The use of simulation in analysis of femoral prostheses fatigue

Rodrigo Cesar dos Santos, Wilson Carlos da Silva Junior, Givanildo Alves dos Santos and Edson Bispo Ferreira
Department of Mechanical
Sao Paulo Federal Institute
Sao Paulo, Brazil
rodrigo.mecanic@gmail.com, wcdsjr@gmail.com, givanildo@ifsp.edu.br, bispo@ifsp.edu.br

Vinicius Torres dos Santos and Márcio Rodrigues da Silva
Salvador Arena Foundation Educational Center
Termomecanica São Paulo S.A.
São Bernardo do Campo, Brazil
vinicius.santos@termomecanica.com.br, marcio.rdrgs.slv@gmail.com

Antonio Augusto Couto
Materials Engineering Department
Mackenzie Presbyterian University, UPM
São Paulo, Brazil
antonioaugusto.couto@mackenzie.br

Abstract

The human activity of walk and run leads to the join femur-hip a cyclic load and a fluctuant stress and strain that is able to produce cracks or fracture due to fatigue that is a progressive and permanent change in material endurance. Brazilian standards define the position, intensity and number of cycles of the load to simulate the real life of a new protheses designed. The aim of this study is to predict the failure progression of ASTM F75 alloy femoral prostheses under fatigue analysis whit finite element method for simulation. The alloy F75 shows satisfactory results in static analysis, but in the dynamic analysis nether exceeds 5 million cycles and it presents fail in the safety factor to fatigue.

Keywords: Femoral hip protheses, simulation, fatigue, finite element method.

1. Introduction

The use of simulations in the factories is becoming increasingly necessary due to the search for productivity and competitiveness, allowing the testing and improvement of processes and products still in the design phase, reducing costs and design and production time. CAE systems (for computer-aided engineering) are computer systems associated with product design and simulations by finite element modeling. Design systems and software include geometric modeling, engineering analysis packages such as finite element modeling, design review and evaluation, and automated drafting (Groover, 2013). This work is focused on the area of modeling and simulation, a greater emphasis is given to femoral prostheses fatigue simulation, as it involves important technological concepts of product development.

Metallic biomaterials are used for load bearing applications and must have sufficient fatigue strength to endure the rigors of daily activity. The main property required of a metal as biomaterial is that it does not illicit an adverse reaction when placed into services, that means to be a biocompatible material. As well, good mechanical properties, osseointegration, high corrosion resistance and excellent wear resistance are required. That is, the material used as implants are expected to be highly non toxic and should not cause any inflammatory or allergic reactions in the human body (Santos, 2017; Dos Santos et al., 2020).

ASTM F75 is an alloy used for biomedical applications, specifically in total hip joint replacement. The main functions of the hip include supporting 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 (Queiroz, 2014). The hip is a complex structure, composed of bones, ligaments, and structural muscles, responsible for transmitting stability to the body. This joint is crucial for physical activities and is often exposed to efforts such as torsion, flexion and compression (Kehr, 2017).

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 car and sports accidents (Ebrahimi, 2012). 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/cm^3. Bone is an anisotropic material with mechanical properties that differ in longitudinal and transverse directions (Callister, 2012).

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 (De Oliveira, 2012). Metal implants that replace fractured bones, such as artificial joints, bone plates, and total hip prostheses, are conventionally used under severe cyclic loading conditions (Yang and Ren, 2010). Approximate 10% of the world population have allergy to metallic alloys with nickel, some chemistry elements present in stainless steels, leading to toxic reactions in the host body, which are only diagnosed after a sufficiently long post-implantation period (Chen and Thouas, 2015).

The ASTM F75 alloy is typically characterized by two crystalline phases: face-centered cubic (FCC) and hexagonal closed-compact (HCC). 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 molybdenum (Baldissera, 2007).

The production processes involved in implants manufacturing also affect their corrosion resistance, specifically those that influence the surface finishing. Studies related to manufacturing technology show the influence of processes on the performance of products (Miranda et al., 2016; Miranda et al., 2017; Nascimento et al., 2017; Nascimento et al., 2018; Nascimento et al., 2019; Santos et al., 2017, Da Cruz et al., 2020; Dos Santos et al., 2020). Laser engraving is usually one of the commonly applied processes and also results in corrosion implications (Pieretti et al., 2014). 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 (Revell, 2014).

The Finite Element Method (FEM) is a numerical method that approximates the original 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 (Queiroz, 2014). FEM simulations allow apply realistic loads and complex geometries, that is possible to know the displacement, stress and strain fields, that simplify and improve the design process (Stolk, 2002). The finite element analysis allows both quantitative and qualitative simulation of complex mechanical assays, helping to prevent potential failures (Borie 2013).

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 (Larosa, 2010). Chromium is mainly responsible for the corrosion resistance due to the formation of an oxide film firmly adhered to the alloy surface (passivation layer) (Huang, 2003). 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 (Callister, 2012).

2.Material and Methods

The complete cycle of the march is divided in two main phases, being a support and another of transition that include activities that begins 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 (Norkin, 1992).

Figure 1 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.

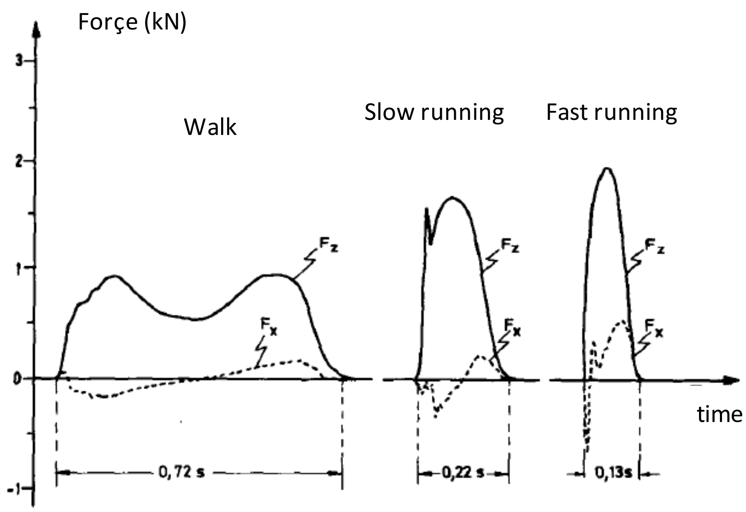


Figure 1. Function curve Force X time for walk, slow running (3.5 m/s) e fast running (6 m/s). (Amadio et al., 2007).

According to the requests loads by Amadio et al. (2007) and of what is predicted in the standard ABNT 7206 (2008) the force adopted in this study will be of 2.3 kN. The position of the force is also demonstrated in the standard, 10 degrees with respect to the angle of the frontal plane and 9 degrees angle of the lateral plane. Paul (1976) carried out a study addressing the position of the requests in the hip shown in the Figure 2.

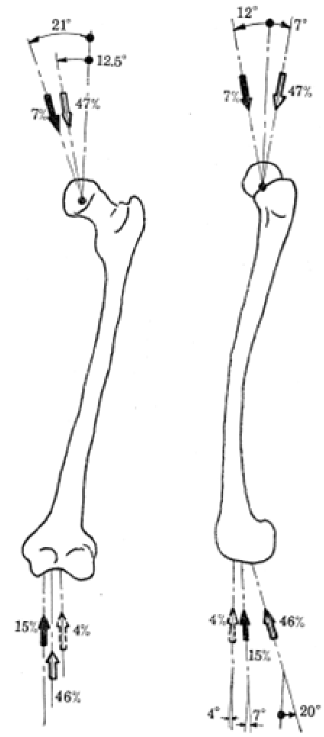


Figure 2. Relative direction of forces at the hip joint. (Paul, 1976)

For FEM analysis was utilized Adina, Autodesk® Inventor® (2013) and Autodesk® Simulation (2015). The virtual model of the prosthesis was developed through the technical design provided by the company Ortosíntese. The geometry of the stem shown in the Figure 3 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.

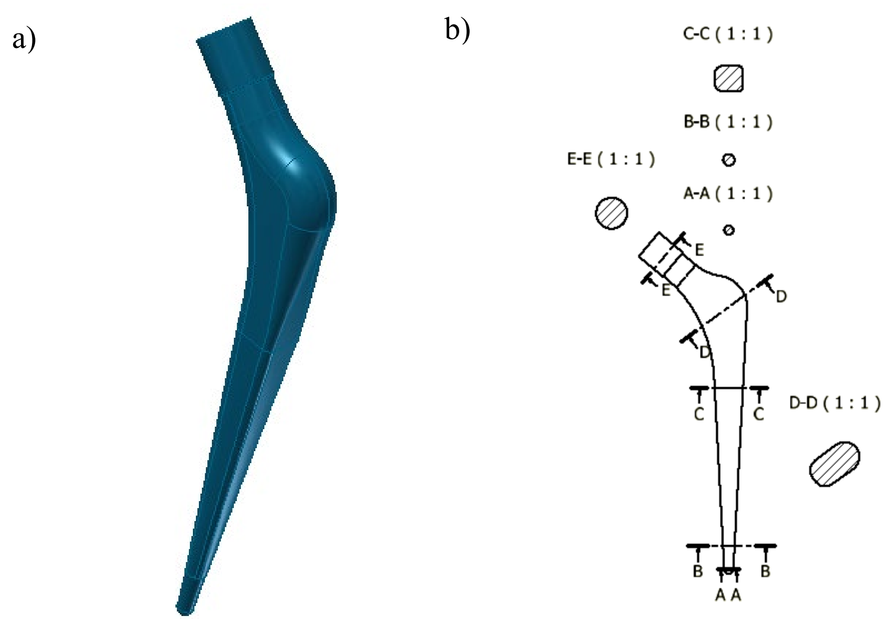


Figure 3. a) Isometric view of the femoral stem model. b) Detail of the different transverse sections in the prosthesis.

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 (Cé, 2010). Table 1 shows the chemical composition of the ASTM F75 alloy.

Table 1. Chemical Composition of the ASTM F75 alloy

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

(Giacchi, 2011)

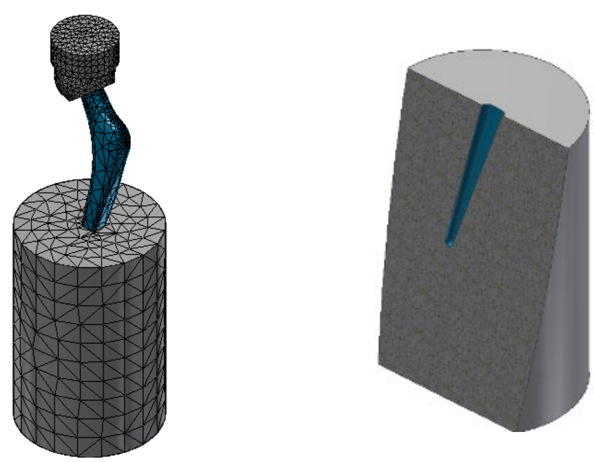
Among the inputs required to perform the virtual simulation are the mechanical properties of the material studied, Table 2 shows the input values.

Table 2. Mechanical Properties of Material.

Material	Young's Modulus (GPa)	Density (g/cm3)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Bone	15,2 – 40,8	1.6 – 1.7	114	250
ASTM F75	210	8,8	448	655

(Ratner, 2004)

In order to simulate the condition closest to the real one, a universal device show in Figure 4 a) and b) 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 effecting the limitation of the movement of the required component.



(a) (b)

Figure 4. a) FEM mesh and b) Protheses locus in the support.

In Adina, the properties of the material were assumed as plastic bilinear and 0.3 for Poisson ratio in Figure 5 for ASTM F75.

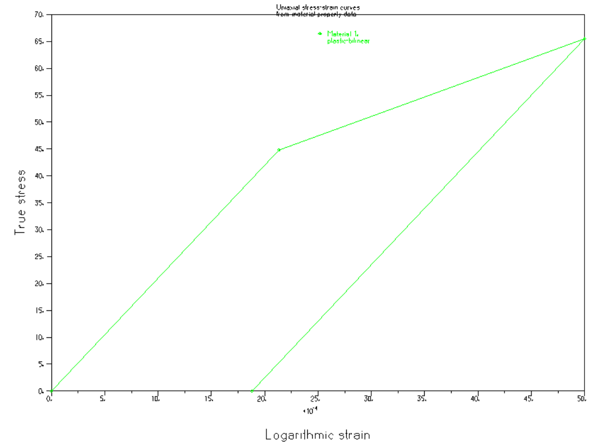


Figure 5. Protheses locus in the support.

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 cyclic load of intensity 2.3 kN was applied to the flat surface of the beaker in accordance with Figure 6. 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. The element in Autodesk ®Inventor®2013 is tetrahedral with ten nodes and 8 nodes 3DSolid in Adina. Von Mises (Equivalent Stress) criteria were used to calculate normal stress, 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 (Zameer, 2015).

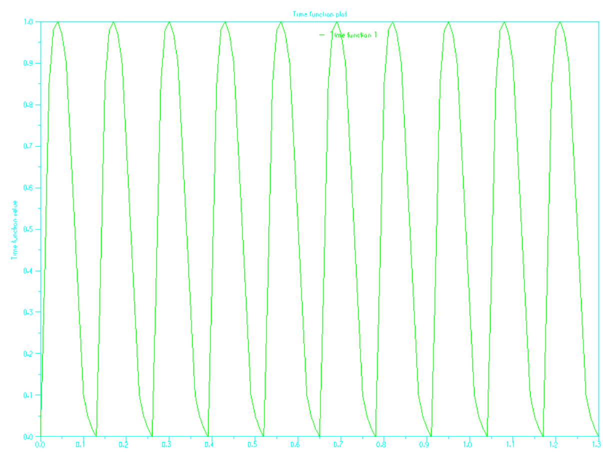


Figure 6. Load time history.

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.

Regarding the deflection shown in the Figure 7 there was no significant displacement, since the Brazilian standard predicts maximum displacement of up to 5 mm. 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 2.3 kN generated a coefficient of 0.82 shown in the Figure 8, 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.

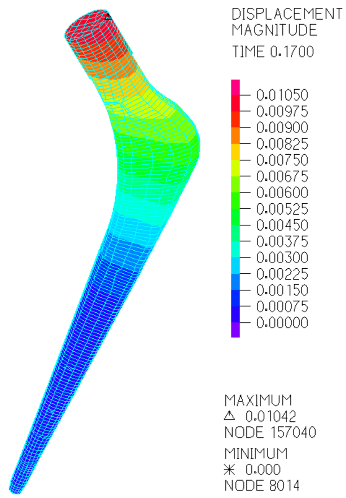


Figure 7. ASTM F75 – Displacement (cm)

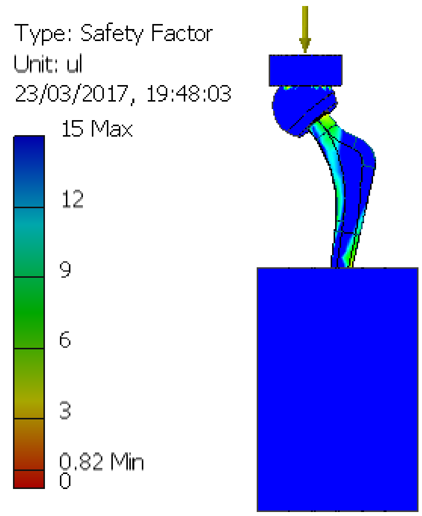


Figure 8. ASTM F75 - Safety Factor to fatigue

The model submitted to the dynamic test shown in the Figure 9 demonstrates 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 ASTM F75 alloy, the virtual model would not meet the Brazilian standard criterion of 5 million cycles only with the request of 2.3 kN. It is important to emphasize that the software used in this study does not predict the influence of corrosion on its results. Table 3 shows the results in a simplified way.

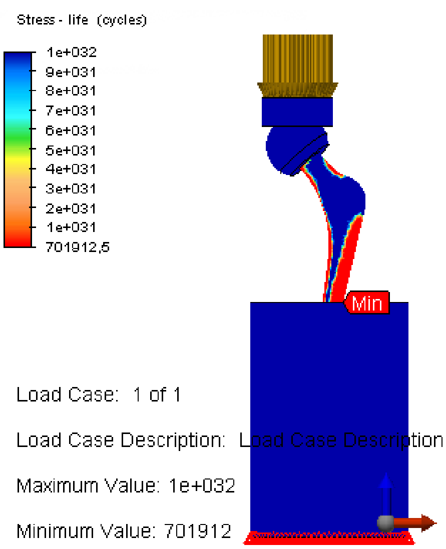


Figure 9. ASTM F75 - Number of cycles

Table 3. Results for load of 2.3 kN.

Load = 2.3 kN	ASTM F75
Displacement (mm)	0.105
Safety Factor	0.82
Number of predictive cycles	$7.02 \cdot 10^5$

4.Conclusions

Based on the results of the simulations, we can conclude that the finite element method (FEM) is a tool that allows complex calculations to be performed in a simplified way. In the context of the material tested, the design is not safe using the ASTM F75 alloy.

In the application of 2.3 kN (rapid race request) in ASTM F75 alloy, 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 Brazilian standards.

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Biographies

Rodrigo Cesar dos Santos Graduated in Mechanical Engineering from the University of São Judas Tadeu, 2012 and Master in Mechanical Engineering at Sao Paulo Federal Institute (IFSP), 2017. He is currently a Technology Specialist at SENAI-SP (since 2010). He has experience in Mechanical / Production Engineering, with emphasis on CAD / CAM Programming, mold modeling for elastomers, application of the Finite Element Method and Lean Manufacturing Consulting.

Wilson Carlos da Silva Junior Mechanical Engineering from the University of Mogi das Cruzes-UMC, 1983, Master in Engineering from Department of Metallurgy and Materials of the Polytechnic School of USP, 2000, Doctor in Biomedical Engineering from the University of Mogi das Cruzes-UMC, 2010, post-doctorate by the Institute of Energy and Nuclear Research (IPEN), 2017. Has experience in: Materials strengh, Mechanical Vibrations, Materials. develops research related to: surgical implants, biomaterials, mechanical properties, corrosion, prostheses, orthoses and rehabilitation. He is a professor at Sao Paulo Federal Institute, Campus Guarulhos and the Master's program Academic in Mechanical Engineering IFSP campus São Paulo. Currently, he has completed five Scientific Initiation projects on failure in hip prostheses. He has four master's students concluded with his guidance on the following themes: biomaterials, finite element analysis and six in progress with the themes: tests for failure analysis and signal acquisition, additive manufacturing of prostheses (microstructural characterization and mechanical resistance), behavior in fatigue biomaterials and aluminum alloys, and machining modeling analysis of metal alloys.

Givanildo Alves dos Santos Lecturer in the specialty Behavior and Selection of Materials for Mechanical Engineering by the Polytechnic School of the University of São Paulo (EPUSP), 2019. He received a Ph.D. in Aerospace Engineering from the Technological Institute of Aeronautics in 2010, Master in Aerospace Engineering from the Technological Institute of Aeronautics in 2005, with Post-Doctoral in the area of Science and Technology of Materials held at the Institute of Energy and Nuclear Research (IPEN), 2016. He is currently a professor in the area of Mechanics and the Postgraduate Program in Mechanical Engineering at Federal Institute of São Paulo (IFSP). He has experience in the area of Mechanical Engineering and Materials and Metallurgical Engineering, working mainly on the following topics: materials technology, product development and manufacturing processes.

Edson Bispo Ferreira Graduated in civil engineering with an emphasis on structures from Universidade Estadual Paulista Júlio de Mesquita Filho, 1996, master in Mechanical Engineering at Federal Institute of São Paulo,2018. He is currently Professor at Sao Paulo Federal Intitute (IFSP). Has experience in the area of Civil Engineering, with emphasis on Estruturas: Cold forming of metal sheets, spring back, Finite Element Analysis.

Vinicius Torres dos Santos received the M.S. in Mechanical Engineering from the Federal Institute of São Paulo, Brazil. He is a research and development engineer at Termomecanica Industry and a professor at the Salvador Arena Educational Center.

Márcio Rodrigues da Silva received the M.S. in Mechanical Design and Manufacturing Engineering from the Polytechnic School of the University of São Paulo, Brazil. He is Coordinator of Research and Development, Laboratories and Product Inspection in the Termomecanica Industry and a professor at the Salvador Arena Educational Center.

Antonio Augusto Couto received the Ph.D. in Nuclear Technology from the University of São Paulo, Brazil. He is a professor at Mackenzie Presbyterian University and a principal researcher at the Nuclear and Energy Research Institute. His research subjects are: materials used in high temperatures; aluminum alloys; biomaterials; creep, fracture and fatigue behavior.