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Stress-strain analysis of the femoral component of ZIREMA total hip endoprosthesis

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Analysis and modelling

ABSTRACT

Purpose: The results of the research project, which relates to the original design for total hip joint replacement, are presented in this paper. Solution of this project was recommended and supported by the Government Office of the Slovak Republic.
Design/methodology/approach: Research methodology of total hip joint replacement has focused on a comprehensive analysis of this type of implants, which are implanted into patients around the world. Based on this knowledge and experiences of many years of leading Slovak orthopedists as well as experts in the field of material engineering such analysis was carried out in this study to and test a new type of femoral component.
Findings: The result of the project was the design and implementation of original new type of hip replacement.
Research limitations/implications: The new type of femoral component was experimentally tested in prestigious laboratories and is ready for clinical application in patients.
Practical implications: After the completion the entire research and development it will be available for use in the SR situation.
Originality/value: Product of research and development is an original Slovak cementless hip joint replacement coxal pull-up marked as ZIREMA.
Keywords: Total endoprosthesis; Stress-strain analysis; FEM; Cyclic fatigue; Femoral part

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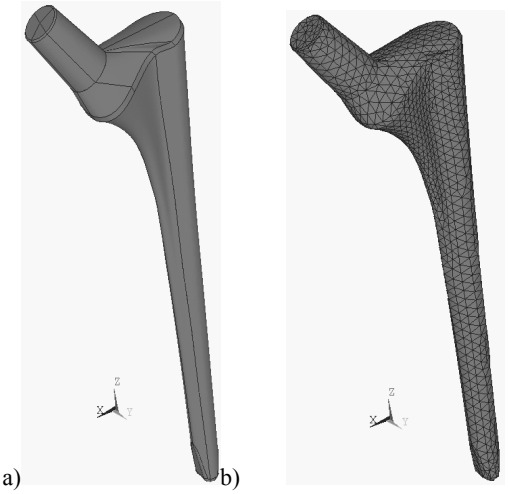
1. Introduction

In the years from 2004 to 2006, the joint project of the Slovak Technical University in Bratislava [1] and Comenius University in Bratislava [2] solved scientific-research project focused on research and development of implants in the human skeleton. The decision to solve this project was recommended [3] by the Government Office of the Slovak Republic.

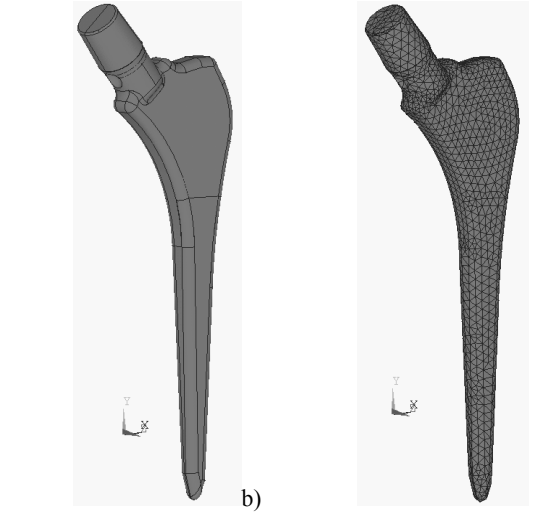
The project concerned the scientific research and development of original Slovak cementless femoral component of total hip joint replacement prosthesis. Presented conceptual designs for total hip joint replacements were designed on the basis of many years of experience of leading Slovak experts in the field of orthopedics and experience of experts from the scientific field of "material engineering".

With the financial support of this project, the structural design of the femoral components (Fig. 1a and Fig. 2a) of total hip joint replacement was developed. Three-dimensional model of femoral part of total hip joint replacement as shown in Fig.2, was later named ZIREMA.



a) b)

Fig. 1. Virtual 3D model of the femoral part with circular cross section - Model 0.a) geometry;b) FEM model (Note: This 3D model was not used at project [4])



a) b)

Fig. 2. Virtual 3D model ZIREMA of the femoral part with rectangular cross section - Model 02 [5-7].a) geometry; b) FEM model

One of the criteria was to design and develop a simple model of femoral part of a total hip joint replacement. The model 02 has achieved a significant reduction in production cost as well as significant material savings. This design reduces the weight and the cost of the endoprothesis. Weight of the Model 02 was reduced by approximately 44% compared with the model 01.

Based on the experience and knowledge obtained from the scientific and technical literature, it was decided that femoral part of total hip joint replacement would be prepared from a titanium alloy with the trademark Ti64.

After implantation into the human body, the total hip joint replacement is exposed to various loading conditions. These loading effects are largely periodic in nature. As a result, after a certain number of loading cycles, the fatigue damage may occur, which can lead to disintegration of the implanted prosthesis. In order to achieve the maximum possible "operational" life and reliability of the implants, it is necessary to take into account all relevant loading conditions. Based on the evaluation of the stress-strain state, the appropriate modifications in the design of the femoral component of total hip joint replacement can be made, which result in reduction or elimination of stress concentrations caused by the applied load.

Predictions of the stress-deformation properties of femoral parts of total joint replacements were calculated for both types of femoral components.

2. Computational models of femoral components of total hip joint replacement

The problem of determination of the location and values of stress concentrations in the stem of the femoral component can be determined using numerical simulations on the so-called virtual computer models of the implant. One of the suitable methods for numerical simulations is the finite element method (FEM). To determine the stress-strain states in the femoral component of the total hip joint replacement, which are presented in this article, the FEM software ANSYS was used.

For the designed geometric shapes of the total hip joint replacements, the deformation and areas of the greatest stress concentrations were determined based on numerical simulations.

Generally, for loading (also for experimental testing) of the total hip joint replacement the time-dependent periodic force (Fig.3) with parameters: mean value F_m = 1.9 kN, amplitude F_a = 1.6 kN and frequency of the loading force is f = 10 Hz was applied.

For the calculation of extreme stress and strain states in the stem of the total hip joint replacement, the loading represented by the concentrated static force was considered. The force was established to take into account of the extreme loading conditions and to determine the location of deformation and stress concentrations in the stem of the total hip joint replacement. Value of the force was considered F = 3.5 kN, which is equivalent to load acting on the joint of a man weighing 80 kg, landing on one leg from a height of 1.0 m. The center of the loading force in a computer model was placed in a point inside the cone pin of the femoral component. This point lies on the axis of the cone pin in

the distance $l_F = 40$ mm from the vertical axis of the implant shaft axis (Fig.4).

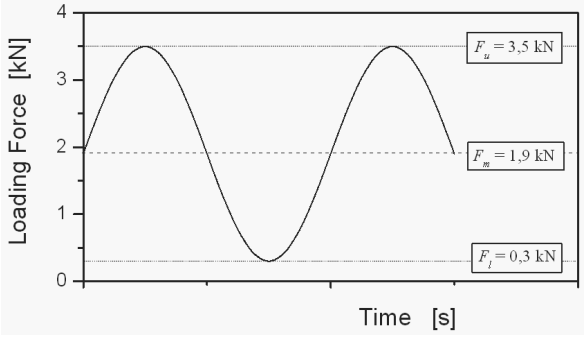


Fig. 3. Time-dependency loading force plot

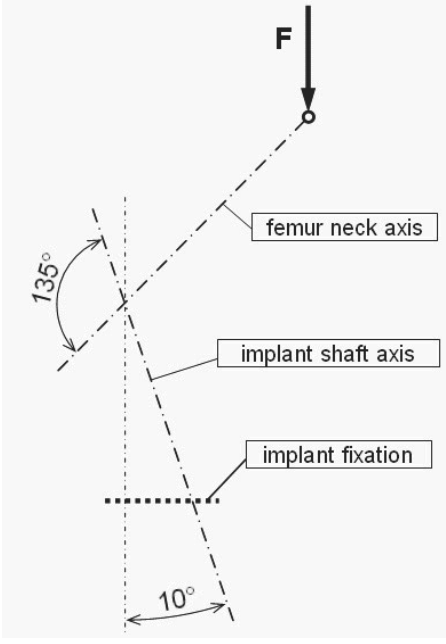


Fig. 4. Loading scheme of the femoral part

For the purposes of numerical analysis, the model of the femoral component was first created in the Autodesk Inventor CAD system. Then, the models were transformed into the graphic formats (Parasolid), which can be imported into the simulation software ANSYS. Subsequently, the geometric models were modified in ANSYS environment, so that the finite element mesh was created efficiently. Models were modified so that the loading and boundary conditions could be easily applied for the purpose of numerical simulation. Using ANSYS mesh generator were by using of 20-node volume elements (SOLID186) created finite element models of developed femoral parts of total hip joint replacement (Fig. 1b, Fig. 2b). In the nodes of simulation computational model, which are in contact with the femoral bone, boundary conditions were defined - for these nodes all the degrees of freedom were taken.

Basic parameters of the computational models:

- Model 01

Finite element model summary:			
	Largest Number	Number Defined	Number Selected
Nodes	52392	51610	51610
Elements	32328	32328	32328

- Model 02

Finite element model summary:

Finite element model summary:			
	Largest Number	Number Defined	Number Selected
Nodes	22877	22877	22877
Elements	14525	14525	14525

Material of the femoral component of implant has the trademark Ti6Al4V. The following mechanical properties were considered in numerical simulations:

- Young modulus: $E = 114$ GPa
- Poisson ratio: $\mu = 0.33$
- tensile yield stress: $\sigma_{y,tensile} = 830$ MPa
- compressible yield stress: $\sigma_{y,compressile} = 860$ MPa.

3. Results of numerical simulations

In this section, the results of numerical simulations of both virtual models of femoral components are presented. In (Fig. 5) the fields of deformations of the femoral component of endoprosthesis in the vertical direction are shown. From the calculated results of deformation of both femoral component models it is clear that Model 02 has a greater flexural stiffness, which is positively reflected in the reduction of deflection values (approx. 20%) in view of the Model 01.

The stress-strain states resulting from the load for both models are shown in Fig. 6 (Model 01) and (Fig. 7) (Model 02). A comprehensive overview about stresses at the critical points of the femoral part (i.e. the stress concentrations) are given in these figures by means of displaying the stress fields represented by principal stresses (S1, S2, S3) and also Mises (SMISE) stress.

4. Experimental testing

Based on the analysis of production and material efficiency as well as the results of numerical simulations, it was decided that an experimental test would be performed on Model 02 (Fig. 8).

Experimental testing of the femoral component of endoprosthesis ZIREMA was carried out in two independent laboratories, i.e. Welding Research Institute in Bratislava [9] and Endolab in Germany [8]. Methodology for experimental testing of implants was carried out in accordance with ISO 7206-4.

a) b)

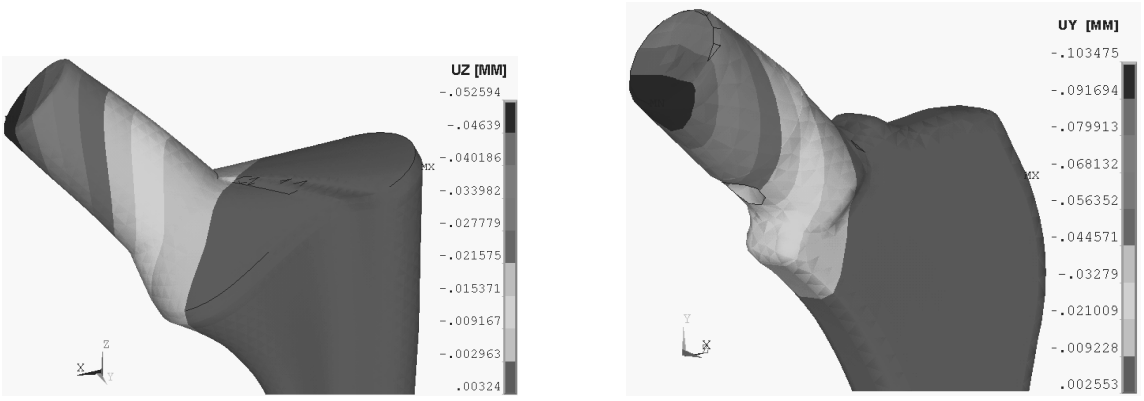


Fig. 5. Deformation state of total hip joint replacements a) Model 01, b) Model 02

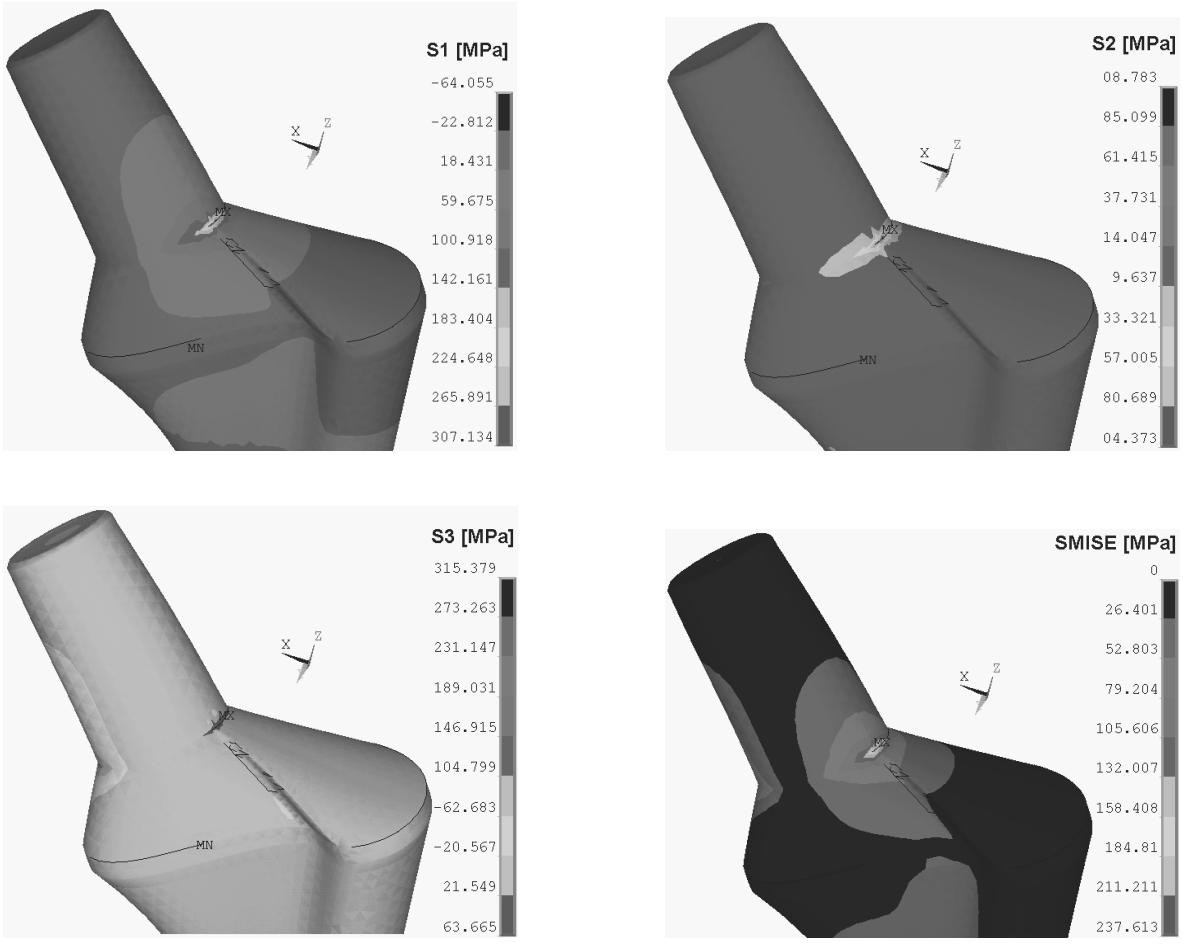


Fig. 6. Model 01 - principal stresses (S1, S2, S3) and equivalent Mises stress (SMISE)

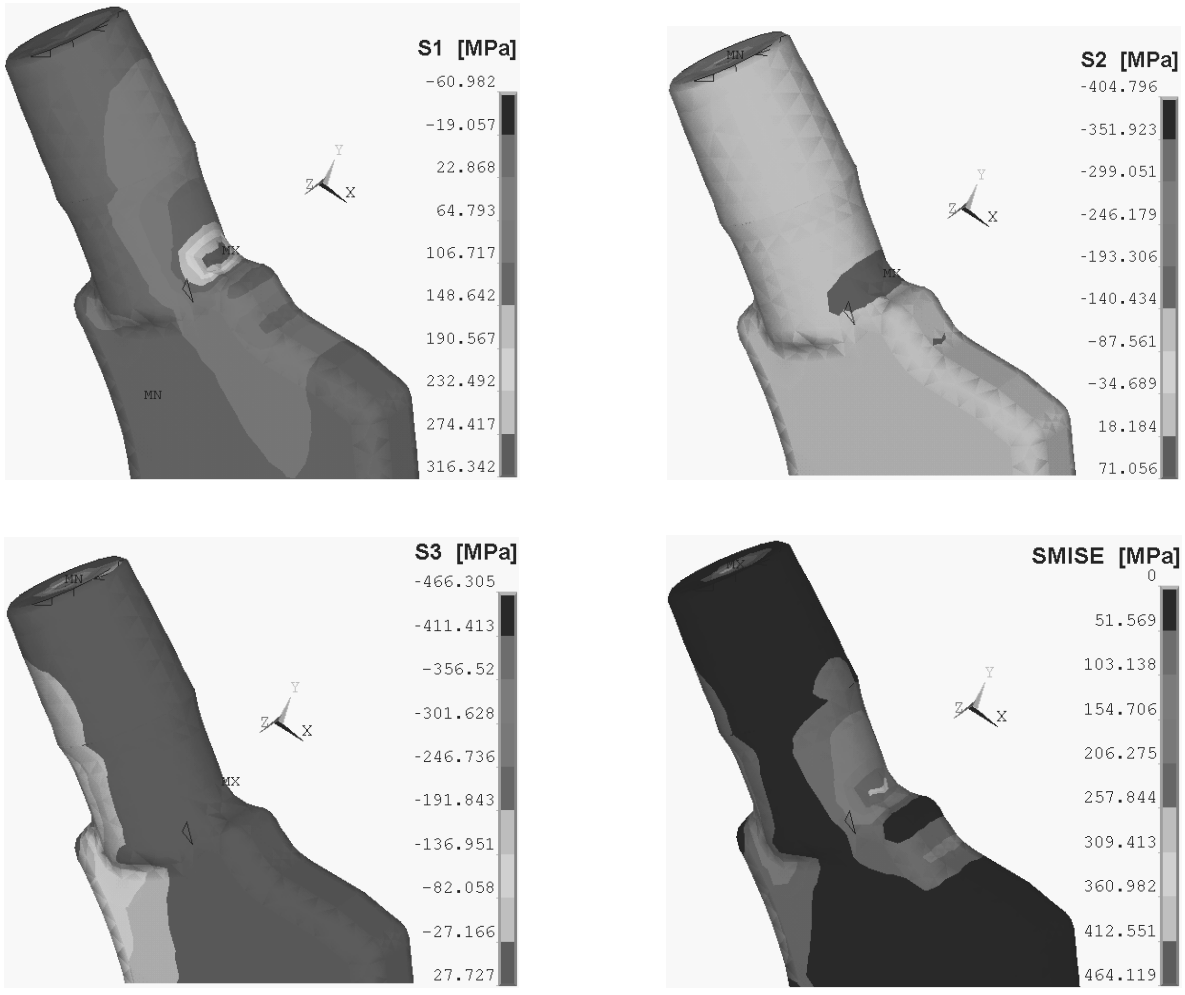


Fig. 7. Model 02 - principal stresses (S1, S2, S3) and equivalent Mises stress (SMISE)

4.1. Results of experimental testing from Endolab in Germany

Table 1.
Test parameters

Test parameter	Value
Frequency	15 Hz
Fluid test medium	Ringers solution aerated
Temperature	37°C
Embedding medium	Filled epoxy casting resin
Offset angle α (frontal)	10°
Offset angle β (sagittal)	9°
Femoral head size	Ø 28 mm, neck length L, 12/14
CT-Value	150.3 mm
Embedding (0.4*CT)	60.1 ± 2 mm
Articulation	Ceramic/Polyethylene

Fig. 8 Specimen tested - Model 02

Table 2.
Results of the dynamic test according to ISO 7206-4

Specimen	F_{min} [kN]	F_{max} [kN]	Cycles	Result
1	0.23	2.30	5,000,000	No failure
2	0.23	2.30	5,000,000	No failure
3	0.23	2.30	5,000,000	No failure

All three specimens of the ZIREMA femoral part tested at a maximum load of 2.3 kN did not fail up to 5 million cycles.

4.2. Results of experimental testing from Welding Research Institute Bratislava in Slovakia

Table 3.
Test parameters

Testing equipment	resonant pulsator RUMUL
Loading	sinusoidal pulsating cycle F_{max} = 4 kN F_{min} = 055 kN
Frequency	140 Hz

Results of the dynamic test - tested specimen of implant showed no defects or damage after 20 million load cycles.

5. Conclusions

Two virtual models of the femoral component were subjected to loading. These models have different geometry. The displacements calculated in Model 01 are higher then in Model 02, which has a higher flexural stiffness. When comparing the stress concentrations of both models, the greater stress values were found in Model 02. The value of the maximum Mises stresses reaches for the Model 01 approximately 29% of yield stress of material and for the Model 02 is this value of approximately 56% of yield stress.

These maximum stress values confirm the suitability presented of both femoral endoprosthesis designs. By taking into account the production and material costs, Model 02 can be clearly recommended.

Design of the femoral component of the developed total hip joint replacement, which was created by investigators within the project, clearly demonstrates that the metal femoral part of the implant meets all requirements. On the basis of numerical simulations carried out on virtual prototypes and experimental tests on cyclic fatigue good perspectives for application of the developed type of femoral part and for its use in the human skeleton were confirmed. The reliability of the examined femoral component and its multi-dimensional stability were experimentally tested in two reputable laboratories, i.e. Welding Research Institute in Bratislava and Endolab in Germany (Tab. 1, 2).

Total joint replacement ZIREMA has been successfully tested according to EU requirements. It is patented in Slovakia, EU and USA. I. Orthopaedic and Traumatology Clinic of the Medical Faculty, University Hospital, Comenius University in Bratislava (Tab. 3). and the State Health Institute, Ružinovská 6, 826 06 Bratislava have prepared 74 pieces of total endoprothesis in sterilized packaging for implantation in selected patients.

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