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RAPID PROTOTYPING OF A CUSTOM UPPER LIMB BIONIC PROSTHESIS

Abstract: *The field of bionics has shown rapid and notable improvements in the recent years due to technological advances in various fields of medicine and engineering. We have reached a point where upper and lower limb exoprosthesis can reproduce most of the fundamental movements of a biological arm or leg, some of the newer models even having the function of producing movements which would be impossible for the human body to re-create. The aim of this paper is to design and optimize an upper limb bionic exoprosthesis by using patient's parameters and morphological dimensions. Due to the latest trends in additive manufacturing, such a prototype can be used as a template which can be modified according to the morphological landmarks of each individual, so that it can be as close as possible to the patient's anatomy being used as an alternative for people from disadvantaged areas, due to the low production costs.*

Key words: *bionics, exoprosthesis, additive manufacturing, design, rapid prototyping.*

1. INTRODUCTION

Currently, there are various models of the upper limb prosthetics available on the market. Their prices are highly influenced by the degree of functionality and materials used in manufacturing. Bionic arms and legs are usually used as a replacement for patients who have undergone amputations due to accidents or disease. Their purpose is to partially restore the functionality of the lost limb. In regards to complexity, bionic prosthetics can be of several types: rigid models, which can perform only a few basic movements (for example, a grip movement performed by activating two or three joints) and models that can reproduce compound movements, by activating multiple joints simultaneously.

The aim of this paper is to design a virtual prototype of a bionic exoprosthesis for the upper limb, by addressing multiple theoretical and practical concepts, such as design characteristics, most suitable material choice, economic aspects and model validation tests using finite element analysis.

Nowadays, the field of bionics has seen considerable improvements and achievements, its fast progress being highly influenced by the evolution of various branches of engineering and medicine. Over time, surgery, a field with a very important connection to bionics, has shown considerable progress. Latterly, most of the amputations performed centuries ago can be considered inhumane or even barbaric. Before the emergence of chloroform, anesthesia would be realized using other mixtures which often contained opioids. Such a mixture, containing mandragor root and opium was used as an anesthetic in the mid-13th century by the Italian surgeon Hugh Borgognoni [1].

An important step towards the advancement of antiseptic surgery was Joseph Lister's research regarding the use of carbolic acid as a microbicide [2]. His experiments have led to the formation of 'antisepsis system' in the 1870s, which helped drastically decrease the number of post-surgery deaths caused by infections.

With the development of the medical system and the introduction of new technologies in each of its branches, new possibilities emerged. Currently, after an amputation is performed, survival is guaranteed, and the main focus of the physicians is finding a functional replacement for the lost limb.

Another method used for replacing a lost limb is a transplant. Such an intervention was successfully performed in 1999, on a 37 – year old patient [3]. It has been proven that a transplant can be successful, however, because of its complexity and numerous disadvantages, it is still an inferior method when compared to a bionic replacement. The probability of finding a donor whose arm is of similar size is very low. Two other important disadvantages are the long-term administration of immunosuppresives and the possibility of acute rejection, thus requiring another surgical intervention [4]. In most cases, a bionic replacement is the desired choice, because it offers a higher degree of safety.

Ever since ancient times, various replacements were used for lost limbs. According to a writing by Plinius the Elder in Naturalis Historia, one of the first prosthetics encountered in history was an iron hand which belonged to the Roman general Marcus Sergius. Before the 17th century, iron hands were used in most cases by knights to hold a shield or ride a horse, so they can return to battle even after the loss of an upper limb [5].

The first body-powered prosthetic arm was developed at the beginning of the 19th century by the German dentist Peter Baliff [5]. The concept of a body-powered prosthetic represented a very important discovery as most of the bionic arms that exist today are built using the same functional principle.

Currently there is a variety of upper-limb prosthetics on the market, their price and availability being directly influenced by factors such as: build complexity, materials used and degree of functionality. A safer and more accessible model is the myoelectrical prosthetic arm. Its motors are activated when an electrical impulse caused by muscle contraction is detected [6]. Other types of bionic arms, such as the ones that use intraneural electrodes to ensure a bidirectional connection between the nervous system of the user and the prosthetic, can re-create the sensation of a real limb to a higher extent [6]. The disadvantages created by using such technologies include: invasive surgeries, a possibility that the electrodes will be rejected due to low biocompatibility, risk of infections and high costs.

Another very important but often forgotten aspect is the rehabilitation process that each amputee should go through. Ideally, it is desired that the rehabilitation process begins before the amputation surgery, the initial stage consisting in creating a plan to restore functionality of the lost limb by using a prosthetic [7]. In the next stage, it is very important that the patient heals and receives the necessary psychological therapy in order to overcome this trauma. The last stage should be represented by acquiring a prosthetic replacement and training offered to the patient in order to integrate their artificial limb into their day to day life [8]. For many patients, the rehabilitation process stops after the second stage, because of financial reasons or limited availability of prosthetics in their areas.

2. PROSTHESIS VIRTUAL PROTOTYPING

One of the main objectives set when designing this prosthetic arm was the implementation of a high degree of functionality in a light and visually pleasing model. The device represents a myoelectrical upper-limb prosthesis, with 22 parts, 7 of them being duplicates. From a functional point of view, there are 15 joints, capable of producing movements, independently of one another (Figure 1). A particular characteristic possessed by this model is the palm's capability of performing a 360 degree rotation, which a biological hand may not be able to execute.

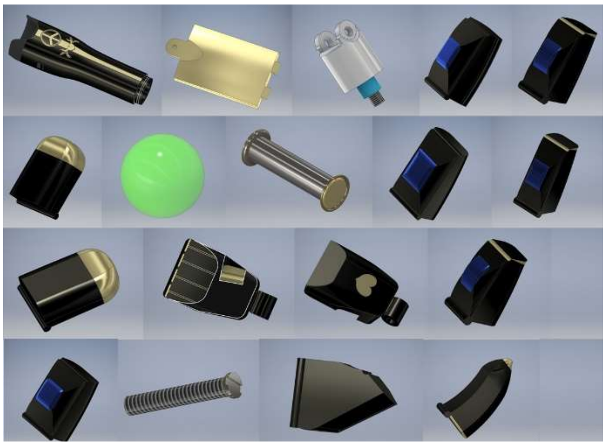

Figure 1 Exoprosthesis main elements

One of the features pursued in restoring functionality of a lost limb, take into consideration the body rebalancing from a gravitational point of view. After an amputation, the center of mass usually shifts, which results in a posture change, accompanied by scoliosis or other possible complications, which can develop over time [9]. That's why the prosthetic arm needs to be as dimensionally accurate as possible, mimicking the morpho-anatomical landmarks of the lost arm (Figure 2). Precision represents a very important factor when judging the prosthesis quality, and so, most of the measurements were made on the author's forearm, thus creating the concept of a personalized prosthetic.

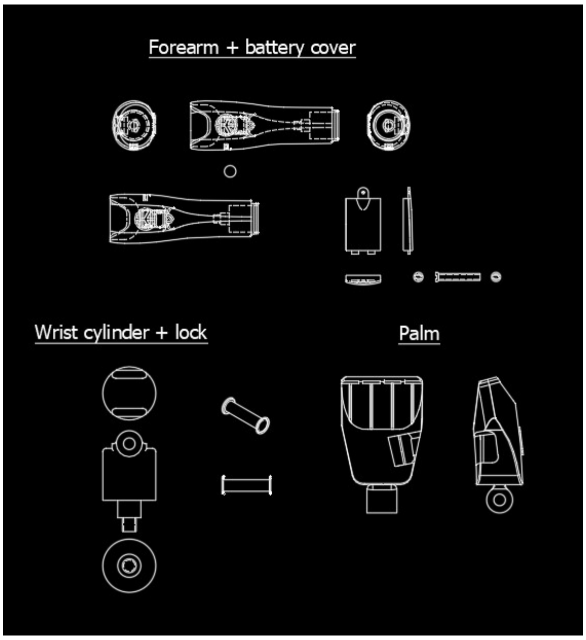

Figure 2 Forearm, battery cover, wrist cylinder with lock and palm prosthetic components

Regarding aesthetics, our goal was to offer each client the possibility of having a personalized device. The loss of a limb represents a psychological trauma, and the aspect of the artificial replacement can help boost the user's morale [10]. It is very important for artificial limb producers offer various customization options to their clients. Such personalization options can range from plain colors to inscriptions and engravings (Figure 3).

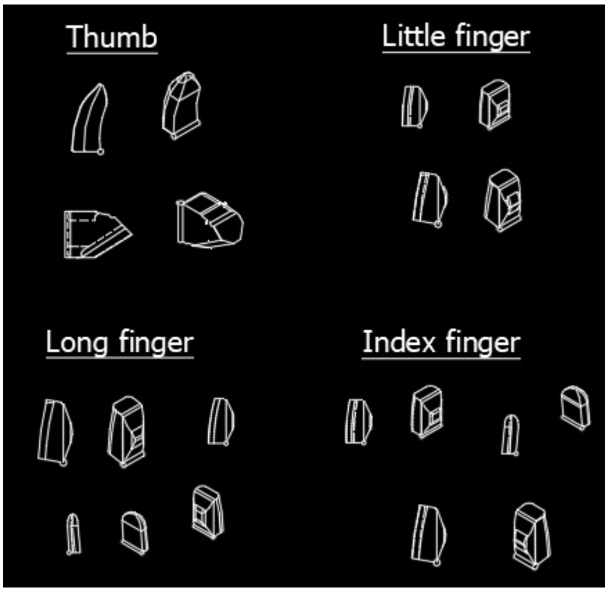

Figure 3 The overall elements that make up the finger joints

3. MATERIAL ASSIGNING

Figure 4 Bionic arm prototype

Another very important stage of designing a bionic prosthetic arm (Figure 4) is the material selection. The most important factors taken into consideration when selecting materials are mechanical properties and prices. Some of the materials commonly used in bionic arm construction are: Plexiglass, Polystyrene, Carbon Fibers, Nylon 6 and Nylon 66 [11]. The prosthetic should be light, flexible, but also flexible and resistant to shocks and loads, which may arise from activities or incidents that can happen in daily life (Figure 5). Given these requirements, the materials selected for this study are Nylon 6 and Carbon Fiber.

Nylon 6 is a homopolymer material obtained by polymerization of caprolactam [12]. Due to its properties, such as high mechanical and chemical resistance, it is used in various industries, such as automotive, textile and biomedical industry. One of the disadvantages of using Nylon 6 is that it readily absorbs water, thus deteriorating its properties [13]. One possible solution for this problem is adding a 30% fiberglass content in the material, so that the absorption rate will be decreased [14].

Carbon fibers are classified as fibers with a 92% carbon content or greater [15]. The precursor of industrial carbon fibers is polyacrylonitrile (PAN), a synthetic resin, obtained by mixing acrylonitrile with two or more co-monomers, such as methyl acrylate and itaconic acid. Manufacturing consists of three stages: the rotation of polyacrylonitrile fibers, thermal stabilization and carbonization [16].

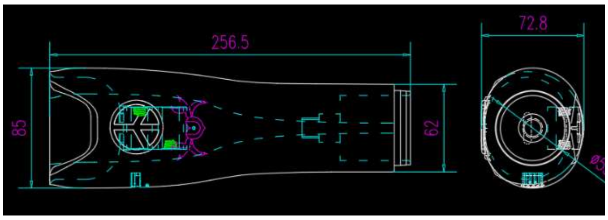

Figure 5 Arm model dimensions

The most important step is represented by the thermal stabilization. It consists of a series of exothermic reactions which greatly influence the properties of the material. Due to its excellent characteristics, such as low density, torsion resistance, high thermal and chemical stability, high electrical and thermical conductivity, carbon fiber is often used in industries such as aerospace [16].

4. FEA OF THE PROSTHETIC MODEL

In order to test the durability of the material and model, a Finite Element Analysis (FEA) study was conducted using CAD software, such as Solidworks.

The material analyzed in this study is Nylon 6, a durable plastic, often used in bionic prosthetic construction. The characteristics of Nylon 6 used in this study are shown in *Table 1*. The part used for the study is the prosthesis base, namely the forearm.

The geometry of the forearm was embedded in the lower part, more precisely on the face where the battery insertion area is located. The boundary conditions were chosen to simulate a strong impact with a force of 3000N on the outer surface of the arm, the force being distributed and acting as a normal to the model’s faces. This force represents the equivalent of a hit or an accident from which injuries or trauma may result.

The model shows no interferences and the hypothesis assumed regarding the Nylon 6 material was of a homogeneous, isotropic and linear material.

Table 1

Nylon 6 mechanical properties

Property	Value	Unit of measurement [SI]
Elastic modulus	2.76	GPa
Poisson’s ratio	0.35	N/A
Density	1110	kg/m³

Figure 6 shows the constraints and the boundary conditions of 3000N force, which acts as a shock on the bionic virtual model.

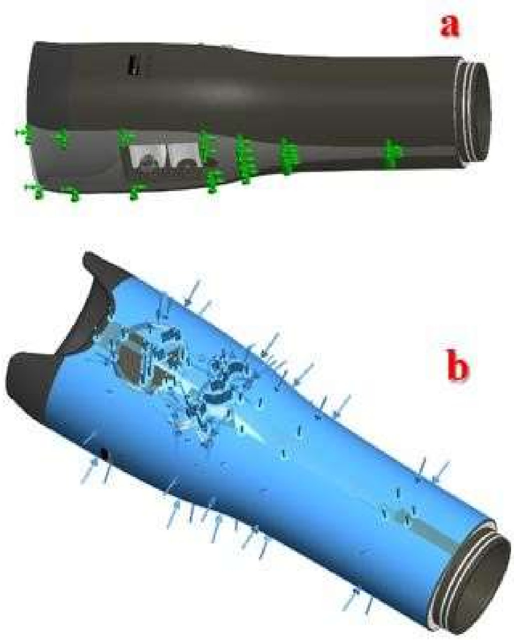

Figure 6 a) Constraints applied to the model;
b) Forces applied to the surface of the model.

In *Table 2*, we can observe the sum of the applied forces and the resultant on each coordinated axis.

Tabel 2

Sum of the forces applied to the prosthetic model [N]

OX sum	OY sum	OZ sum	Resultant
139.03	368.58	-9.86	394.06

A high quality, solid mesh was used. It has 4 Jacobian points, 28211 nodes and 17158 total elements. The stress results showed a minimum von Mises stress recorded in node 4705, with the value of 0 MPa and the maximum von Mises stress recorded in node 5185 with the value of 3.338 MPa. The stress results can be observed in Figure 7.

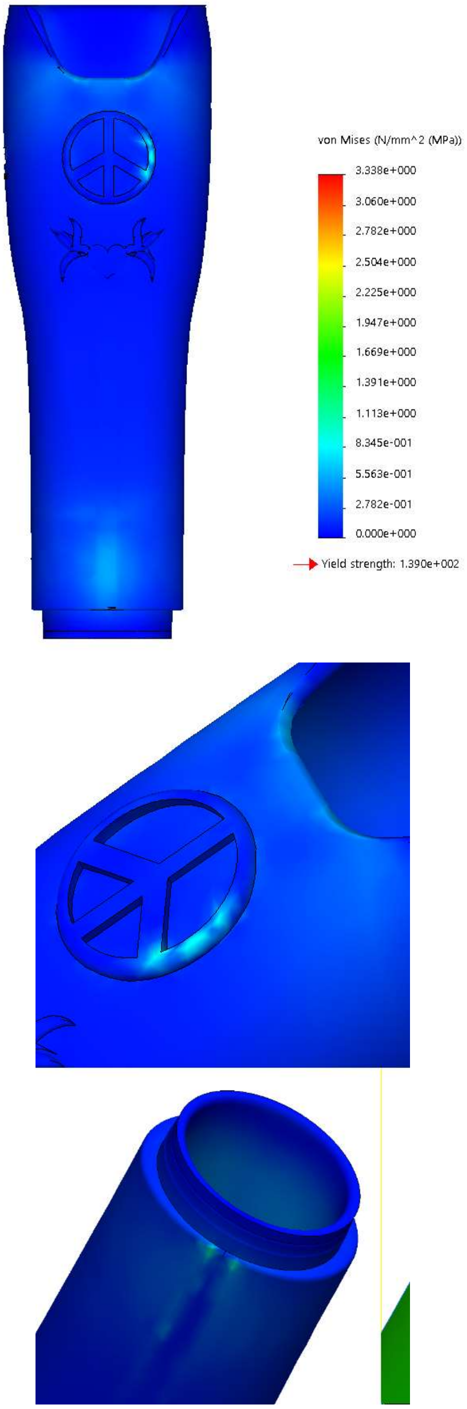

Figure 7 Bionic prosthesis stress results

The maximum displacement, with the value of 2.959×10^{-3}mm, appears in node 5181, and the minimum displacement, with the value of 0mm in node 52. The results can be visualized in Figure 8, where we can see that there are notable displacements in the model's extremities. However, the maximum displacement does not significantly deteriorate the model and it does not damage the material, the model suffering a small displacement compared to the high applied force.

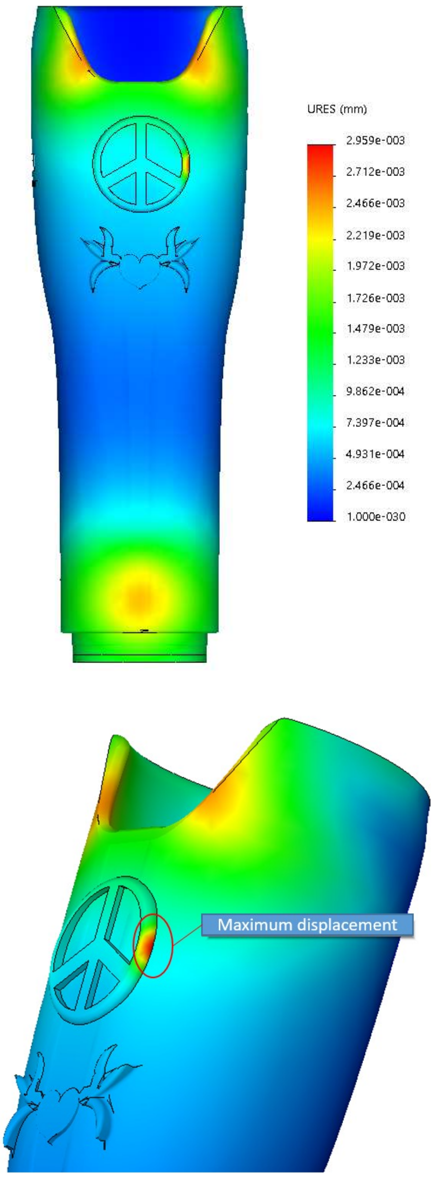

Figure 8 Bionic prosthesis displacement results

The strain results, shown a maximum strain value of 1.387×10^{-4} ESTRN [Equivalent Strain] and appears in element 6069, the minimum strain value instead is of 4.113×10^{-14} ESTRN [Equivalent Strain] and appears in element 6449. Figure 9 shows the model's strain results.

The conclusion of the FEA study is that the material could easily withstand the body mass of any patient, and in the case of a shock, the deformation will be almost null.

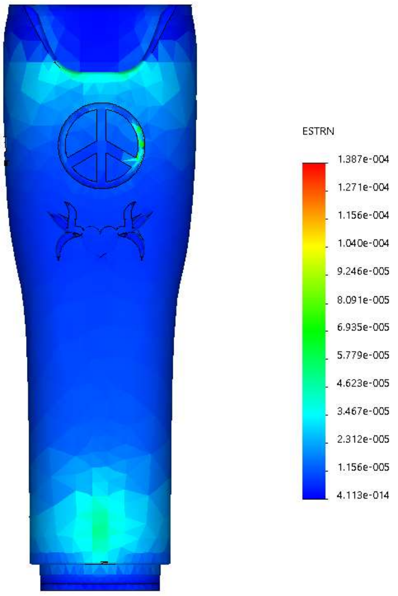

Figure 9 Bionic prosthesis strain results

5. CONCLUSION

Nowadays, due to the AM technology and their accessibility, virtual models can be manufactured much easier. Such an exoprosthesis model of the upper limb designed using the author's anatomical landmarks is a customized product that can be manufactured at low cost.

The main goal set for the future is to create a physical prototype of the presented model, through 3D printing and to conceive a system that creates functionality of the prosthetic arm, thus offering the possibility of performing tests on a physical model. Also, creating a study in which patients can use the bionic prosthesis would be beneficial. The collected data, together with the participant's feedback will allow further improvements to the bionic concept design. In conclusion, the presented bionic arm model can be used as a template in order to raise design standards and to optimize myoelectric prostheses, thus offering the possibility of being set up according to the morpho-anatomical characteristics of each individual and of being constructed using a 3D printer.

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