

Analysis of the porous bone-implant fixation – experimental verification of numerical model

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Abstract. In this paper a new type of endoprosthesis THRA with needle-palisade fixation system has been described. A numerical model of such fixation has been created. The developed model was subjected to experimental verification. During the test, the prototype of the needle palisade structure was inserted into the cancellous bone. The test results were compared with numerical simulation.

Keywords: bone, implant, numerical model, bone-implant connection

1 Endoprosthesis

The hip joint is one of the most exposed to overload-degenerative changes elements of the osteoarticular human system. Its function is to transfer loads both static and dynamic generated by body mass, muscle strength acting on the joint and the accelerations occurring during movement. The most common types of hip injuries are:

- fracture of femoral neck,
- congenital hip/birth defect (eg. hip dysplasia),
- avascular necrosis of the femoral head,
- postinflammatory and posttraumatic changes,
- osteoporosis,
- cancer.

Hip injuries cause severe pain, disabling movement and normal functioning in everyday life. Currently, the only method of treatment of overload and degenerative lesions of the hip is surgical treatment, which involves replacement of damaged joint surfaces with implant.

Depending on the severity of the disease, more or less invasive treatments are used. For more invasive treatment the endoprosthesis with long stem is used (Fig. 1a). It is used when the disease is very advanced or during revision surgery. For less invasive treatment the BHR (Birmingham Hip Resurfacing) method is used (Fig. 1b). In this case the endoprosthesis with short stem can be used. This method allows for the exchange of diseased areas of the acetabulum and femoral head surfaces. The bone loss is minimal, and there is also minimal risk of dislocation and loosen of implant.

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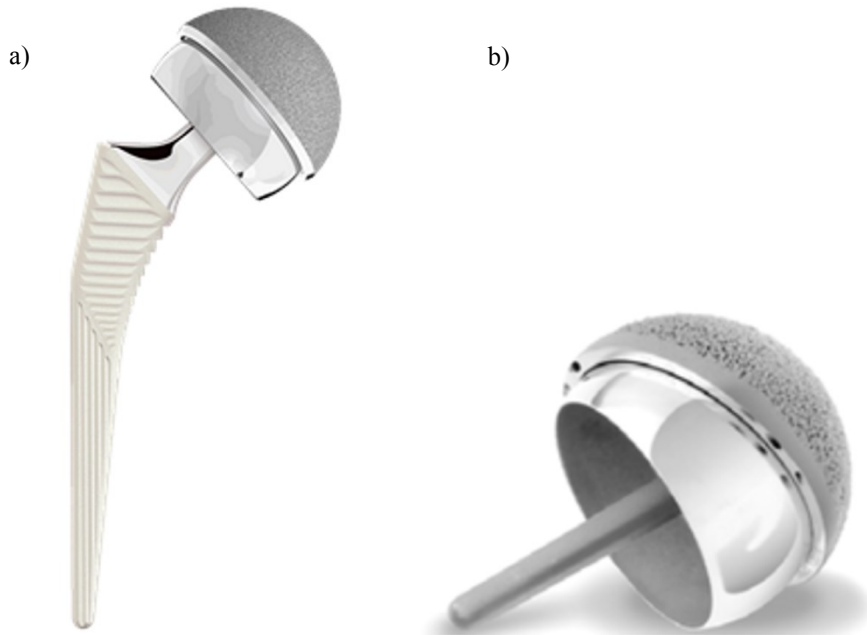


Fig. 1. Hip endoprosthesis: a) endoprosthesis with long stem [1], b) endoprosthesis with short stem so-called BHR (Birmingham Hip Resurfacing) [2]

There are different types of implants and different are methods of mounting it into bone (with cement or without) but there no matter what we do, always after some time, the new surgery and new implant is needed. It is caused by non-physiological load distribution in the bone – implant connection that causes an improper bone reconstruction. There is bone weakness, loosening of the implant and even bone fracture.

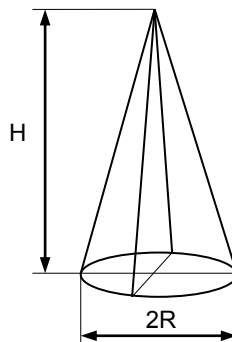


Fig. 2. A sketch illustrating geometric assumptions of modeled needles

The solution of this problem could be the application of a new type of bone-implant fixation. Instead of using a single stem, one can use many small stems similar to pins [3, 4, 5, 6]. This type of solution proposed P. Rogala [7], but he didn't determine a shape of the needle. In the patent are only guidelines and geometric assumptions between high of the needle and a radius of the circle described on the polygon in the base of the needle (Fig.2.). The finally geometry of the needles was determined during analyzes and research, which allowed us to design a prototype of the implant presented in Fig. 3. The implant consists of

two parts: a cap with a projection of pins on the inside and a acetabulum with a structure of pins on the outside. Fig. 3c.

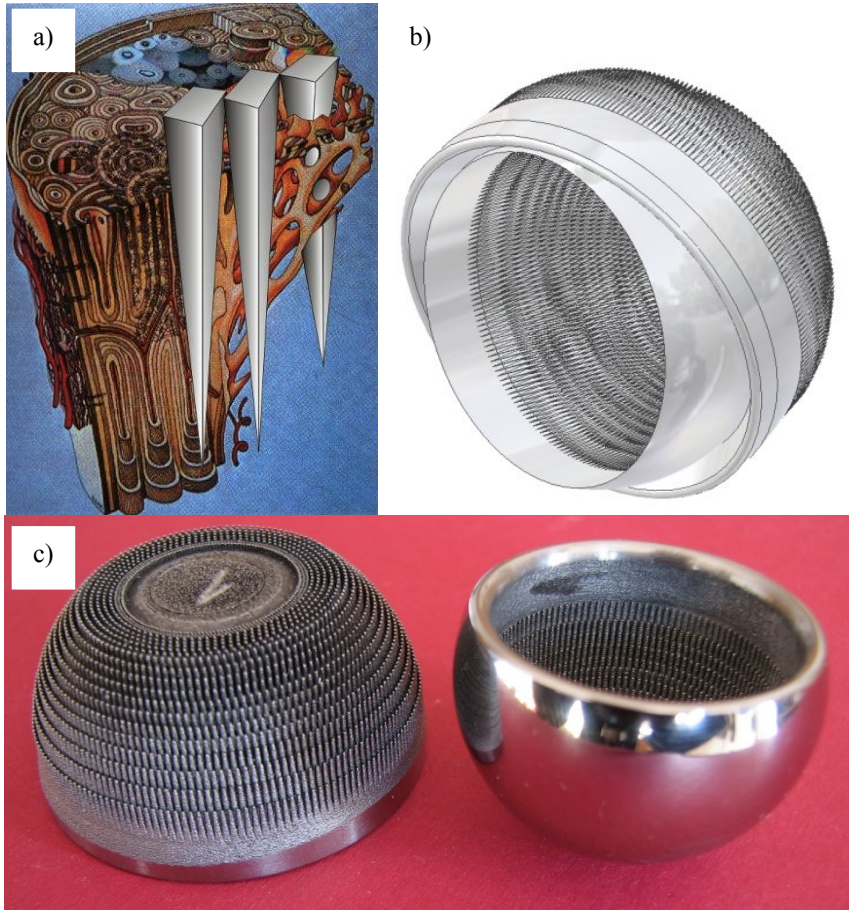


Fig. 3. The idea of the new type of endoprosthesis: (a) needles penetrate into cancellous bone [8]; (b) model of the endoprosthesis with needle palisade fixation system based on the European Patent EP072418 B1; (c) prototype made with SLM technology from titanium alloy.

2 Numerical analysis

The aim of the study is to build a numerical model of porous biomaterial and its application in modeling bone-implant fixation by numerical representation of the process of insertion of needles into the cancellous bone.

The geometric model was built from two parts: a bone model and a model of needles which will be inserted into the bone (Fig. 4). The needles are arranged concentrically on a base of about 8mm radius. Because of the amount of finite element needed to generate the calculations, and due to the complexity of the model, some simplifications were made to the actual object used in the tests. The base has been omitted in modeling, replacing it with appropriate bindings. The second modeled object was the bone in which the pyramid palisade was pressed. It was modeled as a cylindrical object with hollow square-shaped tubules. The arrangement of the tubules corresponded to the placement of the needles in the first object. During the simulation, the needle system is lowered and the pyramid are

inserted into the bone model. In the model there was defined contact between the surfaces of the needles and the channels.

The prepared geometric model was discretized with finite elements. There were used a eight nodal hexagonal elements. The bone has been modeled as a deformable material. Titanium needles were modeled as a non-deformable body by giving the "rigid body" constrain. In the described model, material was used as isotropic, elastic-plastic with values $E=0,2$ GPa and $\nu=0,03$. Calculations were made in the Abaqus program.

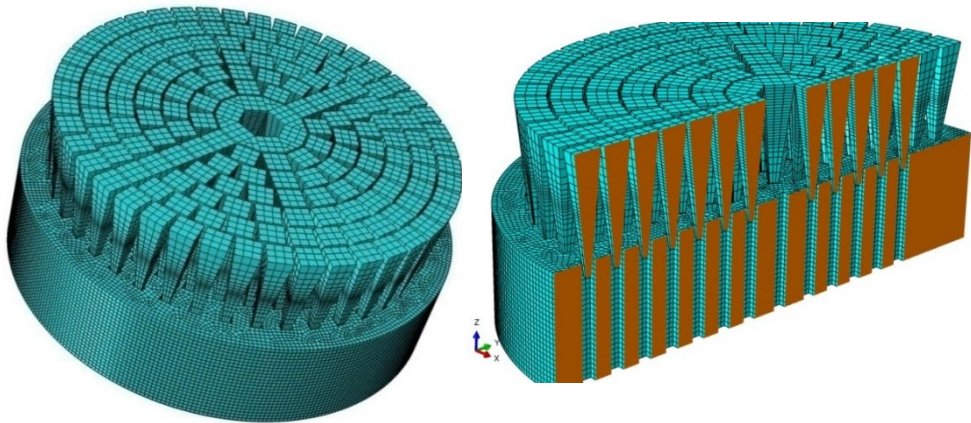


Fig. 4. Numerical model of the bone – implant connection

The figures presented below (Fig. 5, Fig. 6) show the results of the calculations. Based on the results, significant deformations of the bone material in the area between pins were observed. Hollowing of needles, of the order of 50% of the length, already causes distortion far beyond the yield point. This leads to permanent destruction of the trabecular structure of the bone, the breaking and thickening of the bone material, which consequently wedges between the pins.

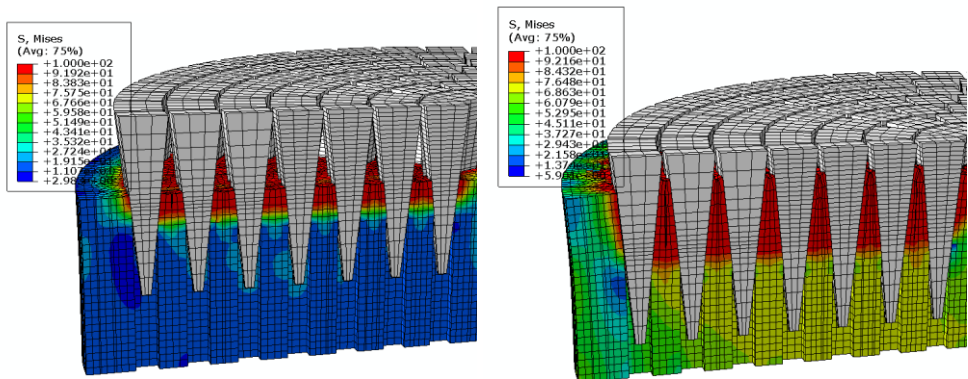


Fig. 5. Changing the stress distribution during the insertion of needles into the cancellous bone

The results of these analyzes confirm the studies. During the extraction of the samples, the bone fragments jammed between the pins. By analyzing the results, it can be seen that not only the material in the space between the needles, but also the lower one, is affected by deformation. The crushed and compacted bone forms with the specimen a type of punch that presses on the underlying layers of material causing it to deform. With large forces can

lead to the destruction of the material theoretically not taking part in bone implant connection.

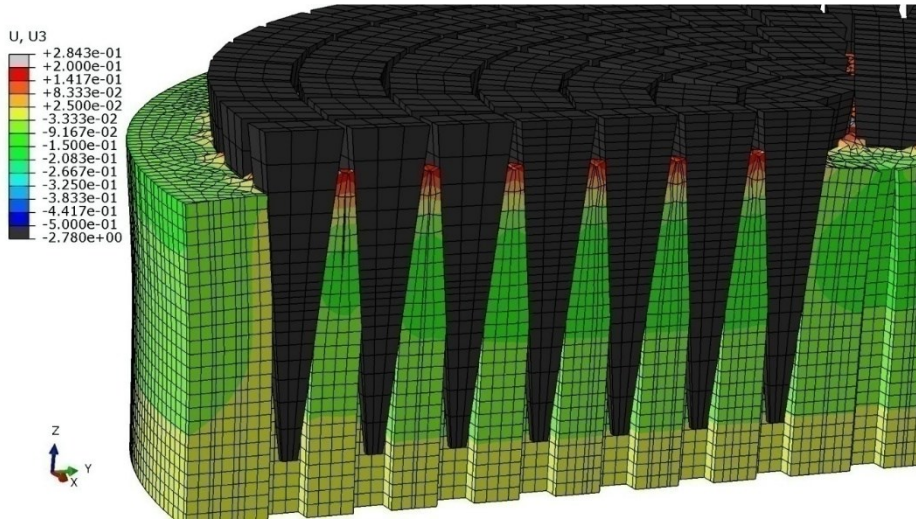


Fig. 6. Distribution of displacement in the vertical direction

3 Experimental verification of numerical model

The study aimed to find the relation between the force and the value of depth of the insertion of needle for different types of pyramids forming needle - palisade fixation system.

These characteristics will be used also to verify the numerical model of mentioned connection. It is also important to observe the changes and deformations that occur in the bones when making a connection.

The samples were designed with a cylindrical base on which a pyramid system of pins was placed. The base diameter was 16mm and its height was 6mm. Samples were made using rapid prototyping technology. With available methods, the SLM (Selective Laser Melting) were chosen. The titanium alloy powder Ti6Al4V has been used. This material has been successfully used in prosthetics for many years.

Samples were pressed in pork bone imported from a slaughterhouse. The bone was used in the research within several hours of slaughter and was stored under refrigeration. Preliminary bone processing, ie removal of soft tissues, cartilage and cutting to 1/3 of the length, took place in the slaughterhouse. Before testing, the bones were laid in a box and covered with gypsum. This solution provides a cheap and stable mounting with the desired high stiffness.

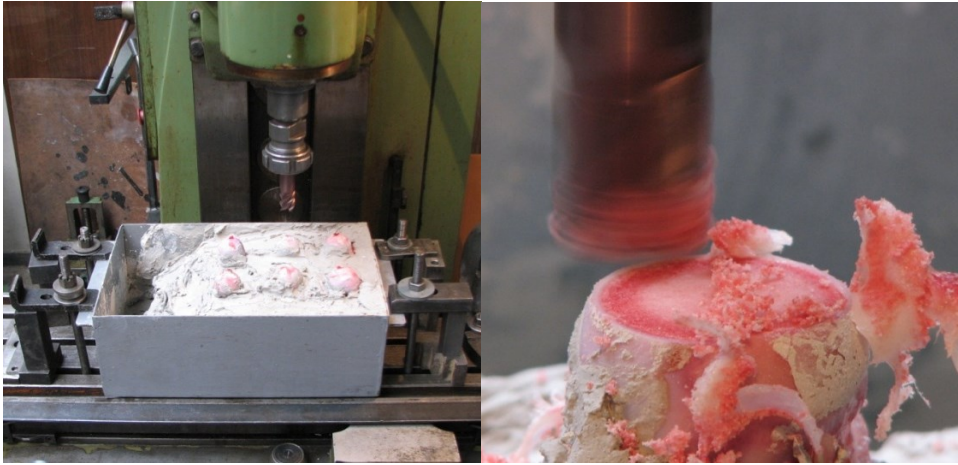


Fig. 7. Preparation the bone for tests - milling the bone head

After the gypsum dried, the bones were milled to obtain a flat surface (Fig.7). The tests were done on a machine TIRA test 2450. The insertion process took place at a speed of about 2mm / min.

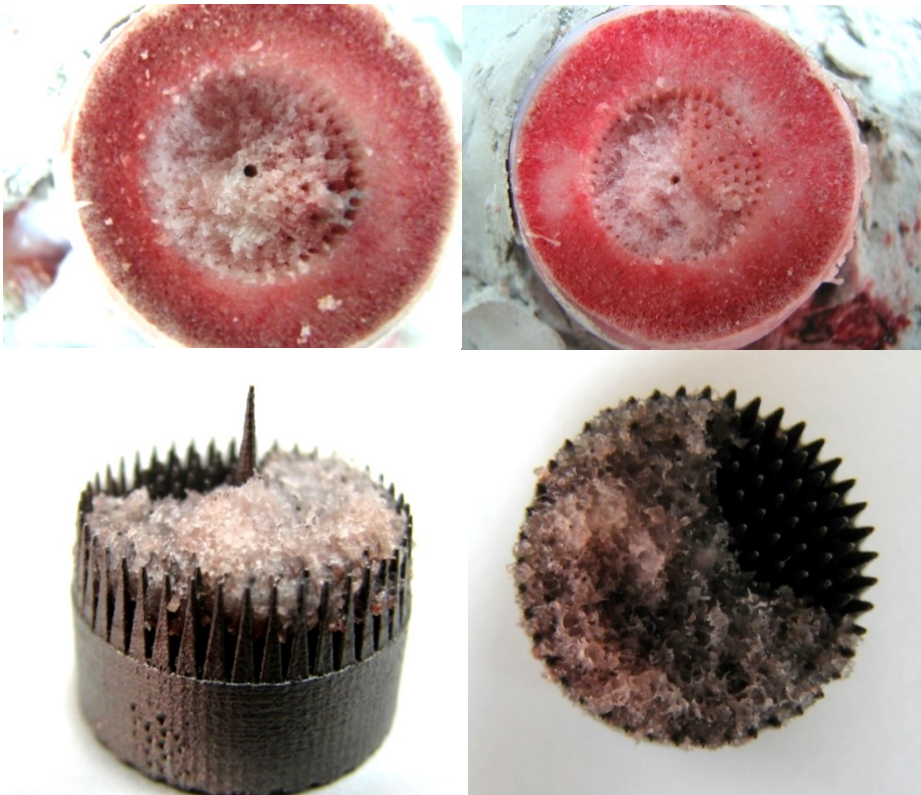


Fig. 8. The bone and the samples after tests

The studies mentioned above showed, that it is not possible to completely press the needle structure into the cancellous bone. In extreme cases, when the strength reached high values there was a cracking of the bone and its breaking. Nevertheless, there has never been

a process of total depression. In situations when the needle injection into the bone was interrupted earlier, and then an attempt was made to extract the needles from the bone, in many cases the bone fragments was pulled out (Fig. 8). This situation always appeared when the needles were pulled down over 50-60% of their height.

With this in mind, a series of studies were conducted to determine the maximum needle depth that would not break the bone fragments during the sample extraction. The studies let to collect a data (the force as a function of displacement) when the needles are inserted into the cancellous bone (Fig. 9).

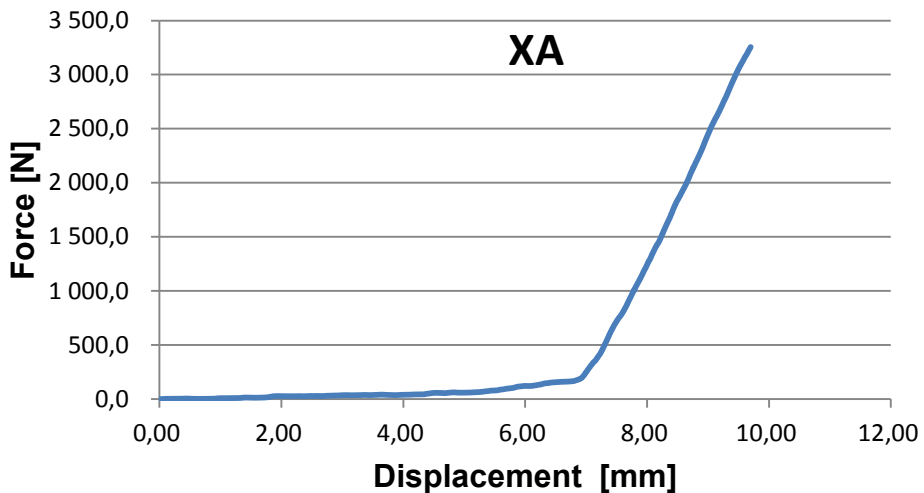


Fig. 9. Graph of dependence of the force on the needle displacement into cancellous bone. Sample with the needles in the form of pyramids with square base and dimensions: base area 1 mm² , ratio A/H=1:5

The average value of the force required to insert the needles into a given depth is shown in the Table 1. It was combined with the force value obtained by numerical simulations. The difference between those values is less than 10%.

Table 1. Summary of research results with numerical simulation results

Shape of the base	Needles' high A/H	displacement [mm]	Force		
			Tests [N]	Simulation [N]	Difference [%]
Square	1:5	2.1	2645	2902	8.8
Square	1:9	3.7	3143	2951	6.1
Triangle	1:5	2.0	2690	2938	8.4
Triangle	1:9	3.5	3890	3626	6.8

Conclusions

The aim of the study was to verify the numerical model of implant - bone connection. The numerical model will be used to study the process of insertion of needles into the cancellous bone. The results of the study will be necessary to formulate guidelines for the design process of implant - bone connection. The results of the research presented in this paper indicate the correctness of the constructed numerical model. However, the effect on the convergence of the experimental and simulation results is largely determined by the material (bone), the accuracy of the needle geometry mapping in the SLM process and the numerical simplicity and assumptions adopted in the numerical model.

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