PRÓTESES PARA DEDOS: projeto e fabricação por impressão 3D

FINGER PROSTHESES: design and fabrication through 3D printing

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Resumo

A Manufatura Aditiva (MA), ou Impressão 3D, abrange tecnologias que permitem a criação de modelos físicos por meio da adição de material em camadas. Essas tecnologias possibilitam a fabricação eficiente de geometrias complexas e personalizadas, reduzindo custos e tempo de produção de protótipos e peças funcionais. O objetivo deste trabalho é apresentar o estudo de caso do desenvolvimento e fabricação de próteses para os dedos indicador e médio, utilizando tecnologias digitais de projeto e manufatura. Inicialmente, foram fabricados e digitalizados modelos das mãos, e projetadas as próteses. Em seguida, foram realizadas as impressões utilizando os processos de Fabricação por Filamento Fundido (FFF) e Digital Light Processing (DLP). As próteses foram avaliadas e resultados indicam que a inclusão de um processo indireto de moldagem das mãos pode ter ocasionado uma imprecisão dimensional, resultando na necessidade de ajustes nas próteses. As próteses fabricadas por DLP apresentaram melhor acabamento e maior conforto ao usuário.

Palavras Chave: próteses para dedos; manufatura aditiva; escaneamento tridimensional.

Abstract

Additive Manufacturing (AM), or 3D Printing, encompasses technologies that enable the creation of physical models through the addition of material in layers. These technologies facilitate the efficient fabrication of complex and customized geometries, reducing both costs and production time for *prototypes and functional parts. The goal of this work is to present a case study of the development and fabrication of prosthetics for the index and middle fingers using digital design and manufacturing technologies. The recipient was a male young adult with loss of the distal phalanx and limited articulation on the distal inter-phalangeal joint. Hand models were fabricated and digitized, and the prostheses were designed. Subsequently, the prostheses were printed using Fused Filament Fabrication (FFF) and Digital Light Processing (DLP) techniques. The prostheses were fitted on the recipient and tested. The results indicate that the inclusion of an indirect hand molding process may have caused dimensional inaccuracies, requiring adjustments to the prostheses. The prostheses fabricated using DLP had superior finish and greater user comfort.*

Keywords: *finger prostheses; additive manufacturing; three-dimensional scanning.*

1 Introduction

According to the World Report on Disability (WORLD HEALTH ORGANIZATION, 2011), more than one billion people worldwide have some form of disability, and among these, at least 110 million experience significant functional difficulties. Such disabilities hinder basic daily activities, especially in terms of physical movement. For individuals facing the absence of a limb or mobility challenges, prostheses and orthoses play a crucial role.

In the same report, the World Health Organization (WHO) states that the "Prostheses (artificial limbs and hands) and orthoses (braces and splints) enable individuals with physical disabilities or functional limitations to live healthy, productive, independent, and dignified lives, and to participate in education, labor market, and social life" (WORLD HEALTH ORGANIZATION, 2011).

Over the years, these devices have played a crucial role in reintegrating individuals into daily life and restoring mobility and autonomy. However, their development faces challenges, and in this context, innovation and the use of new technologies are essential.

1.1 Challenges in Manufacturing

Currently, the prosthetics industry faces a series of challenges. From a manufacturing perspective, factories often encounter the task of balancing mass production with the criterion of customization, that is, being able to meet the individual needs of each user. Customization, however, tends to significantly increase production costs, making the balance between mass production and personalization a complex challenge. Increasing the amount of value added to products can sometimes make the production process unviable for manufacturers and unaffordable for those in need of prostheses (GOSHE; KASSEGNE, 2022).

On the other hand, from the user's perspective, prostheses often present limitations in functionality and adaptability that affect their quality of life. The lack of mobility and adaptability can result in discomfort and even discourage the use of the prosthesis in daily life (COSTA et al., 2015).

Thus, the high customization of products leads to elevated acquisition costs, consequently making them accessible to only a small portion of the population or necessitating public sector investments for their purchase and distribution. In Brazil, for example, prostheses are sometimes provided by the government [1]. Despite current technology, the design and development of prostheses still present limitations.

In this context, there is a need for innovation in the design and construction of prostheses. The assistive devices market seeks to solve these challenges more efficiently and accessibly for this vulnerable population. In this regard, additive manufacturing emerges as a technological innovation alternative in the field (MAIA et al., 2015).

1.2 Additive Manufacturing

Additive Manufacturing (AM), popularly known as 3D Printing, has emerged in recent decades as an innovation in the fabrication of three-dimensional objects. Its manufacturing principle involves building 3D objects layer by layer from various materials, in contrast to traditional methods of material subtraction. This approach has provided unprecedented versatility in creating complex

[1] By Sistema Único de Saúde (SUS)

and customized parts (VOLPATO et al., 2017; SILVA et al., 2023).

Over the years, Additive Manufacturing has evolved from a promising technique to a widely adopted set of technologies across various sectors. Initially restricted to rapid prototyping applications, AM has been refined to meet the demands of industrial-scale production (GIBSON; ROSEN; STUCKER, 2010). The precision and diversity of materials used in 3D Printing have advanced significantly, making it a viable option for the mass production of highly complex components.

In the context of prostheses and orthoses, AM plays a crucial role. These technologies have enabled the creation of highly personalized devices tailored to the anatomical and functional needs of each user. Notable projects, such as the "Enabling The Future" initiative by the e-NABLE organization (Figure 1), demonstrate the potential of this technology by connecting volunteers and healthcare professionals to produce low-cost, high-quality prostheses for people worldwide. The e-NABLE organization is a global network of volunteers who use their 3D printers, design skills, and personal time to create 3D-printed prosthetic hands free of charge for those in need – with the aim of providing them to underserved populations around the world (ENABLING THE FUTURE, 2015).

Figure 1 - Various prostheses and orthoses produced by the "Enabling The Future" project.

Fonte: OWEN (2022).

Additive Manufacturing has been applied in the development of precision orthoses, providing support and mobility to individuals with specific needs. Currently, 3D printing is an essential tool in rehabilitation and orthopedics. It not only offers customized solutions but also accelerates the production process, reducing lead times and associated costs. This evolution in AM represents a significant milestone in the advancement of assistive technology, promoting inclusion and improving the quality of life for thousands of people worldwide (GOSHE and KASSEGNE, 2022). Figure 2 presents examples of different types and purposes of prostheses obtained through various AM processes.

Figure 2 - Prostheses of different types and purposes manufactured by AM.

Fonte: SILVA et al (2023).

Thus, it is observed how AM and digital technologies can significantly contribute to the field of assistive technologies, especially in the development of customized and on-demand prostheses. These innovations have the potential to make prostheses more financially accessible to individuals in greatest need, promoting resource democratization and improving life quality.

1.3 **Research Problem**

Given the potential of AM and digital technologies in the design and fabrication of prostheses, the research focused on designing and manufacturing prostheses for the index and middle fingers of the right hand of an individual who experienced partial amputation due to a household accident. The amputation resulted in hypersensitivity in the amputated extremity, preventing touch, which is crucial as typing is part of their professional activities.

1.4 **Goals**

The goal of this paper is to present the project and fabrication method of prostheses for the index and middle fingers of an individual by using digital design and manufacturing technologies, such as three-dimensional scanning, computer-aided design (CAD), and additive manufacturing. Initially, the specific goals are to fabricate molds of the patient's right and left hands (negative molds) to enable the reproduction of the user's hands (positive molds). Subsequently, perform three-dimensional scanning of the hand models to then proceed with the design of the prostheses. Finally, manufacture the finger prostheses using additive manufacturing with different materials and processes, and evaluate them.

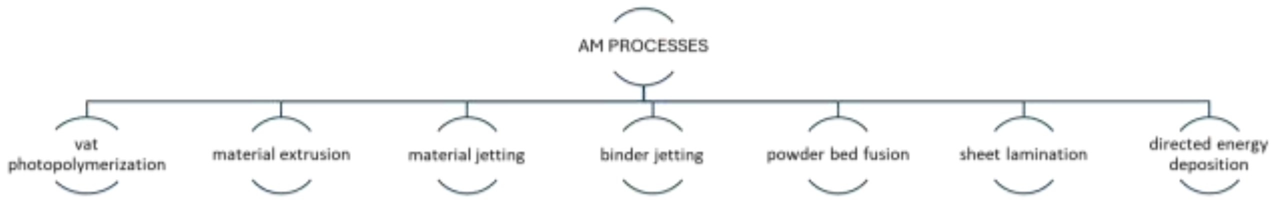
This study presents theoretical and applied research related to the development of prostheses using additive manufacturing technologies and processes, followed by a detailed description of the methodology employed. Subsequently, the obtained results and their respective analyses are presented.

The research and results obtained in this study are of significant relevance both to the academic community and to prospective prostheses recipients. The explored digital technologies have the potential to reduce fabrication time, enhance design process precision, and lower costs for the end user.

2 Additive Manufacturing Technologies

There are different classifications of technologies involved in Additive Manufacturing, with the most common being based on the physical state of the raw material, which can be solid, liquid, or powder. On the other hand, ISO/ASTM 52900 proposes a classification based on categories of technologies that group processes according to the same principle of layer addition (VOLPATO et al., 2017). These groups are presented in Figure 3.

Figure 3 – Classification of AM processes according to the layer addition principle.



Source: adapted from VOLPATO et al. (2017) and ASTM (2021).

There are various AM processes available for respectively group of technologies, each with unique characteristics, advantages, and disadvantages that vary significantly among the different options (VOLPATO et al., 2017). Currently, the most accessible processes are found in the group of material extrusion and vat photopolymerization technologies. Over the years, the costs of these technology groups have decreased for several reasons, making them more accessible and widely available for retail purchase, while other additive manufacturing technologies are commonly aimed at corporate or industrial customers due to their high cost and greater complexity in use (PAIVA and NOGUEIRA, 2021).

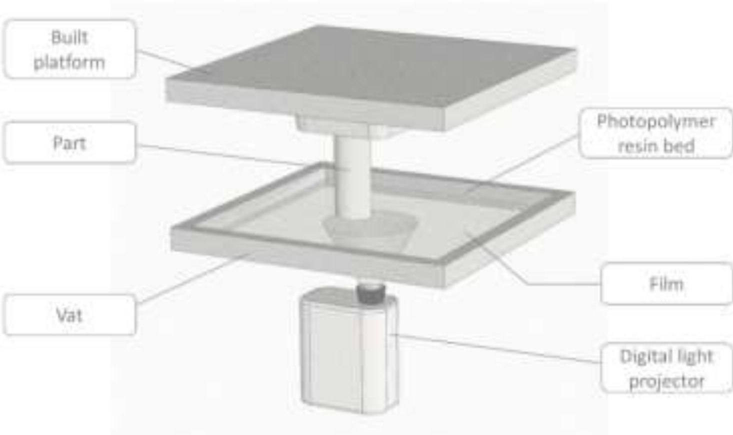
2.1 Vat Photopolymerization

Vat Photopolymerization Processes (VPP) are characterized as a group of additive manufacturing processes that selectively cure a liquid photopolymer, utilizing light-activated polymerization (ASTM, 2021).

The pioneering vat photopolymerization process was Stereolithography (SL), introduced in 1987, which uses a laser to cure the photopolymer resin. In 1990, other polymerization methods emerged, such as Mask Projection Photopolymerization. This process involves projecting an image corresponding to the layer being fabricated. The most well-known process is Digital Light Processing (DLP), which is less costly than SL technology because it utilizes UV lamps instead lasers (VOLPATO et al., 2017).

The operation of DLP technology involves curing a liquid and photopolymerizable thermoset resin placed in a reservoir (or vat - Figure 4). The base of this reservoir consists of a transparent film that allows the digital light projector to polymerize the resin layer between the film and the build platform (and as the part is built, between the end of the piece and the film). After each layer is built, the build platform moves in the Z direction, and the space between the end of the part and the vat base is filled again with resin, at the desired layer thickness (VOLPATO et al., 2017; SILVA et al., 2023).

Figure 4 - Principle of mask projection or DLP imaging process.



Source: adapted from SILVA et al. (2023).

According to Volpato et al. (2023), currently, these devices allow for the construction of parts with high precision and dimensions in the order of 300 µm with layer thicknesses from 25 µm to 200 µm. Some technologies use LCD projectors, for example, with screen resolutions of 11520 x 5120 pixels (12 K). These devices are often popularly referred to as "LCD printers" or "DLP/LCD printers. This technology is advancing rapidly, and there may currently be devices with even better resolutions, used in a wide range of applications where parts with excellent surface quality are required, as shown in Figure 5.

Figure 5 - Model manufactured using the DLP process.

Source: SILVA et al. (2023).

Despite the advantages of these technologies, there is still a limited variety of materials available, as they must be light-polymerizable. Additionally, post-curing of the manufactured parts is necessary (VOLPATO et al., 2017). Moreover, since thermoset resins are used, there is no possibility of recycling discarded materials, and some materials may have a greater environmental impact compared to other processes, such as material extrusion.

2.2 Material Extrusion

Material Extrusion Processes (MEX) are denoted by their manufacturing method of selectively depositing material through a nozzle or orifice (ASTM, 2021). According to Volpato et al. (2017), in theory, any material that can be brought to a pasty state and then hardened by physical or chemical action can be processed with this principle.

In the case of using thermoplastic polymers, the pioneering technology was Fused Deposition Modeling (FDM) in 1992. Over the years, with the expiration of the manufacturer's patent, various processes emerged in the last decade, resulting in non-industrial-scale equipment, popularly known as ‘Desktop’. In these cases, the process is known as Fused Filament Fabrication (FFF) (RELVAS, 2018; SILVA et al., 2023).

FDM or FFF processes operate similarly and essentially involve using a thermoplastic filament that, when entering an extrusion head or nozzle, is heated and then expelled or extruded through an extrusion nozzle that deposits it in selected locations during the slicing process, forming a layer (Figure 6). After the deposited material solidifies, a new layer can be deposited, and so on successively, until the desired geometry is formed (RELVAS, 2018; SILVA et al., 2023; VOLPATO et al., 2017). Some machines use two extrusion heads and two materials, one structural and the other support material. The support material can be removed manually or after a soaking cycle, where it is dissolved (SILVA et al., 2023).

Figure 6 – Principle of FDM or Fused Filament Fabrication (FFF) process.

Source: adapted from SILVA et al. (2023).

One advantage of this process is the simplicity of the deposition principle and the possibility of using various thermoplastics, from commodities to engineering or high-performance materials. The resulting parts can have mechanical properties that allow for functional or end-use parts, and because thermoplastics are used, unused materials can be recycled. On the other hand, parts may have lower dimensional precision (compared to DLP processes, for example), the process is considered slow, and parts require post-processing such as finishing and support removal (VOLPATO et al., 2017).

2.3 Considerations on Manufacturing for AM Technologies

In the current additive manufacturing market perspective, the most accessible and widely used technologies are material extrusion (FFF, such as MakerBot, RepRap, Fab@Home) and vat photopolymerization (Stereolithography, CLIP[2], DLP) (VOLPATO et al., 2017).

When manufacturing devices like prosthetics, it is crucial to select an AM technology that offers the best set of attributes to meet user needs. For instance, if higher quality surface finishing is required, the DLP/LCD process fulfills this requirement more efficiently. According to Creality® equipment specifications, DLP/LCD technology can build layers between 50 µm and 100 µm thick (Z-axis precision) and XY resolution of 16.8 x 24.8 µm (1 pixel size). In contrast, material extrusion methods typically produce layers between 100 µm and 350 µm thick (Z-axis precision) (CREALITY, 2022). This difference in layer thickness is visually perceptible and affects the surface finish of the object, with the built layer height increasing proportionally (Figure 7).

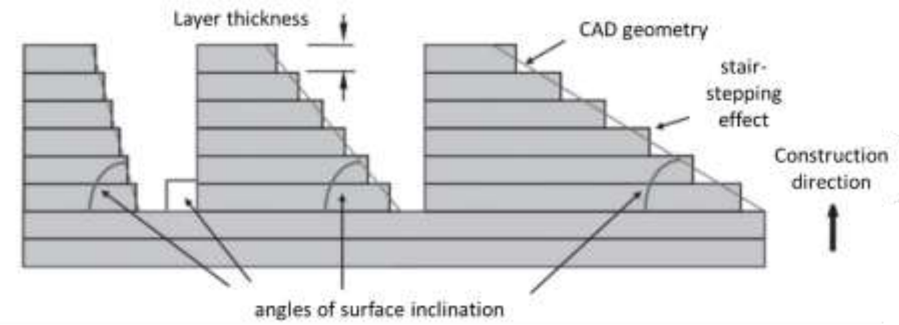
Figure 7 – Comparison of manufacturing the same object using different processes: FFF (left) and DLP (right).

Source: Formlabs (2024).

As illustrated in Figure 7, the amplification of parts built by the FFF process versus DLP technology shows that the thicker layers produced by FFF lead to a more pronounced "stair-stepping effect" (Figure 8). This effect is influenced by both layer thickness or height and the angle of surface inclinations. Smaller incline angles exacerbate the stair-stepping effect, while thicker layers also increase this effect (VOLPATO et al., 2017).

[2] *Continuous liquid interface production (VOLPATO et al, 2017)*

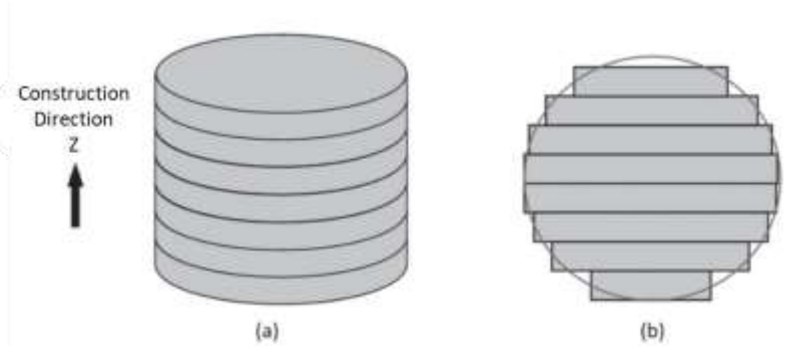
Figure 8 – Variation in surface finish on the same part due to different surface incline angles and resulting stair-stepping effect.



Source: adapted from Volpato et al. (2017).

Orientation of objects during printing must also be considered to achieve the desired surface quality. Figure 5 demonstrates this with a cylinder, where the printing orientation affects surface finish (Figure 9).

Figure 9 – Stair-stepping effect on cylinders due to orientation (a) vertical and (b) horizontal.



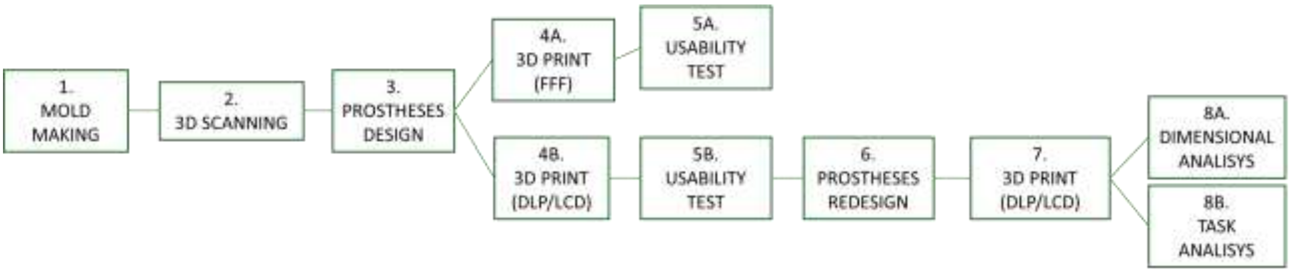
Source: Volpato et al. (2017).

Thus, DLP technology holds potential for detailed geometric profiles and superior surface quality in manufactured products, whereas FFF enables the production of parts using a broader range of thermoplastic raw materials, closely resembling conventional manufacturing processes like injection molding and extrusion.

3 Methods

To carry out the work, we started with the planning the activities, complemented by a literature review on topics relevant to the project, using books, articles, conference proceedings, among others, to provide the theoretical foundation for its execution. Based on this planning, the experimental research method based on a case study was structured as illustrated in Figure 10.

Figure 10 – Graphic scheme of the method used in the experimental work and its stages.



Source: the authors.

The experimental work began with a user's demand after they had their fingertips (index and middle fingers) amputated in an accident and experienced significant pain upon touch following reconstructive surgery. Given the necessity of their fingers for their profession, prostheses were required for both fingers.

Therefore, the strategy was adopted to obtain a CAD surface of the opposite hand and use this information to mirror-image the fingers for the prosthetic design. To acquire these surfaces, molds of the hands were first created (Stage 1).

Among the possible materials for making the hand molds, Ezact Kromm alginate produced by Coltene was chosen for its rapid setting time and low toxicity. For each hand, two packages of 410 g of alginate were prepared in a volume ratio of 1:3 with water. Mixing was performed directly in 4.5-liter containers measuring 19 x 17.5 x 22.5 cm, using a screwdriver with a helical rod for mortar mixing. After mixing for 45 seconds, the hand was carefully introduced into the mixture until the alginate reached its setting time. This process was repeated to produce the mold of the other hand. As a precaution, a 24-hour waiting period was observed for complete curing and removal of moisture residues from inside the molds.

For molding the hands, white plaster stone produced by Asfer was used due to its superior mechanical strength compared to common plaster. Each mold required a mixture of 1 kg of plaster mixed with 370 g of water. Mixing was conducted in a 2-liter container measuring 15.6 x 14.4 x 18.5 cm, using a screwdriver with a helical rod for mortar mixing. The mixture was homogenized and then poured into the alginate molds. After 24 hours, the plaster was sufficiently hardened for demolding, which was done gradually using scalpels to separate the materials without breaking them.

From the hand models, the procedure for obtaining 3D geometries was then carried out (Stage 2) using the Hexagon Romer Absolute 7520SEI-3 three-dimensional scanning equipment with an RS2 laser scanner module (Figure 11), a metrological system enabling three-dimensional scanning through laser profilometry.

Figure 11 - Devices used in laser profilometry: a) Hexagon Romer Absolute; b) laser scanner module.

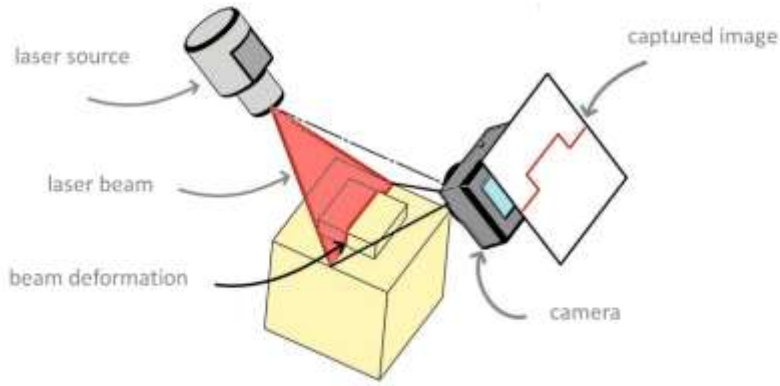
(a)

(a)

Source: Hexagon (2024).

Laser profilometry (Figure 12) is a technique for shape measurement or scanning, performed contactlessly based on active optical principles. The process essentially involves directing a laser onto the surface to be scanned and capturing reflections with a camera to determine the generated geometry (SILVA et al., 2023).

Figure 12 – Illustration of the laser profilometry process.



Source: adapted from Silva et al. (2023, p. 185).

3D scanning equipment can obtain coordinates of different points on an object, resulting in a point cloud. Using the "Inspector" and "Modeler" modules of the Polyworks™ software, it was possible to transform this point cloud into an editable CAD surface. The surfaces generated from the 3D scanning were used to design the prostheses (Stage 3).

According to Hassan et al. (2022), scanning a person's hand and fingers can prove to be a challenging task. The primary issues include occlusions between the fingers and the lack of anchor points for the scanner's tracking software to rely on. Consequently, the choice of an indirect method (molding and subsequent scanning) was made due to the number of surfaces to be scanned and the limitations of the scanning technology used. There was a concern that even slight movements by the user could lead to accuracy errors in the prosthesis.

The initial stage of prototyping the finger prostheses (Stage 4a) was based on using an entry-level AM technology, characterized by low cost, ease of use, customization capability, and a variety of raw materials. Specifically, the selected technique was FFF of thermoplastic materials.

The production process using FFF began with planning the 3D printing in a computational environment. The three-dimensional models of the objects to be manufactured, in .STL file format, were imported into the open-source slicing program PrusaSlicer® (version 2.5.0).

In the program's setup environment, the system user can manipulate the 3D model (rotation, position, dimensions, scale factor, etc.), select the printing equipment, and adjust process parameters — the latter according to technical and economic requirements. Details of the print parameter adjustments applied in this project are presented in Table 1.

Table 1 – Configuration of processing parameters for the FFF process and Creality® Ender 3 3D printer.

Processing parameter	Configuration
Layer thickness (mm)	0,1
perimeters (a.u.)	2
Infill percentage (%)	10
Deposition strategy (a.u.)	Grade
Infill speed (mm/s)	30
Perimeter printing speed (mm/s)	20
Extrusion temperature (°C)	225
Heated bed temperature (°C)	70
Extrusion multiplier (a.u.)	1
Filament retraction length (mm)	2

Source: the authors.

The prototypes were manufactured using a Creality® Ender 3 3D printer equipped with a 0.4 mm diameter nozzle extruder head. The material used for constructing the parts was a 1.75 mm diameter Thermoplastic Polyurethane (TPU, 92A) filament, transparent, supplied by Slim3D. TPU is characterized as an elastomer, meaning a flexible material, which aids in analyzing the functionality of the prototype not only in terms of degrees of freedom but also by promoting less aggressive contact with body parts.

To produce parts using the DLP process (Stage 4b), Chitubox® software was used for print planning (slicing). Printing of the models on this stage was carried out using the Anycubic Photon® equipment, which enables additive manufacturing through the DLP mask projection process via an LCD screen. The resin used was Anycubic Standard Clear and Gray. The processing parameters are detailed in Table 2.

After printing, the resin models were washed (in isopropyl alcohol) and post-cured using the Anycubic Wash and Cure equipment®, for 5 minutes each procedure. Following the post-curing of the parts, post-processing was performed including removal of supports and finishing by sanding.

Based on the prosthetic models fabricated using both FFF and DLP/LCD processes for both fingers, the user conducted usage empiric tests (Stage 5a and 5b) to evaluate fit, comfort, textures, and potential adjustments, which were made based on the initial model.

Table 2 – Configuration of processing parameters for the DLP/LCD process and Anycubic Photon® printer.

Processing parameter	Configuration
Room temperature (°C)	25
Material temperature (°C)	25
Layer thickness (mm)	0,05
Base layers (a.u.)	5
UV exposure time for base layers (s)	60
UV exposure time for normal layers (s)	8
Z-axis retraction speed (mm/min)	150

Source: the authors.

Throughout the research, modifications were made to the original design (Stage 6), focusing on considerations for DLP/LCD manufacturing for both prostheses. Adjustments were made to thicknesses and internal geometries to achieve better geometric fit, seeking greater user comfort.

These new designs were then manufactured using the DLP/LDC process (Stage 7), with print planning conducted in the Chitubox® software. Unlike the previous stage, these models were printed using the Creality® LD006 equipment and Anycubic Standard Clear resin. The processing parameters used in this stage are detailed in Table 3.

Table 3 – Configuration of print parameters for the DLP process and Creality® LD006 printer.

Processing parameter	Configuration
Room temperature (°C)	20
Material temperature (°C)	20
Layer thickness (mm)	0,05
Base layers (a.u.)	5
UV exposure time for base layers (s)	40
UV exposure time for normal layers (s)	2
Z-axis retraction speed (mm/min)	150

Source: the authors.

Immediately following the prints, these models underwent a bath in isopropyl alcohol using an ultrasonic bath equipment for 8 minutes to remove excess resin from the models. Subsequently, the models were post-cured with UV lights for 10 minutes. After post-curing, post-processing was performed, involving support removal and finishing by sanding, to complete the prostheses manufacturing.

The redesigned models manufactured through the DLP/LCD process underwent dimensional analysis and task analysis (Stage 8). Dimensional measurements were taken at the lower end thickness of the prostheses to ensure dimensional stability of the printed parts. For this analysis, a digital caliper from the Vonder brand was used.

According to Pazmino (2015), task analysis involves observing, describing, and identifying positive and negative aspects related to the use of the product or service. Recording with video or photographs indicating discomfort aspects and possible solutions to improve usability and experience. Thus, a list of criteria related to prosthetic comfort during use was developed for analysis, where the user evaluated each manufactured prosthesis. The resulting information was entered into an evaluation matrix for further analysis.

4 Results and Discussion

In this part of the study, we present the results obtained throughout the research, accompanied by analysis and discussion. Each stage of the method, as described in the previous section, will be systematically presented and commented upon. This organization will allow a clear understanding of the advantages, limitations, and challenges of the techniques employed.

The use of alginate proved effective for producing hand molds (Stage 1); however, due to the short mixing time (about 45 s), achieving homogeneity with the amount used was compromised. In a preliminary test, proper mixing was not achieved, resulting in molds with areas that hardened unevenly, rendering the attempt unsuccessful. Success in obtaining the hand molds was achieved by using a container with adequate volume and more efficient mixing methods (Figure 13).

Figure 13 – Obtaining alginate molds: a) waiting for setting time; b) result after removing the hand.

Source: the authors.

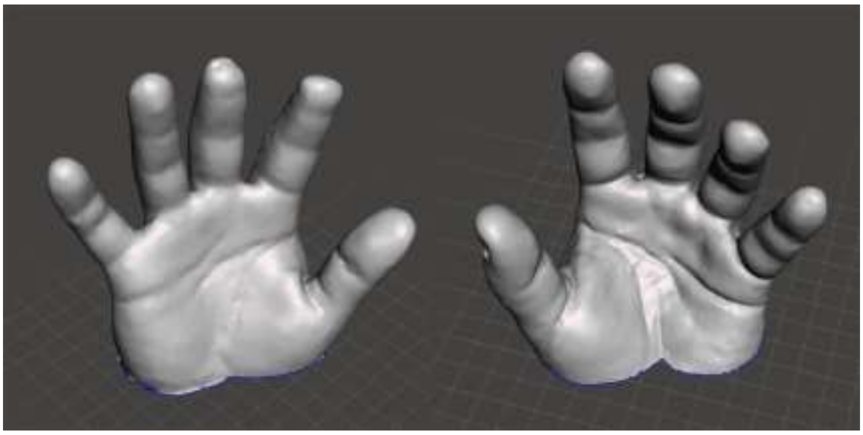
The molding of the hands in plaster proved to be a relatively simpler procedure due to the greater fluidity of the mixture, which allowed for a very satisfactory completion of the hand molds, as can be observed in Figure 14. The figure shows some imperfections caused by bubbles present in the alginate mold. Due to the short working time, it was not possible to eliminate the bubbles generated during mixing or those resulting from the introduction of the hands.

Figure 14 – Result of molding the hands with plaster.

Source: Authors' elaboration.

The shape of the hand posed a challenge for digitization (Stage 2). To ensure good scanner access to various parts, the strategy of keeping the fingers separated proved effective. Multiple scans were performed in various positions until the necessary points were obtained for a complete reproduction of the hands. However, there was a greater focus on collecting data from the index and middle fingers of both hands, as these geometries were of primary interest. The CAD surface obtained through 3D digitization is shown in Figure 15.

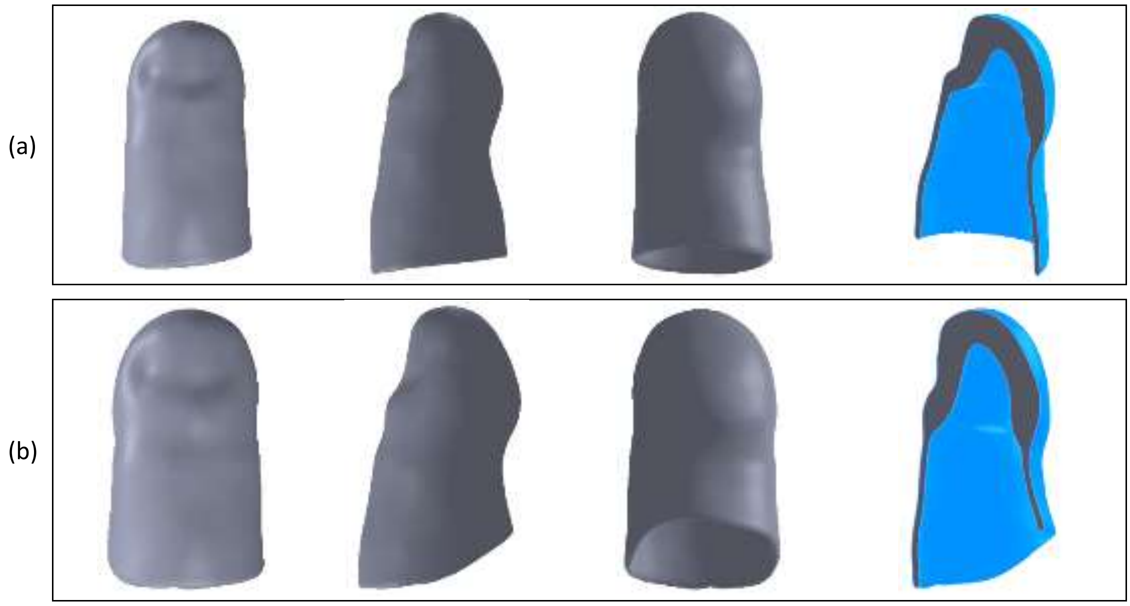
Figure 15 –CAD surface obtained after 3D digitization.



Source: Authors' elaboration.

The CAD surface was used for designing the prostheses (Stage 3). The process was similar to that conducted by Hassan et al. (2022) and Wallace et al (2024). The scan data from the affected-side hand was used to design the socket part of the prosthesis, while the scan data from the intact hand was utilized to obtain the shape of the finger prosthesis. The finger data from the intact hand was trimmed and mirrored along the sagittal plane to create the finger prosthesis shape. Meanwhile, the data from the affected-side hand was cropped to form the socket shape. These two parts were manually aligned and combined to form a single part. Key design requirements included avoiding hypersensitivity in the amputated fingertips and providing comfort while ensuring a good fit around the stump circumference. The designed prostheses are shown in Figure 16.

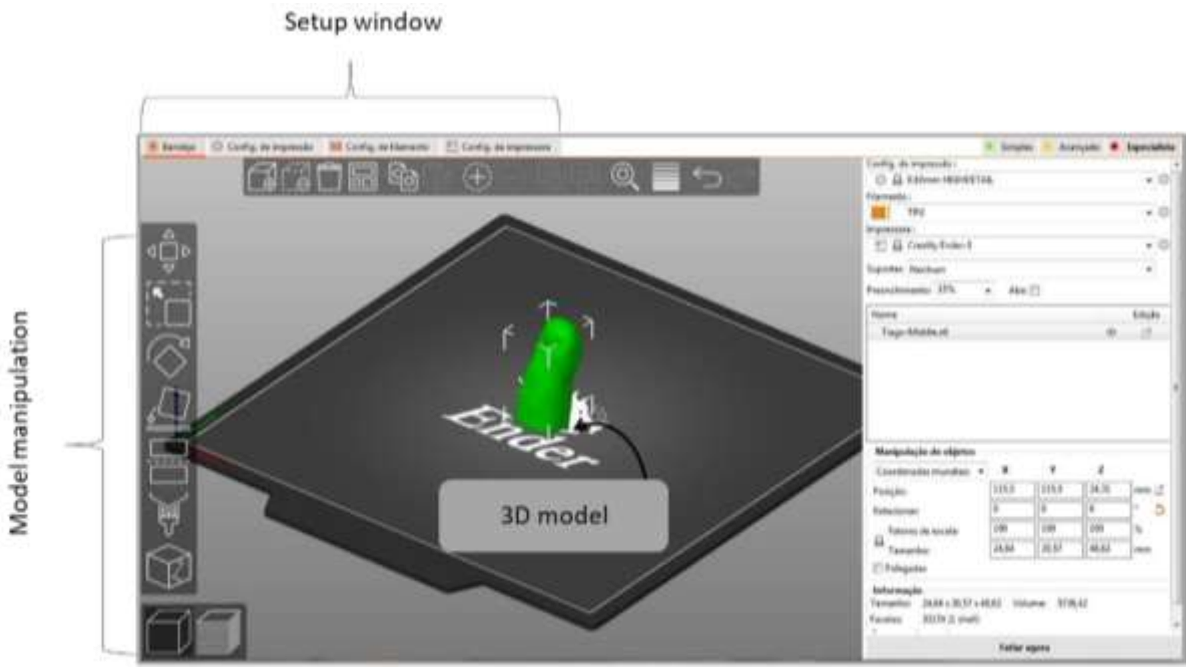
Figure 16 – Views of the designed prostheses for (a) index finger and (b) middle finger.



Source: Authors' elaboration.

After the prostheses were designed, the process of producing the parts via FFF started (Stage 4a). In the PrusaSlicer program's setup environment, as shown in Figure 17, the system user can manipulate the 3D model (rotation, position, dimensions, scaling factor, etc.), select the printing equipment, and adjust the process parameters according to technical and economic requirements.

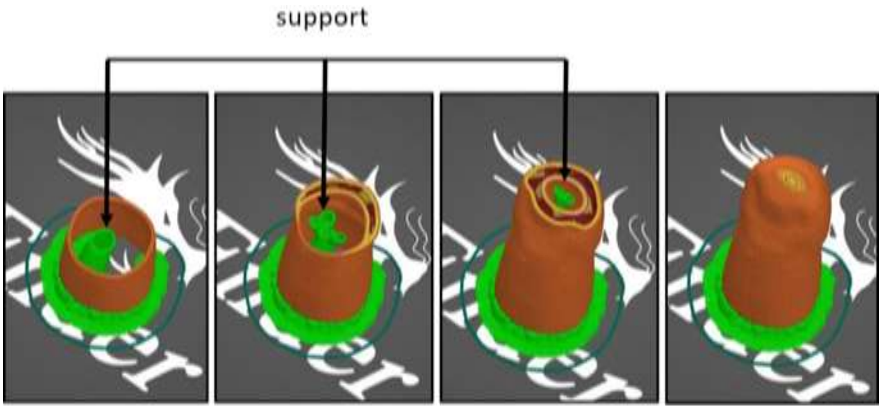
Figure 17 – PrusaSlicer slicing program interface.



Source: Authors' elaboration.

Regarding the printing configuration, it's important to note that a vertical build orientation was employed, with the length of the finger or the largest dimension along the Z-axis of deposition — distal phalanx pointing upwards, as depicted in Figure 18. This strategy was chosen to avoid using support structures on the outer walls of the part, which could potentially damage surface finish and alter dimensions, geometries, and functionalities. However, support elements were necessary to assist in building the internal structure of the part. Since the finger models were hollow, the upper closure lacked self-supporting regions.

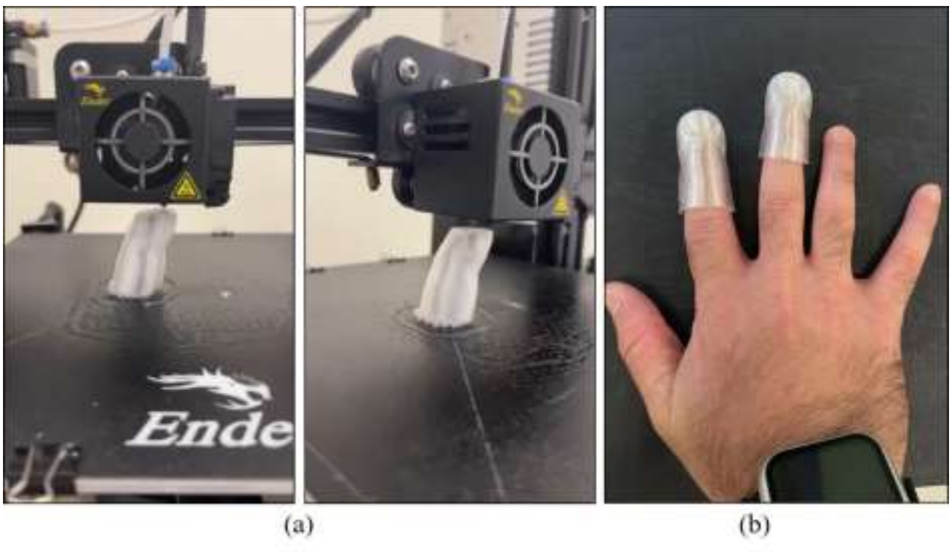
Figure 18 - Construction strategies and supports visualized in the PrusaSlicer program.



Source: Authors' elaboration.

These supports were manufactured using the same material as the parts. To facilitate their manual removal with the aid of wire cutters, an organic type of structure was adopted due to its thin profile and low density, making it easily detachable. The printing process and the final models are depicted in Figure 19.

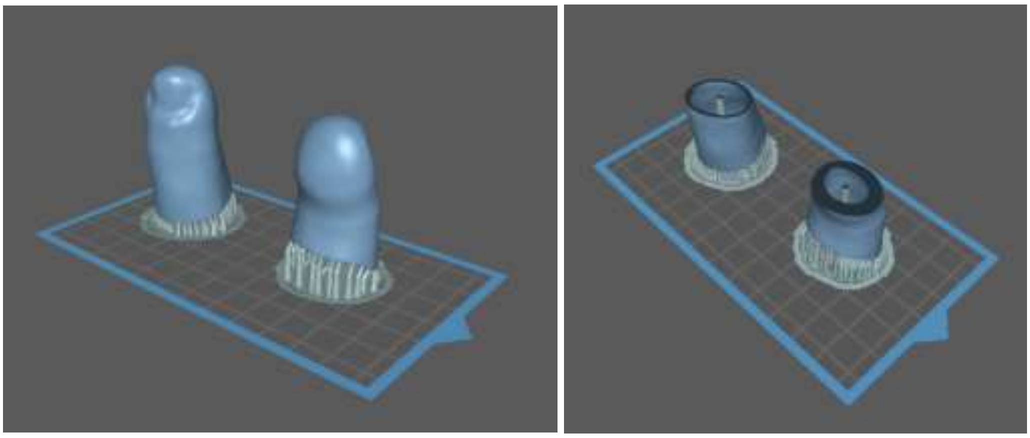
Figure 19 - FFF 3D printing of parts (a) and final models (b).



Source: Authors' elaboration.

The DLP/LCD printing process (Stage 4b) began with the printing process planning in the Chitubox® software, where the model can be manipulated, the printing equipment selected, and processing parameters adjusted. The models were positioned vertically so that necessary supports for the upper part were located internally (Figure 20). The quantity of supports at the base of the models is crucial to prevent detachment during printing and ensure the organic geometry of the base.

Figure 20 - Construction strategies and supports visualized in the Chitubox® program.



Source: Authors' elaboration.

Figure 21 illustrates the completion of the resin printing process and the printed parts. Due to the number of supports at the base, after post-processing and support removal, a 300-grit sandpaper was necessary for finishing the base geometry.

Figure 21 - DLP/LCD resin models.

Source: Authors' elaboration.

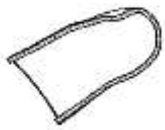
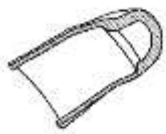
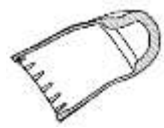
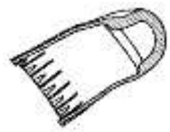
After printing the prostheses using both processes and materials, the user conducted usability tests during daily activities. These tests were conducted empirically based on the user's experience. According to the user, all models exhibited looseness, causing them to detach during use, rendering them unusable for daily activities. The origin of the looseness may have stemmed from the hand molding process, where slight movements during molding or demolding could have led to variations in finger thickness. In fact, Hassan et al. (2022) suggests that scanning from a mold should be considered a last resort in this type of project.

Additionally, the user reported that the resin prostheses provided better touch comfort due to a smoother texture with less stair-step effect from the process. Texture and touch are crucial requirements as the user has hypersensitivity in the amputated extremities.

Another important point raised was that the tips of the prostheses were much farther from what the user remembered as the original ones. Consequently, a request was made to reduce the distance between the end of the upper internal part and the upper external part, thereby reducing the final length of the finger with the prosthesis. Furthermore, the prostheses need to fit more snugly on the fingers.

Thus, other design approach was conducted in the subsequent research phase (Stage 6), addressing the user's needs. Modifications to the original design were made considering the DLP/LCD process. Instead mixing the external and internal surfaces of the hand’s models, only the external surfaces of the prostheses of the existing design was used. These surfaces were thickened from the outside to the inside using thicknesses ranging from 1.25 mm to 1.75 mm. Based on these design criteria, four prosthetic models were conceived: with uniform thickness throughout the entire length (Table 4a); with a thicker tip limiting finger depth (Table 4b); with a thickened base (Table 4c) aimed at better fit at the prosthesis base; and with a grooved base aimed at providing flexibility at the base (Table 4d).

Table 4 – Redesign of prostheses using different configurations and their respective references.

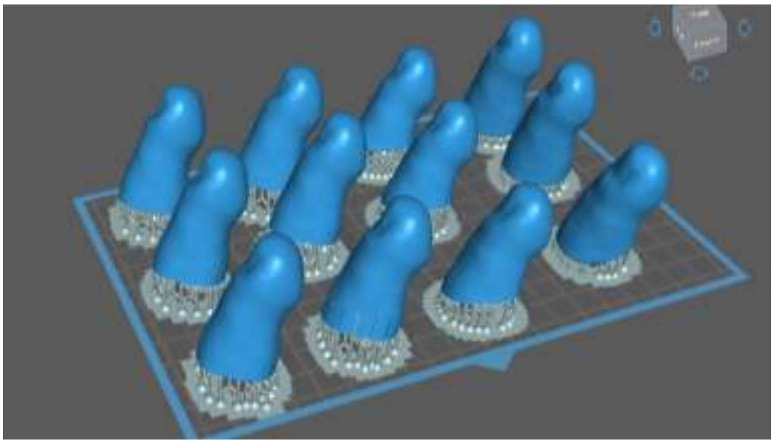
	(a) Smooth, uniform thickness	**(b) Smooth, thick tip**			**(c) Thick tip, boss base**	**(d) Thick tip, boss and grooves at the base**
						
thickness (mm)	*1,30*	*1,25*	*1,50*	*1,75*	*1,00*	*1,00*
Index finger	IF-A	IF-B	IF-C	-	IF-E	IF-F
Middle finger	MF-A	MF-B	MF-C	MF-D	-	-

Source: Authors' elaboration.

The CAD modeling files were then converted to STL files, a format accepted by the Chitubox® software. The print planning was carried out in Chitubox® and adjusted as shown in Figure 22. The Creality LD006 printer has a larger print area than the Anycubic Photon, allowing all models to be printed simultaneously.

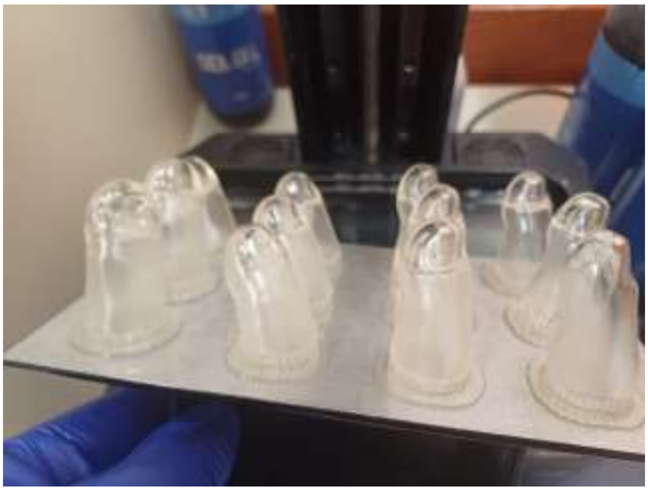
These new designs were manufactured using the DLP process (Stage 7). Although the process may seem straightforward, several print attempts were made with minor adjustments throughout the process to properly define the processing parameters for acceptable model construction, as shown in Figure 23.

Figure 22 - New prosthesis models during DLP/LCD print planning in Chitubox®.



Source: Authors' elaboration.

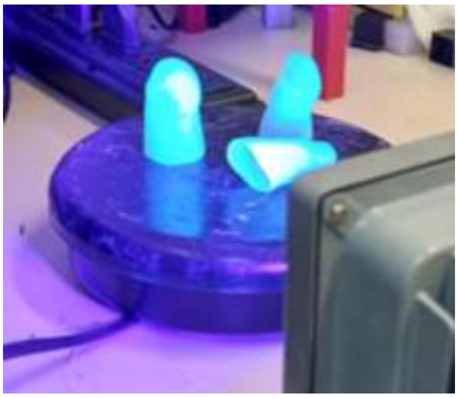
Figure 23 - Redesigned prosthesis models after DLP/LCD printing.



Source: Authors' elaboration.

When removed from the printer, the models remain heavily impregnated with uncured resin from the vat where they are submerged. Therefore, the models must undergo a washing process. Upon leaving the printer, the pieces are quite flexible because the printing process involves only a "pre-cure" of the material to allow construction and handling. Thus, a post-cure (Figure 24) is necessary to make the models rigid enough for use. The supports are removed only at the end of the process (post-processing) with the aid of cutting pliers.

Figure 24 - Pieces being cured with a UV light lamp in a rotational platform.

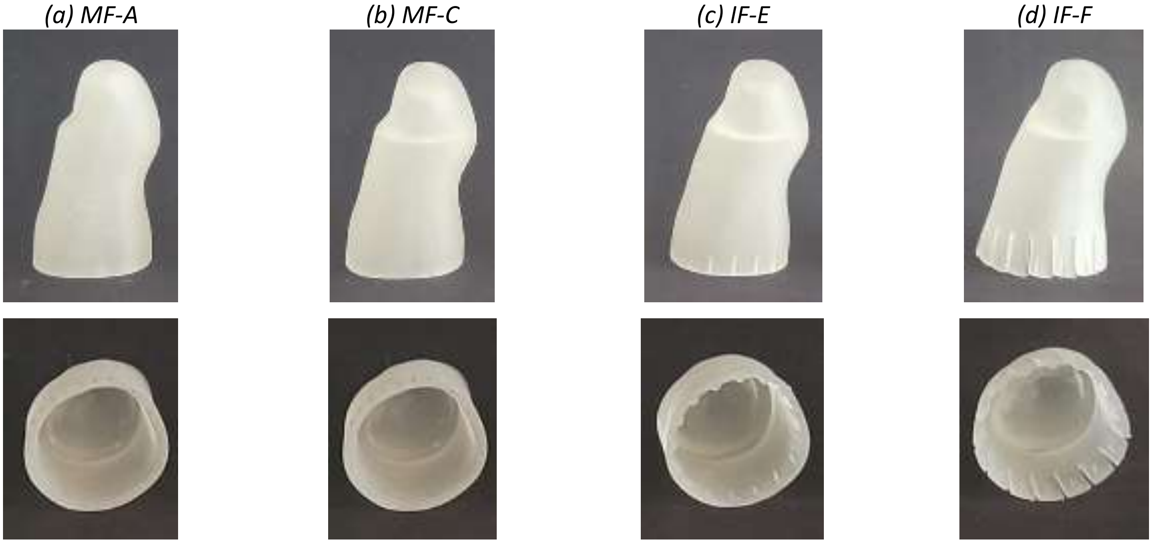


Source: Authors' elaboration.

The redesigned printed models of the prostheses for the index and middle fingers are presented in Figure 25. After post-processing the prostheses, dimensional analysis of the obtained parts can be performed. The measurement results, including the mean, standard deviation, and dimensional variation, are presented in Table 5.

Figure 25 - Finalized parts after post-processing (side and bottom view.

(a) MF-A *(b) MF-C* *(c) IF-E* *(d) IF-F*



Source: Authors' elaboration.

It can be observed that the dimensional measurement results of the base of the parts (Table 5) were satisfactory. For most of the parts, contraction was minimal, falling within the manufacturer’s specified range of 4.5 to 5.5% (ANYCUBIC, 2024). However, contraction behavior was not observed in the IF-B and MF-B parts, where expansion occurred instead. This may have been caused by the excessive use of supports at the base of the parts, resulting in an increase in thickness in that area. This analysis is crucial to ensure that the project dimensions meet user needs. If significant shrinkage occurs during molding, adjusting the design may be necessary to compensate for the observed shrinkage percentage.

Table 5 – Results of the dimensional evaluation of the thickness of prostheses manufactured by the DLP process.

part Ref.	nominal value	M1	M2	M3	M4	M5	M6	$\overline{x}$	σ	%
IF-A	1,30	1,30	1,29	1,30	1,29	1,29	1,30	1,30	0,01	-0,38%
MF-A	1,30	1,31	1,30	1,31	1,28	1,29	1,28	1,30	0,01	-0,38%
IF-B	1,25	1,29	1,27	1,29	1,33	1,29	1,31	1,29	0,02	3,20%
MF-B	1,25	1,27	1,26	1,23	1,28	1,25	1,24	1,26	0,02	0,40%
IF-C	1,50	1,46	1,49	1,49	1,50	1,47	1,50	1,49	0,02	-0,67%
MF-C	1,50	1,46	1,47	1,48	1,50	1,48	1,49	1,48	0,01	-1,33%
MF-D	1,75	1,69	1,71	1,70	1,70	1,69	1,65	1,70	0,02	-3,14%
IF-E	1,00	0,95	0,92	0,92	0,94	0,97	0,95	0,95	0,02	-5,5
IF-F	1,00	0,99	0,97	0,98	0,99	0,99	0,99	0,99	0,01	-1,0

Source: Authors' elaboration.

From the printed models, the task analysis was conducted, and the results are presented in Table 6. Each prosthesis was evaluated based on the evaluation criteria, assigning values for each criterion on a scale from 1 to 5, with 5 being the highest rating. The score for each prosthesis is determined by the sum of the ratings obtained.

Table 6 – Evaluation matrix of criteria vs. printed pieces to assist in the task analysis evaluation.

	DLP/LCD parts printed								
evaluation criteria	IF-A	IF-B	IF-C	IF-E	IF-F	MF-A	MF-B	MF-C	MF-D
General perception	4	2	1	4	4	2	4	3	3
Internal fit	3	2	1	4	3	2	2	2	2
Tip length	3	2	1	4	3	2	3	2	2
score Σ	**10**	**6**	**3**	**12**	**10**	**6**	**9**	**7**	**7**

Source: Authors' elaboration.

The highest-rated prosthesis was the IF-E, with a thickness of 1,30 mm and a protrusion at the base, providing better grip in that area and greater comfort for the remainder of the finger within the prosthesis. The IF-F model also received favorable evaluations but exhibited deformations at its base, as shown in Figure 25. During user testing, an increase in deformation was noted, leading to material failure. This likely occurred because the material used has a low elastic modulus (1300 GPa) and low elongation at break (12 to 16%) (ANYCUBIC, 2024). To properly test this model, it would be necessary to use a flexible or semi-flexible resin to ensure the adequate functionality of these features. The IF-A model also received positive feedback, primarily due to its uniform thickness, resulting in the absence of a defined tip, allowing the user to adjust the finger depth for a better fit.

Therefore, an excellent option was found for the index finger, the IF-E model. However, during the analysis, it was noted that for the middle finger, further adjustments are still needed, as the user reported discomfort in some sensitive areas. Even in the best alternative tested, there was considerable looseness in the fit with the finger, which could cause the prosthesis to fall off during use.

Thus, the results indicated that the prosthesis design for the index finger was considered satisfactory by the user, while the prosthesis for the middle finger still requires adjustments. It is important to highlight that the design of the prosthesis with the highest score for the index finger was not created for the middle finger, as it was a conceptual alternative currently under testing. Therefore, a similar alternative should be developed for the middle finger to find the best fit for the user.

5 Conclusion

The aim of this study was to present case study of a method to develop and manufacture prostheses for the index and middle fingers using digital design and manufacturing technologies such as 3D scanning and additive manufacturing.

The fabrication of hand molds proceeded as expected; however, there may have been variations in the final model geometry, which served as the basis for the 3D scanning process, necessitating subsequent adjustments to the prosthetic design. The indirect method of surface acquisition was employed due to the number of surfaces to be scanned and the characteristics of the scanning equipment, with the expectation of avoiding precision errors. But, as indicated in the literature, the use of this indirect method should be considered a last resort only if direct scanning of the patient hand and fingers are not feasible.

Upon acquiring the 3D surfaces, prosthetic designs were developed and subsequently manufactured using FFF with TPU and DLP/LCD with thermoset resin. Prostheses manufactured by DLP provided better comfort, although dimensional adjustments to the design were necessary for optimal fit on the user.

Various iterations of the prosthetic design were explored, incorporating different thicknesses aimed at offering diverse adjustments for both fingers. Following user evaluation through task analysis, an acceptable option was found for the index finger; however, adjustments are still required for the middle finger. Dimensional evaluation of the prostheses indicated minimal variation in thickness compared to the reference (CAD model), in most cases falling within the contraction limits specified in the resin technical datasheet.

This case study identified the need for improvements in surface acquisition methods. However, it also highlights the advantages of additive manufacturing (AM) for rapid prosthetic production, demonstrating a high level of detail and precision essential for enhancing user comfort. Therefore, additive manufacturing emerges as a powerful tool with significant potential to assist in the fabrication of personalized prostheses with complex geometries.

Future extensions of this work aim to optimize prosthetic comfort through the use of multimaterial additive manufacturing (AM) and flexible materials, as well as by exploring alternative surface acquisition methods and conducting tests with additional subjects to validate the approach. Additionally, there are plans to develop prostheses with electrical properties to enable tactile interaction with devices such as smartphones and tablets.

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7 References

ALVES MAIA, I. et al. Desenvolvimento de dispositivos de tecnologia assistiva utilizando impressão 3D. Uberlândia, MG. **In: Encontro Nacional De Engenharia Biomecânica**, 2015.

ANYCUBIC. Standard resin. **Resin parameters.** 2024. Disponível em: https://store.anycubic.com/products/colored-uv-resin. Acesso em: junho de 2024.

CREALITY. **HALOT-MAGE PRO.** HALOT-MAGE PRO: hyper-speed 8k resin printing. 2023a. Disponível em: https://www.creality.com/products/halot-mage-pro-3d-printer?spm=..index.header_1.1 . Acesso em: 9 jun. 2024. a

_______. **Ender-3 V3.** Ender-3 V3: core ZX 3D Printer. 2023b. Disponível em: https://www.creality.com/products/creality-ender-3-v3 . Acesso em: 9 jun. 2024.

COSTA, C. R. DA et al. Dispositivos de tecnologia assistiva: fatores relacionados ao abandono. **Cadernos de Terapia Ocupacional da UFSCar**, v. 23, n. 3, p. 611–624, 2015.

FORMLABS. **FDM vs. SLA:** compare filament and resin 3d printers. 2024. Disponível em: https://formlabs.com/blog/fdm-vs-sla-compare-types-of-3d-printers/ . Acesso em: 9 jun. 2024.

GIBSON, I.; ROSEN, D. W. STUCKER, B. **Additive Manufacturing Technologies:** Rapid Prototyping to Direct Digital Manufacturing. New York/ Heidelberg/ Dordrecht/ London: Springer. 2010.

GOSHE, M. Tibebu; KASSEGNE, S. Kinde. **Three-dimensional (3D) printing:** cost-effective solution for increased access to prosthesis of lower extremity - case of ethiopia. 2022. Disponível em: https://www.researchgate.net/publication/364952298_3D_Printing_Cost-Effective_Solution_for_Increased_Access_to_Prosthesis_of_Lower_Extremity . Acesso em: 9 jun. 2024.

HASSAN, Modar et al. Rapid and flexible 3D printed finger prostheses with soft fingertips: technique and clinical application. **IEEE Access.** v. 10. p. 60412-60420. 2022.

HEXAGON. **Products. Products by Division. Metrology hardware. Portable measuring arms.** Disponível em: https://hexagon.com/products/product-groups/measurement-inspection-hardware/portable-measuring-arms . Acesso em: junho de 2024.

OWEN, Jen. **e-NABLE is still going strong 10 years later**. Enabling The Future. 2022. Disponível em: https://enablingthefuture.org/2022/09/27/e-nable-is-still-going-strong-10-years-later/. Acesso em: 9 jun. 2024.

PAIVA, Thiago Neves; NOGUEIRA, Cássio Cipriano. Estudo comparativo das principais tecnologias de impressão 3D no brasil. **JNT-Facit business and technology journal**. Março 2021. nº 24. v. 1. p. 193-212.

PAZMINO, Ana Veronica. **Como se cria:** 40 métodos para design de produtos. São Paulo: Blucher, 2015.

RELVAS, Carlos. **O mundo da impressão 3D e o fabrico digital.** Porto: Quântica, 2018.

SILVA, Francisco (coord) et al. **Impressão 3D:** tecnologias, materiais e aplicações. Porto: Engebook, 2023.

VOLPATO, Neri (org) et al. **Manufatura aditiva:** tecnologias e aplicações da impressão 3D. Paraná: Editora Blucher, 2017.

WALLACE, L.; HASSAN, M.; SHIMIZU, Y.; KIKUCHI, A.; SUZUKI, K. **Functional 3D-printed finger prosthesis with compliant fingertips for support of iADLs**, 2024 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Sarawak, Malaysia, 2024.

WORLD HEALTH ORGANIZATION; BANK, W. **World report on disability 2011**. 2020. Disponível em: Who.int. Acesso em: junho 2024.