Numerical Simulations of 3D Model of Knee-prosthesis Assembly with Antero-posterior Tibial Slope

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Abstract: In this paper, starting from the virtual model of the human knee joint, and existent knee prosthesis, often used in total knee arthroplasty, we developed 3D models of all prosthetic components. The study investigates the effects of antero-posterior tibial slope on contact stresses in all components of total knee prosthesis using finite element analysis. Using Ansys Workbench 15.07 software, the stress and displacements maps are obtained for healthy knee, for osteoarthritic knee and for knee-prosthesis assemblies. Two loading force are considered: 800N and 2400N. For each prosthesis-knee assembly, two cases were considered: an antero-posterior slope of 0° and 5° respectively. The results, confirmed by clinical observations, suggest that the antero-posterior tibial slope of 5° is favourable.

Keywords: 3D virtual knee prosthesis, total knee arthroplasty, finite element method, von Mises stress, antero-posterior tibial slope,

I. Introduction

The knee joint is one of the most complex human joints taking into account the number of its components, their spatial geometry and their mechanical properties, the contacts between elements and the pressures acting on them. Virtual models were analyzed with finite element method in order to analyze much better the tibio-femoral contact area, the stress and displacements developed in the human knee joint under different solicitations. Virtual modeling of human knee joint has been addressed in several articles [1-19]. An important benefit of human joints numerical analysis lies in the flexibility of the modelling processes which can control of motion, loading and boundary conditions in the studies of joint response. The finite element method is becoming one of the most important tools in orthopaedic biomechanics.

The finite element models of lower extremity are used to simulate a behavior of a healthy knee joint in-vivo [1-4]. In [5-10] studies regarding the development of osteoarthritis in knee joint which represent one of the most important disease which lead to total arthroplasty, are presented. In [11] the influence of the contact force model, contact geometry, and contact material properties on the dynamic response of a human knee joint model is studied.

In the last decades major advancements in artificial knee replacement have improved the outcome of the surgery greatly. Finite element (FE) modeling allows implants to be tested and has been used in several biomechanical studies [12-31].

FE method is used to evaluate biomechanical behavior of cancellous bone on patellofemoral arthroplasty [12], to evaluate and compare the proposed design of a custom femoral component with a conventional design [13-15], to evaluate the tibio-femoral contact stress [16, 17]. The influence of different designs of the joint area on tibial component fixation, kinematics and clinical outcome after a cemented total knee arthroplasty was studied in [18]. In [20-22, 26-27], the finite element method is used to simulate the loading conditions applied to the prosthesis device during the walking cycle in order to estimate the contact area, the contact pressure and the stress status of the polyethylene tibial components.

Posterior tibial slope that is created during proximal tibial resection in total knee arthroplasty has emerged as an important factor in the mechanics of the knee joint and the surgical outcome [29-31]. In [31] the wear behavior of four different posterior tibial slopes to find out the appropriate posterior slope is presented.

The objective of this study was to investigate the effects of posterior tibial slope on contact stresses in all components of total knee prosthesis using 3D finite element analysis.

2. Virtual modeling of the knee prosthesis components

2.1 Geometric modeling

A knee prosthesis is made up of three parts:
- The tibial component that replaces the top of the lower bone, the tibia, being attached directly to the bone;
- Polyethylene tibial component that provides the bearing surface;
- The femoral component that replaces the two femoral condyles and the groove where the patella runs on the distal femur.

We used, as model, Scorpio Stryker type knee prosthesis, a common prosthesis used by orthopaedic surgeons in the Emergency Hospital of Craiova. The real models of the three prosthetic components are presented in Fig.1.

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To design the virtual model of the knee prosthesis, the DesignModeler application which is a pre-processor of AnsysWorkbench15.07 [32] is used. Using the effective measurement made on real components and after the identification of the simple shapes, the modeling operation was started. We have taken into account the 3D virtual model of healthy knee joint (Figure 2) elaborated by our team based on CT images [9,10].

Solids were built over the geometrical model of healthy human knee joint, and they were cut with profiles made in various planes, in conformity with the surgical guides used in knee total replacement. Using „Slice, Body Operation, Extrude, Boolean Operation” commands and different features, the three prosthesis components were developed (Fig.3-4). We verified the positioning on bones to be without penetrations and gaps. Contact areas between the femoral component and the polyethylene insert were performed using operations such as “Subtract, Check Body Entity”, which are particularly important for finite element analyses.

After achieving the virtual model of the prosthesis, we aimed at an accurate positioning over bone ends, eliminating possible penetrations and gaps. Images for virtual models of knee joint with prosthesis are presented in Fig.5. To emphasize the polyethylene insert, we used a lighter colour than for the other 2 components of the prosthesis.

### 2.2 Mesh generation

For the realisation of numerical simulations of prosthesis joint, the following components that make up joint-prosthesis assembly have been considered: femur, tibia and the 3 components of the prosthesis: femoral, tibial and polyethylene insert. These components have been placed in a global XYZ system, which is required for proper placement of loads and degrees of freedom for the entire assembly. The structural analysis is statically nonlinear, nonlinearity being present by nonlinear contacts between the surfaces of polyethylene insert and femoral prosthesis component. Correct positioning of components and the analysis with finite element method has been achieved in the simulation environment of AnsysWorkbench15.07 application. This application is
intended for CAE field which allows advanced modeling and discretization using finite element method. The mesh geometry was realised using hexahedral elements of Solid186 type and tetrahedral elements of Solid 187 type, both of them being solid elements with middle node. Middle nodes are necessary for better approximation of results and their accuracy. For prosthesis components, “Sweep”, “Patch Conforming” and „Hex Dominant” methods were used for advanced discretization of complex areas in hexahedral elements, for control element formation. For an efficient discretization, elements with dimensions of 1 mm and 1.5 mm respectively, for the areas of maximum interest were used (femoral prosthesis-femur, femoral prosthesis - polyethylene insert, polyethylene insert - tibial prosthesis and tibial prosthesis - tibia contact areas). The transition from this dimension to a larger dimension of 4 mm for less complicated areas is possible by means of the options “Smoothing” on medium and “Transition” on fast. In Fig. 6 the mesh structure of the knee joint-prosthesis ensemble is presented. For each of studied cases: healthy knee (HK), osteoarthritic (OA) knee and knee-prosthesis assembly the virtual model is discretized individually, the contact areas are readjusted and the analysis is run.

In Table 1 the numbers of nodes and elements for knee joint bones and for prosthesis component corresponding to the joint-prosthesis model at 176° are presented.

![Image](image1)

**Fig. 6. a) Human knee joint with prosthesis – Local view of node and element network; b) Isometric view of prosthesis mesh network;**

<table>
<thead>
<tr>
<th>Component</th>
<th>Nodes</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femur</td>
<td>144024</td>
<td>46321</td>
</tr>
<tr>
<td>Tibia</td>
<td>85185</td>
<td>26050</td>
</tr>
<tr>
<td>Femoral component</td>
<td>36180</td>
<td>10605</td>
</tr>
<tr>
<td>Tibia component</td>
<td>30479</td>
<td>8295</td>
</tr>
<tr>
<td>Polyethylene component</td>
<td>55456</td>
<td>15857</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>351324</strong></td>
<td><strong>107128</strong></td>
</tr>
</tbody>
</table>

**Table 1. The network of nodes and elements**

2.3. Boundary conditions

“Bonded” and “No Separation” type contacts were used for the prosthesis components contacts. The calculation algorithm used for contacts is of “Augmented Lagrange” type. This algorithm adds an extra control to automatically reduce penetrations, being recommended because of its flexibility features. To impose a better interpretation of the areas that define the contact, “Bonded”, “No Separation” and “On Gauss Points” commands were used. A contact radius of 0.1 mm was also assigned by means of the option “Pinball Region”, which supposes that the solver shall assess these areas more efficiently before the components enter into contact. We must check these contacts to be closed using “Sticking” and, respectively, “Sliding” options (Fig. 7).

![Image](image2)

**Fig. 7. Visualisation of different control methods for the contacts between knee components: a) Visualisation of free spaces between components; b) Visualisation of penetrations; these may occur between the components participating in the contact.**

The material properties are assigned to the different components of the assembly based on previously published data and they are found in Table 2.

<table>
<thead>
<tr>
<th>Component</th>
<th>Young’s Modulus MPa</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femur</td>
<td>17600</td>
<td>0.3</td>
</tr>
<tr>
<td>Tibia</td>
<td>12500</td>
<td>0.3</td>
</tr>
<tr>
<td>Femoral component</td>
<td>210000</td>
<td>0.3</td>
</tr>
<tr>
<td>Tibial component</td>
<td>210000</td>
<td>0.475</td>
</tr>
<tr>
<td>Polyethylene component</td>
<td>1100</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The settings for the analysis and the boundary conditions are the following:

- taking into account the large number of nodes and elements but, also, the presence of nonlinear contacts, for solving the analysis it is necessary to implement a “smaller steps” system; solver was set as Preconditioned Conjugate Gradient level 2 iterative types.
- on the proximal head of the femur bone there is applied a 800N force and 2400 N force in the -Z axis direction; 
- on the same location it is applied the "Remote Displacement" that allows offset Z and RotY around the femur which allows movement of the hip; 
- on the tibia distal head is applied "Remote Displacement", which allows RotY (movement of the ankle around the tibia).
3. Results

Using AnsysWorkbench 15.07 software, the numerical simulations and FEM analyses were processed for healthy knee joint, for OA knee joint with a deviation angle of 6° and for knee joint-prosthesis assemblies with antero-posterior slope of 0° and 5° respectively. The two variants of 0° and 5° tibial slope were chosen because Stryker Company offers both variants of complete surgical instruments for total knee arthroplasty for these two cases. Clinical observations show that for the case of 5° tibial slope is easier to mount the knee prosthesis components during total knee arthroplasty and, after surgical act, the flexion movement is improved (the range of motion increases). Two loading forces were taken into consideration: 800 N and 2400 N.

Applying a loading force equal to 800N for entire biomechanical system of healthy knee (HK) a maximum total displacement equal to 7.24 mm and a maximum von Mises stress equal to 6.98MPa, developed near the distal femoral head, are obtained (Fig.8). Von Mises stress was colour-coded where red represented the highest stress, while the blue represented the lowest.

Von Mises stresses maps obtained for healthy knee corresponding to a loading force equal to 800 N in femoral cartilage, tibial cartilage and menisci are presented in Fig. 9. The images represent Top and Bottom views.

Table 3. Von Mises stress for healthy knee (HK) and for osteoarthritic knee (OAK) with a varus inclination of 5°

<table>
<thead>
<tr>
<th></th>
<th>HK</th>
<th>OAK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femoral cartilage stress [MPa]</td>
<td>2.41</td>
<td>3.42</td>
</tr>
<tr>
<td>Tibial cartilage stress [MPa]</td>
<td>2.17</td>
<td>3.01</td>
</tr>
<tr>
<td>Menisci stress [MPa]</td>
<td>2.12</td>
<td>2.54</td>
</tr>
</tbody>
</table>

Applying a loading force equal to 800N, for entire biomechanical system of prosthetic knee (PK) with antero-posterior slope of 5°, a maximum total displacement equal to 2.37 mm and a maximum von Mises stress equal to 18.14MPa are obtained (Fig.10).

Table 4. Displacements and stress for entire biomechanical system

<table>
<thead>
<tr>
<th></th>
<th>HK</th>
<th>PK 0°</th>
<th>PK 5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total displac. [mm]</td>
<td>7.24</td>
<td>2.37</td>
<td>2.62</td>
</tr>
<tr>
<td>Lateral displac. [mm]</td>
<td>7.17</td>
<td>2.35</td>
<td>2.47</td>
</tr>
<tr>
<td>von Mises stress [MPa]</td>
<td>6.98</td>
<td>18.14</td>
<td>14.08</td>
</tr>
</tbody>
</table>

Von Mises stresses maps (Top and Bottom views) obtained for a loading force equal to 800 N in polyethylene insert, tibial prosthesis and femoral prosthesis for an angle of 176° with 0° antero-posterior slope are presented in Fig. 11.

For the case of 5° antero-posterior tibial slope, the maps are presented in Fig.12.
The maximum stress values obtained for each analysed component of knee joint-prosthesis assembly for a load equal to 800N and 2400 N, in both cases: 0° and 5° antero-posterior slope, respectively, are presented in Table 5. The displacements values are presented in Table 6.

Table 5. Von Mises stress maximum values

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
<td>800N</td>
<td>18.14</td>
<td>16.82</td>
<td>17.28</td>
<td>10.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2400N</td>
<td>53.78</td>
<td>50.12</td>
<td>51.84</td>
<td>31.29</td>
</tr>
<tr>
<td></td>
<td>5°</td>
<td>800N</td>
<td>14.08</td>
<td>12.85</td>
<td>13.25</td>
<td>6.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2400N</td>
<td>40.15</td>
<td>37.73</td>
<td>38.41</td>
<td>19.73</td>
</tr>
</tbody>
</table>

Table 6. Displacements maximum values

<table>
<thead>
<tr>
<th>Antero-post. slope</th>
<th>Case</th>
<th>Total Displ.[mm]</th>
<th>Lateral Displ.[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
<td>800N</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2400N</td>
<td>7.13</td>
</tr>
<tr>
<td></td>
<td>5°</td>
<td>800N</td>
<td>2.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2400N</td>
<td>7.87</td>
</tr>
</tbody>
</table>

Analyzing the results obtained by numerical simulations, presented in Table 5, we can see an increase of stress for OA knee joint versus the case of healthy knee joint for all components: femoral cartilage, tibial cartilage and menisci. The OA knee is exposed to greater stress at the medial compartment of the articular cartilage of the tibia and femur. The maximum values of von Mises stress increase with about 50% in OA case. The results show that misalignment (varus variation) could damage the articular cartilage because they increase the stress magnitude that progressively produces articular cartilage damage. In knee-prosthesis assemblies, we can observe that for a slope of 5° the stress decrease with about 20%. The decrease of stress values proves an improvement in knee stability and rehabilitation. The distribution of von Mises stress was more uniform with 5° than 0° posterior tibial slope and the peaks of von Mises stress were smaller with 5° slope, one of the explanation being that in this case the contact areas increase.
4. Conclusion

In this paper, starting from the virtual model of the human knee joint and existent knee prosthesis, we developed 3D models of prosthetic components: femoral component, tibial component and polyethylene insert. Antero-posterior tibial slope that is created during proximal tibial resection in total knee arthroplasty represents an important parameter in the knee joint post surgical biomechanics for recovery of the knee joint function and preventions of complications. Using AnsysWorkbench15.07 software, the stress and displacements maps are obtained for healthy knee, for OA knee joint and for analyzed knee-prosthesis assemblies. The Finite Element Method is used to investigate the effects of antero-posterior tibial slope on contact stresses in the tibial polyethylene component of total knee prostheses and to obtain the diagrams and the maximum values of von Mises stress and displacements. The findings of this study confirms the clinical observations of surgeons, that the posterior tibial slope of $5^\circ$ is favourable. The main advantage of the numerical simulations and FEM analysis consists in the fact they can be done in order to evaluate the biomechanical behaviour of human joints without an invasive intervention. A finite element analysis of the normal and prosthetic knee model will help surgeons and biomechanical researchers to develop improved devices for rehabilitation movements of patients suffering diseases.

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References

[32] www.ansys.com