ANALYSIS OF THE APPLICATION OF TI-35NB-7ZR-5TA IN A PROSTHETIC LEG USING THE FINITE ELEMENT METHOD

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Abstract. *This paper consists in analyzing, through the Finite Element Method, the behavior of the Ti-35Nb-7Zr-5Ta alloy when employed in a sprint prosthetic leg design and comparing it with other one made in carbon fiber. It The results were analyzed in a static stress analysis in two cases: in the first one the behavior was with both materials when applied a force relative to a person with a mass of approximately 100 kg. In the second case, it was applied a force until the design reaches its yield strength, to find the maximum mass that the prosthesis supports without strain. It was also made the dynamic analysis, where the prosthesis was induced to resonate and it was studied if it compromises the design. Finally, it was made a fatigue analysis over the Ti-35Nb-7Zr-5Ta alloy, under the high cycle fatigue analysis. It was concluded that the prosthesis developed in this paper when employing the Ti-35Nb-7Zr-5Ta alloy is feasible.*

Keywords*: prosthetic leg, finite elements method, Ti-35Nb-7Zr-5Ta alloy*

1. INTRODUCTION

Nowadays, it is very discussed about the question of the accessibility of disabled people. In sports, it is held the Paralympics Games each four years, immediately after their Olympics Games. Among their modalities, there is the sprint race.

For disabled people to run in this modality, it is necessary a specific prosthesis, developed to support big efforts. These legs are produced currently on carbon fiber and are considered very efficient.

> Carbon fibers are referred normally as graphite fibers, however just the carbon fibers of elevated elasticity modulus with tridimensional graphite structure can be denominated properly graphite fiber. By virtue of the carbon fiber have elevated values for ultimate tensile strength, elasticity modulus extremely high and low specific mass, comparing with other materials of the engineering, they are used predominantly on critical applications involving mass reduction. The carbon fibers commercially available can duplicate their elasticity modulus values in relation to other reinforcement fibers, as aramid and glass S, and exceed the ultimate tensile strength in metals. When using composite materials of carbon fibers, their strength and elasticity modulus can be oriented optimally to minimize the final mass. Beyond the strength and stiffness, the carbon fibers have excellent fatigue strength, vibration damping characteristics, thermal resistance and dimensional stability. The carbon fibers also have good electrical resistance and they are chemically inert, except for the oxidation. (Lebrão *apud* Callister, 1997, p. 19).

One of the ways to develop prosthesis is using a Computer-Aided Design (CAD) software which allows the creation of a virtual model, so that after this it can be analyzed over a Computer-Aided Engineering (CAE) software. One of the mathematical methods to simulate and obtain approximated values of real static and dynamic parameters is the Finite Element Method.

In line with the carbon fiber, the Titanium alloys have been gaining highlight on the prosthesis composition, but these more specifically in implants, due to many physical and chemical properties, specially because of their biocompatibility.

> Titanium and its alloys are materials widely used as biomaterials and applied in biomedical devices, due to their superior properties, as grater biocompatibility, lower toxicity, grater corrosion resistance and low elasticity modulus comparing to other metals used in implants as cobalt-chromium and stainless steels. The corrosion resistance, one of the properties that determine the success of a material as biomaterial, is conferred by the formation of a passive film and adhering to the surface, which consists mainly of amorphous Titanium dioxide (TiO_2), also responsible to the biocompatibility of the material. (Manhabosco *et al.*, 2009, p. 1).

The Titanium alloys that seem more advantageous to these types of characteristics are the ones in the β group.

> The beta titanium alloys is one of the most promising groups of the titanium alloys. This fact is due to the good formability, mechanical properties and potential applications; moreover, these alloys present the highest level of mechanical, fatigue and corrosion resistance. (Taddei, 2004a, p. 683).

Among the β group alloy, the Ti-35Nb-7Zr-5Ta alloy is highlighted, because it presents a lower Young modulus, close to the human bone tissue.

> Ti-35Nb-7Zr-5Ta (TNZT) presents the lowest elasticity modulus among the metal alloys ever developed and it is composed just by elements considered biocompatible. This alloy presents specific mass of 5,72 g/cm^3 and it is classified as metastable-β. Its microstructure after the solubilization consists of grains of recrystallized β. The mechanical properties of this alloy can be improved by changing the content of interstitial elements (O, C, N, H). Increasing the oxygen content in the alloy TNZT results in increased mechanical strength and fatigue limit, with a small increase in eslasticity modulus. (Taddei *et al.*, 2004b, p. 69).
>
> Ti–35Nb–7Zr–5Ta has lower modulus of elasticity (55 GPa) than other typically used metal alloys, and its modulus is close to that of bone. (Taddei *et al.*, 2004a, p. 684).

This paper proposes the development of a design based on models already on the market and its analysis, employing as material the Ti-35Nb-7Zr-5Ta alloy. The main proposal is the study of the behavior of this alloy when applied in the developed design. As secondary proposal, it is made a comparison between the prosthesis using as the Titanium alloy as the carbon fiber.

In this work, the statics, dynamics and fatigue analysis responses are analyzed.

2. OBJECTIVES

Analyzing the behavior of Ti-35Nb-7Zr-5Ta alloy when applied to a prosthesis model for sprint developed and compare its performance in a model composed of carbon fiber.

3. METHODOLOGICAL PROCEDURES

3.1 DESIGN

The design presented in this paper is based on studies over existing designs in the market. The model that fits to the proposal and that is the basis of the studies for the creation of design is the Flex-Run©, of the enterprise Össur, which can be seen in Fig. 1.

(a)

(b)

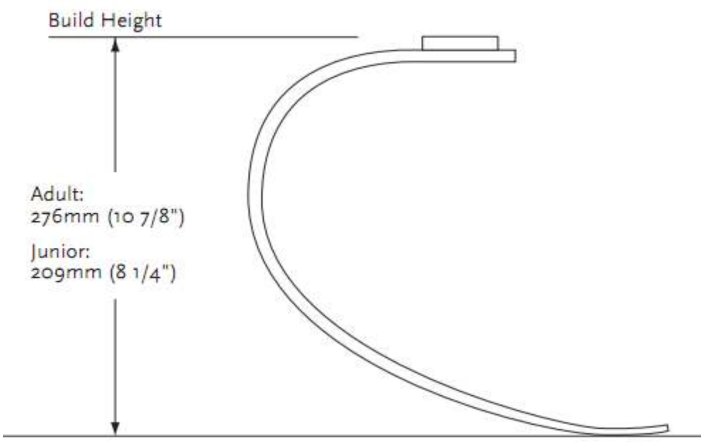

Figure 1. Flex-Run©, by Össur. At (a), a photo of the prosthesis. At (b), the design with the height showed as in millimeters as inches.

The finished design is showed in Fig. 2. Some modifications around the model showed in Fig. 1 were made and researches around the design are being made, with the objective of improvement of it.

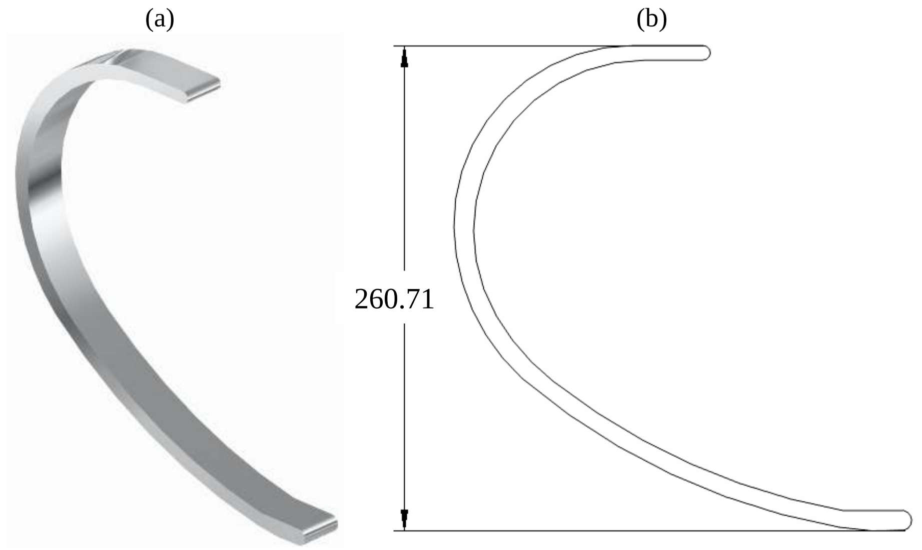

Figure 2. Prosthesis design developed. At (a), the prosthesis model and at (b), the design with its height showed in millimeters

3.2 SIMULATION PROPERTIES

For the simulation, it was made the meshes for both prosthesis and its properties and other, can be seen in Tab. 1. Figure 3 shows the meshed prosthesis.

Table 1. The simulation properties for both prosthesis

Properties	Ti-32Nb-7Zr-5Ta	Carbon Fiber
Element type	8-node brick	8-node brick
Number of elements	12103	25774
Number of nodes	15993	39439
Final mesh size (mm)	2.38	2.40
Material model	Isotropic	Quasi-isotropic

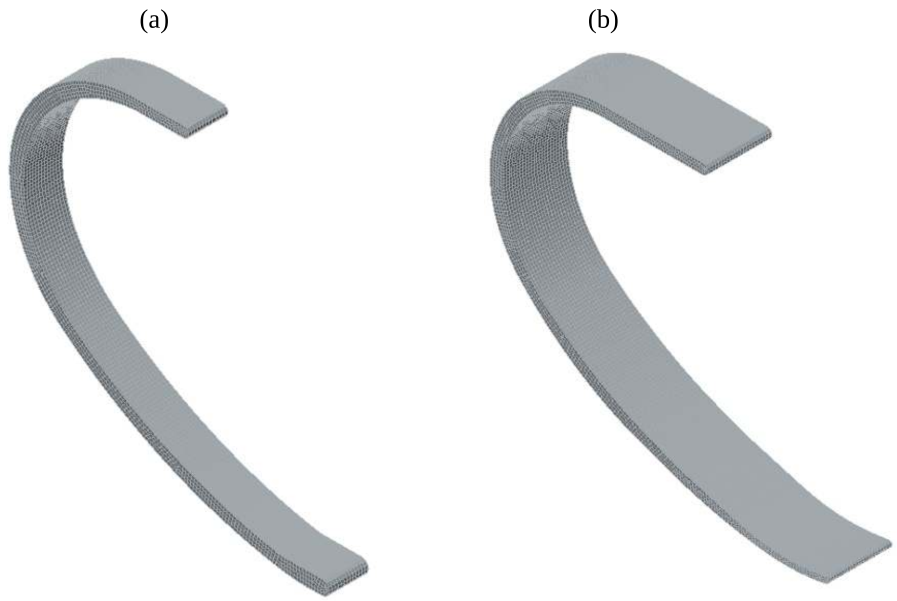

Figure 3. The prosthesis meshes. In (a), the mesh of the Ti-35Nb-7Zr-5Ta prosthesis and in (b), the mesh of the carbon fiber prosthesis

As the prosthesis is composed by many plies with different orientations, it was adopted an approximation of the material model to quasi-isotropic. The present work is an initial research of the use of carbon fiber in this kind of prosthesis and, in future works, this structure will be simulated using a layered shell model, which the plies orientations and an orthotropic material model for each layer will be considered.

3.3 STATIC ANALYSIS

The static analysis consists of applying static forces or moments, that don't vary over time, doing the design reach a stress and displacement proportional to the forces and moments of force applied.

In this static analysis, four forces are applied on the top of the prosthesis, as can be seen from Fig. 3, and after this, the stress and displacement are analyzed in two cases:

- At the first case of the analysis, a total force of 980 N is applied, to simulate a person with a weight of approximately 100 kg.
- At the second case, a force is applied until the design reaches its yield strength, to obtain the maximum weight that the prosthesis supports without deformation.

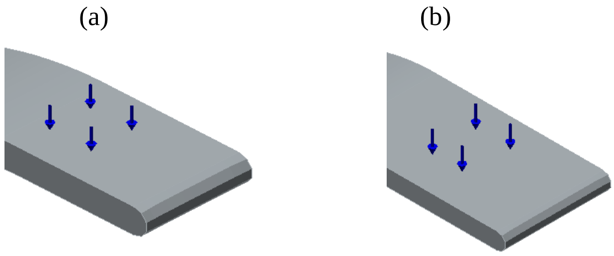

Figure 3. Detail from the top of the prosthesis. In (a), the top of the prosthesis with Ti-35Nb-7Zr-5Ta and in (b) in carbon fiber

For the simulations, it is necessary the introduction of some data concerning the mechanical properties of the materials, as the Young modulus, specific mass, shear modulus, ultimate tensile strength and Poisson's ratio. Tab. 1 shows these properties of Ti-35Nb-7Zr-5Ta alloy. All these data are obtained from references (Liu *et al.*, 2004) (Taddei *et al.*, 2004b) (Oldani and Dominguez *apud* Niiomi, 2007)(Lee *et al.*, 2006), except the shear modulus, which can be obtained from the relation between the Young modulus, Poisson's ratio and the shear modulus, as showed in Eq. 1.

$$E = 2G(1+\mu) \quad (1)$$

Where:

E = Young modulus;
G = Shear modulus;
μ = Poisson's ratio.

Manipulating Eq. 1:

$$G = \frac{E}{2(1+\mu)} \quad (2)$$

Table 1. Mechanical properties of Ti-35Nb-7Zr-5Ta alloy

Alloy properties	Ti-35Nb-7Zr-5Ta	Carbon
Young modulus (GPa)	55	235
Specific mass (kg/m³)	5720	1770
Shear modulus (GPa)	21	98
Yield strength (MPa)	530	-
Ultimate tensile strength (MPa)	590	4400
Poisson's ratio	0.33	0.20

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3.4 MODAL ANALYSIS

To make dynamics simulations with the software, it was needed, at first, to realize the modal analysis, for founding the natural frequencies of the system.

The natural frequencies are frequencies at which a system tents to vibrate and they can be determined over the properties of the materials. When a system is excited in one of these, it comes in a phenomenon called resonance, making the system reaches a larger displacement than the designed to operate and can compromise the entire system.

Five natural frequencies were presented for each material and the lower one is employed to the dynamic analysis, since the lower frequencies are the easier to the systems reach.

3.5 DYNAMIC ANALYSIS

In this paper, after the modal analysis, it was made a transient stress analysis by modal superposition. In the software, the system was excited by a harmonic force that, according to Ripper (2007), is a special class of periodic motion (the one that repeats in a constant interval of time), whose temporal function *F(t)* is a sinusoid represented in Eq. 3.

$$F(t) = F_0 sen(\omega t + \varphi) \quad (3)$$

Where:

F_0: Force amplitude (N);
ω: Pulsation or circular frequency of the harmonic motion (rad/s). When this is given in Hertz (Hz), it can be replaced by $2\pi f$, where f is the frequency in Hertz;
φ: Phase angle introduced in the expression to accommodate non-homogeneous initial conditions of the motion.

As the maximum displacement of the dynamic response is desired, the prosthesis was induced to resonate, making the frequency ω coincides the natural frequency. It was used a damping factor of 0.05. As to the loads, it was applied a total amplitude of 980 N, to simulate a person with approximately 100 kg. This force is distributed equally in four nodes, as can be seen in Fig. 3.

About the time simulation, it was simulated 60 seconds, with an interval of 0.1 second each step.

Table 2 presents the values for the harmonic excitation function.

Table 2. Values required for the generation of harmonic excitation curve

Constraints	Ti-35Nb-7Zr-5Ta	Carbon Fiber
Frequency (Hz)	107.18	314.96
Phase angle (rad)	0	0

Because the harmonic force is dependant of natural frequency and this one depends of the employed material, it is necessary to generate two curves to induce the prosthesis to resonance, one for each material used. Figure 4 shows both curves generated.

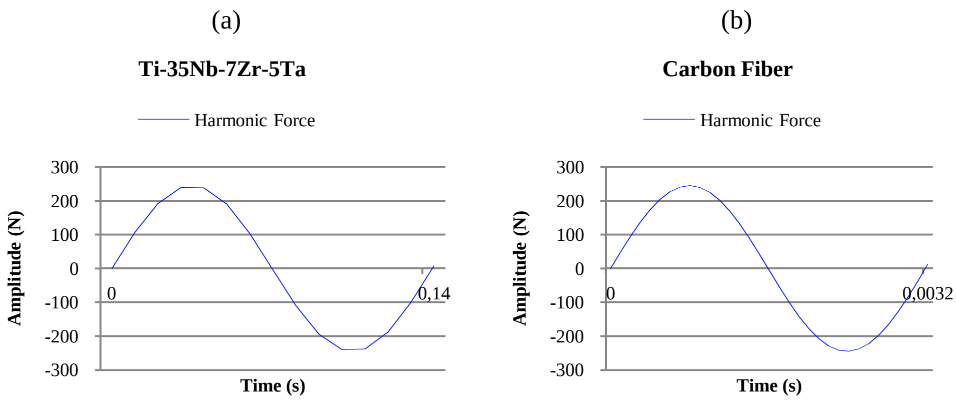

Figure 4 – One cycle of the curve generated from the harmonic forces function for each material employed in the prosthesis. At (a), the curve of harmonic force of Ti-35Nb-7Zr-5Ta alloy. At (b), the curve of carbon fiber

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3.6 FATIGUE ANALYSIS

The rupture of a material can be caused by the application of its tensile strength (UTS) or by its wear due to cyclic solicitations of stress or strain. This last phenomenon is called fatigue, and its study in biomaterials is very important, according to Li (2004), because the implants are solicited constantly.

According to Nicholas (2006) and Schijve (2001), there are two kinds of study of this behavior: the high cycle fatigue and the low cycle fatigue. In the study of high cycle fatigue, the analysis is done based on the control of stress, it involves low amplitudes and the design analyzed works only on its elastic limit. In these conditions, the design reaches a life greater than 10^5 cycles. In the study of low cycle fatigue, the analysis is based on strain, it involves high amplitudes, the analyzed design works with its plastic area and its life is usually less than 10^4 cycles. The design studied in this paper was framed at the analysis of high cycle fatigue. Only the behavior of Ti-35Nb-7Zr-5Ta is analyzed.

This analysis was done through software and the data needed to perform it can be seen in Tab. 3 (Niiomi, 2007).

Table 3. Alloy properties of Ti-35Nb-7Zr-5Ta needed to the analysis

Alloy Properties	Ti-35Nb-7Zr-5Ta
Young modulus (GPa)	55
Tensile strengh (MPa)	590
Poisson's ratio	0.33
Fatigue strength (MPa)	275
Number of cycles	10^7

The software executes the analysis from a static analysis. In this case, the results obtained in the first and second case of the static analysis for Ti-35Nb-7Zr-5Ta were used. It is also necessary the insertion of a cyclic curve that the design is submitted. The curve used was the same generated by the harmonic force function applied in the dynamic analysis that can be seen in Fig. 4a, except the amplitude, which in this case is 1. It happens, because it is a multiplier curve.

4. RESULTS

4.1 STRESS

4.1.1 STATIC ANALYSIS

From the performed analysis, it was obtained the values in Tab. 4 detailing the data obtained in the first and second case of the static analysis.

Table 4. Data obtained from the analysis

Case	Analysis Properties	Ti-35Nb-7Zr-5Ta	Carbon Fiber
Case 1	Total applied force (N)	980	980
	Approximated mass applied (kg)	100	100
	Maximum stress (MPa)	350.25	530.75
Case 2	Total applied force (N)	1484	8138
	Approximated mass applied (kg)	151.43	830.41
	Maximum stress (MPa)	530.38	4400.5

Figure 5 show the results of Tab. 4, representing the simulations done at the first case.

4.1.2 DYNAMIC ANALYSIS

Table 5 and Fig. 6 show the stress that the design reaches in dynamic analysis for both materials.

Table 5. Stress obtained through the dynamic analysis

Analysis Properties	Ti-35Nb-7Zr-5Ta	Carbon Fiber
Total force applied (N)	980	980
Maximum stress (MPa)	529.01	1939.4
Time of maximum displacement (s)	0.4	9.1

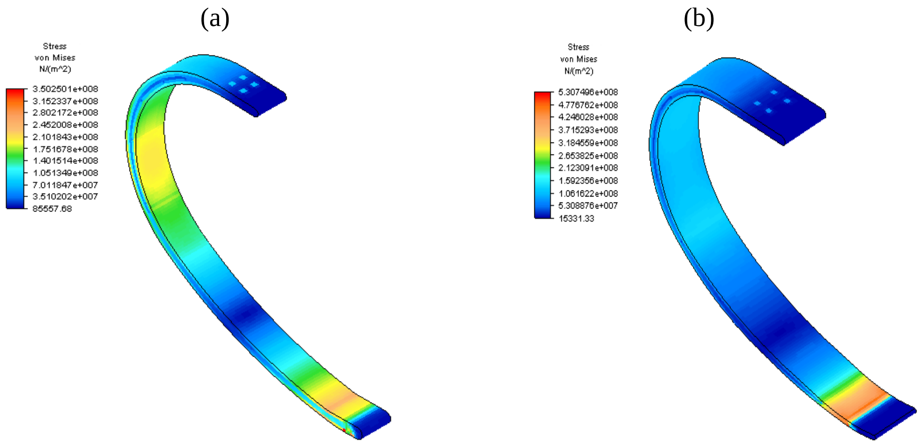

Figure 5. Stress data from static analysis of the prosthesis design when was applied 980 N. In (a), it was employed the Ti-35Nb-7Zr-5Ta allow while in (b) is utilized carbon fiber

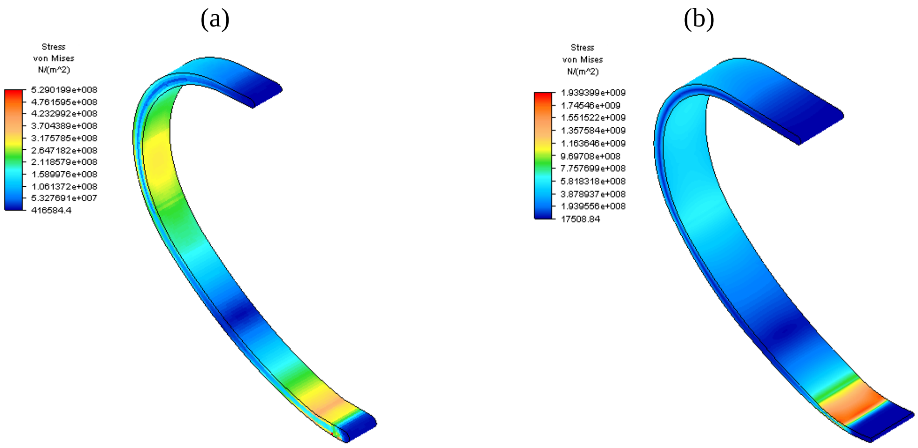

Figure 6. Stress reached by the prosthesis in dynamic analysis. In (a), Ti-35Nb-7Zr-5Ta was used and while in (b), the carbon fiber was used

4.2 DISPLACEMENT

4.2.1 STATIC ANALYSIS

Parallel to the stress, it was founded the displacement that the design reaches in both cases and the results can be seen in Tab. 6. Figure 7 shows the simulation of the first case for both materials.

Table 6. Displacement obtained over the analysis

Case	Analysis Properties	Ti-35Nb-7Zr-5Ta	Carbon Fiber
Case 1	Displacement (mm)	17.93	8.08
Case 2		27.15	66.98

4.2.2 MODAL ANALYSIS

The results from modal analysis can be seen in Tab. 7. It was shown the first five natural frequencies encountered for each material. Figure 8 shows the behavior of the prosthesis at the first natural frequency founded, which was used for the dynamic analysis.

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Table 7. Natural frequencies obtained from modal analysis

Natural Frequency	Ti-35Nb-7Zr-5Ta	Carbon Fiber
1	107.18	314.96
2	304.79	754.48
3	388.35	1114.43
4	610.09	1407.13
5	958.38	2411.59

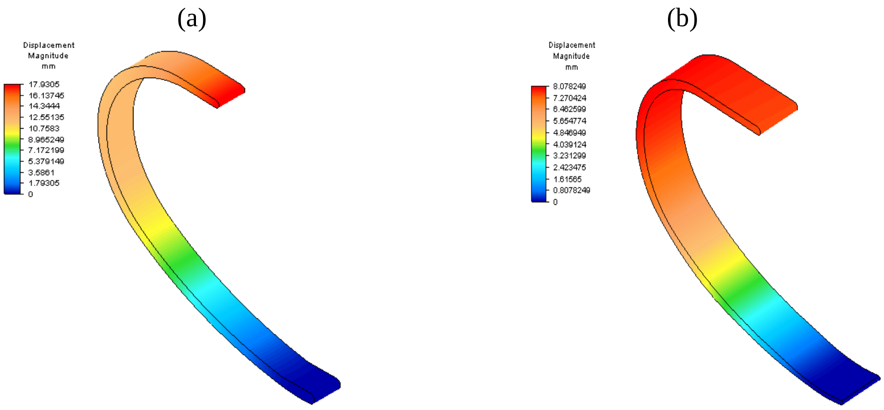

Figure 7. Displacement data from the first step of static analysis, when it was applied 980 N at the top of the prosthesis. In (a), it was employed the Ti-35Nb-7Zr-5Ta allow while in (b) it was utilized carbon fiber

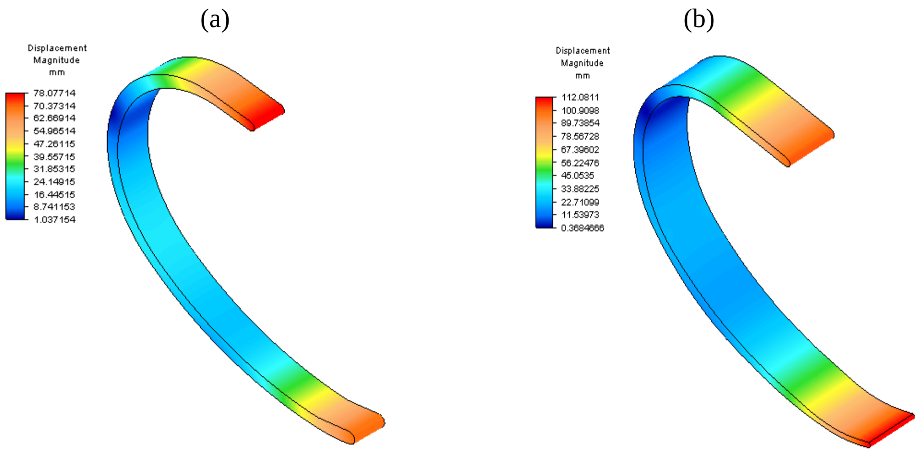

Figure 8. The behavior of displacement of the prosthesis at the first natural frequency obtained from the modal analysis. In (a), the material is Ti-35Nb-7Zr-5Ta and it reaches a maximum displacement of approximately 78.08 mm. In (b), the material is carbon fiber and it reaches a maximum displacement of approximately 112.08 mm

4.2.3 DYNAMIC ANALYSIS

The results obtained in the dynamic analysis by transient stress can be seen in Tab. 8. Figure 9 shows the moment that the design reaches the time step of 0.4 seconds for Ti-35Nb-7Zr-5Ta and 9.1 seconds for the carbon fiber, when it gets the maximum displacement for both materials.

Table 8. Displacement obtained in dynamic analysis

Analysis Properties	Ti-35Nb-7Zr-5Ta	Carbon Fiber
Total force applied (N)	980	980
Maximum displacement (mm)	26.74	30.65
Time of maximum displacement (s)	0.4	9.1

(a) (b)

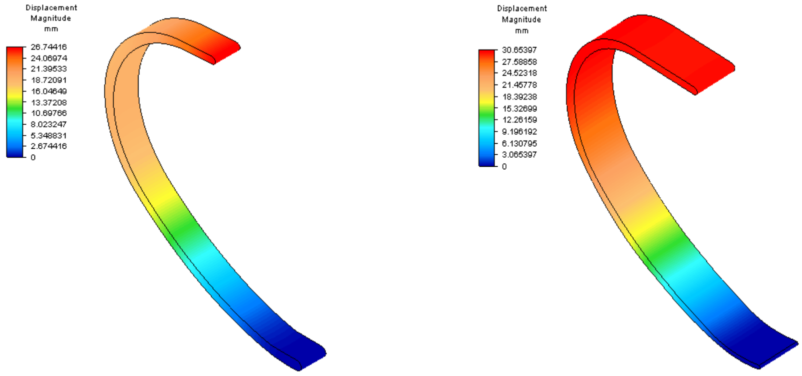

Figure 9. Maximum displacement reached by the prosthesis in resonance. In (a), the material used was Ti-35Nb-7Zr-5Ta and in (b) was carbon fiber

4.2.4 FATIGUE ANALYSIS

The results from the first and second cases of fatigue analysis can be seen in Tab. 9.

Table 9. Values referring to the fatigue of Ti-35Nb-7Zr-5Ta alloy when applied on the design

Case	Analysis Properties	Ti-35Nb-7Zr-5Ta
Case 1	Total force applied (N)	980
	Planned number of cycles	456935.5
Case 2	Total force applied (N)	1484
	Planned number of cycles	1362.9

5. DISCUSSION OF RESULTS

Analyzing the first case of static analysis, both materials keep quite distant of their yield strength, but the carbon fiber shows more resistance than Ti-35Nb-7Zr-5Ta alloy, considering the first material remains approximately 8.29 times lower than its yield strength (in this case, as carbon fiber is a brittle material, it is considered its ultimate tensile strength), while the second remains only approximately 1.51 times lower. Still analyzing the situation, the carbon fiber shows higher stress than Ti-35Nb-7Zr-5Ta alloy. Considering the displacement from the case 1, the prosthesis shows a lower value with the carbon fiber, but, even a higher value, the prosthesis with the Titanium alloy shows an acceptable behavior.

As to the maximum value of mass applied, both materials show applicable, since the Titanium alloy presents a value higher than the conventional (100 kg). Once again, the carbon fiber presents more resistance. It occurs because its value of ultimate tensile strength is much higher than the Titanium alloy.

When in resonance, the prosthesis shows an acceptable displacement, which, according to its amplitude, it does not compromise neither the prosthesis, nor its user. This behavior can be seen in both materials. About the stress, the prosthesis reaches a higher value in dynamic analysis than in the static with both materials, as expected. Despite the stress value reached the yield strength for the Titanium alloy, it can be considered a value that the prosthesis will not reach in practice, because it will only happen when excited in its natural frequency of 107.18 Hz, but human step frequency in running is close to 3 Hz (Cavagna et al., 1997, p. 679).

Regarding fatigue, the analysis indicates a very high value for the fatigue life of Ti-35Nb-7Zr-5Ta alloy in the developed design.

6. CONCLUSIONS

After these analyses, it is possible to say that this design supports high quantity of mass in the case which the prosthetic leg is with its basis static, in other words, without motions at its bottom.

In relation to the prosthesis mass, the one of carbon fiber shows, approximately, the mass 40 percent lighter than the one with Ti-35Nb-7Zr-5Ta alloy. It can be very relevant, since it increases the effort of its user.

In relation to the fatigue, the analysis indicates that the application of Ti-35Nb-7Zr-5Ta alloy in the developed design is satisfactory because the value of cycles is high for the first case of fatigue analysis.

From these analyses, it can be concluded that the Ti-35Nb-7Zr-5Ta alloy can be used for the production of the prosthesis developed in this paper, however it might present some mechanical limitations, like the mass, when

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comparing to the prosthesis that uses the carbon fiber as material. New studies are being made and they point to a best behavior of fatigue strength.

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