Strain Measurements Exhibited by a Steel Prosthesis Protected with Au Nanoparticles

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Abstract The design and manufacturing of a customized femur prosthesis is presented. Besides, the application of a coating of Au nanoparticles embedded in titanium dioxide is evaluated. For this purpose, a customized femur prosthesis for a Labrador Retriever dog was manufactured. It was 7 years old and its weight was 35 kg. The main geometrical characteristics of the prosthesis are the following. Its femoral neck angle is 75.84°, the smallest and largest diameter of the shaft is 2.7 and 6 mm, respectively, while the diameter of the femur head is 20 mm. The material used for this purpose was stainless steel. Initially, a tomographic study of

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the hip and femur was carried on. All the data was collected in .DICOM files. From this information, solid models were obtained. The new data was saved in .STL files. From such files, quick prototypes were carried out. They were made with ABS material, following a stereolithography procedure. All the dimensions were checked. Once the customized model was approved, the structural integrity was determined with the finite element method. In the next step it was manufactured. In the final part, a 250 nm coating, which was made of Au nanoparticles embedded in titanium dioxide, was applied. An indentation test was carried out. A 65° Berkovich indenter, made with diamond, was used. The modulus of elasticity of the coating was 941 MPa. The stress field during the indentation test was obtained.

Keywords Hip · Femur prosthesis · Nanostructured thin solid film coating · Canine femur · Computed tomography

1 Introduction

Prostheses required for humans must satisfy diverse requirements. In general terms, they have to be manufactured with biocompatible materials and they must have an adequate structural integrity. In this way, infections or replacements after small periods are avoided. Regarding the hip prosthesis, the femoral head is subjected to wear conditions. All these points have to be considered in its design. Also, clinical regulations have to be observed. In the case of Mexico, they are established by the medical regulatory body, COFEPRIS. They are summarized in [1].

Actually, hip prostheses have received much attention. They have been widely used in older patients, mainly. Nowadays, they are optimized continuously. Thus, diverse prototypes are developed. Several tests have to be approved before such prostheses can be used in a clinical treatment. For this reason, they are tested with some animals. Several candidates can be proposed. At the first instance, primates can be used. However, they require special cares and there are some species, which are in danger of extinction [2, 3]. In accordance with Skurla et al. [4], dogs can be used for this purpose. Goel and coworkers [5] have established the following reasons why dogs are adequate. Their femoral anatomy is similar to the human beings and their femur size is appropriate for the technique which is applied in the total reconstruction of a hip. The canine vascular anatomy is similar to the humans. Besides, dogs are sufficiently active for the use of a prosthesis and the kinematic articulations of their hip are similar to those of a human hip. However, the main disadvantage is that dogs are quadrupeds.

Accordingly, the purpose of this chapter is the design of a prototype of a customized hip prosthesis for a dog. After the design was approved, the femoral head was coated with Au nanoparticles embedded in titanium dioxide. For this reason, the mechanical behavior of the coat was evaluated with indentation tests in conjunction with the finite element method.

2 Materials and Methods

This research work was carried on with a Labrador Retriever dog. It was 7 years old and its weight was 35 kg (Fig. 1). In the case of dogs, dysplasia takes place when they are more than 6 years old. This is the reason why such a dog was selected.

Initially a model of the canine femur was developed. The procedure proposed by Beltrán-Fernández et al. [6] was followed. For this purpose, a Lightspeed computational tomograph was used. It can take 16 slices per second. For the problem at hand, 513 slices of the canine femur were taken. All the data was digitalized and saved in DICOM® files [7]. Figure 2 shows the 3D model that was obtained.

In the next step, the ScanIp® code was used. The tomographies mentioned above, were reproduced [8]. Masks were developed. They were used in the selection of the area of interest of the femur. Cortical (Fig. 3) and trabecular (Fig. 4) bone were differentiated. The first one is in blue, while the second is in purple. All the data was collected in *.STL files. The design and manufacture of a customized prosthesis require uniform and smooth surfaces, avoiding sharp edges. Thus, the surface of the model was reshaped with the Power Shape® code.

In the next step, plastic prototypes of the prosthesis of the canine femur were obtained. The clinical treatment was discussed with the orthopedic team, considering such prototypes. It was decided which part of the femur had to be cut. Therefore, it was possible to generate the prototype of the femur-prosthesis system. For this purpose, the axial axis of the diaphysis was localized. This parameter is important in order to establish the maximum and minimum diameters of the stem of the prosthesis. They are 6 and 2.7 mm, respectively. This information was used to establish the length of the stem and to determine which surfaces of the stem had to be anchored. In this way, the prosthesis does not loose easily. Also, the angle between the femoral head and the axial axis of the diaphysis and the diameter of the femoral head were established. They are 75.84° and 20 mm, respectively. Finally, the good adjustment of both elements was checked. Figure 5 illustrates how this prosthesis is coupled with the femur and Fig. 6 shows the solid model of the prosthesis.

3 Finite Element Analysis

The finite element mesh was developed from the solid model of the system femur-prosthesis (Fig. 7). For the evaluation of the structural integrity, it was considered that the prosthesis was made of stainless steel 316LVM. Its modulus of elasticity and Poissońs ratio are 210 GPa and 0.3, respectively [9]. Besides, the modulus of elasticity of the cortical bone of the femur is 10 GPa and its Poissońs ratio is 0.3. The modulus of elasticity of the trabecular bone is 1 GPa and its Poissońs ratio is 0.3 [10–12].

Fig. 1 Retriever dog before its femur tomography was taken

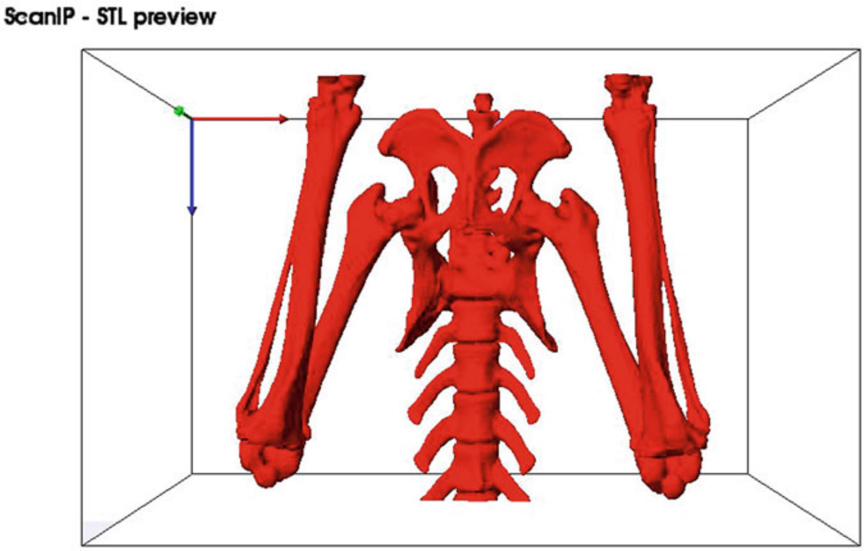

Fig. 2 3D model of the rear femurs of the dog

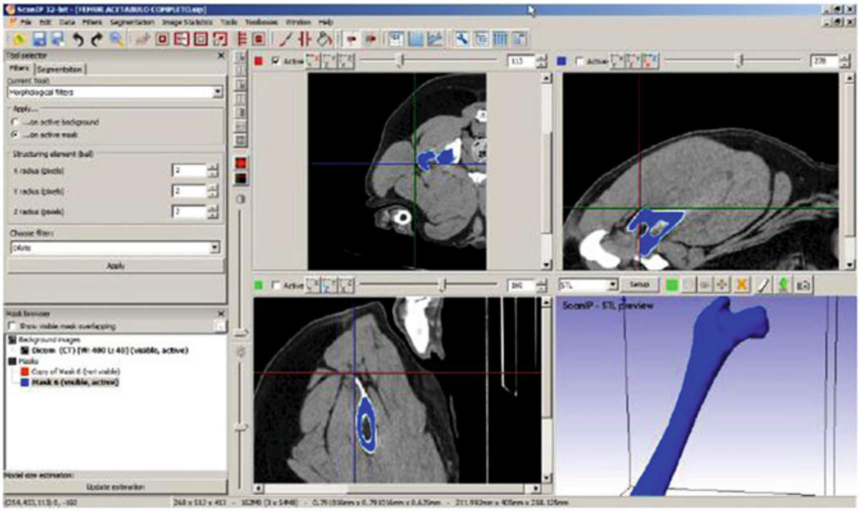

Fig. 3 3D model of the cortical bone of the canine femur

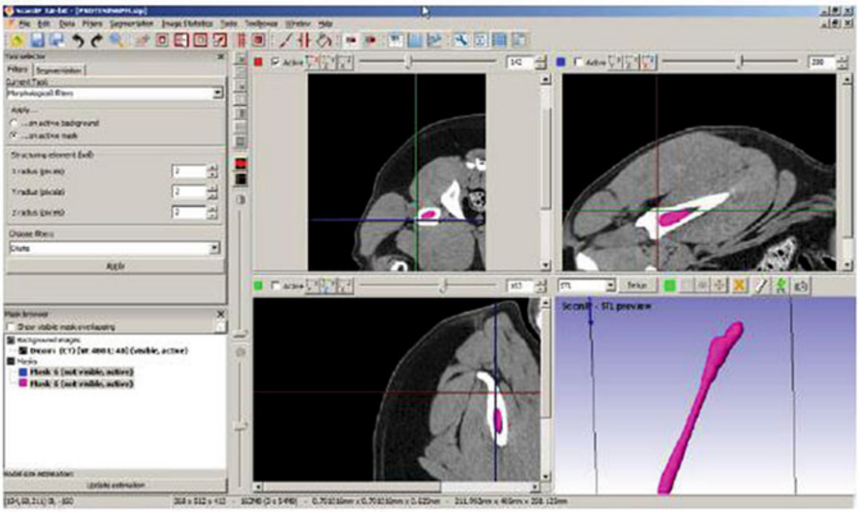

Fig. 4 3D model of the trabecular bone of the canine femur

The finite element analysis was carried out with the ANSYS code and the mesh was developed with quadratic tetrahedrons of ten nodes. Each node has three degrees of freedom. The numbers of elements and nodes are 59,827 and 75,039, respectively (Fig. 8). For the purpose of this analysis, the stem of the prosthesis

Fig. 5 System femur-prosthesis coupled with the hip

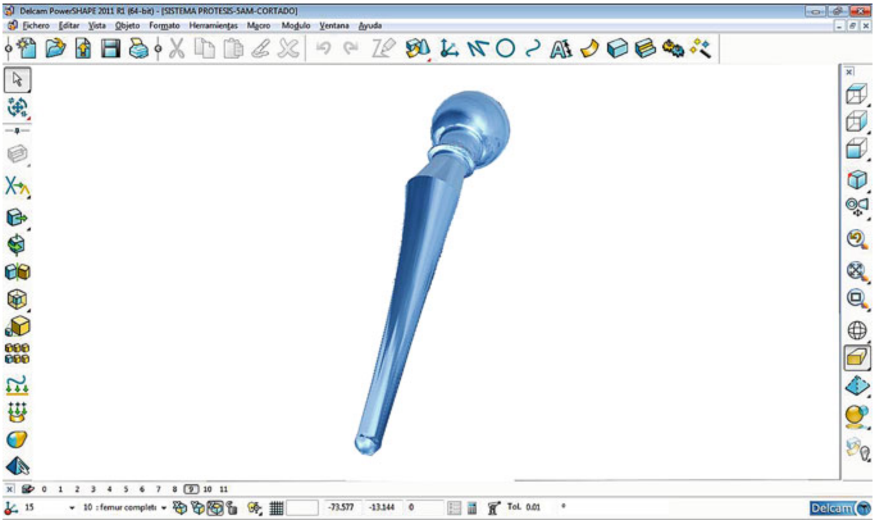

Fig. 6 Solid model of the femur prosthesis of the dog

was fixed at its distal end. Therefore, the boundary conditions applied in this analysis considered that the nodes at such end were anchored.

Regarding the loading conditions, Kim et al. [13] tested a femur prosthesis of dog under compression. The maximum load was in the range between 27 and 33 kg. In an extreme condition, a compression load of 370 N was considered. This is the weight of the dog supported only by one leg and is applied at the femur head of the prosthesis. The components of such force are $F_x = -82.75$ N, $F_y = 19.83$ N, $F_z = -360.62$ N (Fig. 9) [14].

The results of the finite element analysis show that the maximum displacement was 0.001253 mm (Fig. 10). Besides, the maximum von Mises stress was 673.214 kPa. It is located at the medial part of the diaphysis (Fig. 11). It can be

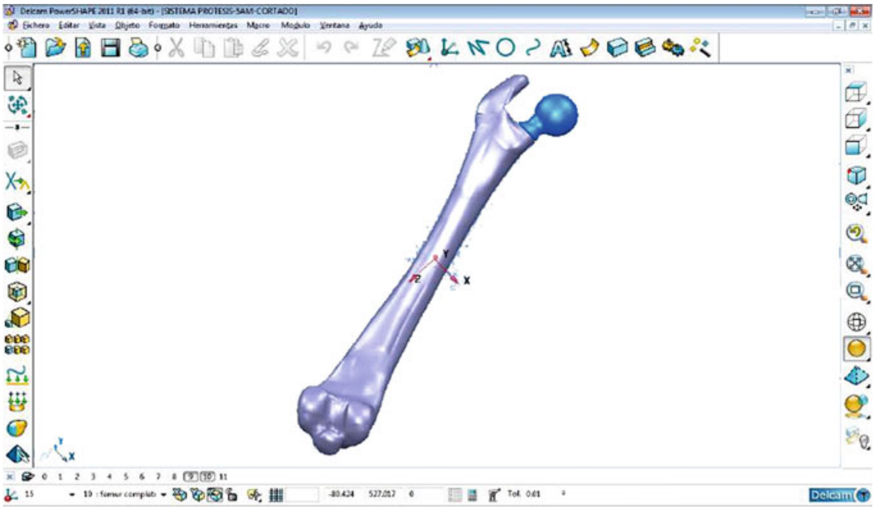

Fig. 7 Solid model of the femur-prosthesis system

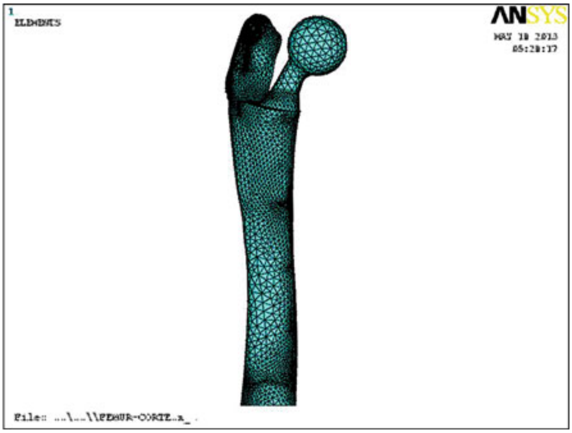

Fig. 8 Finite element mesh of the system femur-prosthesis

considered that this arrangement has an adequate structural integrity and it cannot be loosen easily.

4 Manufacture of the Prosthesis

With the information obtained in the development of the model and the prototypes, the dimensions of the customized prosthesis of the dog were obtained. It was manufactured with a conventional procedure of manufacture (Fig. 12).

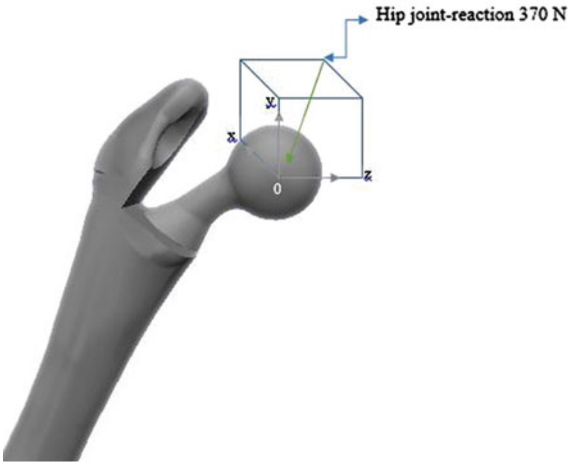

Fig. 9 Hip joint load

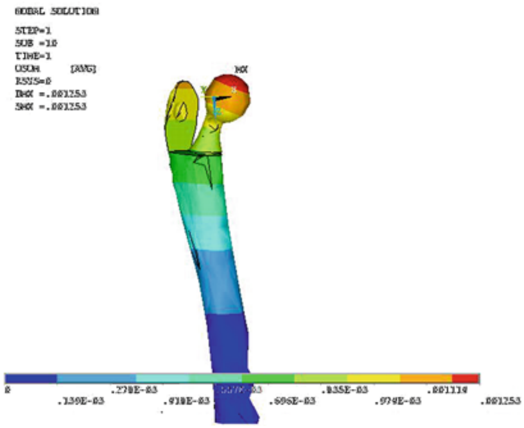

Fig. 10 Deformation in mm of the system femur-prosthesis

In the next step it was coated the femoral head with Au nanoparticles embedded in titanium dioxide (Fig. 13).

5 Nanostructured Thin Solid Film Coating

Hydroxyapatite has been widely used in diverse prostheses. However, an alternative is the use of nanometric building blocks to fabricate scaffolds. For this purpose, high quality nanoparticles with extremely high purity and crystallinity are required. Also, it is important to understand the load-bearing capacity, when these materials are used in implants. When the mechanical properties of an implant do

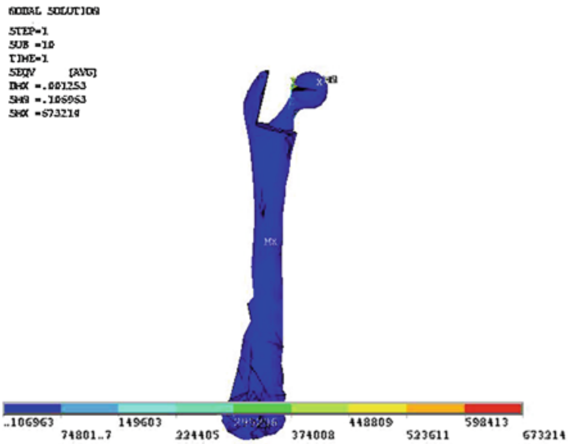

Fig. 11 Resultant von Mises stresses in Pa on the system femur prosthesis

Fig. 12 Femur prosthesis manufactured

Fig. 13 Head of the femur prosthesis coated with AuNP

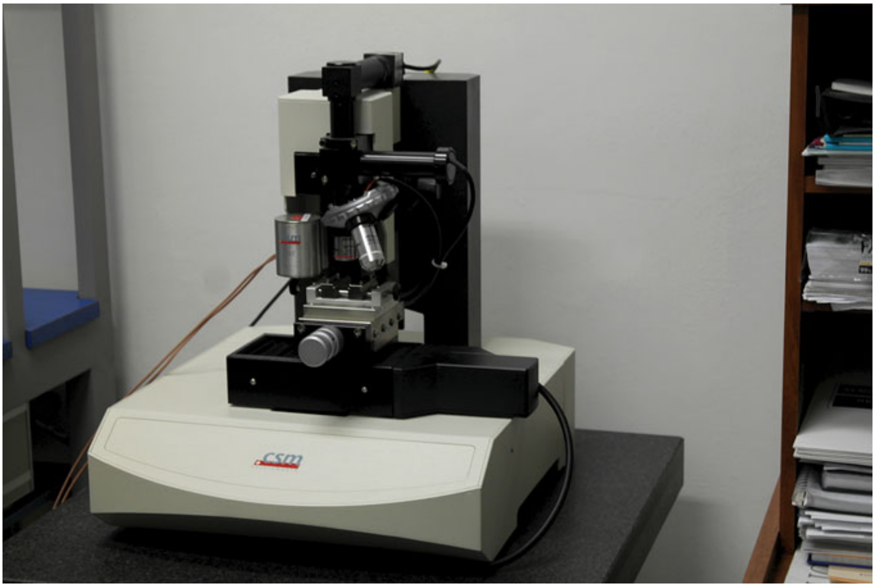

Fig. 14 Nano hardness tester

not match with bone, stress shielding can be developed. This can lead to bone resorption and loosening of the implant. In this way, biocompatible Au nanoparticles have gained considerable attention recently [15].

For the problem at hand, the femur head is under compression load and its joint is in constant wear movement. Therefore, it is expected that a film coating with Au/TiO2 can avoid the premature wear. At the same time, it is expected that the stem of prosthesis does not loose. For this purpose, a coat was applied with the sol-gel technique in the specimen. It is simple and it is cheap to obtain a thin film of metallic oxides, which can be doped with nanoparticles. This procedure can be done at room temperature.

The titanium oxide film doped with gold NPs was synthesized. Initially a SG1 solution was obtained. For this purpose, titanium i-propoxyde [Ti(OC3H7)4] solution with C = 0.05 Mol/L, pH = 1.25 and water/alkoxyde with molar ratio (rw) of 0.8 were used. The resultant solution was stored in a dark place for at least 1 week before using it in the synthesis step.

The required gold nanorods precursor solution was an Aldrich standard solution for AAS analysis with a gold nominal concentration of 1000 mg/L. This solution was used as received. It was added drop by drop into the bottle which contained the SG1 solution. Then after, it was stirred vigorously with a magnetic stirrer plate. The molar ratio of the Au/Ti(OC3H7)4 mixture was 0.76 % (mol/mol). This new solution was called SGG1.

The photocatalytic reduction of the gold ions was carried out in a homemade UV-reactor, which has twelve UV light sources. Each one has a black light blue

Table 1 Mechanical properties of the materials involved in the nano-indentation test

Material	Modulus of elasticity	Poissońs ratio
Steel substratum	200 GPa	0.33
AuNPs coating	0.941 GPa	0.27
Diamond indenter	1141 GPa	0.07

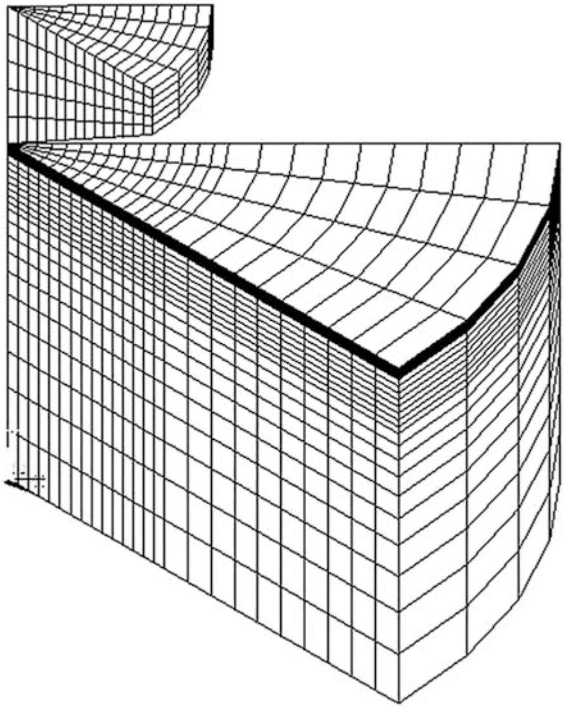

Fig. 15 Finite element mesh used in the stress analysis of the indentation process

UVA lamp (8 W, Hitachi). Under these conditions, the range of UVA light provided is between 320 to 390 nm with λ_{max} (emission) = 355 nm and a light intensity of 732 $\mu W/cm^2$.

Ten ml of the SGG1 solution was exposed to this light source. This event lasted between 15 and 20 min. Then, the light source was switched off and the irradiated sol-gel solution was used to coat the customized prosthesis. This was done with the dip coating technique. The thickness of the resulting samples was around to 250 nm. An atomic force microscope (Dimension 3,100, Nanoscope IV) was used to measure the size and density of the Au NPs [16, 17]. Figure 13 shows a spot of the AuNPs coat.

In the evaluation of the hardness of the coating, a steel substrate was coated with AuNPs. A nano hardness tester NHT of CSM instruments was used. This

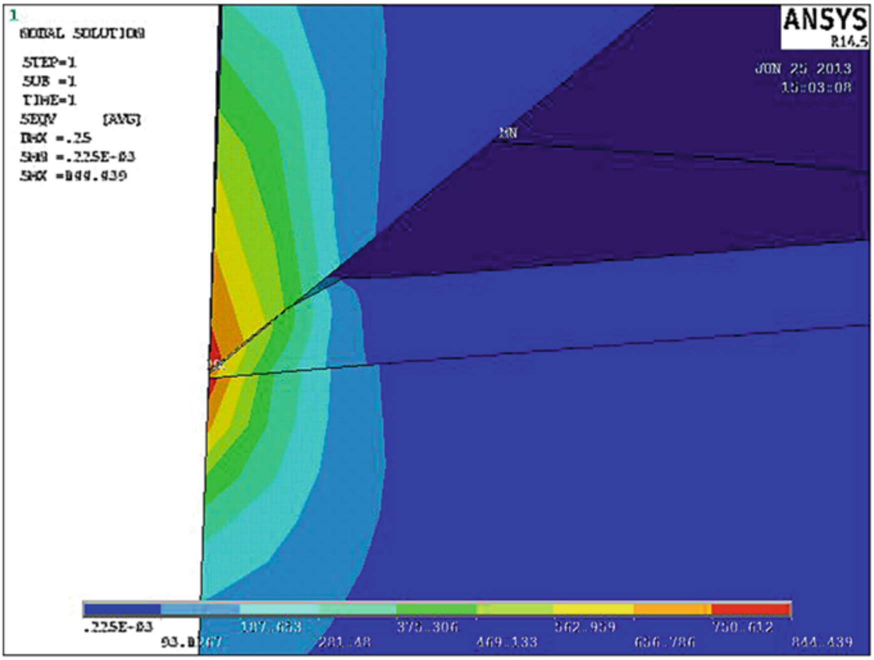

Fig. 16 von Mises stress field in Pa at the point of indentation

device has a load range of indentation between 0.1 and 500 mN and its load resolution is 0.04 μN. The maximum indentation depth is 200 μm (Fig. 14).

The mechanical behavior of the AuNPs coating was evaluated with an indentation test. 20 mN was the maximum load applied. The load and unload rates were 100 mN/mim in both cases. The thickness of the coating was 250 nm. A Berkovich indenter, made of diamond, was used. Its angle was 65°. The modulus of elasticity of the coating was obtained. It was 941 MPa.

A finite element analysis was carried out with the ANSYS code in order to obtain the resultant stress field. The mechanical properties of the involved materials are reported in Table 1. The model was considered axisymmetric. The main considerations of Bouzakis et al. [18] were followed. For this reason, only one eight of the domain of interest was modeled (Fig. 15). Symmetry conditions were considered along the symmetric planes and over the axial axis. The top surface of the indenter was anchored. The nodes on the bottom surface of the substratum were free to move along the vertical direction. In this way the nano-indentation was simulated. The top surface of the coating was pressured against the bottom surface of the indenter. The surfaces of the indenter and the coating were simulated with contact elements (CONTA174 and CONTA170). 3,745 nodes and 3,858 elements were required.

A penetration of 250 nm was simulated. In this way, all the coating thickness was penetrated. The maximum von Mises stress was 844.349 Pa (Fig. 16).

6 Conclusions

In this chapter, a manufacture process of a customized femur prosthesis has been proposed. The information technology plays an important role and optimizes the procedure in the manufacture. The main advantage is that an invasive procedure is not required. Thus, the contact with the human tissues is reduced.

The plastic prototypes of the prosthesis were useful in the discussion and the establishment of the manufacture procedure and the orthopedic treatment. Previously to the manufacture of the femur prosthesis, its correct adjustment with the femur and hip was checked. The results of the finite element method show that the system femur-prosthesis has an adequate structural integrity. It is important to observe that the deformation of the system femur prosthesis is small. Therefore, loosening will not be expected. In this case, a suitable prosthesis for the dog was obtained.

A film coating of Au nanoparticles embedded in titanium dioxide was applied to the femur head of the prosthesis at the end of the manufacture process. The mechanical behavior of this coating was evaluated with indentation tests. Encouraging results have been obtained. The technique that was followed was easy to implement and a uniform layer was obtained. Besides, it was possible to obtain the stress field at the coating during the indentation process.

However, a more detailed analysis is required in order to evaluate its biocompatibility and benefits. At the same time, the guidelines established by the clinical regulatory bodies have to be followed. More tests are demanded before a prosthesis with such coating is used in the implant of an individual.

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