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# CONSTRUCTION AND EXECUTION OF A MECHANICAL FEASIBILITY STUDY IN FEM IN AN OPEN SOURCE PROSTHESIS

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**Abstract.** Additive manufacturing is a widely used technology in various fields, enabling the rapid production of parts with different shapes and geometric complexities. This study focuses on conducting a mechanical feasibility analysis of two open-source hand prostheses: the K1 Hand (KH) and the Raptor, using three-dimensional printing technology. The prosthetic models were obtained from online platforms such as e-NABLE and Thingiverse, which freely share open-source digital design files, including upper limb prosthetic models. The KH prosthesis will undergo mechanical testing through Finite Element Method (FEM) simulations to evaluate its mechanical properties. The Raptor model will be printed and constructed according to predetermined printing parameters. These prostheses aim to replace and meet the needs of individuals with permanent physical disabilities, serving essential functional and psychological purposes. In this context, the main objectives of this work are to assess the mechanical behavior of the KH prosthesis through FEM simulations, analyzing its mechanical performance in situations involving compression of solid objects, static force simulations, and reactions at the fingertips of the prosthesis. For the Raptor prosthesis, aspects such as dimensional precision of the prosthetic model, ease of assembly, construction speed, and low production cost will be evaluated. The study seeks to contribute to the understanding of the mechanical performance of these hand prostheses, verifying their mechanical viability and assessing their functionality and applicability in the context of the needs of patients with physical disabilities.

**Keywords:** Additive Manufacturing, Finite Element Method, Low Cost, Open Source, Mechanical Hand Prosthesis

## 1. INTRODUCTION

There are many causes that lead to the condition of physical disability, which affects the function or structure of the body, resulting in significant limitations in mobility, coordination, muscle strength, or other physical abilities. These causes can be congenital, meaning present from birth, or acquired throughout life due to injuries, diseases, accidents, or medical conditions (Zuo et al., 2014; Biddis; Chau, 2017).

Therefore, in the case of partial or total absence of the upper limb, medical devices such as mechanical or automated hand prostheses have been an area of research and development in constant evolution, with the purpose of restoring function and quality of life for individuals who have experienced traumatic or congenital amputations (Gallagher et al., 2021; Romero et al., 2021).

The partial or total loss of the hand represents a significant challenge, as this body part plays a crucial role in daily activities and social interaction with the environment. It is through the hand that manipulation and grasping movements, non-verbal communication, artistic expression, fine motor skills, and positioning are achieved (Romero et al., 2020; Highsmith et al., 2021).

Within this context, orthopedic devices such as prostheses play a crucial role in meeting the functional and aesthetic needs of amputated limbs. Prostheses are external artificial medical devices designed to fully or partially replace a missing or structurally altered body part. Their main objective is to provide a permanent replacement for the removed limb, enabling individuals with physical disabilities to perform functions and meet the demands of daily life (Ministry of Health, 2013; Dally et al., 2015).

Prostheses offer a range of significant benefits for those who use them. In addition to restoring functionality to the affected limb, they also promote social reintegration, independence, and improved quality of life. These devices are designed taking into consideration ergonomic, biomechanical, and aesthetic factors, with the aim of providing a personalized and tailored solution to the individual needs of each patient (Lemaire et al., 2021).

However, currently, most conventional pre-fabricated prostheses pose a challenge in terms of personalized fitting, as they are based on generalized sizes obtained through dimensional estimates. This often results in discomfort during use and decreased therapeutic effectiveness (Ministry of Health, 2013).

Therefore, Additive Manufacturing (AM), also known as 3D printing, has shown to be a promising technique for the production of custom-made prostheses. Through this approach, it is possible to create prostheses that perfectly adapt to the anatomical and functional characteristics of each individual, resulting in greater comfort and performance (Dally et al.; King et al., 2015; Xiong et al., 2017).

Furthermore, AM allows for the integration of complex components into a single structure, which can improve the functionality and aesthetics of prostheses. This technology also facilitates quick adjustments and modifications, enabling a more agile and efficient manufacturing process.

By leveraging the advantages of AM, it is possible to overcome the limitations of conventional prostheses, offering personalized and functional solutions that can more accurately meet the individual needs of users. Thus, the use of AM in prosthetic production has the potential to significantly improve the quality of life for individuals with physical disabilities, providing more comfortable, functional, and tailored devices adapted to their unique characteristics (Pillet et al., 2001; Zuo et al., 2014; Williams et al., 2018).

In light of this, the objective of this work is to conduct a mechanical feasibility study through FEM of an Open Source (OS) human mechanical hand prosthesis model called K1 Hand (KH) and to construct another OS device model called Raptor using AM. For the KH hand prosthesis, mechanical performance was assessed in a scenario involving compression of a solid object, static force simulations, and reaction forces at the fingertips of the prosthesis. For the Raptor device, the dimensional accuracy, ease of assembly, construction speed, and low production cost were evaluated in conjunction with the prosthetic model file and rapid prototyping process.

## 2. METHODOLOGY

Three methodological steps were necessary for the conception of this work, namely: (1) selection and acquisition of the virtual OS models of orthopedic devices available for free download on the Thingiverse and e-NABLE websites; (2) execution of computational simulations through an FEM study on the KH prosthesis; and (3) construction of the Raptor mechanical hand prosthesis through 3D printing. The selection phase of the mechanical hand prosthetic models was obtained freely in STL file format, an extension widely used for rapid prototyping and computerized manufacturing, available on the Thingiverse and e-NABLE websites. These prostheses are intended for patients who have undergone amputations at the levels of Metacarpophalangeal Disarticulation or Transmetacarpal levels, amputation levels that preserve wrist flexion movements, allowing mechanical activation, via muscular propulsion, of the movements performed by the prosthesis through cable and elastic traction. Figures 1 and 2 show the mechanical devices of the KH and Raptor prostheses, respectively, available on the aforementioned OS platforms.



Figure 1. Mechanical hand prosthesis K1 Hand.  
Available from: <https://hub.e-nable.org/s/e-nable-devices/wiki/K1+Hand>

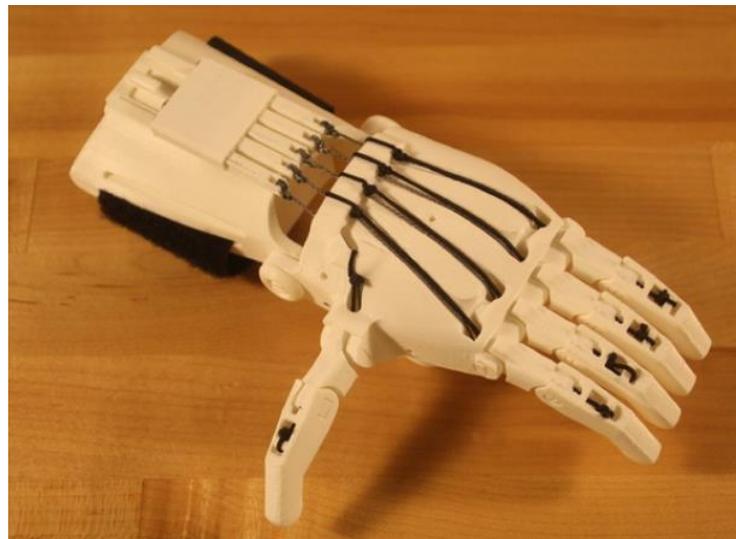


Figure 2. Mechanical hand prosthesis Raptor.  
Available from: <https://www.thingiverse.com/thing:596966>

The second stage involves virtual simulations performed on the KH model by applying static forces, aiming to demonstrate and evaluate the mechanical integrity of the prosthesis and ensure its theoretical feasibility of functioning. The finite element method (FEM) model was based on the penta-digital gripping force that a prosthesis exerts when pressing a cylindrical object with a diameter equivalent to the maximum opening of the metacarpophalangeal joints of the device. The mechanical properties such as maximum stress, modulus of elasticity, and Poisson's ratio were considered for Acrylonitrile Butadiene Styrene (ABS), a material widely used in 3D printers. This simulation phase was conducted using ANSYS software, developed by the American company Ansys Inc.

Lastly, the third and final stage consisted of the printing and physical construction of the Raptor prosthetic model using a fusion deposition modeling (FDM) 3D printer from the Brazilian brand Factor 3D, and employing ABS filament from the brand 3DFila, a material known for its impact resistance, good thermal resistance, and durability (3DFila, 2023).

After defining the material for the three-dimensional printing of the Raptor prosthesis, it is crucial to establish the printing parameters as they have a direct impact on the printing process and the quality of the final product. The technology used is fused deposition modeling (FDM), in which the material is preheated from a coil, typically composed of polymers or certain metals, to allow for flow to an extrusion nozzle. This extrusion nozzle consists of a movable head with a heating block, which melts the material and deposits it in a controlled manner, layer by layer, through a nozzle, onto a build plate, resulting in the final construction of the printed product (3DFila, 2023). The adopted printing parameters are detailed in Table 1. For surface finishing, only sanding with a fine-grit sandpaper was used, eliminating the need for additional post-processing of the part.

Table 1. Printing parameters for the Raptor prosthesis.

Nozzle size	0,4 mm
Layer High	0,2 mm
Initial Layer High	0,3 mm
Wall Thickness	1,2 mm
Infill Density	25%
Infill Pattern	Hexagon
Printing Temperature	250°C
Build Plate Temperature	110°C
Print Speed	40 m/s

### 3. RESULTS AND DISCUSSION

As mentioned in the previous section, the finite element model was based on the penta-digit grasping force exerted by the prosthesis when pressing a cylindrical object with a diameter equivalent to the maximum opening of the metacarpophalangeal joints of the prosthesis (Figure 03). The grasping force was allocated at the distal ends of fingers 01 to 05, while the fixation constants were allocated at the representation of the stopper closest to the force allocation. In this specific case, the fixation constants were allocated at the radial end of the interphalangeal joints of fingers 01 to 04 and at the metacarpophalangeal joint of finger 05.



Figure 3. The penta digital functionality of the prosthesis

Considering the representation of maximum stress in the FEM study, the model exhibited stress concentration in the region corresponding to the distal interphalangeal joint of finger 01 (Figure 4). Although the maximum stress exerted, with a magnitude of 5.81 MPa, did not show apparent surface rupture or material deformation in the model, this representation provides guidance for structural reinforcement in the highlighted region to avoid potential geometry damage due to usage fatigue.

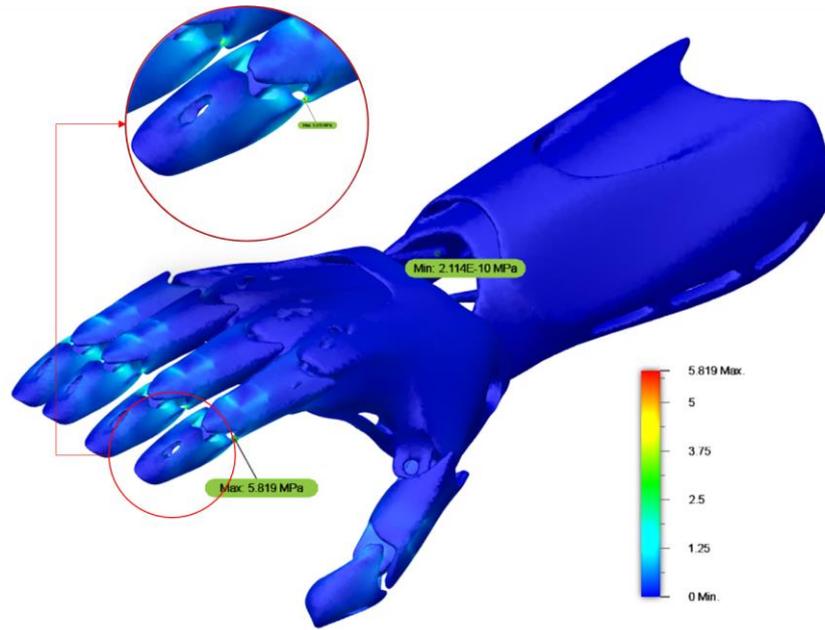


Figure 4. Representation of color maps for the FEM study of maximum stress

As shown in Figure 5, the maximum displacement as a function of the applied force in the model was 0.075 mm. This force was observed at the distal end of the third finger. Due to the magnitude of the displacement in relation to the functionality of the cylindrical penta digital pressure, the mentioned displacement does not compromise the functionality of the prosthesis.

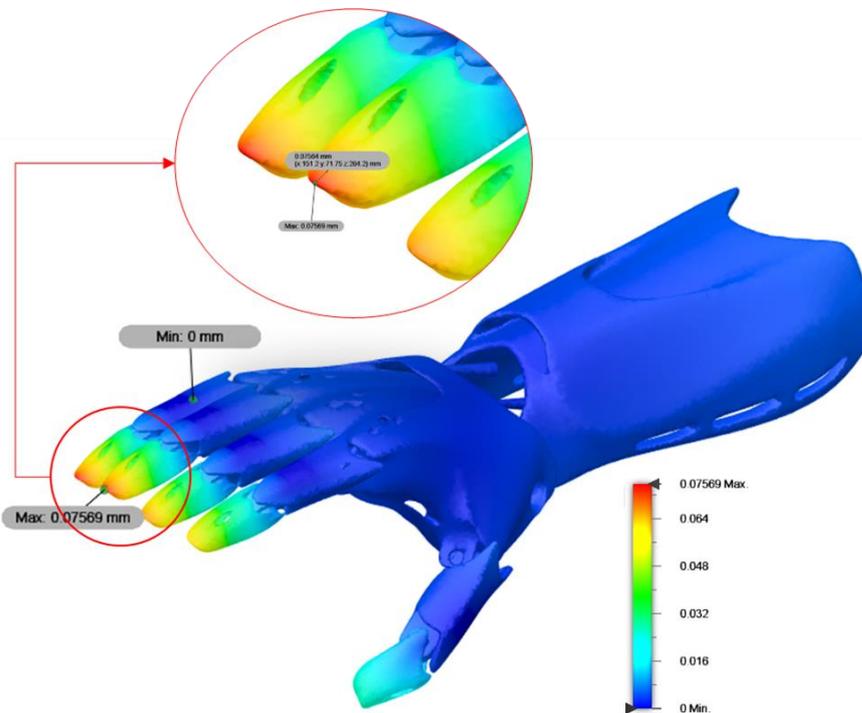


Figure 5. Representation of color maps for maximum displacement in the FEM study.

To assess the operational strength, the safety factor study demonstrated mechanical feasibility, with a minimum coefficient of 3.43 as shown in Figure 6. The safety factor was obtained by the ratio between the maximum stress and the yield stress observed in the material when subjected to the analyzed forces, according to equation 01.

$$Fs = \frac{\tau_f}{\tau_d} \quad (1)$$

Where  $F_s$ ,  $T_f$ , and  $T_d$  represent the safety factor, yield stress, and observed stress, respectively.

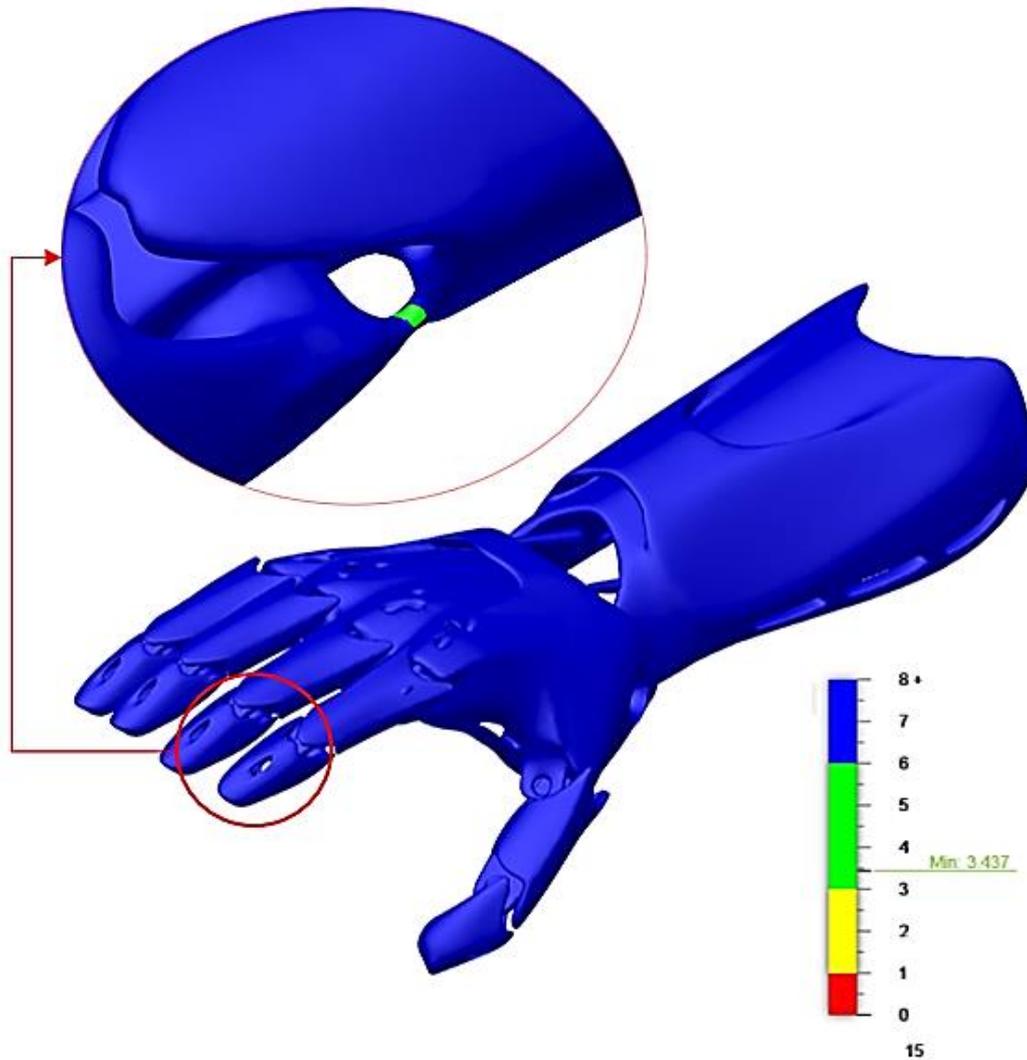


Figure 6. Representation of color maps for the safety factor in the FEM study.

The printing of the Raptor prosthesis was made possible through the use of a three-dimensional printer incorporating FDM technology. Figure 7 shows the constituent elements of the prosthesis made with ABS filament after the 3D printing process.

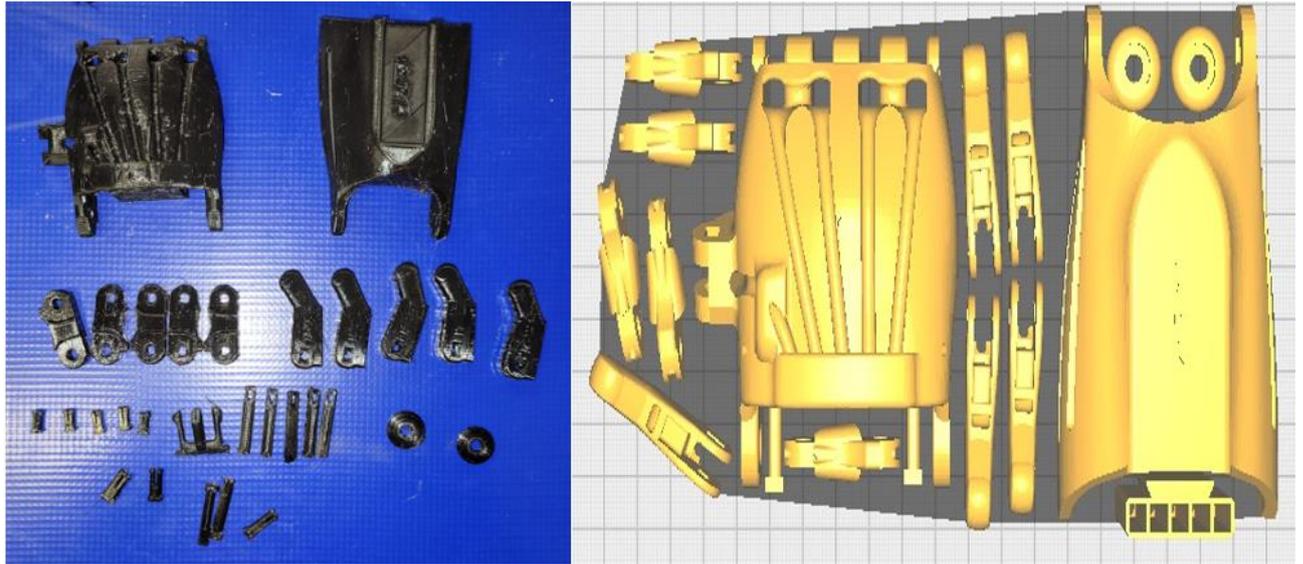


Figure 7. Constituent elements of the Raptor Prosthetic printed with ABS on the FDM printer

Figure 8 shows the construction process of the Raptor after the 3D printing process is completed. The assembly and printing of the Raptor demonstrated good mechanical strength, fast production, low cost, relative ease of assembly, and regular surface finish.



Figure 8. The construction process of the Raptor prosthesis

The complete printing of the Raptor prosthesis took approximately 15 hours. After the printing was finished, it took around 5 hours for finishing and assembly. The final weight of the device, after assembly, was 222.36 g. The estimated production cost of the device is approximately R\$ 185.00 (US\$ 38.70), which represents a relatively low cost compared to other conventional devices available in the market.

According to the reference table of the Brazilian Unified Health System (SUS), conventional prostheses in Brazil have an average price of approximately R\$ 850.00 (US\$ 177.82). However, in the global market, there are prostheses with sophisticated operating systems, including electronics, sensors, and actuators, which can cost up to US\$ 58,000.00. An example is the BeBionic commercial prosthesis, manufactured by the British company Steeper Group.

Devices printed through AM can be up to 90% cheaper than conventional devices. Additionally, the lightweight nature of the prosthesis, weighing less than 300 g, is crucial for patient adaptation, especially in the case of children or individuals with compromised arm strength. In this regard, materials like ABS are ideal as they are lightweight while being able to withstand static loads of approximately 250 kg. PLA has a density of 1.04 g/cm<sup>3</sup>, an elastic modulus ranging from 1.8 GPa to 2.4 GPa, and a yield strength ranging from 40 MPa to 60 MPa—typical and relevant values when seeking

to combine low weight and high strength. In comparison, materials like Polypropylene, commonly used in conventional prostheses, have an elastic modulus of 1100 MPa, a density of 0.91 g/cm<sup>3</sup>, and a yield strength of 35 MPa.

In addition, components manufactured through 3D printing exhibit variations in dimensional accuracy depending on the geometry of the element and the printing position. However, parts printed in the horizontal position (according to the ASTM 52921-13 standard - Standard Terminology for Coordinate Systems and Test Methodologies for Additive Manufacturing) tend to have better dimensional accuracy. This means that, at the end of the 3D printing process, the printed parts have nearly the same dimensions as the original design. As a result, after the construction of the device, it can be used by the patient in a functional and comfortable manner, as reported by users. Furthermore, surface roughness varies among surfaces, printing direction, and the thickness of the top layer. Therefore, parts printed in the horizontal position not only exhibit good dimensional accuracy but also have lower roughness values, with a maximum Ra value of 30 µm.

#### 4. CONCLUSION

The objective of this study was to demonstrate, through virtual simulations of static stress, the theoretical feasibility of a 3D-printed prosthesis using ABS material. To assess its operational strength, the factor of safety study demonstrated mechanical viability, with a minimum coefficient of 3.43.

When evaluating the mechanical functionality of the prosthesis through static force simulations using FEM and considering the reaction forces at the fingertips, it was found that the ABS-based prosthesis demonstrated mechanical viability by withstanding compression from solid objects. No plastic deformations or surface ruptures were observed on the device. The maximum recorded reaction in the prosthesis was 5.81 MPa, concentrated in the connecting structure between the distal and middle phalangeal region, with a maximum displacement of 0.075 mm at the fingertip of the ring finger. These results indicate that the KH prosthesis exhibits good mechanical strength under the analyzed conditions.

The main conclusions of the Raptor hand prosthesis construction process are as follows: (1) the prosthetic model file, along with the rapid prototyping process, resulted in a prosthesis with good dimensional accuracy and an acceptable surface finish; (2) the assembly of the device is somewhat complex due to the presence of different types of specific constituent elements of the prosthesis; and (3) the device can be constructed quickly and exhibits good mechanical strength.

In summary, it is possible to obtain a mechanically functional hand prosthesis with low production costs through additive manufacturing.

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