# MEASUREMENT OF PRESSURE DISTRIBUTION IN KNEE JOINT REPLACEMENT

**J. Volf[1], V. Novák[1], V. Ryzhenko[1], D. Novák[2]**

[1]*Faculty of Engineering, Czech University of Life Sciences Prague, Czech Republic*
[2]*Faculty of Natural Sciences, Matej Bel University Banská Bystrica, Slovakia*

**Abstract**
The paper describes the measurement procedure of pressure distribution in knee arthroplasty and it verifies the accuracy of mathematical model of the pressure in the artificial joint. First it briefly presents the composition of the artificial joint. Then it describes in detail the measurement procedure, i.e. the measuring machine, which simulates a human step cycle, and the layout and type of used sensors. Finally, the measured pressure data are compared with those from the mathematical model and its accuracy is evaluated.

**Key words:** sensor, transducer, pressure distribution, biomechanics, knee joint replacement, knee arthoplasty.

## INTRODUCTION

In some specific or particularly serious cases of impairment of human knee joint it is necessary to perform a total replacement of the joint with an artificial one – the knee arthoplasty. In order to maintain the functionality of the leg, the replacement should meet the kinematical requirements on a healthy joint, and – as an implanted part of human's body – it should exhibit excellent reliability to avoid repeating interventions into the body of the patient, for more detail see ZACH ET AL. (2004).

A titanium plate is attached onto the tibia bone; on the top of this plate is fixed a polymer-based layer with cut u-shape groove, into which fits in the third steel part that is attached to the femur bone. The polymer layer is necessary to prevent a direct contact between two metallic parts of the artificial joint and to enable reasonable friction between them. As the polymer part is especially susceptible to mechanical wear, the aim of the study is to check the pressure distribution in the contact layer and to compare the results with calculated theoretical values, according to mathematical model by ZHU AND CHEN (2004), and to determine the places with highest load and its magnitude.

## MATERIALS AND METHODS

The artificial replacement joint, see Fig. 1, consists of following parts, as marked at the picture:

(1) femoral component
(2) tibial plateau
(3) basis of tibial component
(4) spindle of tibial component
(5) compensatory support
(6) compensatory support

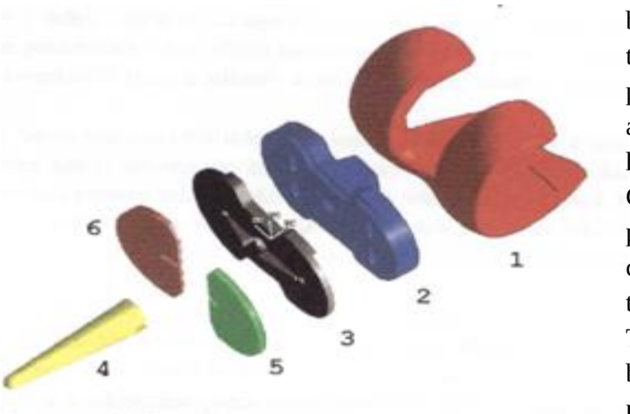


**Fig. 1.** – The structure of artificial knee replacement

Different materials are used for various components of knee arthroplasty. The femoral component is made of metal material (mostly cobalt alloy – Vitalium), tibial component is made of the same material, too, but contact area (tibial plateau) is from ultra high molecular polyethylene (UHMWPE).

New femoral components from oxide ceramic (Zirconium dioxide $ZrO_2$ and Alluminium dioxide $AlO_2$) are being developed. Metal materials are used because of their strength and elasticity, but they are not abrasion-proof and their life-cycle is shorter. Ceramic materials are bioinert and exhibit good friction characteristic; however, their disadvantage enhanced is fragility. Ceramic femoral component has different geometric parameters. We use combination of metal femoral component, i.e. UHMWPE tibial plateau and metal tibial component.

The geometric model of knee replacement was created by finite element method. Detailed description of this method is commented by DONÁT (1997). This mathematical model corresponds as much as possible the real knee joint. The geometric model was formulated in CAD system EDS/Unigraphics, developed by firm Walter, a.s. Prague. Theoretic results were obtained in system ABAQUS. The mathematic model of pressure distribution was created only for femoral component (upper part) and tibial plateau (lower part), which are depicted from another point of view in Fig. 2.

**Fig. 2.** – Femoral component and tibial plateau

Some simulations of pressure distribution in knee joint deal with a physiologic knee, i.e. with a complete knee with muscles and fibrous apparatus. We use a simplified model of knee replacement which doesn't comprehend lattice ligaments and the pressure distribution is slightly different according to KONVIČKOVÁ (2000). This simplified model is created for first verifying study. We used only stress of tibia-femoral contact area with pressure, which corresponds ca. 2.5 times average body weight. We suppose this about 70 kg, corresponding with force about 1 800 N.
Within the experiment, we used semiconductor strain gages. Although they exhibit significant dependency of electrical resistance on the temperature and a non-linear dependency of the measured resistance on the deformation, we consider the negatives being compensated by their accuracy and stress-fatigue resistance. The temperature error may be compensated by small thermometers. We use monocrystalline semiconductor strain gages with N conductivity, which exhibits more linear dependency on press deformation, length of 2 mm from producer VTS Zlín, Czech Republic. These strain gages were developed specially for our workplace, further details about biomechanical measurements in VOLF (2002).
The sensor placement in human knee joint isn't simple, because the sensor must fulfill several conditions. The main condition is, that sensor mustn't influence the surface shape of knee components. If sensor changes geometry of tibial plateau, it would change also the contact areas and thus contact pressures, as by MOOTANAH (2006) and ANDERSON ET AL. (2006).
According to the mathematical model the maximal stress values are not in geometric minimum, but they are shifted. Thus sensors are allocated at four places in supposed maximal pressure area – see Fig. 3, (A) – (D). Because the sensors mustn't change the surface shape of knee components, they are placed in special holes with 3 mm diameter that are bored into the tibial plateau from below, which is demonstrated in Fig. 4. The number of holes is limited in order not to influence the tension course within the material.


**Fig. 3.** – Placement of the sensors

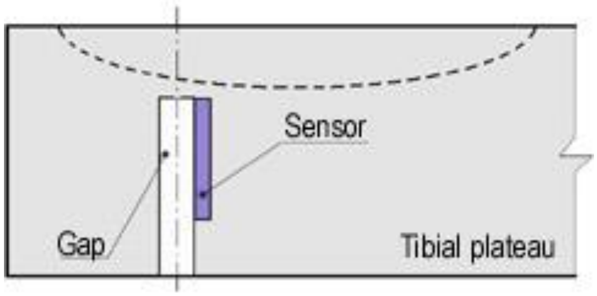


**Fig. 4.** – Hole in tibial plateau with sensor placement

The sensors are fixed in these gaps; placement of sensor is parallel with axis of gap. The gaps' depth is limited by elastic area of UHMWPE material of tibialplateau, the bottom of the hole may not be closer than 3 mm to the contact surface of the tibial plateau with the femoral component. After fixing into the hole the sensors are covered by silicone. One hole contains in addition a thermometer to compensate the temperature error of the semiconductor.

The measurements were performed on a movement simulator, a PLC controlled machine, which models the movements of a human knee joint. We performed the measurements according to norm ISO 14243-3:2004(E) that prescribes exactly the movements of individual parts of the joint in relation to each other, in order to simulate accurately the movement of a natural knee joint, further details about the simulation by Zhu and Chen (1999). This device is placed in the biomechanics laboratory of Czech Technical University, Faculty of Machine Engineering in Prague. The device with the artificial joint is depicted in Fig. 5.

**Fig. 5.** – Knee movement simulator and artificial joint

**RESULTS AND DISCUSSION**

Calculated values according to the mathematical model by ZHU AND CHEN (2004) exhibit no significant differences in stress distribution between individual replacement materials. The stress is concentrated into two nodes, as may be seen in Fig. 3. Maximal intensity of contact stress is 8.23 MPa with metal femoral component and 8.19 MPa with ceramic femoral component. Contact stress is much more less than value of limit stress for UHMWPE. This material has limit stress 13 MPa. Maximal values of reduced stress on tibial plateau is 7.05 MPa for both metal and ceramic femoral component. Maximal values of reduced stress are 5.73 MPa for metal and 7.35 MPa for ceramic femoral component. According to calculations, the limit stress values of replacement materials are not exceeded. The calculated pressure distribution is represented graphically in Fig. 6.

The machine simulated one human step so that we could measure the pressure in dependency on the flexion of the joint in determined angles from 0° to 25° in 5° steps. The results are depicted graphically in Fig. 7 – gap B and Fig. 8 – gap D. The pressure was measured increasing and decreasing of acting force in range 0 – 1 730 N on knee replacement for determined angles.

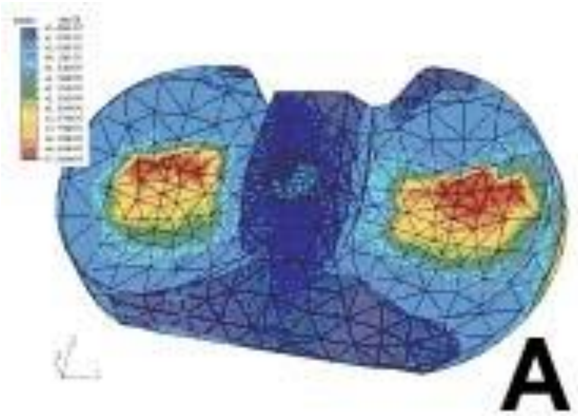


**Fig. 6.** – Calculated pressure distribution in artificial knee replacement

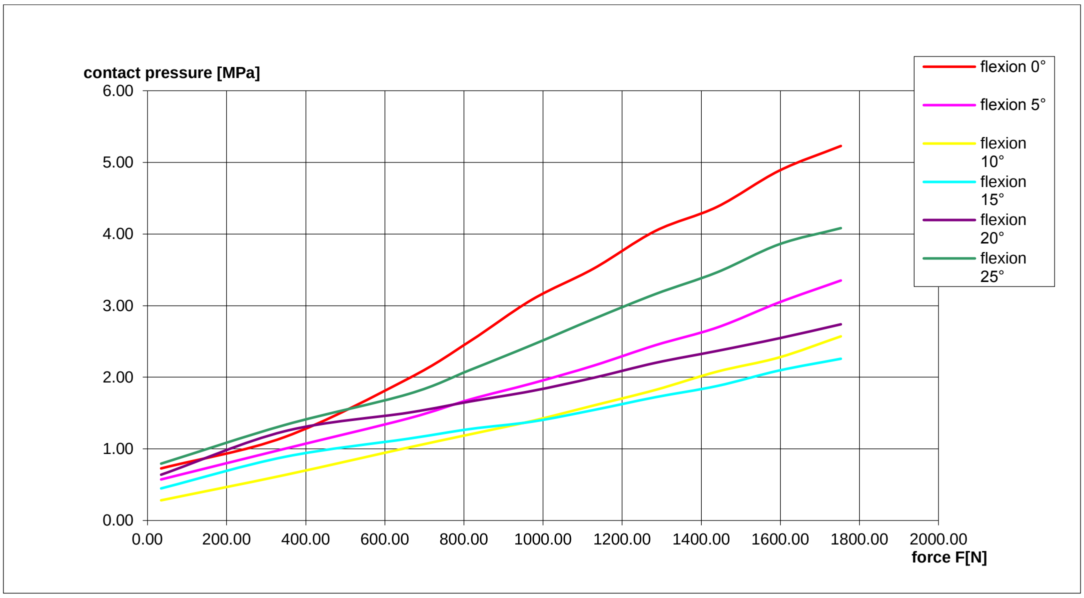


**Fig. 7.** – Contact pressure, gap B

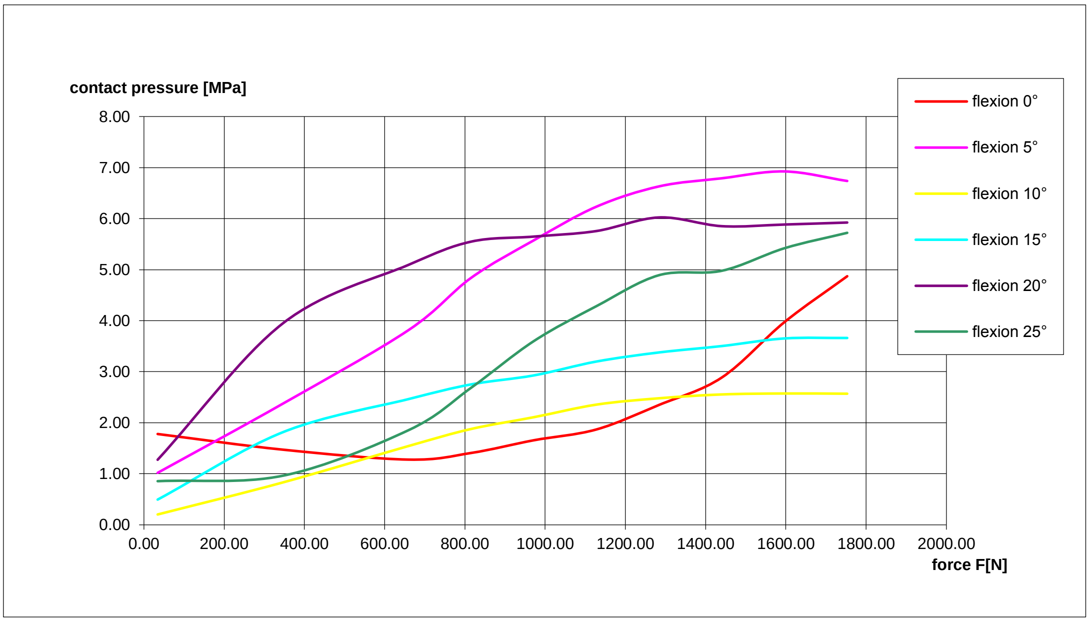


**Fig. 8.** – Contact pressure, gap D

The precedent figure represents the contact pressure values in knee arthroplasty for six defined flexion values (angles 0° to 25°) in dependency on the load force. The pressure increases quasi-linear with force in the contact point B, but the dependency on the flexion degree cannot be determined; the two highest pressure values (for maximum load) are obtained for the flexion 0° and 25°. The contact point D exhibits significant different course of the pressure with increasing load. Given the flexion 0°, the contact pressure slightly decreases, then it increases significantly. By the other flexion degrees, the contact pressure increases with the load, however, some curves reach their local maximum. Such irregularities of pressure dependency process in knee replacement are given by the geometry of contact areas, which affects significantly the pressure distribution.

Some hysteresis of deformation process by loading and unloading was found out in calibration. This is caused by material properties of UHWPE, from which the plateau is produced. This hysteresis can by substituted by average value without significant influence on the next measurements.

The subject of pressure distribution in knee joint was reflected by ZHU AND CHEN (1999, 2004), who created a mathematical model of pressure distribution in a knee joint. Calculations of the pressure distribution basing on the model are provided by DONÁT (1997) and ZACH ET AL. (2004). We verified the calculations by previously mentioned authors with the actually measured values. The comparison of the calculated and measured pressure values in points B and D is shown in Tab. 1., values are given for the flexion 0° - according to the mathematical model.

**Tab. 1.** – Calculated and measured pressure values in points B and D

| | Gap B | Gap D |
|---|---|---|
| calculated value | 6.7 MPa | 5.1 MPa |
| measured value | 5.3 MPa | 4.8 MPa |

The measured data in the respective points correspond with the calculated ones. However, it has to be pointed out, that an exact conformity and a direct comparison of the values are not possible. The maximal load obtained by the movement simulator is limited due to simulator's construction to 1 730 N and the pressure values calculated by the mathematical model base on the force of 2 300 N. An extrapolation of the measured force is not possible due the irregular shape of the curve (i.e. nonlinear dependency of the pressure on the applied force, mainly at the point D, see Fig. 8, which is given by slight rotation of the joint surfaces). The maximal pressure values reached up to 5.3 MPa (gap B) and 6.9 MPa (gap D). These values are way below the limit of the material, which is 13 MPa. These values are in correspondence with the mathematical model given above. Hereby we proved that the mathematical model describes accurately the load of knee arthroplasty and that such mathematical model can be used to design artificial joints. We further conclude that no one of the sensors exhibited unexpected or unacceptable pressure peak that could endanger the functionality of the artificial joint.

## CONCLUSIONS

The aim of our work was to verify the mathematical model of pressure distribution in an artificial knee replacement. We modelled the real movement of the knee joint according to norm ISO 14243-3:2004(E) in the simulating machine. To measure the pressure, we used semiconductor strain gages placed in holes bored in tibial plateau component in the artificial joint. We conclude that the contact stress values correspond with the calculated ones, without any unpredicted deviations, so that we verified the mathematical model to be useful and accurate by designing artificial joints.

## ACKNOWLEDGEMENT

The measurements were carried out within the IGA project No. 31200/1312/3118 of the Faculty of Engineering, Czech University of Life Sciences in Prague.

## REFERENCES

1. ANDERSON, I. A., LIM, K.: Force Measurement. In: Wiley Encyclopedia of Biomedical Engineering, 2006.
2. DONÁT, A.: The Calculation of Contacts Pressures by Knee Joint Replacement [Diploma thesis]. Prague, Czech Technical University, 1997 (in Czech).
3. KONVIČKOVÁ, S., VALENTA, J.: Biomechanics of humans' joints and their replacements. Vienala, Prague, 2000 (in Czech).
4. MOOTANAH, R.: Pressure Sensors. In: Wiley Encyclopedia of Biomedical Engineering, pp. 1-16, 2006.
5. VOLF, J. ET AL.: System for Measurement of Static and Dynamic Pressure Distribution in Biomechanics. In: Automa, vol. 11/2002, pp. 17-19, 2002.
6. ZACH, L., KONVIČKOVÁ, S., RŮŽIČKA, P.: MKP Model of Knee Arthoplasty – Pressure Analysis (in Czech). In: WAM 2004, Prague, Czech Technical University, 2004.
7. ZHU, Y., CHEN, J. X.: 3D Knee Modeling and Biomechanical Simulation. In: Computer in Science Engineering, pp. 82-87, 1999.
8. ZHU, Y., CHEN, J. X.: Simulation and Visualization of Knee Joint Contact using Deformable Model. In: The Fourth International Conference on Computer and Information Technology 2004, 2004.

**Corresponding author:**
prof. Ing. Jaromír Volf, DrSc., Department of Electrical Engineering and Automation, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6, Prague, 16521, Czech Republic, phone: +420 22438 3203, e-mail: volf@tf.czu.cz