Obtaining the predicted number of cycles of femoral prosthesis manufactured with ASTM F138 and ASTM F75 alloys, applying the method of finite element.

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Abstract. This study aims to calculate the predictive number of cycles applied to femoral prostheses made with ASTM F138 and ASTM F75 alloys. A hip prosthesis is typically subjected to cyclic loads commensurate with the patient's weight in response to each step and hence requires a cyclic compression stress approach. Austenitic stainless steels have been used in surgical applications over many years due to low cost, good mechanical properties and resistance to corrosion. The CrCoMo alloy features higher corrosion resistance compared to ASTM F138 stainless steel. In order to perform finite element analysis, two software were used: Autodesk® Inventor® 2013 and Autodesk® Simulation 2015. The formatting of the simulation followed the parameters established in the ISO 7206-4: 2016 ABNT NBR standard, the applied load was 2,3 kN with an angle of 10 degrees with respect to the frontal plane and 9 degrees with respect to the lateral plane. As for the static analysis, the prosthesis composed of ASTM F138 material presented satisfactory results, and the prosthesis made with the ASTM F75 alloy failed. Both prostheses did not exceed 5 million cycles in the dynamic load application.

Keywords: finite element, prosthesis, femur, hip, F138, F75.

1. Introduction

The main functions of the hip include the support of the body weight and the movement for locomotion, its articulation is formed by a joint between the head of the femur, acetabulum and articular cartilage [1]. The hip is a complex structure, composed of bones, ligaments, and structural muscles, responsible for transmitting power to the body. In this way, this joint is crucial for physical activities and is often exposed to efforts such as torsion, flexion and compression [2].

Fracture of the femur is an important research topic in orthopedic and mechanical engineering. Normal and healthy femur lesions are usually caused by high demands, as well as automotive and sports accidents [3]. Bone tissue is a complex natural composite consisting of soft and strong protein collagen, which has a density between 1.6 and 1.7 g/cm³. Bone is an anisotropic material with mechanical properties that differ in longitudinal and transverse directions [4].

Orthopedic prostheses in Brazil are mainly produced in stainless steel due to two factors: low cost, compared to cobalt or titanium based metals and their alloys, and demonstrate excellent mechanical and chemical resistance [5]. Metal implants that replace fractured bones, such as artificial joints, bone plates, and total hip prostheses, are conventionally used under severe cyclic loading conditions [6]. According to recent studies 10% of the world population have allergy to metallic alloys with nickel, an element present in stainless steels, leading to toxic reactions in the host body, which are only diagnosed after a sufficiently long post-implantation period [7]. Due to the unsatisfactory
performance of 316L, ASTM F138 steels were developed, with better mechanical and corrosive performance [8]. The ASTM F75 alloy is typically characterized by two crystalline phases: cubic (CFC) and hexagonal compact (HC). The cubic structure, coupled with its low stacking failure energy, is considered responsible for high resistance values, which can be increased by the addition of hardening agents such as chromium, tungsten and [9].

Prostheses are designed to be based on a simple geometry and as light as possible [10]. The production processes involved in implants manufacturing also affect their corrosion resistance, specifically those that influence the surface finishing. Laser engraving is usually one of the commonly applied processes and also results in corrosion implications [11].

An important parameter for the development of total hip prostheses is the surface finish of the cup / acetabulum, because the lower the roughness of these surfaces, the longer the prosthesis will last [12]. MEF simulations allow realizing the stress distribution, to be determined, throughout the mathematical model, not just in discrete points. The effects of design changes can be analyzed quickly. They also allow you to apply realistic loads in complex geometries [13]. In this way, it is possible to request a system of forces at any point and / or direction, thus generating data on the displacement and the degree of stress caused by these loads [14]. The finite element analysis allows both quantitative and qualitative simulation of complex mechanical assays, helping to prevent potential failures and deformations in the bone [15].

The Finite Element Method (MEF) uses numerical methods that approximate problem solving of ordinary or partial differential equations by means of polynomial interpolation throughout the discrete system by means of a set of individual solutions of each element [1].

The degradation of metallic implants inside the human body can, in addition to damaging the integrity of the material, generate problems such as infections or allergic reactions, leading to the premature withdrawal of this implant [16]. Chromium is mainly responsible for the corrosion resistance due to the formation of an oxide film firmly adhered to the alloy surface (passivation layer) [17]. The failure that occurs by the simultaneous action of a cyclic stress and chemical attack is termed corrosion fatigue. Corrosive environments have a deleterious influence and produce smaller lives in fatigue [4]. Fatigue behavior which occurs below the critical failure strength is a common phenomenon in all materials [18].

2. Materials and Methods

For the analysis of finite elements, two software Autodesk® Inventor® 2013 and Autodesk® Simulation 2015. The virtual model of the prosthesis was developed through the technical design provided by the company Ortosintese. Macro procedure for applying the finite element method (Figure 1).

The geometry of the stem (Figure 2) was designed to provide a better distribution of stresses by minimizing the points of greatest stress concentration and also its surface generates an excellent attachment to PMMA (polymethylmethacrylate), which in turn will be in contact with the bone.

In order to simulate the condition closest to the real one, a universal device (Figure 3) was developed to encompass the base of the studied stem. At the lower end of the device the restriction of a fixed support was applied thus affecting the limitation of the movement of the required component.

The properties of the material were assumed as isotropic and linear elastic with Poisson coefficient equal to 0.3, obeying Hooke's Law [19]. The assembly of both parts was carried out following the restrictions of the project. In the stress analysis environment, the surface to be fixed, the mesh type (Figure 4) and the force to be applied during the simulation are defined.

The authors have experience with finite element calculations and electronics [20,21,22].
Figure 1 - Summary flow for application of the Finite Element Method.

Figure 2 - a) Isometric view of the femoral stem model. b) - Detail of the different transverse sections in the prosthesis.

Figure 3 - Device to support the stem, the region with cyan coloration is where the rod will be inserted.
The implanted stems work under the action of complex mechanical stresses in saline, which requires the material to be resistant to corrosion. Due to this fact, it is necessary to properly select the biocompatible metal [23]. Tables 1 and 2 show the chemical composition of the alloys ASTM F138 e ASTM F75.

**Table 1. Chemical Composition ASTM F138 [5]**

| Element | C  | Si  | Mn  | P  | S  | Cu  | Ni  | Cr  | Mo | Fe  | Ni  |
|---------|----|-----|-----|----|----|-----|-----|-----|----|-----|-----|
| Wt%     | 0,03 | 0,75 | 2,00 | 0,02 | 0,01 | 0,50 | 14,00 | 18,00 | 2,00 | -   | 0,10 |

**Table 2. Chemical Composition ASTM F75 [24]**

| Element | C  | Si  | Cr  | Mo | W  | Ni  |
|---------|----|-----|-----|----|----|-----|
| Wt%     | 0,35 | 1,00 | 30,00 | 7,00 | 0,20 | 0,10 |

Among the inputs required to perform the virtual simulation are the mechanical properties of the materials studied, Table 3 demonstrates the input values.

**Table 3. Mechanical Properties of Materials [25]**

| Material     | Young’s Modulus (GPa) | Density (g/cm³) | Yield Strength (MPa) |
|--------------|------------------------|-----------------|----------------------|
| Bone         | 15,2 – 40,8            | 2               | 114                  |
| ASTM F138    | 190                    | 8               | 792                  |
| ASTM F75     | 210                    | 8,8             | 450                  |

The complete cycle of the march is divided in two main phases, being a support and another of transition that include activities that begin when there is the initial contact from one end with the ground and another one when the same end again has contact with the ground [26].

Figure 5 shows the quantification of soil reaction forces parameters for a 75 kg individual as the main overload indicator for the hip joint, considering different displacement velocities during the support phase with the soil in the floor.
According to the requested loads by [27] and of what is predicted in the norm ABNT 7206: 2008 the force adopted in this study will be of 2.3kN. The position of the force is also demonstrated in the norm, 10 degrees with respect to the angle of the frontal plane and 9 degrees angle of the lateral plane. Carried out a study addressing the position of the requests in the hip (Figure 6) [28].

In the stress analysis environment, the type of interaction between the stem and the base is defined, the objective is to investigate the stress in the stem and according to this input the selected interaction will be of perfect union. The 2.3kN request will be applied to the flat surface of the beaker. On the lower surface of the base, a restriction of the nozzle is applied, restricting its translation and rotation movements in the x, y and z axes. As ASTM F138 and ASTM F75 stainless steels were not contemplated in the material library of the software Autodesk Inventor 2013, it was necessary to insert the data concerning the mechanical properties of both. The type of mesh available in Autodesk Inventor®2013 is tetrahedral with ten nodes. The mesh was generated in the automatic mode and by
obtaining the critical regions the refinement was made in the areas that demanded more attention, until the solution converged.

From the mathematical point of view, the von Mises (Equivalent Stress) criteria were used to calculate normal and shear stresses, which is a classic approach in the field of mechanical engineering. The criterion of approval of the model is established by comparing the stress of Von Mises, generated in the simulation, with the yield stress of the material [29].

3. Results
With the aid of the map of stress and deflections the displacement and maximum stress can be observed as a function of the incidence of the vertical force of compression. The number of nodes generated by the software on the stem is 2835 and the number of elements is 12097.

Material ASTM F138 static test.

Figure 7 – Von Mises Stress, load 2.3kN, material ASTM F138.

Figure 8 – Displacement, load 2.3kN, material ASTM F138.
Regarding the deflection (Figure 8) there was no significant displacement, since the ANBT standard predicts maximum displacement of up to 5 mm. The color gradient shown in the figures indicates the region of greatest criticality in relation to the criterion evaluated. In this way the region of the neck (place of greater discontinuity) and also the point closer to the base, were the points that presented greater concentration of stress.

The request of 2.3kN generated a coefficient of 1.44 (Figure 9), which reveals an index that meets the expectations of the project. According to the static loads by which the virtual model was submitted it can be concluded that the design is safe using the ASTM F138 alloy (considering the static test).

Material ASTM F75 static test.
The request of 2.3kN generated a coefficient of 0.82 (Figure 12), which reveals an index that does not meet the expectations of the project. According to the static loads by which the virtual model was submitted it can be concluded that the design is not safe using the ASTM F75 alloy. Finite element method, applied to obtain the number of predictive cycles.

The models submitted to the fatigue test (Figures 13 and 14) demonstrate a behavior analogous to the static test, so that regions that would fail prematurely would probably be in the neck and the region of the stem which shows the indication "MIN". With the application of both materials, the virtual model would not meet the criterion of 5 million cycles only with the request of 2.3kN. It is important to emphasize that the software used in this study does not predict the influence of corrosion on its results. Table 4 shows the results in a simplified way.

4. Conclusion

With the research, it is concluded that the finite element method is a mathematical tool that allows complex calculations to be performed in a simplified way. The user must convert the actual demand into coherent inputs respecting the boundary conditions provided in the project. In the context of the materials tested, the ASTM F138 steel in both the static and fatigue tests presented better performance than the ASTM F75 steel, since in the virtual study there are limitations on the prediction of the corrosion resistance of the alloys.

In the application of 2.3kN (rapid race request) in both materials, the regions of the neck and the area closest to the cradle presented stress that exceeded the Yield Strength, showing that the developed
stem would not meet the resistance criteria pre-established in the Standard ABNT NBR ISO 7206-4: 2016.

Figure 13 – Number of predictive cycles, applied force 2.3kN, material ASTM F138.

Figure 14 – Number of predictive cycles, applied force 2.3kN, material ASTM F75.
Table 4. Results for load of 2.3 kN.

| Load 2.3kN | ASTM F138 | ASTM F75 |
|------------|------------|----------|
| Von Mises Stress (MPa) | 549.6 | 547.4 |
| Displacement (mm) | 0.25 | 0.23 |
| Safety Factor | 1.44 | 0.82 |
| Number of predictive cycles | $1.69 \times 10^6$ | $7.02 \times 10^5$ |

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