the human body have been defined. The geometric models of the bone components were generated from different tomographic images taken from many patients. A revolutionary technique was used to identify the different tissues in the human body, based on the specific shades of gray. Special CAD techniques and specific three-dimensional scanning methods were used whereby the initial "point cloud" was transformed into virtual solids. But, this database, which consists of the joint geometries, can be considered ideal, because the pathology is different for each patient. Different pathological situations were created on these ideal models, which required elements of implant or prosthesis. The surgical techniques specific to each pathological situation were considered, so that the bone components were virtually prepared for virtual prosthesis or implantation. The virtual prosthetic joint was tested using the finite element method for different loads determined under normal situations. These results were compared with those obtained in the normal joint. Finally, different conclusions were pointed out.

1. Introduction

The human knee is one of the most complex human joints, by the number of components (femur, tibia and patella), by the requests to which it is subjected, by the complicated spatial geometry of the components and by the existence of multiple contacts between the different components [1], [2], [3].

The femur-tibial joint is a joint with only one degree of freedom and consequently has two main movements: flexion and extension, movements to which are added and other secondary movements such as: internal rotation and external rotation. The joint also has very low lateral tilting movements in amplitude. The average amplitude of the active movements of flexion and extension is 135°, and of the passive ones of 150°. The movements are executed in sagittal plane, around a transverse axis that passes through the two femoral condyles. The knee joint acts according to the principle of a 3rd degree lever, by moving the femur on the fixed tibia (as in the support on the ground), by moving the tibia on the femur ca (as in the sitting position), or by simultaneously moving the two bones (as in walking, when the leg is pendulous) [4], [5], [6].

Normally, all these components that make up the knee joint work harmoniously. But a certain situation or accident can disrupt this harmony and cause pain, decreased muscle power and decreased mobility [2], [7], [8].
The first knee prosthesis surgery (knee arthroplasty) took place in 1968. Since then, innovations in surgical materials and techniques have significantly contributed to improving the performance of this intervention, with total knee arthroplasty being one of the most successful procedures in all of medicine [5], [9], [10].

Prosthetic alignment is one of the most important factors, both in terms of the proper functioning of the neo-articulation and in the survival of the knee arthroplasty. Significant changes in the alignment of prosthetic components affect the distribution of stresses at the knee joint. These changes may also affect the distribution of stresses on the contact surface, the soft joints of the knee and the underlying bone that has the tendency to reshape under the action of these forces [8], [11], [12], [13].

Given these aspects, the need for implant elements to be introduced in parameterized virtual environments to be modeled and tested is becoming more and more popular. These parameterized virtual environments allow the simulation of different situations that occur in the orthopedics of the knee, such as: simulation of normal walking, running, different pathological cases or pre, intra or post-surgical situations. Also, implant or prosthesis elements can be tested using the finite element method [10], [14], [15], [16].

2. Obtaining virtual models of the normal knee joint
Several methods of obtaining virtual bones have been identified:
- a method is based on three-dimensional scanning, but in this situation, the models contain only external geometry, without medullary channels [8], [17], [18], [19];
- a method that is based on three-dimensional reconstruction using CT images (computer tomography) that uses many software techniques and involves the use of several programs. This method, from which several sub-methods have been developed, allows to obtain models almost identical to those of the patient undergoing CT operation starting with the identification of bone tissue from shades of gray [8], [20], [21], [22].

In order to obtain the bone components that make up the knee joint, three bones were taken from a cadaver: the tibia, fibula and patella. For the femur, a similar procedure was performed using tomography on a femur taken from a corpse. The tomographic images were uploaded to the InVesalius program which can recognize the three-dimensional geometries of the different tissues, including the bone, based on the shades of gray. Figure 1 shows the interface of this program [8].

![InVesalius interface for the three bone components after the Create Surface command is applied.](image-url)
Because this program cannot generate virtual solid type structures, the InVesalius model was exported as a .STL format to Geomagic for processing and editing these files. Figure 2 shows the interface of the Geomagic program.

![Figure 2. Geomagic program interface.](image)

Because the support of the CT device on which the three bone components were placed was taken over, it must be removed. A lasou selection was used as shown in Figure 3.

![Figure 3. Selecting the surfaces to be removed (in red - the selection set).](image)

Because the support structure consists of several overlapping layers, the procedure has been repeated several times. Figure 4 shows several stages of the elimination process.
Figure 4. Stages of the support removal process.

The point of view has changed and the process of removing the support is continued (Figure 5).

Figure 5. Completion of the operation to remove additional surfaces.

At that time, the obtained file was considered as a basis from which two components were eliminated. For example, in the following, we will show how the tibia model was obtained, similar to the other bone components. After removal of the fibula and patella, the tibia model was composed of 822278 elementary triangular surfaces. A model that contains so many elements is difficult to transform into a virtual solid. For this reason, the model was subsequently subjected to a decrease operation of this number of elements using the Decimate command. However, this decrease must be accompanied by Quick Smooth finishing operations. These transformations are shown in Figure 6, and the model contained 82313 elemental surfaces.
In the end, with models containing only tens of thousands of elemental surfaces, they were exported to SolidWorks where they were automatically transformed into virtual solids. Images of these bone components are shown in Figure 7.

These virtual bone components were loaded into the SolidWorks assembly module. The result of these operations is shown in Figure 8.
3. Virtual model of the prosthetic knee joint
In parallel with the generation of virtual models of bone components, the two elements of the knee prosthesis were modeled. For this, different modeling techniques were used and a 3D scanner was used. Finally, the components of the knee prosthesis presented in Figures 9 and 10 were obtained.

**Figure 9.** The virtual model of the femoral component.

**Figure 10.** The virtual model of the tibial component.

By analyzing the surgical techniques specific to the knee prosthesis, the bone components were prepared for the virtual prosthesis knee joint system. Figure 11 shows these components.

**Figure 11.** Bone components prepared for virtual prosthesis.

Finally, in the Assembly module, the final model of the human knee was generated as shown in Figure 12.
4. Analysis of normal knee behavior using the finite element method

To study the behavior of the human knee, the virtual model was exported from SolidWorks into the Ansys Workbench where simulation will be performed using the finite element method, as shown in Figure 13.

![Figure 13. The integer knee model in Ansys.](image)

In a first stage, the normal knee model was divided into finite elements, obtaining the structure shown in Figure 14.
The material that was attached to the three bone components has the properties that are shown in Table 1 [23], [24], [25].

| Component          | Material | Density (kg/m3) | Young's Modulus (Pa) | Poisson's Ratio | Shear Modulus (Pa) |
|--------------------|----------|-----------------|----------------------|-----------------|-------------------|
| Femur, tibia, fibula | Bone     | 1400            | 1 E+10               | 0.3             | 8.3331 E+9        |

The force used to load the analyzed system is the characteristic of the normal gait, as shown in Figure 15.

After running the application, maps of stresses, displacements and deformations shown in Figure 16 were obtained.
5. Analysis of prosthetic knee behavior using the finite element method

The model of the knee joint was exported to Ansys where the division into finite elements was realized, as shown in Figure 17.

![Figure 17. The finite elements structure of the prosthetic knee.](image)

In this simulation the same loading system used in the previous simulation was used, i.e., the specific loading of the normal human gait [23], [24], [25]. The materials used and their characteristics are those presented in Table 2 [26], [27].

| Component          | Material      | Density (kg/m³) | Young's Modulus (Pa) | Poisson's Ratio | Shear Modulus (Pa) |
|--------------------|---------------|-----------------|----------------------|----------------|-------------------|
| Femur, tibia, fibula | Bone          | 1400            | 1E+10                | 0.3            | 8.3331E+9         |
| Femoral prosthetic component | Titanium Alloy | 4620            | 9.6E+10              | 0.36           | 1.142E+11         |
| Tibial polyethylene component | Polyethylene   | 950             | 1.1E+9               | 0.42           | 2.291E+9          |
| Tibial metal component | Titanium Alloy | 4620            | 9.6E+10              | 0.36           | 1.142E+11         |

After running the simulation based on the finite element method, stress, displacement and deformation maps were obtained as shown in Figure 18.

![Figure 18. The stress, displacement and strain maps.](image)

6. Discussions and conclusions
Analyzing the results maps it was found that the almost values obtained when simulating the prosthetic knee joint are much higher than in the normal knee situation. Thus, in Figure 19 a comparative diagram of the maximum stress was presented.

![Comparative diagram for maximum stress](image)

**Figure 19.** The comparative diagram for stress.

Figure 20 shows the comparative diagram of the maximum displacements for the two simulations.

![Comparative diagram for maximum displacement](image)

**Figure 20.** The comparative diagram for displacement.

Also, the maximum strains obtained from the two simulations were compared with the finite element method. Because the prosthetic system is much stiffer than the normal knee, the strains are smaller in the normal case. Figure 21 shows the comparative diagram of the maximum strain.

![Comparative diagram for maximum strain](image)

**Figure 21.** The comparative diagram for strain.

Also, it was found that the maximum stresses were found in the area of the femur and tibia diaphysis, but also on the contact surfaces between the femur and tibia, but also on the contact surfaces between the components of the prosthesis, as seen in Figure 22.
The use of the CAD parameterized programs coupled with the use of modern investigation tools (computed tomography, magnetic resonance investigation equipment, 3D scanner, rapid prototyping equipment, three-dimensional reconstruction programs, etc.) allow, at least theoretically, the personalization of studies for groups of patients, but also for each patient. This advantage is given by the fact that, in each individual, in general, the anatomical structures subjected to the study have the same shape, but different dimensions. The methods and techniques proposed by this paper open the way for the integration of research using modern concepts, such as virtual prosthesis, medical diagnosis in virtual reality.

7. References
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Figure 22. Stress in contact areas.
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