FINITE ELEMENT ANALYSES AND OTHER TESTS OF CERAMIC KNEE JOINT REPLACEMENT (WDM SYSTEM)

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Abstract: This article describes the last progress achieved at the Laboratory of Human Biomechanics in the field of zirconia knee joint endoprosthesis and also summarizes all existing findings. The article is focused especially on finite element analyses carried out from the very beginning of a development of this new type of the femoral component which is thought to replace a metal femoral component in WDM (Walter-Dias Modular) system in case of certain patients. Although all the existing analyses are very simplified, more complex models are being prepared.

Introduction

There are several ways how to verify an artificial joint replacement. For example clinical tests, mechanical and physical tests, finite element analyses (FEA) and many others. But what is important, that none of them can not stand alone without the others, it means that only good results of wide range of tests and analyses can serve as a proof of a well designed replacement. Based on this presumption, the most important up-to-now results of a testing of the ceramic total knee joint replacement (TKR) called Walter-Dias Modular (WDM) system will be presented here with the finite element analyses focus.

Description of WDM system

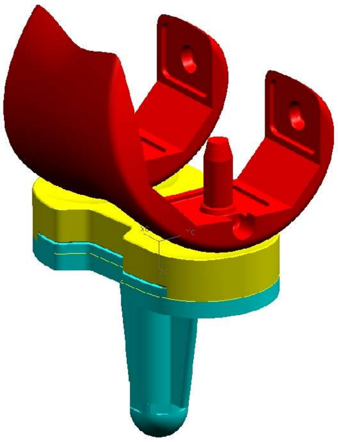

Figure 1: Geometrical model of the knee WD modular system

Since the ceramic (ZrO_2 Y-TZP) femoral component (FC) is the part of the same WDM system as the metal one made of Co-Cr-Mo alloy there are not in fact any differences between the TKRs. Figure 1 shows all the most important parts of the whole endoprosthesis. These are the femoral component (the red one), a tibial plateau (represented in yellow) and a tibial tray (green). As mentioned above, the FC is nowadays produced commercially only in the metal version and only for testing purposes in the ceramic version. The plateau is as usual made of ultrahighmolecularweight polyethylene (UHMWPE). It can differ in its height but also in its width, which usually corresponds to the size of a FC but to compensate an extensive bone resection in certain cases it could be used "one size smaller" (only its base is one size smaller , the articulating surface corresponds to the FC). The metal tibial tray is always implanted corresponding to the base of the plateau. Another devices can be used to stabilise the knee.

For the testing purposes, the FC size 68 has been chosen which is the most common implanted.

There is a long history [1] of a use of the total knee replacements in the Czech Republic (Czechoslovak Republic). The first implantation of the knee endoprosthesis was carried out in 1969 (hinge-type Poldi). In a next decade, first anatomical replacements type Poldi (designed by Rybka) was implanted. It can bee said, that this ceramic femoral component is in some ways its "successor".

Our ceramic knee was designed by several groups and laboratories, among them the Laboratory of Human Biomechanics at the Department of Mechanics of the CTU in Prague. But the main designers are the following two companies. Walter, Prague (Walter MEDICA today) and Dias, Turnov (Saint-Gobain today).

Indications for ceramic femoral component:
- Young, active or heavy patients with high risk of early PE wear occurrence
- Patients with or in the risk of Co-Cr-Mo alloy allergic reactions (4-5% of the population)

There is an effort to develop a complex finite element model because to simplify a verification of the modular system and a future development. Especially contact stresses computed by this method are very valuable. A way of a gradual increasing of complexity of this problem have been chosen.

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Mechanical and physical tests

There have been carried out several tests [2] [3] [4] with the ceramic FC and Zirconia itself with promising results.

"Ring on disc" tests (ISO 6474:1994(E)) [2] of various combinations of materials showed the main advantage of Zirconia – it's low coefficient of friction while articulating with UHMWPE which leads to low wear volume of polyethylene.

Bending tests according to EN 843-1 and microhardness evaluation (Vickers) according to EN 843-4 carried out by Sida [4] showed almost three times higher bending strength than Alumina used for a hip joint and as for the microhardness [4], the measuring of various specimens taken from different places on the FC proved well carried out CIP (Cold Isostatic Pressing) method which was chose among other methods of manufacturing of the femoral part of the endoprosthesis (mean value HV10 1320).

Another static and dynamic experiments with the ceramic FC carried out Sedivka [3]. He aimed to point out the most critical places on the implant so that he proposed a set of tests. The most important are the following ones: static pressure test, static bending test and dynamic impact test (see figure 2). Due to manufacturing costs, the implants used for the tests had some defects.

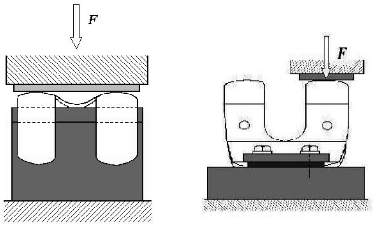

Figure 2: Scheme of static tests proposed and carried out by Sedivka [3]: static pressure test (left), static bending test (right)

During the static tests he loaded the component until its destruction. The dynamic tests were carried out as follows. A weight of 6kg falls onto the FC from height 0.5 – 1m with an increment 0.1m. For each of these increments the impact is executed 10 times for every component for 0 deg, 30 deg respectively.

In general, Sedivka pointed out the most dangerous places of the zirconia FC. It is the area between the condyles, the holes necessary for the fixation of the component and also the inner edge of condyle near its end.

Clinical tests

In December 1999, clinical tests started and until November 2001, 20 components was implanted. All the implantations were performed with only one exception by two experienced orthopaedic surgeons at the First Faculty of Medicine, Charles University in Prague using standard surgical instruments and techniques. Ceramic components were fixed with a bone cement. Patella has not been resurfaced in any of the knees.

Since then, all patients are regularly seeing a surgery. No problem was reported until now and all the patients are satisfied with it. No differences are reported for those patients who have one knee resurfaced with the ceramics and another one with the metal.

Finite -element analyses

As for the FE analyses, I made almost the same job as Donat [5] did. They are both very simplified static models but with different results. Both analysis and a type of a loading corresponds to the figure 3.

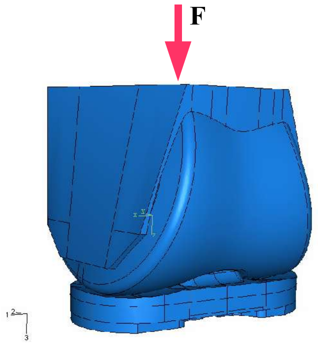

Figure 3: Complex knee joint geometric model

Donat [5] carried out two jobs. The first one with the metal (Co-Cr-Mo alloy) FC and the second one with the zirconia implant. The problem was considered static, non-linear due to a contact defined between the two main parts, the FC and the plateau (coefficient of friction equals 0.2 for the metal-UHMWPE version and 0.05 for the ceramics-UHMWPE).Solution was computed for a full extension, an axial loading force matched present findings for this situation, F=2100N, which corresponds to a three times body-weight. Neither muscles nor ligaments were involved. He found no significant differences between the Zirconia FC and the Co-Cr-Mo alloy FC as for the contact stresses and the stress distribution.

Table 1: Material properties

	FC	Plateau
Donat [5]	$E=4.10^5$ MPa	$E=3,4.10^4$ MPa
	$\mu=0,22$	$\mu=0,35$
Zach	$E=4.10^5$ MPa	$E=3,4.10^4$ MPa
	$\mu=0,22$	$\mu=0,35$ $\sigma_y= 21$ MPa

While Donat found contact stresses to be approx. 8.2MPa, I found out the values more than two times higher in magnitudes (about 20MPa). In fact, there are even higher values (113MPa), but it is due to visible surface irregularities. I remark, that the geometric model of the endoprosthesis was not exactly the same. There was applied the same force 2100N but the PE plateau was thought to be ideally plastic material (see Table 1).

As well as Donat, I used for the analyses the FE code Abaqus (HKS, Inc.). Comparison of the results stated by Donat and of the presented analysis is made below (see figures 4-7).

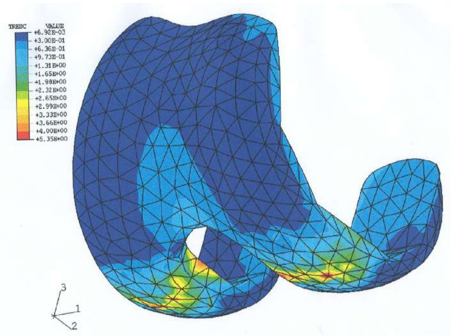

Figure 4: Stress distribution (Tresca theory) in the ceramic femoral component [MPa] [5]

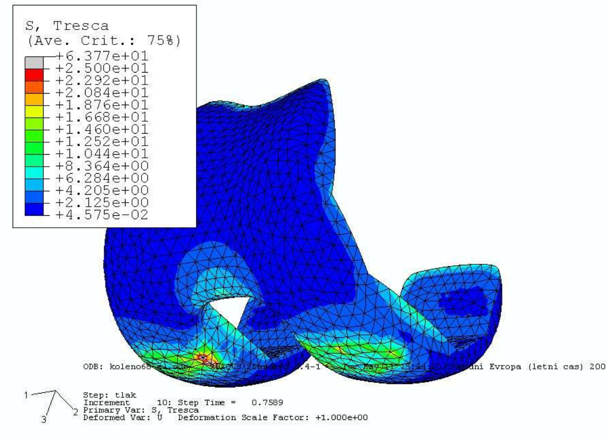

Figure 5: Stress distribution (Tresca theory) in the ceramic femoral component [MPa]

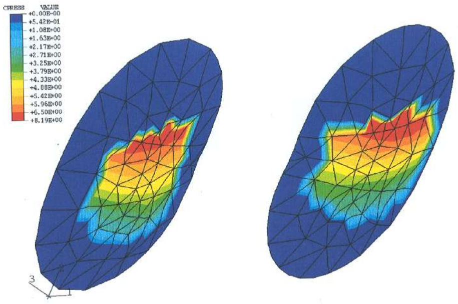

Figure 6: Contact Stress distribution on the UHMWPE plateau [MPa] [5]

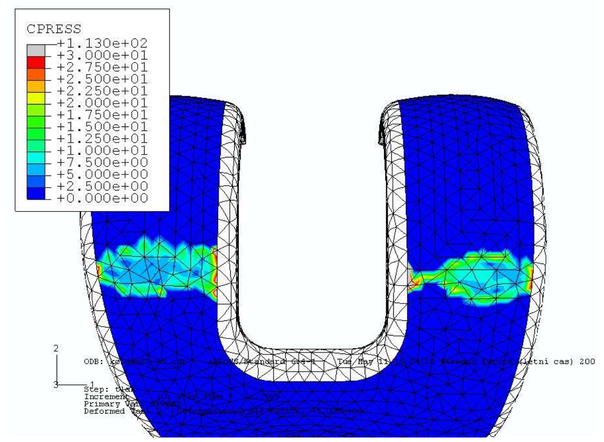

Figure 7: Contact Stress distribution on the ceramic femoral component [MPa]

Discussion

Finite element analysis is not a stand-alone method for the verification and the development of any biomechanical devices but it can be a very useful tool, especially for a determination of contact stresses and also a stress distribution. For this reason, differences in results of this and Donat's [5] work are quite worrying. In addition, those values of about 20MPa (more than two times higher than values found by Donat) are around the yield stress quoted for ultrahighmolecularweight polyethylene. To be sure, whether these discrepancies are given by the different versions of the femoral and the tibial components or whether it is due to the incorrectly defined model an experiment using pressure-sensitive films is being prepared.

Its findings will be applied for our present more accurate FE models for which good geometric models of the articulating bones and the TKR are used. All three articulating bones of the human knee are included. These models were created from the CT images provided by Visible Human Project [6]. Two main bone tissues – a cortical and a cancellous bone – are distinguished..

By now, no bone cement is presented in the problem as well as all soft tissues. The TKR consists of the femoral part, tibial plateau and its metal base. No patella resurfacing is thought (see Figure. 8).

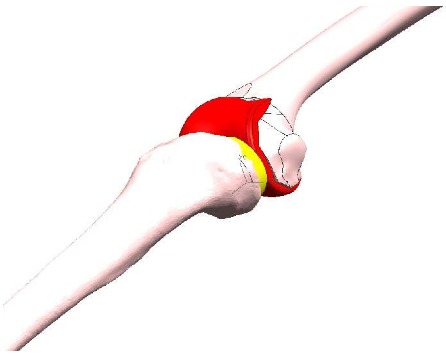

Figure 8: Complex knee joint geometric model

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Conclusions

Nowadays, ceramics is successfully used for hip joint replacement. But Alumina which shows its advantages there as a femoral head prosthesis do not suits for loadings in the knee joint. Although Zirconia is replaced now with new more progressive materials based on ceramics, experience with this femoral component are useful and even the findings of the behaviour of the existing analyses are also generally utile.

There have been carried out several tests with ZrO_2 Y-TZP and zirconia femoral component. All their results are very promising. Results of the finite element analysis (FEA) presented here shows the discrepancy with the existing FEA made by Donat [5]. While Donat states the values of the contact stresses not higher than 8.2MPa, we found the values more than two times higher (around 20MPa). Since these values are around the yield stress quoted for UHMWPE (σ_y= 21 MPa), other experiments using pressure-sensitive films has to be made to assure ourselves whether it is due to the surface irregularities or due to the incorrectly defined model.

This work is only an initial part of a project of the Laboratory of Human Biomechanics which should lead to a final goal – a dynamic FE model useful for verification of the total knee replacement (TKR) and well simulating the force relations inside the human knee. For this reason we chose the way of a gradual increasing of complexity of FE models and permanent validation of such models with laboratory tests. First we want to make a static model as detailed as possible and after that pass over the dynamic model.

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Acknowledgements

This research is supported by a grant of Ministry of Education of the Czech Republic: MSM 6840770012.