STRESS STRAIN ANALYSIS OF KNEE JOINT

Martin Kubíček*, Zdeněk Florian*

This review deals with the stress strain analysis of the normal tibio-femoral joint in its basic position (extension). On the basis of the analysis, a contact pressure between a femoral and tibial cartilage and femoral cartilage and meniscus has been obtained. The geometry of bones (tibia and femur) was described by computer tomography and the shape of cartilage and meniscus was created with the aid of literature [1], [3], [16].

The system was loaded by displacement. Following the Ansys analysis, force representing the load within the knee joint area has been determined.

The problem has been solved as direct 3D task with a numerical simulation through the program system Ansys 10.0.

Keywords: *knee joint, meniscus, stress strain analysis*

1. Introduction

The knee is the largest joint in the human body and among the most important ones to our daily lives. The knee is involved in virtually everything we do from walking to getting up from a chair to driving.

The knee joint may look like a simple joint, but in fact, it is one of the most complex joints. Moreover, the knee is more likely to be injured than any other joint in the body.

As mentioned in the statistics of Czech Orthopedics Society, in 1994 1000 knee replacements were implanted in the Czech Republic while in 2002 it was more than 5500 knee replacements [18].

The knee joint consists of a curved lower end of the thighbone (femur), which rotates on a curved upper end of the shinbone (tibia), and the kneecap (patella), which slides in a groove at the end of the thighbone [1], [3], [13], [16].

The knee muscles which go across the joint are the quadriceps (front of the knee) and the hamstrings (back of the knee). The ligaments are equally important in the knee joint because these ligaments hold the bones together. Basically, the muscles move the joint while the ligaments stabilize it [1].

There are essentially four separate ligaments that stabilize the knee joint. Medial collateral ligament (MCL) and lateral collateral ligament (LCL) lie on the sides of the joint. These two ligaments mainly stabilize the joint in a lateral – medial direction. In the front part of the knee joint center, there is the anterior cruciate ligament (ACL), which is very important femur stabilizer. Another most important function is to prevent rotating and sliding forward tibia during jumping and deceleration activities. Directly behind the ACL is its opposite, the posterior cruciate ligament (PCL). Main function of the PCL is to prevent the tibia from sliding to the rear part of a knee (Figure 1) [1], [16].

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The knee joint is also made of the cartilage. Upper end of tibia and the lower end of femur are covered by hyaline cartilage. A ligament type of cartilage i.e. meniscus is placed between these cartilages. Medial meniscus is a C shaped piece of tissue and it is bigger than the lateral meniscus that is O shaped. Both are placed into the joint between the tibia and the femur, which helps to protect the joint and allows bones sliding freely on each other [1], [3].

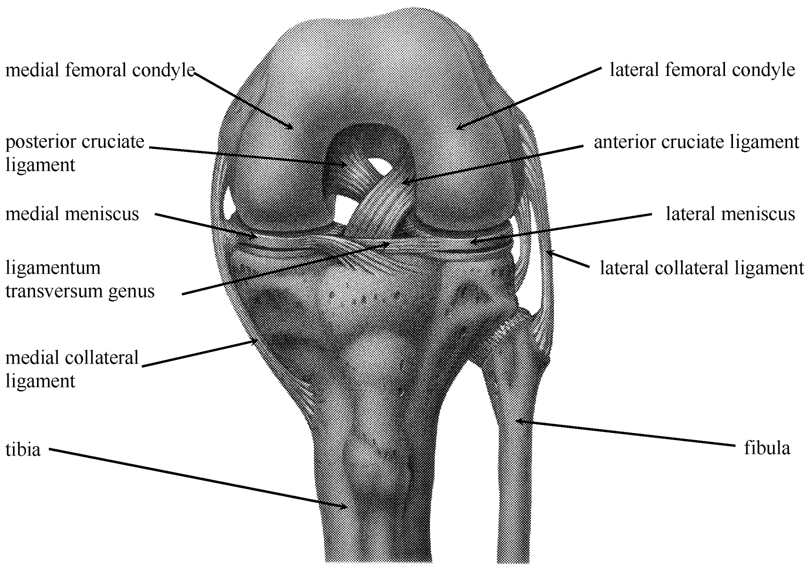

Fig.1: The knee joint

2. Computational modeling

To build a computational model for our research, the finite element system Ansys 10.0 was used. For correct and effective solution it is necessary to create partial models such as geometrical model, material model, finite element model and loading model [6].

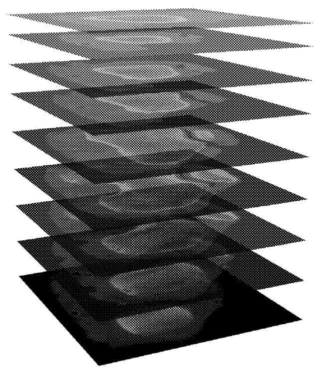

Fig.2: CT femur section

To create a geometrical model of the bones (femur and tibia), computer tomography at St. Anne's University Hospital Brno was used (Figure 2). From these CT sections (distance between individual sections was 1 mm) bones and other soft tissues were separated. For this separation, contrast between bright bone tissue and dark surrounding was used. The bone edge was manually selected and perpendicular to work plane moved. Separated sections were exported as a ∗.iges file format to the finite element system Ansys.

Because of no magnetic resonance imaging data (hereinafter MRI), for cartilage and meniscus geometrical model had to be used literature [1], [3], [13], [16]. Cartilage is the thickest on the load bearing areas and decreases towards the edges. Femur load bearing area thickness was created 2 mm unlike the tibial cartilage thickness, which was created 2.5 mm on the medial side and 3.7 mm on the lateral side.

A wedge-shaped cross-section of meniscus was made 5–7 mm high (Figure 3).

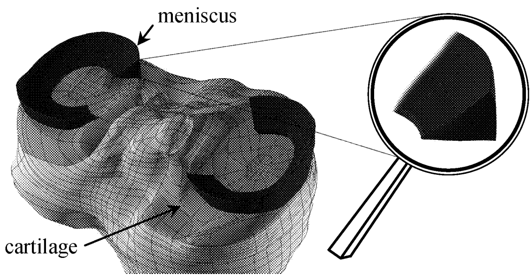

Fig.3: Geometrical model of meniscuses and cartilages

The knee joint has got the most complex and full-strength ligament among all human joints. There are five main ligaments in the knee joint area, such as two collateral ligaments, two cruciate ligaments and ligamentum transversum genus (ligament connecting the front part of both meniscus). The ligaments were created by two node spar elements, which connect ligaments origin. A scheme of ligaments model is illustrated in Figure 4 [1], [16].

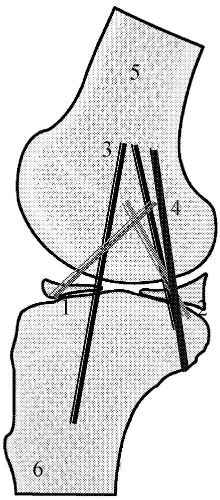

Fig.4: Scheme of ligaments : 1 – ACL, 2 – PCL, 3 – MCL, 4 – LCL, 5 – femur, 6 – tibia

Computer tomography, MRI or any 3D scanners could be used for geometrical model formation.

Mechanical properties of a living tissue are influenced by many factors, such as gender (Figure 5); age (Tab. 1), location of the specimen etc.

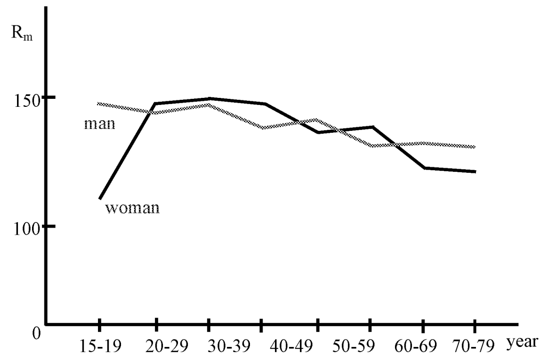

Fig.5: Dependence of ultimate strength on gender and age for femur [10]

age (years)	0–9	10–19	20–29	30–39	40–49	50–59	60–69	70–79
ultimate tensile strength [MPa]	4.6	4,6	4.5	4.2	3.6	2.5	1.5	1.3
Maximal strain [%]	31.2	28.2	25.9	25.5	20.7	16.7	11.2	9.2

Tab.1: Mechanical properties of hyaline cartilage [8]

Material properties of individual models were created as homogenous, isotropic with linear behavior and they were described by Young's modulus and Poisson's ratio. Pursuant to published material characteristic, complex model balance and with regard to solution goals (the comparison of natural healthy knee vs. knee joint with applied replacement) the linear model was used.

	Young's modulus E [MPa]	Poisson's Ratio μ	source
femur compact bone	17 600	0.3	[15]
tibia compact bone	18 400	0.3	[9]
spongy bone	500	0.3	[14]
cartilage	50	0.45	[14]
meniscus	112	0.45	[13]
ligaments	400	0.45	[7]

Tab.2: Employed material properties

The material characteristics are summarized in Tab. 2.

For further step of solution it is necessary to build the **finite element model**. It means to substitute the geometrical model by finite number of elements. Actually we created continuity and unique grid of the elements, which means no gaps between elements; no overlap and the boundary of elements to respect the geometrical shape of the model.

The finite element model of bone consists of two types of elements, because the femur and tibia consist of two types of bone tissue – spongy and compact bone. As depicted on Figure 6, the thickness of compact bone was modeled varying from 1 mm till 2.4 mm [1].

The cortical bone of femur and tibia was modeled with shell elements, while the spongy bone, cartilage and meniscus were created by 8-node and 20-node 'brick' shaped elements and 10-node 'tetrahedron' shaped elements.

Duration of the contact analysis solution directly depends on the contact nodes quantity. In the task the contacts between femoral cartilage and both meniscus were solved. As well as contact between femoral and tibial cartilages (Tab. 3 and Figure 7). 'Conta' elements are used to represent contact and sliding between 'target' surfaces and a deformable surface, defined by these elements [17]. To establish the friction coefficient between cartilage contact surfaces, sensitivity analysis was done. The friction coefficient was set up 0.01 [2].

The load of the knee joint corresponds to the weight of a human body (80–90 kg) standing only on one leg. The model did not contain the whole lower limb but only the thighbone and the shinbone without a foot.

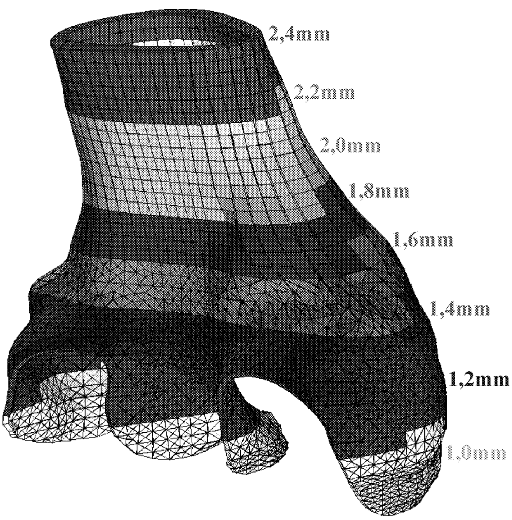

Fig.6: Cortical bone

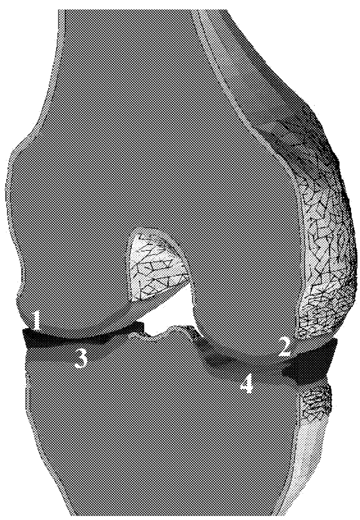

Fig.7: Contact pairs

abeling		contact pair	
cartilage + meniscus	1	femoral cartilage	lateral meniscus
	2	femoral cartilage	medial meniscus
cartilage + meniscus	3	femoral cartilage	lateral tibial cartilage
	4	femoral cartilage	medial tibial cartilage

Tab.3: Contact pairs

The connection between the upper end of the thighbone and the rest of a human body was modeled so that the thighbone was fixed in the transversal plane (Figure 9 – position A). The system was loaded by displacement in z direction (Figure 9 – position B).

As depicted in Figure 8, the results were saved with step 0.1 mm. Reaction force almost 900 N (in nodes in a section at the position A – Figure 9) was attained in second step, when displacement value was 0.2 mm. It means the weight of a one-leg standing human body [11].

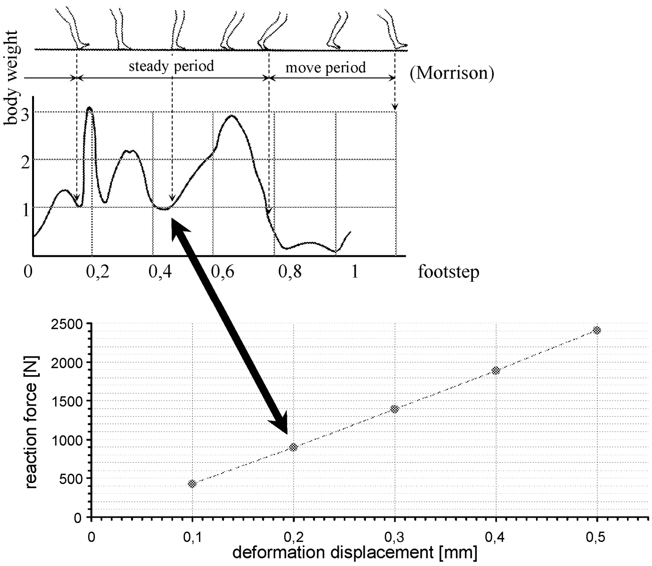

Fig.8: Reaction force – displacement characteristic

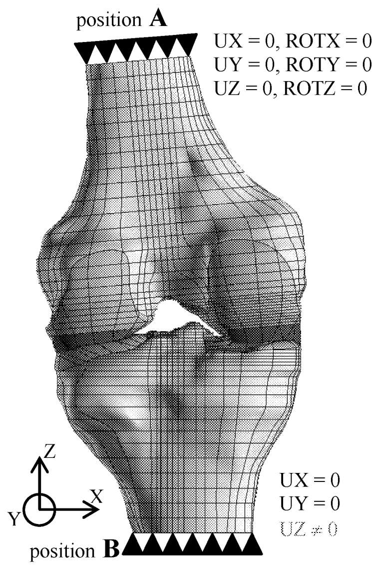

Fig.9: Loading model

3. Results

The stress strain analysis was solved on the presented FE model.

The axial displacement of the tibia is shown in Figure 10 where the maximum value of displacement on the medial tibia condyle is depicted. The same displacement of the femoral condyle can be seen in Figure 11 where two crescent-shaped meniscuses are evident.

Higher load of the medial condyle is shown in Figure 12 and Figure 13 where the displacement of both meniscuses is depicted, in both the lateral-medial direction and the anteroposterial direction. The quantity which describes the interaction between femoral cartilage, tibial cartilage and meniscus is the contact pressure. Distribution of contact pressure is shown in Figure 14. There is depicted highest value of contact pressure on distal part of the medial condyle. This means that the load of medial condyle is higher than lateral one. As it is shown, the load is distributed mainly by meniscus. The contact between femoral and tibial cartilage is only in the parts of the joint.

With deformation of 0.2 mm, the maximum value of contact pressure between femoral cartilage and meniscuses is 2.25 MPa. Reaction force in transversal section nodes of femur is 890 N.

We can compare these results for the knee joint with results of another large human joint, such as hip joint or an elbow joint. The distribution of contact pressure of large human joints is shown in Figure 15. Maximum values for these healthy joints are between 2 and 3 MPa.

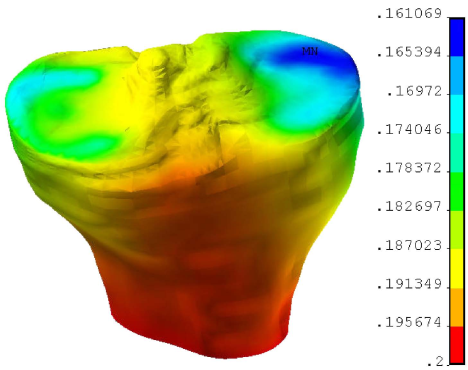

Fig.10: The axial displacement of the tibia (frontal view)

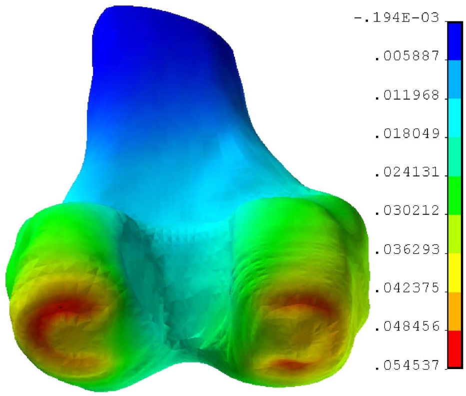

Fig.11: The axial displacement of the femur (back view)

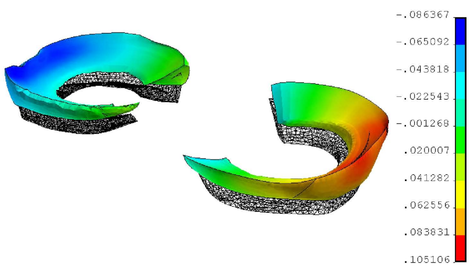

Fig.12: Lateral-medial meniscus displacement

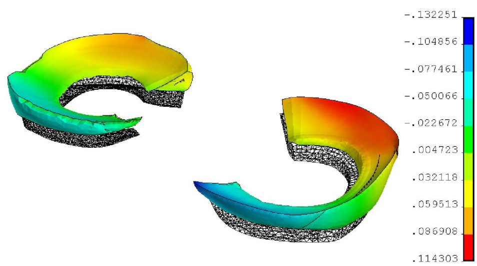

Fig.13: Antero – posterial meniscus displacement

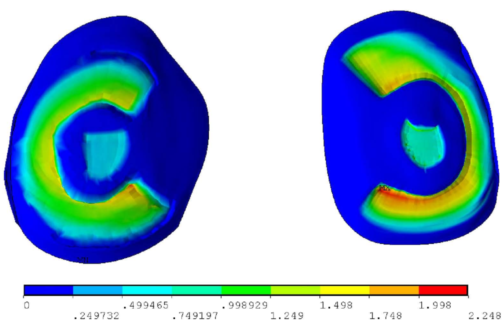

Fig.14: Distribution of contact pressure

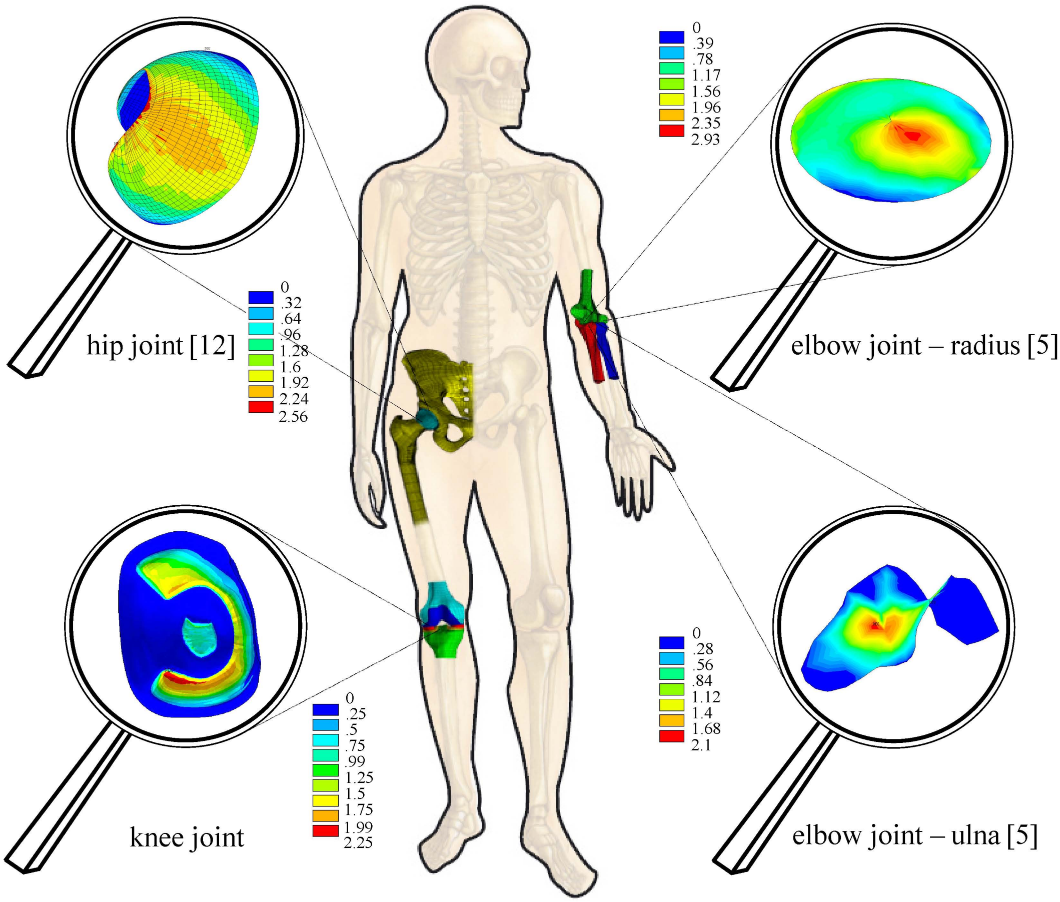

Fig.15: Big human joints contact pressure

4. Conclusion

The geometrical model of bones was created due to the computer tomography data. Other geometrical models were obtained with the aid of literature. The advantage of presented model is complex knee architecture such as bones, cartilage, meniscus and ligaments. The material model of the bones, cartilage, meniscus and ligaments was based on the isotropic linearly elastic continuum. The whole model was loaded by displacement. On the basis of mentioned load, reaction force in the transversal section nodes was obtained (Figure 9 – position A).

The maximum value of the contact pressure between femoral cartilage, tibial cartilage and meniscus is 2.25 MPa – see also Figure 14. From the results (deformation, stress and contact pressure) is evident that the medial condyle is more loaded than the lateral one. This conclusion also confirms clinical practice [4]. Higher verification level was reached by using of meniscus model.

It is not easy to establish the limit state in the sphere of biomechanics. In the next step, knee joint with applied unicondylar and total replacements will be solved and analyzed. Obtained results will be used for comparing with tasks where mentioned implants are applied.

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