Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 9, Issue 4 / 2024, p. 371 - 382

http://doi.org.10.56958/jesi.2024.9.4.371

A. Mechanical Engineering

Received **_20 August 2024_** _Accepted_ **_4 December 2024_**
Received in revised form **_8 October 2024_**

3D Modelling and numerical simulations of menisci in normal and osteoarthritic human knee joint

Daniela Tarnita[1*], Marius Catana[2]

[1]Department of Applied Mechanics, University of Craiova
[2]INAS, Craiova

Abstract. This paper presents 3D virtual modeling of the menisci in the human knee joint, based on CT sections performed on the human knee joint. CT images were processed using advanced modeling and simulation methods as Space Claim and Design Modeler integrated application under Ansys Workbench software package. By using Finite Element Analysis, the stresses and displacements from normal menisci, but also from those affected by osteoarthritis, are studied for the cases of 5 degrees valgus deviation of the mechanical axes of the knee. The study concludes with a comparison between the results obtained from the analysis performed for the healthy menisci, on the one hand, and for the damaged ones, on the other hand.

Keywords: menisci, virtual model, finite element analysis, healthy and osteoarthritic knee, valgus.

1. Introduction

Among the elderly population, falls tend to arise from several interacting factors [1]. These can be biological factors such as a neurological mechanism, a chronic condition such as osteoarthritis, or extrinsic factors such as a wet and slippery floor, an icy road, various obstacles, poor lighting [2,3]. In addition to the immediate physical consequences, such as hip fractures or menisci tears, falls can also generate negative mental health outcomes, such as fear of falling or depression [4].

An individual's stability can be affected by musculoskeletal disorders. Hundreds of millions of people suffer from such conditions, globally, and this number is expected to increase with the aging of the global population [5]. Many such

*Correspondence address: daniela.tarnita@edu.ucv.ro

diseases have the effect of loss of stability and instability causes falls that cause fractures or other traumas that require surgical interventions and unavailability, thus generating a significant economic-social impact. One of the conditions that affect stability is arthritis. Osteoarthritis (OA) is the most common form of arthritis, based on a continuous degenerative process of the cartilages, which will lead, over time, to their complete destruction and loss. [5]. The knee osteoarthritis is the most common disease of this type. This degenerative process is caused by several factors such as: overweight, obesity, exaggerated physical exercises, joint trauma, long periods of immobilization or, on the contrary, an exaggerated hypermobility. In the advanced stage of the disease, when the destruction is very large, an endoprosthesis is required, i.e. a replacement of the joint, leading to a pain reduction and a mobility increasing.

Osteoarthritis of the joints is one of the major chronic diseases, usually found in middle-aged and elderly people, affecting a big number of people and being the third fastest growing disability-related condition, just after diabetes and dementia [6]. Globally it is the 4^{th} most common cause of health problems among women and the 8^{th} most common cause among men. Approximately 40% of people over 70 are affected by osteoarthritis of the knee. Among people with osteoarthritis, approximately 80% have limited mobility [5], and 25% of them can no longer carry out important basic activities of daily life.

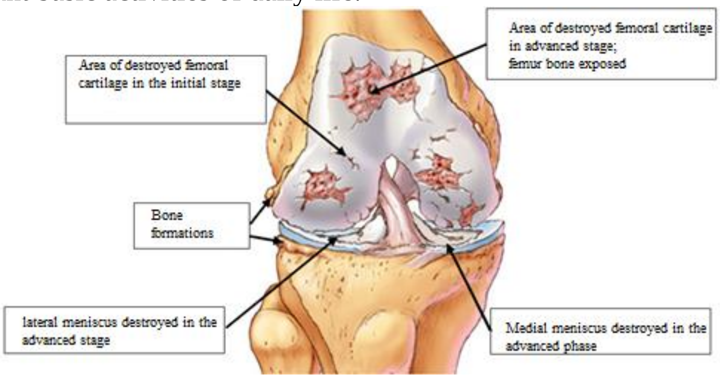


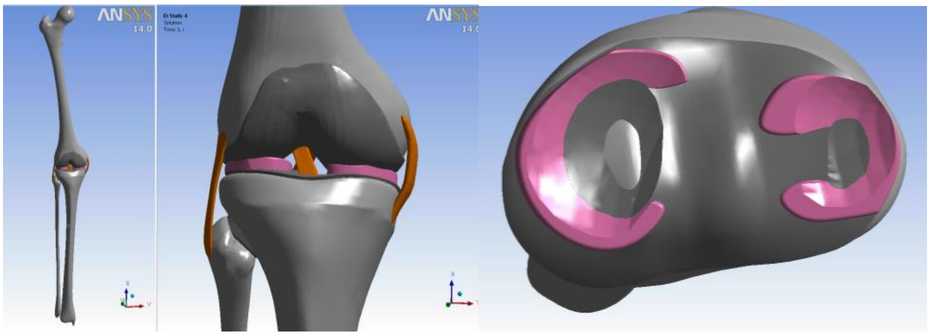
Fig. 1. The osteoarthritic human knee [7]

2. 3D virtual model of healthy and osteoarthritic human knee joint

2.1. 3D virtual model of healthy knee

Over time, researchers have used a whole series of techniques, methods and tools to model the human knee joint, aiming to define more and more precisely the complex shape of the joint components. There are many studies highlighting the contribution to improving the accuracy of the geometric model of the components, taken separately, as well as of the human knee joint assembly [8-11].

Some models of the human knee joint are simpler taking into account only the constituent bones, other are more complex, taking into account the cartilages, the ligaments and menisci [12-16]. The construction and validation of three-dimensional virtual models of human joints, which have an increased anatomical complexity, is extremely difficult if one takes into account the geometry, structure and mechanical properties of their components, as well as their biomechanical behavior. The Finite Element Method is a very useful and complex tool in evaluating and estimating the complex behavior of human joints. Considerations for reporting finite element analysis studies in bones and joints biomechanics and parameters for the validation of musculoskeletal and finite elements joint models are reported in papers [16-24] including the analysis of tibiofemoral and patellofemoral joints, femoral and tibial cartilages deformations and displacements, as well as of menisci, which are important for the assessment of musculoskeletal disorders. Development of the complex virtual spatial model and finite element analysis of the human knee are studied by researchers more and more, with deep analysis of menisci and cartilages, of the relationship between meniscal pathologies, cartilage loss, pain in knee osteoarthritis [17-27] and knee replacement [28-30]. In Fig. 2 the virtual model, elaborated by our team and presented in detail in [12] is shown.



a) b)

Fig. 2. a) Virtual model of healthy human knee; b) Detail: virtual menisci: lateral and medial.

The Ansys Workbench package allows the correct, real location of the components, ensures a correct distance between them as well as a correct geometric structure, ensures the highlighting and control of geometric problems in the contact areas. The components considered for the finite element analysis are: femur, tibia, fibula, femoral cartilage, tibial cartilage, lateral meniscus and medial meniscus. The finite element analysis is a non-linear static type, caused by the occurrence of non-linear contacts at the level of the cartilages and menisci.

The control conditions of the analysis are as follows:

- the analysis was performed in a period of 1s;
- since the non-linear contact and a big number of elements and nodes are present, it is important to implement the analysis in many steps;
- the solver is of the iterative type: PCG level 2;

The boundary conditions of this analysis are:

- in the center of the femoral bone head, a uniformly distributed force of 800N is applied, along the -Z direction;
- rotation around the Y axis of the system is allowed; the rest of the displacements along the X, Y axes, respectively the rotations along the X, Z axes are 0;
- Remote Displacement, support that allows movement from the ankle level, allowing free rotation around the Y axis.

The mesh network of the virtual model is based on Solid 186 hexahedral elements and Solid 187 tetrahedrons of size 1 mm, both of which are solid elements with a node in the middle. Hexahedral elements were used for the cartilages and menisci, and tetrahedral elements were used for the femur, tibia and fibula.

Table 1. Number of nodes and elements for healthy knee components

Geometric component	Number of nodes	Number of elements
Femur	185.402	58.604
Femoral cartilage	80.036	22.061
Tibia	127.919	38.401
Tibia cartilage	33.787	8.795
Lateral meniscus	8.182	2.596
Medial meniscus	7.965	2.519
Fibula	39.118	12.876
Tibia-fibula cartilage	6.678	2.365
Medial ligament	6449	2223
Lateral ligament	7876	2747
Anterior cross-linked ligament	1.660	620
Posterior cross-linked ligament	1.885	679
Total	**488.092**	**148.397**

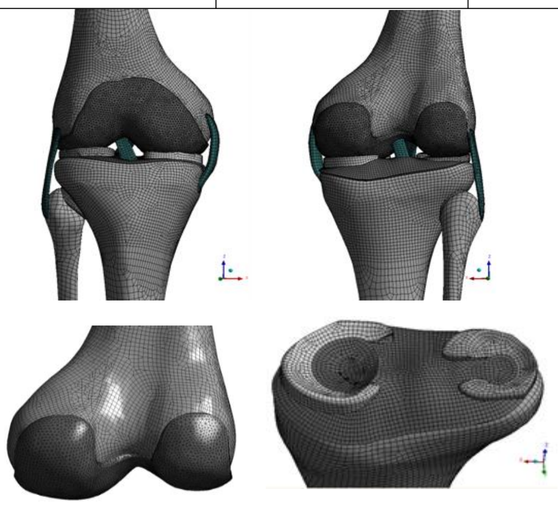


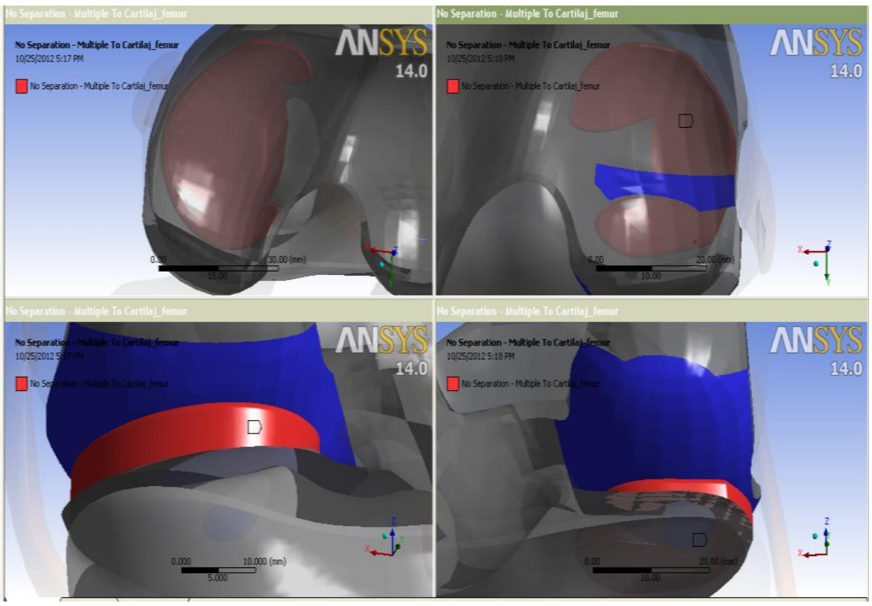
Fig. 3. Nodes and elements network for the healthy knee virtual model.

The characteristics of materials for each geometric component of virtual human knee are taken from literature and they are presented in Table 2.

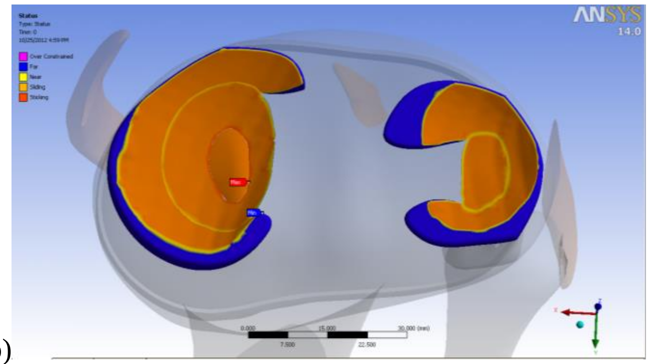
Table 2. Characteristics of materials for each geometric component [9, 19]

Geometrie	Young's Modulus [Mpa]	Poisson's Ratio
Cortical bone- Femur	18600	0.3
Cortical bone - Tibia	12500	0.3
Spongy bone	500	0.3
Cartilage	12	0.475
Menisci	59	0.49
Medial ligament	10	0.49
Lateral ligament	10	0.49
Anterior and posterior cross-linked ligament	1	0.49

The analysis of the contact areas between the knee components was based on the "Augmented Lagrange" calculation algorithm and the "On Gauss Points" detection method. "Bonded" and "NoSeparation" type options were used. These contacts are intended to be "Sticking" or "Sliding" closed. For a rigorous control of the contacts, we used their orientation in "Asymmetrical" mode. Aspects of contact analysis are shown in Fig.4, while in Fig.5 the values of surface areas of both menisci are shown.

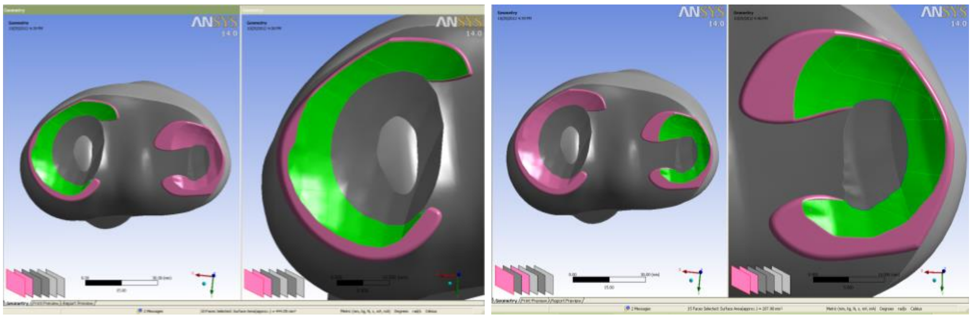


a).



b)

Fig. 4. Status of contacts for menisci. There are no spaces or penetrations between the menisci. The contact is closed "sticcking" - the geometry is in initial contact.



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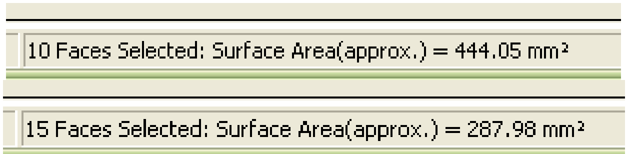


Fig. 5. The value of the contact surface for a) medial meniscus contact and femoral cartilage (445 mm^2); b) the contact of the lateral meniscus and the femoral cartilage (287.98 mm^2).

3D virtual model of osteoarthritic human knee with tilt angle in valgus of 5^0

For the valgus inclination by 5^o, both the femur and the tibia were rotated by 2.5^o compared to the initial geometry in order to form an angle of 171^o between them. The components affected by osteoarthritis are modified by delimiting the areas in the DesignModeler preprocessor, following the transfer of these new geometric models to the simulation environment of the AnsysWorkbench 14.5 application (fig.6). The red area is the one affected by osteoarthritis.

New material characteristics are introduced for the affected areas and these materials are assigned to the affected components. For the affected areas, the modulus of elasticity is changed by 50% compared to the healthy areas. The condition is present in the lateral compartment of the joint (stage 1). This affected

both the proximal head of the tibia and the tibial cartilage on the side of the knee in an early form. The condition has damaged the lateral cartilage of the tibia but also, in an early form, the proximal head of the tibia. The boundary conditions and the materials used are the same as the simulation performed for the healthy knee.
Starting from the initial virtual model of the healthy human knee joint, modify the components affected by gonarthrosis by delimiting the solids in the DesignModeler preprocessor;

- this new geometric model is transferred to the simulation environment of the AnsysWorkbench 14.5 application;
- new material characteristics are introduced for the affected areas and these materials are assigned to the affected components (Table 6.6); the modulus of elasticity for affected areas is changed by 50% compared to healthy areas;
- the coordinate systems placed at the level of the coxo-femoral joint and the ankle joint are repositioned;
- new discretization settings are selected and assigned for these affected areas;
- the network of nodes and elements is resolved, ensuring that the number of nodes and elements is greater in the affected area and its immediate vicinity;
- the contacts are manually redefined using the same settings as in the analysis of the healthy human knee joint;
- boundary conditions and analysis settings are the same as in the initial analysis, they are saved automatically;
- the new analysis is saved under a new name, a new database and another analysis project being created;
- it is solved (runs);
- extract the desired results and edit the post-processing settings;

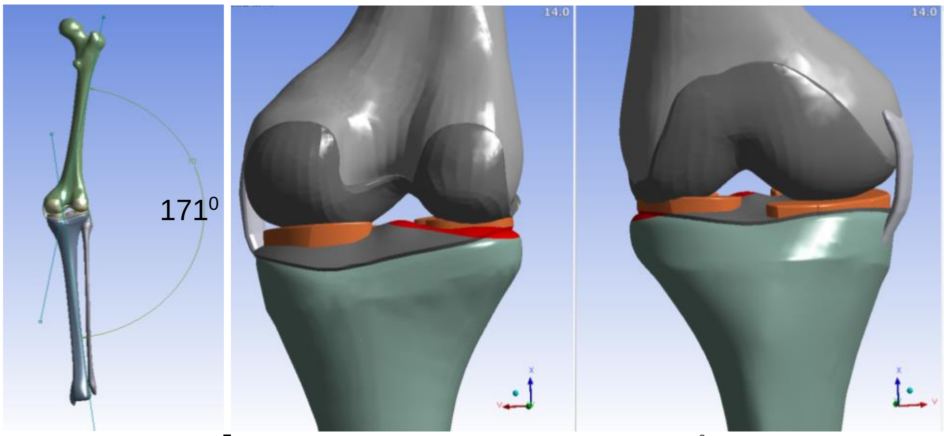


Fig. 6. The virtual model of the knee with a deviation of 5^0 in valgus;

The discretization led to a number of 508727 nodes and 329244 elements, (Fig. 7).

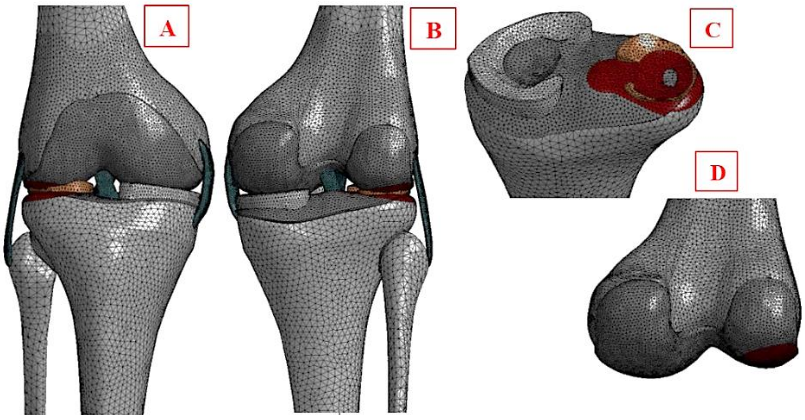
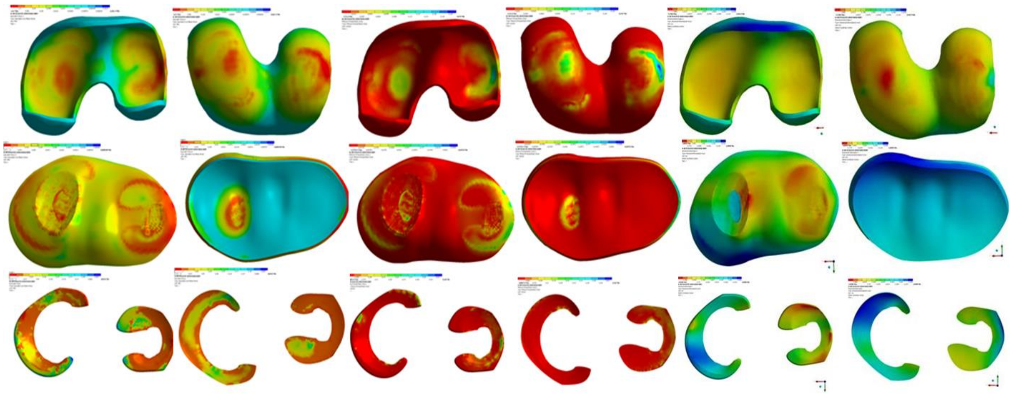


Fig. 7. The network of nodes and elements created for the knee joint affected by osteoarthritis with 5º in valgus: A - Frontal local image; B - Posterior local image; C - Isometric local image for the proximal head of the tibia; D - Local isometric image for the distal head of the femur

3. FEA analysis

After running the analysis with finite elements for the two cases of biomechanical systems of the healthy and osteoarthritic human knee, values were extracted for the maximum equivalent stress (von-Mises), the strain and the lateral displacements for: femoral cartilage (first row), tibial cartilage (second row) and menisci (third row). For healthy knee joint they are shown in Figure 8, while Figure 9 presents the maps of maximum values of strains developed in menisci in both analyzed cases. The maximum values obtained for the analyzed parameters are presented in Table 6.

Von-Mises stress Strain Lateral displacement



Top view Bottom view Top view Bottom view Top view Bottom view

Fig. 8. Maps of von-Mises stress, strains and displacements for femoral cartilage (first row), tibial cartilage (second row) and menisci (third row) for healthy knee joint.

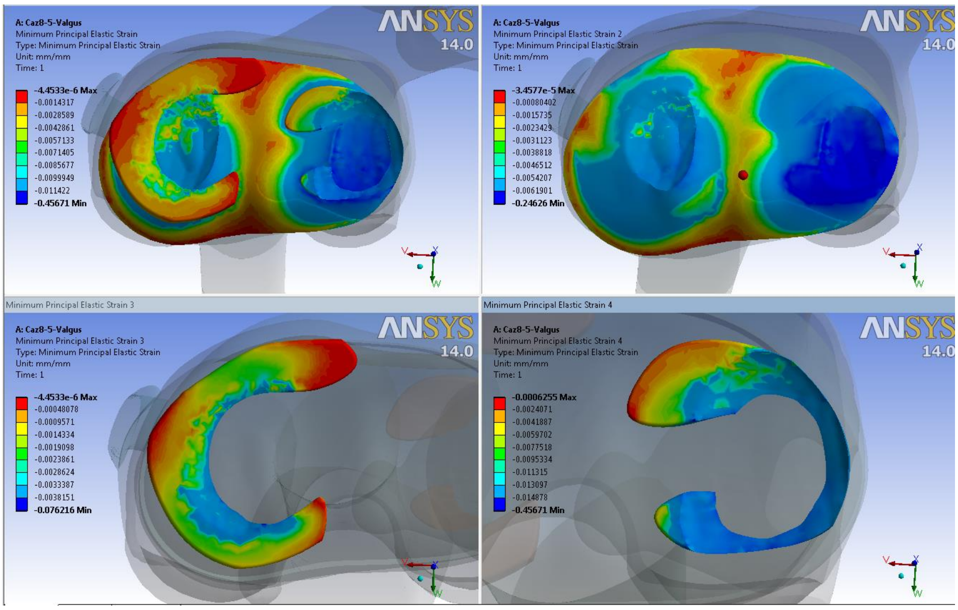
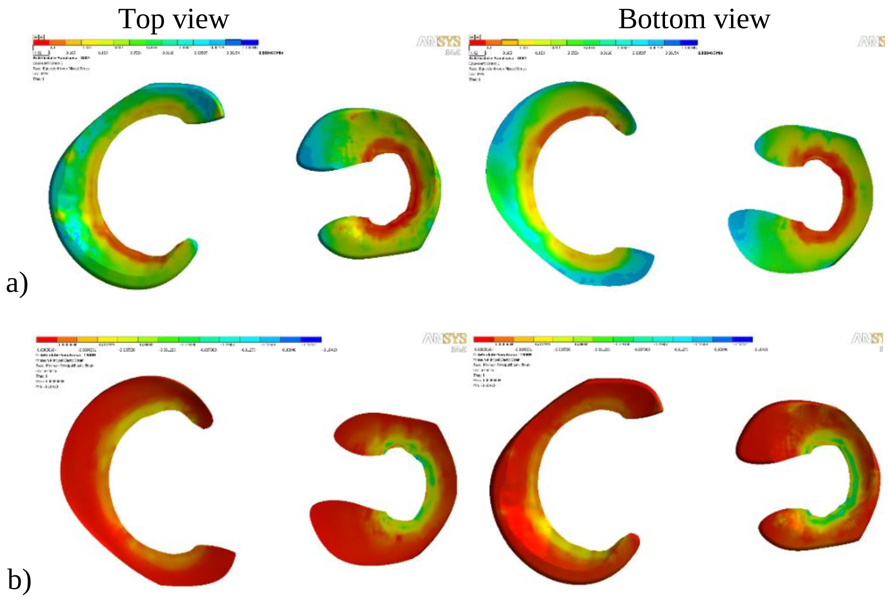


Fig. 9. Deformation due to compression: on the cartilage of the tibia-menisci (left-top); on tibial cartilage (top right); on medial meniscus (bottom left) and on the lateral meniscus (bottom right).

In Figure 10, maps of maximum values obtained by FEA for healthy and affected menisci are shown.



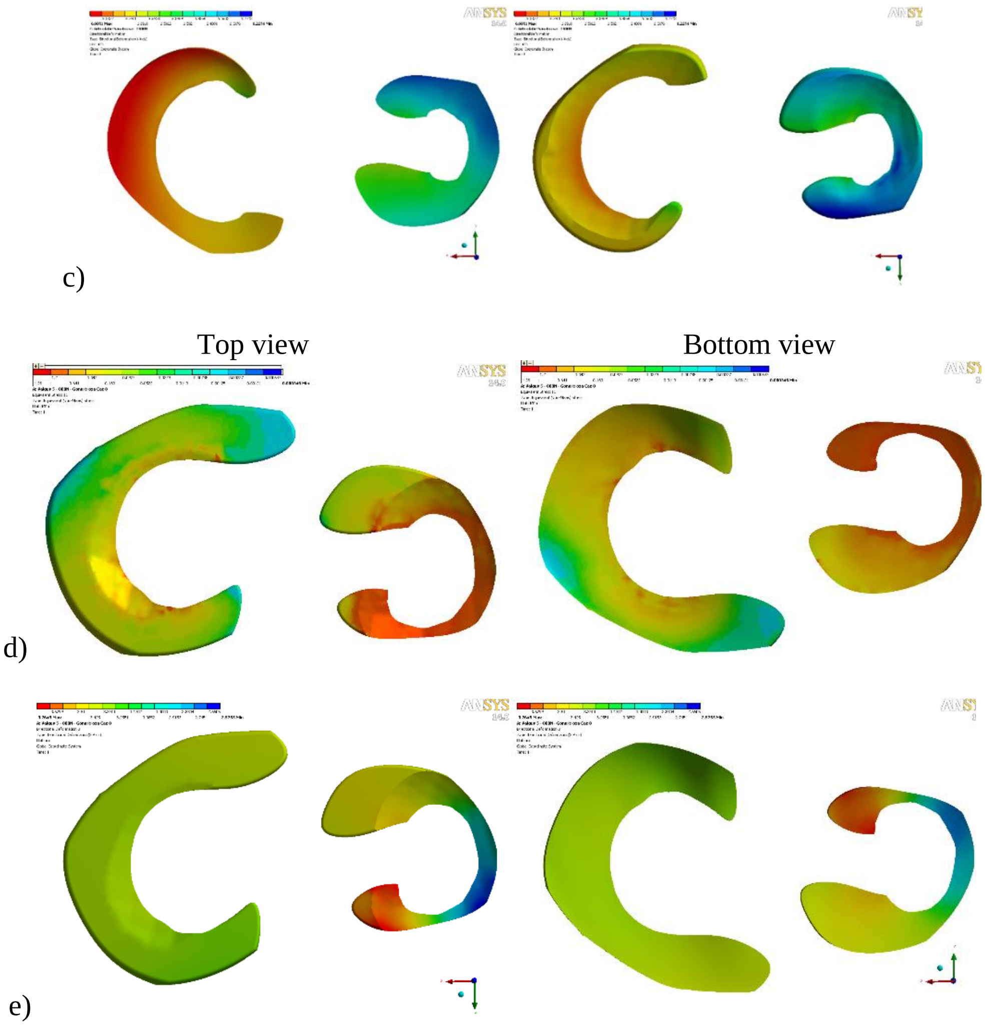


Fig.10. Maps of maximum values obtained by FEA for menisci:
a) von Mises stress-healthy knee; b) strains- healthy knee; c) displacements- healthy knee;
d) von Mises stress – osteoarthritic knee; e) displacements – osteoarthritic knee

Table 6. The values obtained for the menisci for the healthy knee joint
and for the osteoarthritic one with valgus inclination at 5°.

Result	Healthy knee	Knee 5° valgus
Stress Menisci [MPa]	1.12	1.28
Strain Menisci	0.487	0.252
Displacement Menisci [mm]	6.05	3.769

As we can see, the von Mises stress developed in menisci for a loading force of 800N are bigger with about 15% in osteoarthritic knee by comparing with healthy knee. The displacements are smaller in the menisci of the osteoarthritic knee (in this study case, especially in the lateral menisci) because the elasticity of the menisci is decreased.

4. Conclusions

In this paper, the 3D models of healthy and osteoarthritic knees, containing bones, ligaments, menisci and articular cartilages are presented. A finite element analysis led to results as, for example, von-Mises stress, strains and displacements in knee components, with maximum interest for menisci in the present study. The most used method for making virtual models of the components of the knee joint is the use of CT or MRI images. These images must have a very good quality and be as large as possible in order to capture as well as possible the details of the components of the knee joint. Discretization with good quality finite elements is closely related to the quality of geometric models. Avoiding spaces and penetrations between components is necessary for finite element analyzes to determine their clear and correct results. The contacts between the components depend on the geometric correctness of the 3D model. By creating a good quality 3D model of the human knee joint, this is a very powerful tool in estimating the behavior of bones, menisci, articular cartilages and ligaments.

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