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MECHANICAL FEASIBILITY STUDY USING FINITE ELEMENT METHODS IN AN OPEN SOURCE HAND PROSTHESIS

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Abstract. *The use of mechanical prostheses for returning, as close to reality as possible, the motor function of upper limbs in people with hand or arm amputation is becoming increasingly common, especially after the advent of additive manufacturing technology, which enables the manufacture of various part geometries in a fast and relatively inexpensive production system, besides providing easy customization and personalization of the models produced. Several files for the development and construction of these mechanical hand prostheses are available and can be easily accessed on Open Source platform sites worldwide, such as the Thingiverse and e-NABLE platforms, which operate based on a voluntary global community to provide files and project documentation focused on three-dimensional printing. The purpose of this paper is to select a hand prosthesis on the Open Source sharing site (Thingiverse) for a mechanical feasibility study by developing a temperature, stress, and displacement analysis, finding stress, displacement, and temperature concentration points on the surface of the device when static loads are applied, to verify the behavior mechanical e thermals responses using finite element method (FEM) analysis software.*

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

1. INTRODUCTION

The amputation of a limb triggers several physicals, psychological and emotional responses in a person, as it means a major change in their life, having to adapt to perform their daily activities, as in many cases there is impairment of movements (Saradjian *et al* ., 2008). Total or partial amputation of the hand is one of the most common procedures in trauma involving acquired disabilities (Imbinto *et al*., 2016), since manual workers and several activities involve the direct use of this limb. Thus, the individual's manual skills become extremely limited, and in many cases, they are unable to return to their routine and work functions after surgery, which can generate clinical pictures of depression, anxiety and anger after the amputation, not adapting to the new reality (Frierson and Lippmann, 1987).

Therefore, the development of medical devices, such as prostheses, for the resumption of movements and the individual's reinsertion in their activities are increasingly necessary. In this way, to help people who need the use of these devices, there are passive prostheses with aesthetic functions, without the use of electrical and/or mechanical action, which often aim to stimulate the psychological, raising the affected self-esteem due to the absence of the limb. In addition, the development of active use prostheses has been growing in recent years, with the integration of analog and digital control systems, providing flexibility of movements and greater integration between the user and prosthetic device, significantly increasing the range of activities that can be exercised (Sundfeld *et. al*., 2006).

For the development of hand prostheses, several factors must be taken into account during the design and construction, aiming to provide greater comfort and acceptability for the user. Thus, several technologies are being used to improve these devices, with the use of Additive Manufacturing (AM) technology as a major revolution, as it provides greater flexibility in customization, a high degree of customization, lower weight, good mechanical resistance, and more accessible prices, making this technology extremely attractive, accessible and with a lot of applicability. Several open-source sites make CAD articles available for printing hand prosthetics, creating a community that is increasingly interested and engaged in the creation of these prosthetic devices.

Despite representing a significant change in the manufacture of hand prostheses, it is increasingly necessary to analyze the mechanical feasibility of these devices using AM, as a way to ensure their integrity and safety for the user. In this sense, the use of CAD design software, combined with computer numerical simulation software, enables the structural mechanical study of the prostheses, providing the points of maximum stress, displacement, temperature, and gradient of acting forces, providing greater reliability and serving as a basis for future design improvements and creation of new prostheses (Romero *et al*., 2019; Zuniga *et al*., 2015).

In this sense, this article aims to carry out the mechanical feasibility study, through static computer simulation in FEM, to measure and evaluate the distributions of loads, temperature, and displacement on the surface of the evaluated open-source device.

2. METHODOLOGY

First, the selection and acquisition of the constructive and virtual model of the Open Sourcing (OS) mechanical hand prosthesis, called Talon Hand 3.0 (TH), available for free and globally for download on the Thingiverse website, was carried out. Figures 1 and 2 show the constructive design and the selected virtual model of TH respectively.

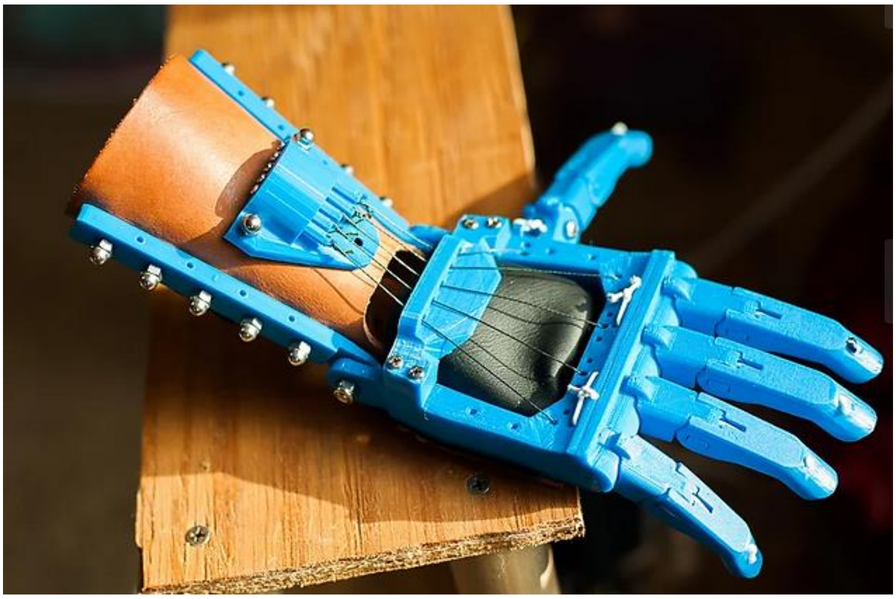

Figure 1. TH Mechanical Hand Prosthesis built
Available from: https://www.thingiverse.com/thing:229620

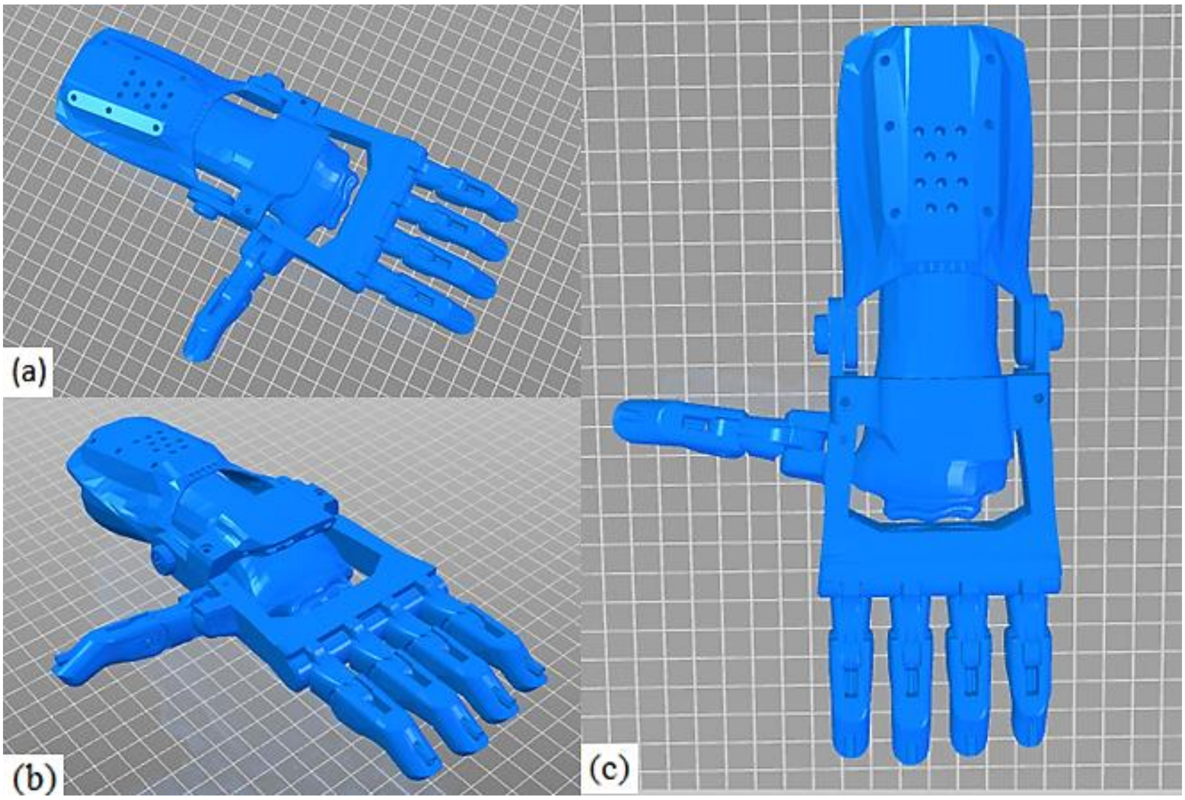

Figure 2. Partial Hand Prosthesis (TH) Project (a) and (b) perspective view (c) upper view
Available from: https://www.thingiverse.com/thing:229620

Subsequently, the virtual prosthetic model was exported to the meshmixer software, from the American manufacturer AutoDesk, where Boolean operations of intersecting parts and repositioning of the prosthetic components were performed to position the prosthetic hand in grip order, with a 15º extension of the wrist, 30º of extension in the metacarpophalangeal joints and 15º of extension of the interphalangeal joints of fingers 2, 3, 4 and 5 (Figure 3).

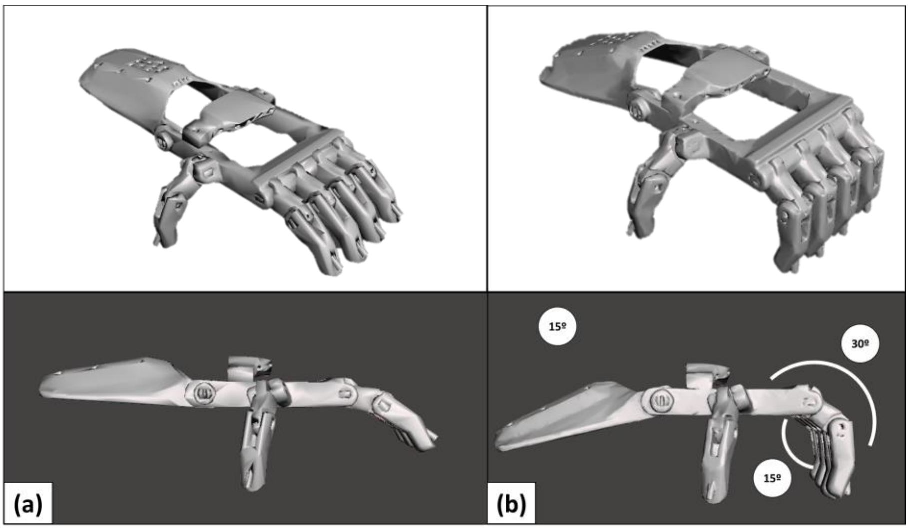

Figure 3: Positioning of the prosthesis (a) initial position (b) final position

After positioning, the prosthesis was discretized in the reduction of tetrahedral elements, without interfering with the geometric and dimensional resolution, to reduce the computational complexity in the development of static forces simulation and thermographic simulation. The initial model was reduced by a percentage of -75% from 30,537 vertices and 61,084 triangles to 13,222 vertices and 2,748 triangles, as shown in Figure 4.

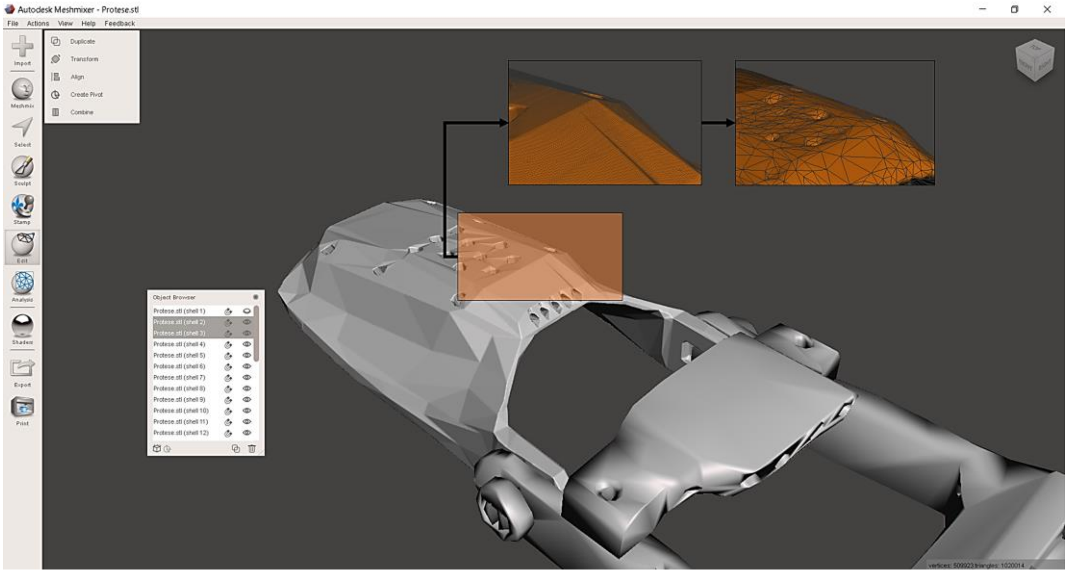

Figure 4: Mesh reduction in the virtual prosthetic model

After the reduction of the computational mesh, the prosthetic model was imported into 3D fusion software, from the American manufacturer AutoDesk, for the development of static force simulations and temperature mapping. For the study of stress and displacement, the input parameters in the software were the definition of fixation constants in the regions of forearm support (Figure 5-a) and allocation of forces in the regions corresponding to the medial and distal phalanges of fingers 2, 3, and 4 and in the proximal and distal phalanges of the finger 1. The forces, 285.0 N (Figure 5-b), were allocated according to the literature (Nilsen, *et al*., 2011; Romero, *et al*., 2020) for the force of prehension of adult males individuals aged 20 to 29 years, dominant hand.

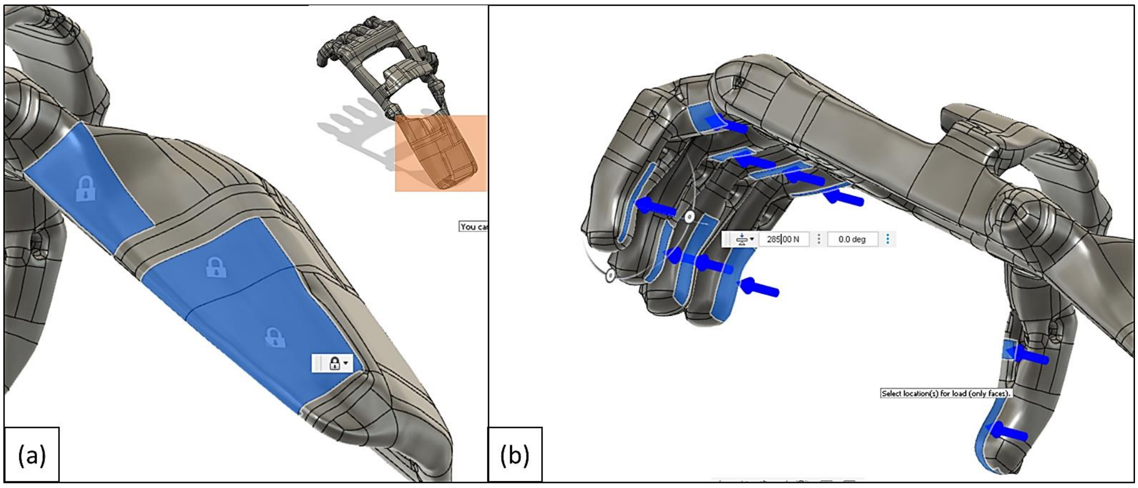

Figure 5: Input Parameters for FEA a) fixation constants b) allocation of forces

For comparison purposes, the simulations were performed with patterns based on two different materials, common in 3D printing, namely Acrylonitrile Butadiene Styrene (ABS) and Lactic Polyacid (PLA). The forces acting on the model demonstrated to exert a leverage effect with a pivot located on the part corresponding to the carpometacarpal joint of the prosthesis. The Finite Element Analysis (FEA) tests were performed considering the impression direction of the highest flexural strength (YZX), according to the technical standard ASTM F3091/F3091M-14, 2014.

For the simulation based on the ABS material resistance parameters, the action of forces caused a maximum stress moment of 70.35 MPa module corresponding to the carpometacarpal joint of the prosthesis, right sagittal plane (Figure 6-a), and maximum displacement of 8, 28 mm in the piece relative to the distal phalanx of finger 2 of the prosthesis (Figure 6-b). In the simulation, the model did not show surface rupture or permanent deformation.

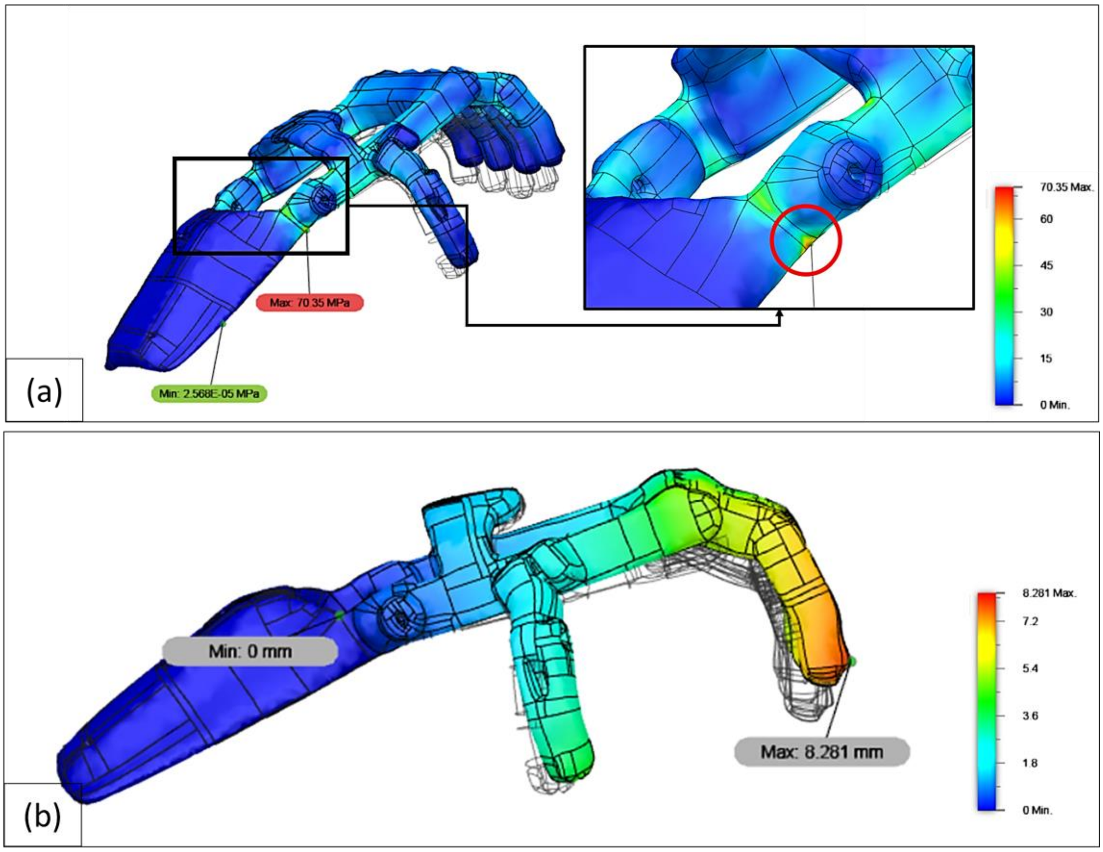

Figure 6: FEA of the prosthesis with ABS parameters. a) maximum stress observed. b) Maximum observed displacement

Finally, a specific methodology for constructive models is not available, since we work on an open code prosthesis available for download on internet sharing platforms and these sites do not provide methodology, they only provide the files for printing. Thus, it is necessary to make basic geometry adaptations, such as reducing the point cloud.

3. RESULTS AND DISCUSSION

The mechanical functionality of the prosthesis was measured in the simulation of static forces through FE analysis. The simulation based on the mechanical parameters of the PLA material showed maximum stress of 207.3 MPa modulus focused below the part corresponding to the carpometacarpal joint of the prosthesis, left sagittal plane (Figure 7-a), and maximum surface displacement of 24.14 mm (Figure 7-b). In this parameter, the prosthesis presented surface rupture for the acting forces under analysis.

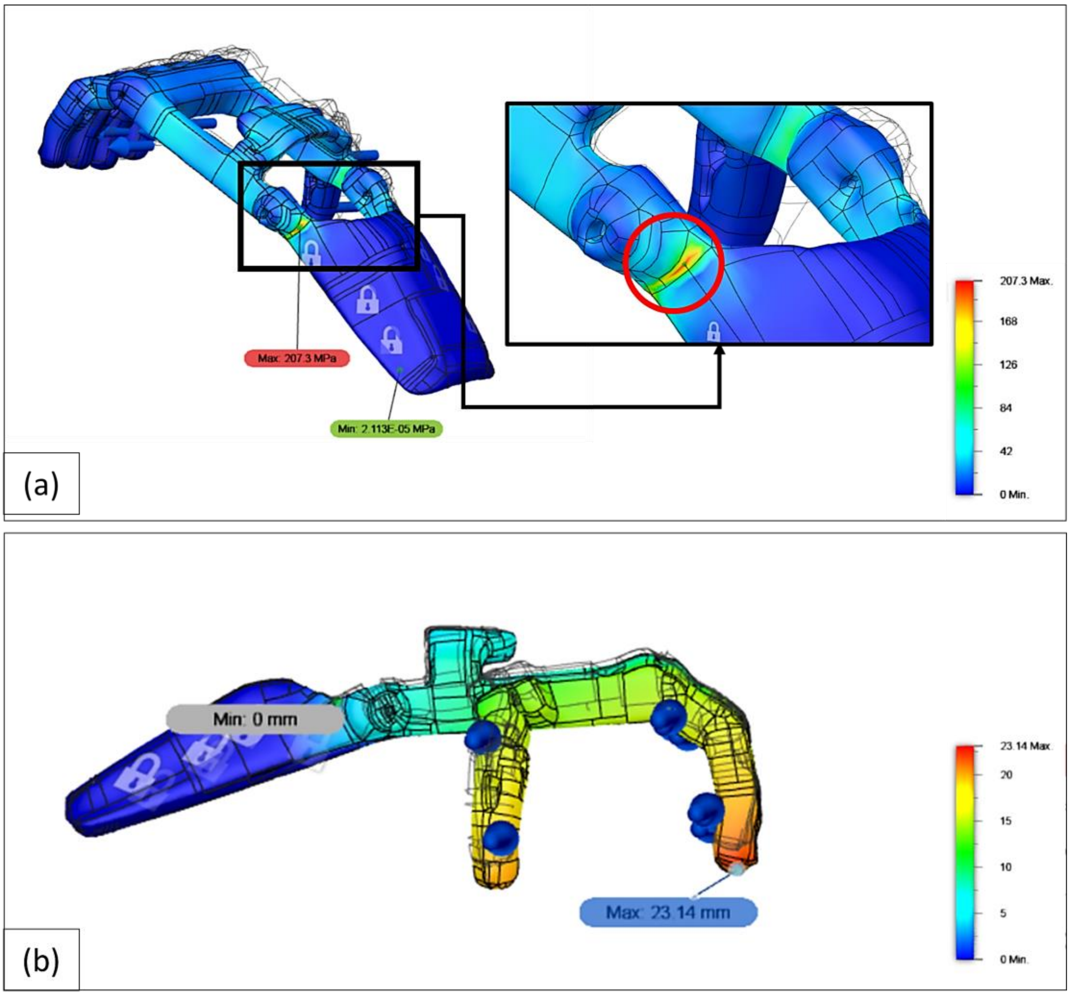

Figure 7: FEA of the prosthesis with parameters in PLA. a) maximum stress observed. b) Maximum observed displacement

The thermographic study was carried out to verify whether the temperature applied in the simulation would prove deformation in the prosthesis according to the material analyzed. The input parameters were established in the palm region of the prosthesis based on ABNT NBR 13970, which establishes limit temperatures of surfaces to establish ergonomic usability (ABNT NBR), 1997. According to this standard, the threshold temperature for contact greater than 01 minute in polymeric materials is 60ºC. The temperature flux in both prostheses is shown in Figure 8. For the ABS parameters, the limit temperature did not cause deformations in the model, while the PLA model presented surface deformations caused by the analysis temperature. It is possible to verify through the generated color map that the regions that concentrate the greatest heat in the device are on the palm sides and the surface equivalent to the centers of the phalanges (fingers) of the device (Figure 8).

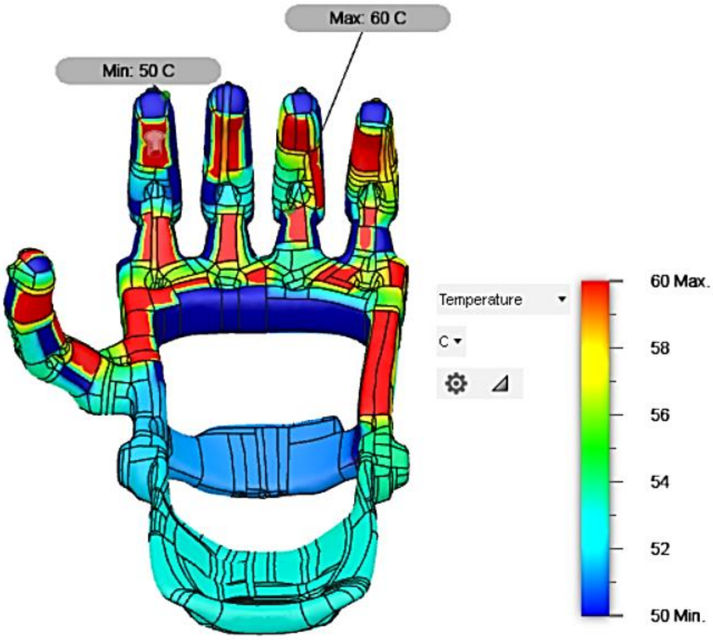

Figure 8. Flowchart of searches and results in the databases used

4. CONCLUSION

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

Assessing the mechanical functionality of the prosthesis, through simulations of static forces, through simulations in FE considering the reaction forces on the surfaces of the device, the simulation based on the mechanical parameters of the PLA material presented maximum stress of 207.3 MPa modulus, focused below of the piece corresponding to the carpometacarpal joint of the prosthesis, left the sagittal plane and maximum surface displacement of 24.14 mm. In this parameter, the prosthesis presented surface rupture for the acting forces under analysis. On the other hand, for these same parameters analyzed and performed for ABS, the prosthesis did not present ruptures, having a good mechanical response.

For the ABS parameters, the limit temperature did not cause deformations in the model, while the PLA model presented surface deformations caused by the analysis temperature. It is possible to verify through the generated color map that the regions that concentrate the greatest heat in the device are on the palm sides and the surface equivalent to the centers of the phalanges (fingers) of the device.

Therefore, ABS compared to PLA had a good performance for the analysis conditions used, showing good mechanical resistance.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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