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DYNAMIC ANALYSIS OF MECHANICAL HAND PROSTHESES MANUFACTURED BY ADDITIVE MANUFACTURING

Rodrigo César da Silveira Romero

Valéria Prata Lopes

Federal University of Minas Gerais, Department of Mechanical Engineering
6627, Antônio Carlos Avenue, Belo Horizonte, MG, Zip Code: 31270-901, Brazil
rodrigocromero.engenharia@gmail.com
pratalopes.valeria@gmail.com

Mirella Gibson de Castro Ho

Paulo Henrique Rodrigues Guilherme Reis

Federal University of Minas Gerais, Department of Mechanical Engineering
6627, Antônio Carlos Avenue, Belo Horizonte, MG, Zip Code: 31270-901, Brazil
mgibson3266@gmail.com
paulogsk@gmail.com

Thiago Teixeira Nardy Barrioni

Federal University of Minas Gerais, Department of Mechanical Engineering
6627, Antônio Carlos Avenue, Belo Horizonte, MG, Zip Code: 31270-901, Brazil
thiago_nardy@hotmail.com

Claysson Bruno Santos Vimieiro

Pontifical Catholic University of Minas Gerais, Department of Mechanical Engineering
500, Dom José Gaspar Avenue, Belo Horizonte, MG, Zip Code: 30535-901, Brazil
Federal University of Minas Gerais, Department of Mechanical Engineering
6627, Antônio Carlos Avenue, Belo Horizonte, MG, Zip Code: 31270-901, Brazil
claysson@pucminas.br

Abstract. Additive manufacturing is a widely used technology in several areas allowing the manufacture of parts with different geometric shapes and a fast production. Within this context and the given relevance of the subject, the aim of the present study is on the execution of the open-source mechanical hand prosthesis (OS), called Partial Hand Prosthesis (PHP), and the manufacture of another distinct model of an OS device called the Prosthetic Hand (PH), using the additive manufacturing technique through three-dimensional printing technology; the prosthetic models are obtained through files from the Thingiverse website. The PHP prosthesis was submitted to mechanical tests, through simulations using Finite Element (FE) software, in order to evaluate the mechanical properties of the model used. The PH model was printed and built with certain print parameters. The present work presents the mechanical feasibility study of the PHP device, as a result: good mechanical performance in a scenario of compression of a solid object; simulation of static forces and reaction forces at the extremities of the prosthesis fingers. For the PH device the results has shown that the file of the prosthetic model, together with the fast prototyping process, presented good dimensional accuracy; relative difficulty in its mountability; fast construction and low cost production.

Keywords: Mechanical Hand Prosthesis; Additive Manufacturing; Mechanical Feasibility; Open Source; Finite Elements.

1. INTRODUCTION

Physical impairment can be caused by several factors, such as: congenital, trauma, vascular disease, diabetes, cancer or infections after injury. In addition, amputation is considered as the main cause that leads to physical disability, since it is one of the oldest therapeutic resources of medicine, and can be characterized by total or partial permanently removal of the limb from the human body (Hawamdeh *et al.* 2008; Gerwin, 2013; Letcher; Zuo *et al.*, 2014).

In this case, orthopedic devices such as prosthetics become a relevant alternative as far as to meet the functional and aesthetic needs of the amputated limb region. The prostheses are characterized by being an externally applied artificial medical device to replace, in whole or in part, an absent or change in structure that aims to permanently replace the removed member performing functions and meeting the daily needs of individuals who have some physical disability (Ministério da Saúde, 2013).

Currently, most of the conventional prefabricated prostheses depend on the generalization of sizes from dimensions, and are often not adaptable to be adjusted in specific individuals, discomfort in use and decrease in therapeutic capacity (Ministério da Saúde, 2013; Romero *et al.*, 2018). Considering this scenario and the scope of the subject, there was a significant increase in the development of studies in which development and construction of prostheses made through additive manufacturing (AM) process. As it is a process with high potential to revolutionize the way in which it can manufacture bodies with different geometries, production and usually with low costs, characteristics that, in the case of the manufacture of prostheses, could reach high degree of personalization impacting positively and directly on the greater use of the potentialities and functionalities of the device (Romero *et al.*; Rodriguês *et al.*; Soriano *et al.*, 2018).

The prosthetic market currently has a wide range of hand prostheses, ranging from prostheses devices that rely on complex and sophisticated technological resources, such as: electronics, actuators and robotics incorporated into your operating system. However, because these devices are not on an industrial scale, they require specialized maintenance and the manufacturing process of these devices, especially the upper limb prostheses, require great operational effort, these prostheses are offered in the consumer market with high production costs, making access to the prosthesis difficult for a considerable number of users (Burn *et al.*, 2016; Xiong *et al.*, 2017; Romero *et al.*, 2018).

From this point of view, disabled people, especially those who are amputees, in poorly developed population, most of which rely on people deprived of have a great difficulty in acquiring prosthetic devices. Given that, individuals who go through the process of amputation see themselves as part of a special group, with the social participation turned to everyday life, due to the sensation of incapacitation, loss of independence, withdrawal from work, pain due to surgical wound, among others (Gabarra *et al.*, 2009; Bragaru *et al.*, 2011; Covre *et al.*, 2012; Dally *et al.*, 2015).

Thus, AM is a technology used in several areas allowing the manufacture of parts with different geometric forms and with a fast production. Through this technology and due to the different fields of application, there are websites like Thingiverse dedicated to the sharing of digital design files where several prosthetics models, including mechanical prosthetics, linked to this platform are developed, created and shared free of charge in OS, ready to be printed using three-dimensional printing (Dally *et al.*; King *et al.*, 2015; Xiong *et al.*, 2017; Rodriguês *et al.*, 2018).

Therefore, the aim of this work is to perform the mechanical feasibility study through FE of a model of human hand mechanical prosthesis called PHP and build another model of device called PH through AM. For the hand prosthesis PHP was verified: mechanical performance in a scenario of compression of a solid object; simulation of static forces; and reaction forces at the extremities of the prosthesis fingers. To PH device, it was evaluated if the file of the prosthetic model, together with the additive manufacturing process, shows good dimensional accuracy and mountability, if the device features fast construction and low productive cost.

Hence, since the hand is one of the most relevant parts of the human body, characterized by the integration of the upper limb, and that it was through it that the fundamental needs for survival and adapting, through the construction of tools for hunting animals, building shelters and making clothing, the human being was able to adapt and survive the environment throughout history. In addition, hands also play an important role in areas such as: expression of the arts and sciences, in cognitive processes through touch, being fundamental to the conventions emphasizing the expressions of movements and gestures, allowing greeting and non-verbal communication, that their absence influence directly on the limitation of the execution of daily activities (Pillet *et al.*, 2001; Sardenberg *et al.*, 2002; Zuo *et al.*, 2014; Willians *et al.*, 2018).

Finally, in this context that the search to develop artificial orthopedic devices as prosthesis hand made through the AM aims to give the deficient region, even in a simple way, movements that have the ability to perform daily tasks bringing greater quality of life, safety and high self-esteem for the disabled person.

2. METHODOLOGY

There were three methodological stages for the accomplishment of this work, they were: (1) selection and acquisition of the OS virtual models of orthopedic devices available for free download on the Thingiverse website; (2) execution of computational simulations through study of FE in the PHP prosthesis and; (3) construction of the hand prosthesis PH mechanic via 3D printing.

The selection phase of mechanical hand prosthetic models was obtained free of charge via STL file format, extensively used for AM and computerized manufacture, served by the site Thingiverse, these prostheses are intended for patients who have undergone amputations at Disarticulation levels Metacarpophalangeal or Transmetacarpal levels of amputations that preserve the movements of wrist flexion allowing the mechanical drive, through muscular propulsion, of the movements performed by the prosthesis by means of cable tracing and elastics. Figures 1 and 2 show the design of the PHP and PH device respectively, available on the Thingiverse website.

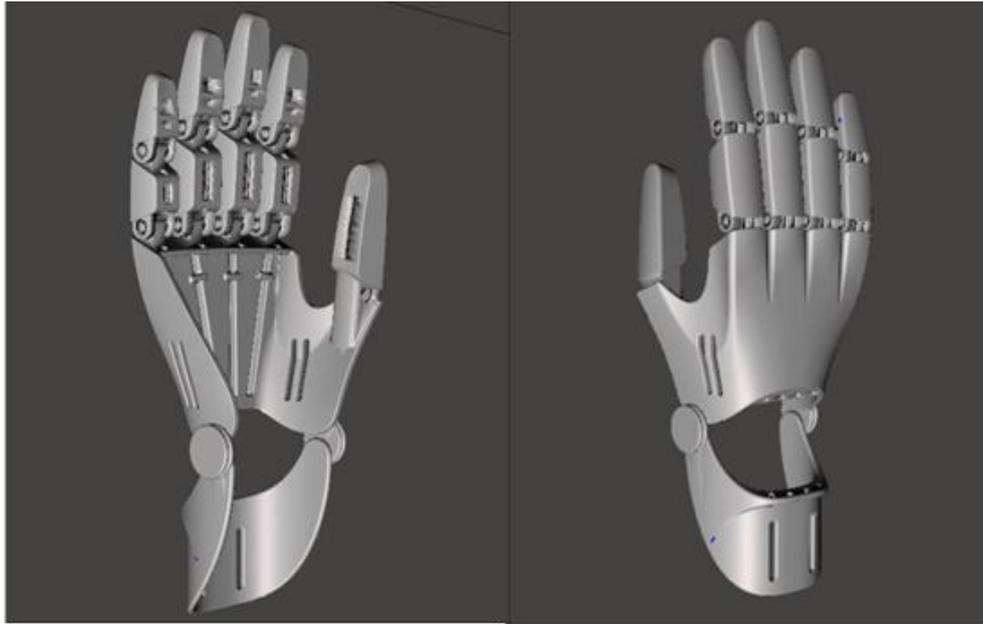


Figure 1. Partial Hand Prosthesis (PHP) Project.
Available from: <https://www.thingiverse.com/thing:2565845>

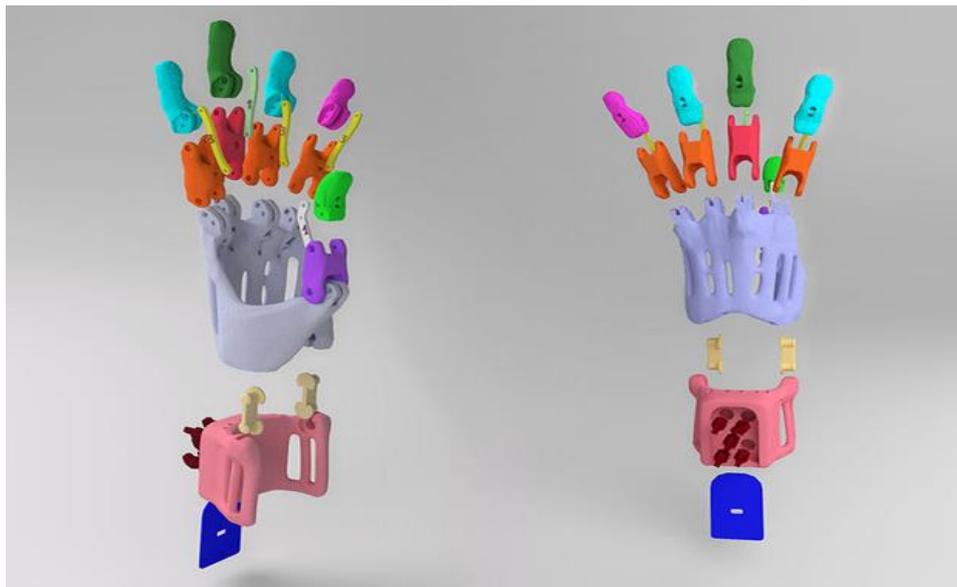


Figure 2. Prosthetic Hand (PH) Project.
Available from: <https://www.thingiverse.com/thing:1489003>

The second step consists of the virtual simulations performed in the PHP model by means of static forces made to verify the mechanical quality of the prosthesis and, in this way, to guarantee the functional viability of the device. This step was performed through the software, which uses the Finite Element Method, ANSYS, of American manufacturer Ansys Inc and the constituent material of the prosthesis considered in the simulation was PLA (acid polylactic), a thermoplastic polyester material made from lactic acid from renewable sources, such as: beet, cassava, corn, among others. This type of filament is commonly documented in the scientific literature and used in 3D printing. Finally, the third and final stage was the printing and construction of the physical model of the PH prosthetic device, manufactured through 3D printer Fused Deposition Modeling (FDM) with the use of the biodegradable PLA printing filament of the Brazilian brand 3DFila.

In step 3 for the printing of the PH prosthesis it is important to define the printing parameters, since they have a direct influence on the printing process and on the quality of the printed product. Three-dimensional die casting (FDM) printing technology consists of preheating material supplied by a coil, usually of polymers or certain metals, to allow material extrusion nozzle, which usually consists of a movable head with a heating block, melting the material which is then deposited in a controlled manner, layer under layer, through a hole in a tray until the final construction of the printed product, which usually consists of a movable head with a heating block, melting the material which is then deposited in a controlled manner, layer under layer, through a hole in a tray until the final result of the printed product (Moreira, 2016). The print parameters are shown in Table 1. Subsequently, as surface finishing, only one smoothing with fine sandpaper (greater granulation) without any other treatment of the piece.

Table 1. Principle imprint parameters PH

| | |
|-------------------------|-------------|
| Nozzle size | 0,4 mm |
| Layer High | 0,3 mm |
| Initial Layer High | 0,3 mm |
| Wall Thickness | 1,0 mm |
| Infill Density | 25% |
| Infill Pattern | Rectangular |
| Printing Temperature | 205°C |
| Build Plate Temperature | 0°C |
| Speed | 60 mm/s |

3. RESULTS AND DISCUSSION

The mechanical functionality of the prosthesis was measured in the simulation of static forces through FE analysis. For the simulation, the reaction forces at the extremities of the prosthesis, made by means of the AM in PLA, were considered in a scenario of compression of a solid object. Pre-defined mean reaction forces were considered by previous studies representing a 7N action on the fingers (Serina *et al.*, 1998).

Stress

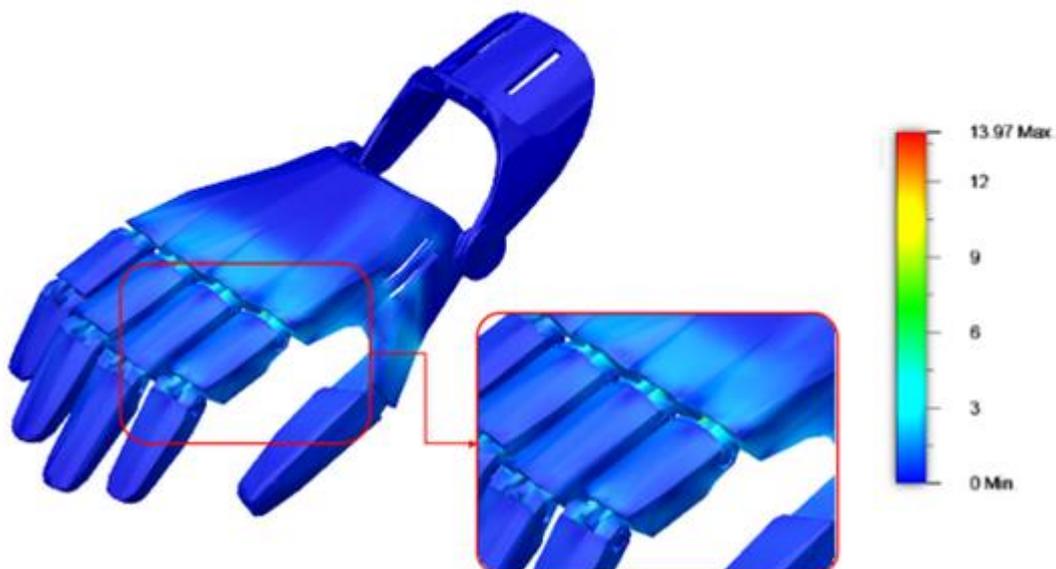


Figure 3. Simulation of static forces acting on the PHP prosthesis

Displacement

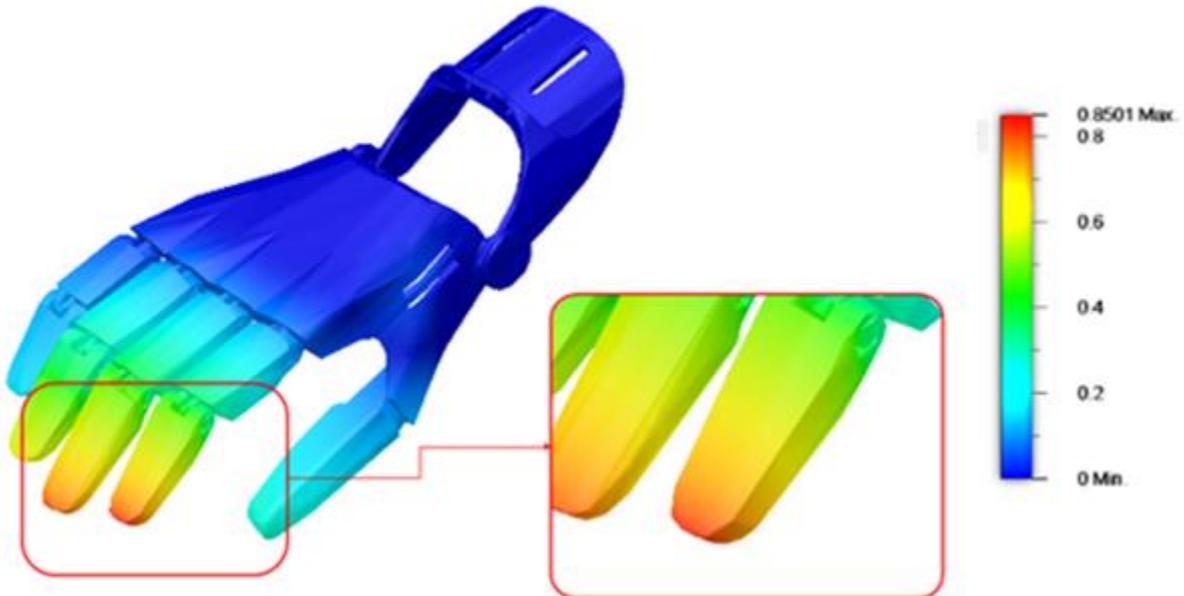


Figure 4. Surface displacement in relation to the forces acting on the PHP prosthesis

The simulation of static forces (Fig. 3) has shown that such prosthesis, made with the specified material, has mechanical viability in the compression of solid objects in a force of 7N, since the object did not present superficial ruptures or plastic deformation. The application of the force showed a maximum reaction of 13.95 MPa concentrated in the structure of connection between the palm of the prosthesis and the fingers. The maximum displacement was 0.85 mm (Fig. 4), concentrated at the tip and middle fingers of the prosthesis (region in reddish color).

Printing of the PH prosthesis was possible through the three-dimensional printer incorporated in FDM technology. Figure 5, below, shows the constituent elements of the prosthesis made with PLA filaments.

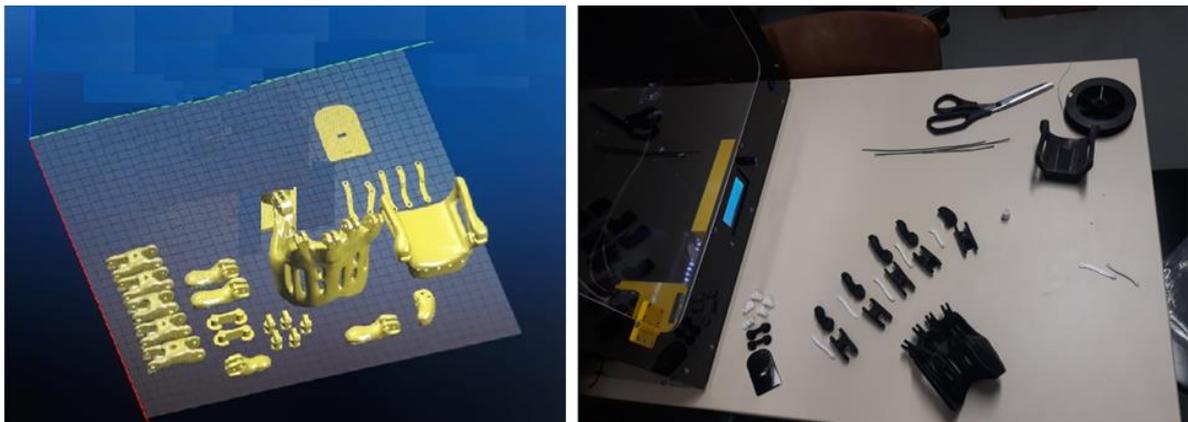


Figure 5. Constituent elements of the Prosthetic Hand (PH) made with PLA filaments

Figure 6 shows the construction process of the PH after the three-dimensional printing process is completed. The assembly and printing of the PH showed fast confection and low cost.

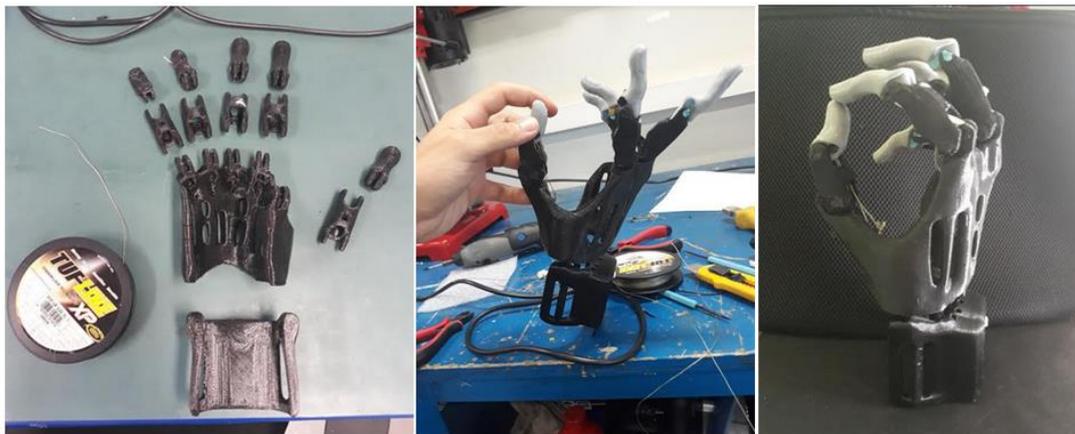


Figure 6. Construction process of the Prosthetic Hand (PH)

The PH took about 20 hours to be fully printed and, after that, it took an average of 4 hours for the finishing and assembly, reaching 235.74 g of weight after its assembly. It is estimated that the productive cost of the device is around R\$ 175,00 (US\$ 42,60), a relatively low cost compared to other conventional devices available in the market.

Currently, according to the reference table of the Unified Health System, the prices of conventional upper limb prostheses in Brazil are around R\$ 850,00 (US\$ 206,78). In addition, in the world market there are hand prostheses with sophisticated electronic systems, sensors and actuators employed in its operating system, which can cost up to US\$ 58,000 per unit, such as the “BeBionic” bionic hand developed by the British Company Steeper Group.

Devices printed through AM can cost up to 90% less than conventional devices. In addition, the lightness of the prosthesis, less than 300 g, is a fundamental part of the new limb adaptation process, especially when the patient is a child or has compromised arm strength. Thus, three-dimensional printing materials such as PLA which, while being lightweight, support approximately 215 kg of static charge, a density of 1.24 g / cm³, a modulus of elasticity of 4350 MPa and yield stress of 66 MPa (3DLab, 2019). Relevant values for the purpose of combining low weight and high strength when compared to materials such as Polypropylene commonly used for the manufacture of conventional prostheses, having a modulus of elasticity equal to 1100 MPa, density 0.91 g / cm³ and yield strength 35 MPa (Incomplast, 2019). Important properties to compare, since the modulus of elasticity provides the stiffness of the material, that is, the greater the modulus of elasticity, the less elastic deformation resulting from the application of a given stress. In addition, there is the value of Limit or yield stress which is the beginning stress of plastic deformation, that is, the higher the value of yield stress, the greater the stress that the material can withstand in its elastic regime without undergoing irreversible deformation. That is, values that show that it is possible to manufacture a printed device via three-dimensional printing in order to confer good mechanical strength on the orthopedic device.

In addition, components made by 3D printing present variable dimensional accuracy depending on the geometry element and the printing position. However, horizontally printed parts (XYZ and YXZ print direction reference according to ASTM Standard 52921-13 - *Standard Terminology for Additive Manufacturing Coordinate Systems and Test Methodologies*) have better dimensional accuracy (Knoop *et al.*, 2015; Santana *et al.*, 2018). In other words, at the end of the three-dimensional printing process, the printed parts present the same dimensions as the generated drawing. Thus, after the device construction process it can be used by the patient in a functional and comfortable way, according to user reports. In addition, surface roughness varies between surfaces, due to print direction and layer thickness. Thus, the pieces printed in horizontal position, in addition to good dimensional accuracy, have lower values of roughness, Ra not exceeding 25 µm.

4. CONCLUSION

The main conclusions of the mechanical feasibility study of PHP are:

Assessing the mechanical functionality of the prosthesis, through simulations of static forces, through simulations in FE considering the reaction forces at the ends of the fingers of the device, the prosthesis in question, the PLA as a constituent material, has mechanical viability in the compression of solid objects in a force of 7 N, seen that the surface of the device did not show plastic deformations and / or ruptures. Concluding that the maximum reaction in the prosthesis was 13.95 MPa concentrated in the connection structure between the palmar region of the prosthesis and the phalanges, obtaining displacement of 0.85 mm concentrated in the end of the index and middle fingers of the device. Therefore, PHP obtained good performance for the analysis conditions employed, showing good mechanical resistance.

The main conclusions of the PH prosthesis construction process are:

- The file of the OS prosthetic model, together with the rapid prototyping process and after the three-dimensional printing process, showed good dimensional accuracy and acceptable surface finish;
- Regarding the mountability of the device, its assembly is rather complex, since there are different types of constituent elements of the prosthesis;
- The device presents rapid construction and good mechanical resistance;
- Finally, it is possible to print and construct a mechanical hand prosthesis obtaining low productive cost through additive manufacture.

5. ACKNOWLEDGEMENTS

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