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Prosthetic Thumb Design and Development by Additive Manufacturing

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Abstract: The proposed work deals with the production of a thumb prosthesis from ASA (Acrylonitrile-styrene-acrylic) material using FDM (Fused deposition modeling) additive manufacturing technology. The prosthesis serves as a substitute for the deformity of the hand (absence of the thumb including the metacarpal bone) and as a support point for grasping objects to restore the lost opposition function of the thumb. The shape of the thumb and the socket of the prosthesis are designed individually based on a 3D scan of the subject's healthy hand. The design of the prosthesis was developed according to the anatomically correct condition and the user's requirements. The socket of the prosthesis sufficiently copies the relief of the subject's hand, which results in a sufficient attachment of the prosthesis to the hand segment and the comfort of the subject while wearing the prosthetic aid.

Keywords: 3D scan; Thumb prosthesis; Additive manufacturing, Hand grip

1. Introduction

The most common upper extremity amputations are finger amputations, resulting in functional limitations that lead to problems with daily activities or employment problems. The cause of the absence of the thumb can also be of a congenital deformity or other health problems, the consequence of which is amputation. An amputated thumb can be compensated with a prosthesis, which can be effective not only in restoring the grip, but also in restoring the natural appearance of the hand. For many years, prosthetic options after finger or thumb amputations were limited to passive prostheses. With the increase in popularity and availability of additive manufacturing, the design and development of prosthetic and orthotic devices is receiving more attention. [1]

Since the thumb is the only digit capable of opposing the fingers, it has an important role in grasping. In the case of congenital deformities, the subject can create his own compensatory mechanism, but for some strong or precise grips that require support, a passive prosthesis is sufficient. [1] [2]

The thumb prosthesis should above all be comfortable to wear and have a natural shape. There are many attributes that a thumb prosthesis should meet such as functionality, wearability, durability, safety, accuracy, and lightness. [2] [3]

This study deals with the design and fabrication of an individual thumb prosthesis. The subject is a 40-year-old man with congenital absence of the thumb and the associated metacarpal bone on the right non-dominant hand, an anomaly of the lengths of the individual segments of the upper limb, and an elbow contracture. The goal was to design a prosthesis using CAD (Computer Aided Design) software, 3D scanning technology and additive manufacturing that fulfills the function of a

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cylindrical grip. [2] [3]

2. Experimental materials and methods

2.1 Characteristics of hand pathology

The right hand is affected by a congenital deformity in which there is an absence of the thumb with its metacarpal bone. The entire metacarpal region of the fingers is hypermobile. There is a dimensional disproportion, because the deformed hand is smaller compared to the healthy hand and the longitudinal arch of the hand is also absent (Fig. 1).

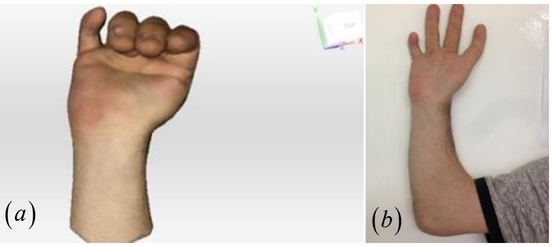

Figure 1: (a) scan of a deformed hand in a cylindrical grip, (b) photo of a deformed hand in a neutral position.

2.2 Materials for the design of an individual prosthesis

Before designing an individual prosthesis, it is necessary to obtain anthropometric and morphological measurements of the hand, which will be used for the CAD design of the prosthetic device. Measurements were acquired using a 3D scanner Artec Eva (Artec 3D, Luxemburg, Luxembourg), with a scanning frequency of 8 fps (frames per second). The scan was performed without any errors. For the design of the prosthesis, a 3D scan of a healthy hand was taken with the thumb in the opposite position to the fingers and the fingers extended.

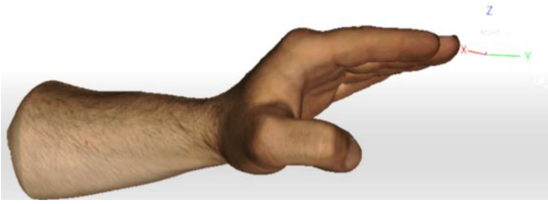

Figure 2: Scan of the healthy hand with fingers extended and the thumb in opposition

This position ensured suitable capturing of the dorsal, and especially the palmar side of the thumb of the healthy hand. The obtained 3D model is used to design the artificial thumb of the prosthesis (Fig. 2). The 3D scan of the pathological hand was used in the design of the thumb prosthesis socket, which surrounds the palmar and dorsal part of the hand. [4]

2.3 CAD modeling of the prosthesis´ socket

After creating a digital positive, its subsequent adjustments were performed in the freely downloadable CAD software Autodesk Meshmixer (Autodesk, Inc., San Rafael, CA, USA), which contains functions for editing 3D models necessary for the creation of orthotic-prosthetic aids (Fig. 3).

The surface of the metacarpal area on the palmar, dorsal, and radial sides of the hand from the acquired 3D model of the pathological hand was used to create the thumb prosthesis´ socket model. This area had to be separated and extruded to obtain the 3D shape of the socket part of the prosthesis. The shape of the designed socket copied the anatomical surface of the palmar and dorsal side of the deformed hand, while space for fitting the prosthesis was omitted on the ulnar side (Fig. 4). The next step was choosing the density of the filling and the thickness of the socket. Since it should be

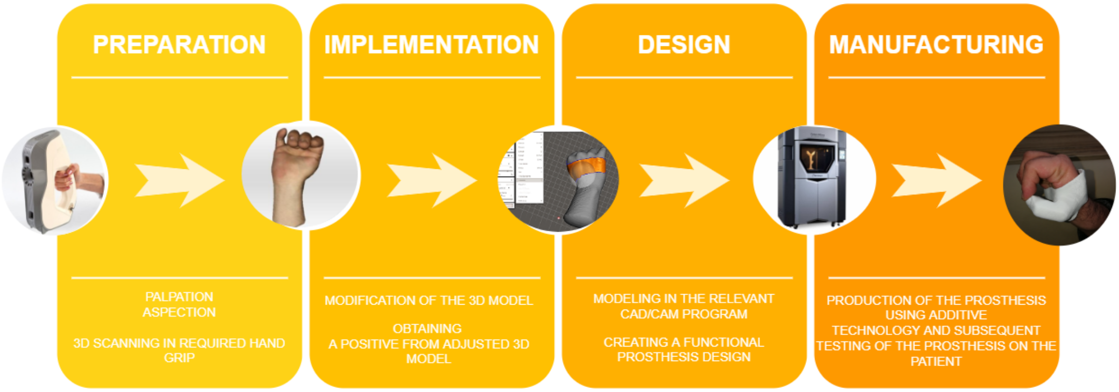

Figure 3: Proposed process for manufacturing a passive prosthesis by 3D printing.

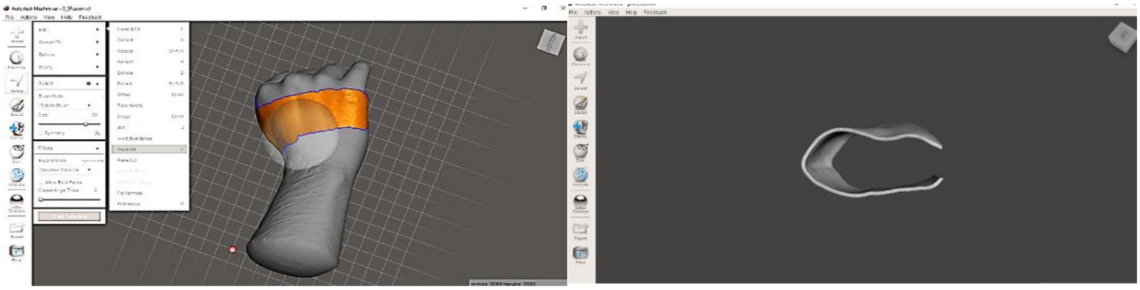

Figure 4: Selecting an area for modeling the socket of thumb prosthesis

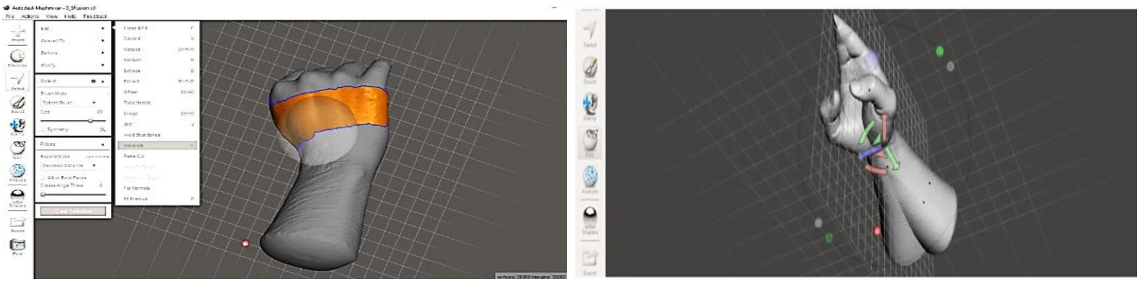

Figure 5: Mirroring and attaching the thumb model of a healthy hand to the socket.

rigid and firmly fix the area of interest, it is necessary to choose a filling density of 100%. The thickness of the socket was set to 2 mm, which should ensure the strength and efficiency of fixation on the hand.

A scan of a healthy hand was used to mirror the thumb in a cylindrical grip that was attached to the designed prosthesis socket (Fig. 5). It was necessary to position the thumb and adjust its dimensions as needed (size disproportion) to get as close as possible to the natural cylindrical grip of the 3D model of a healthy hand.

2.3 Final adjustments of the prosthesis

Based on the subject's anamnesis and his daily activities, the prosthesis model was personalized according to the subject's requirements for its shape and functionality and optimized in terms of efficiency of functionality. The design of the device was supplemented with a pattern of holes on the entire surface, which will ensure weight reduction and maximize the breathability of the prosthetic device (Fig. 6).

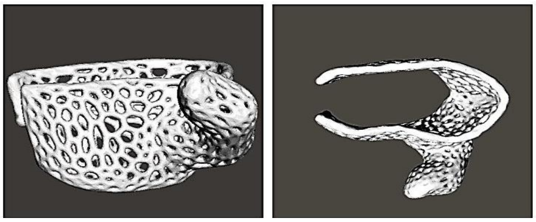

Figure 6: Final model of thumb prosthesis.

2.4 Production of the thumb prosthesis

A 3D printer of the FDM (Fused Deposition Modeling) type, Fortus 450mc (Stratasys Ltd., Rehotov, Israel) was used to produce the prosthesis. The material ASA (Acrylonitrile-styrene-acrylic) was used to produce the device. The given material was chosen due to its mechanical properties, high resistance to weather effects and direct UV radiation. Printing parameters were set as shown in Table 1. [5] [6]

Table 1: Printing parameters during the production of the prosthesis prototype on the Fortus 450mc printer.

Layer height	0,010mm
Filling	100%
Fill style	Solid
Surface	Normal
Support style	Box

3. Results

3.1 Prototype of a printed prosthesis

The first model took approximately six hours to print, where 66,41 cm^3 of ASA-type material and 54,01 cm^3 of support material were used. In the first attempt, two identical prostheses with different filling density (50% and 100%) were manufactured. After simulation of the production in the Insight

(Stratasys Ltd., Rehotov, Israel) software, it was found that a prosthesis with a lower filling density is also satisfactory.

After testing the prosthesis on the subject, it was found that the prosthetic thumb was placed inappropriately for performing a cylindrical grip. It was necessary to turn the thumb more laterally and thereby increase the space between the palmar surface of the socket and the prosthetic thumb. The thumb had to be moved higher and at the same time the distal end of the thumb closer to the fingers. The socket of the prosthesis was satisfactory, i.e., its modification was not necessary (Fig. 7).

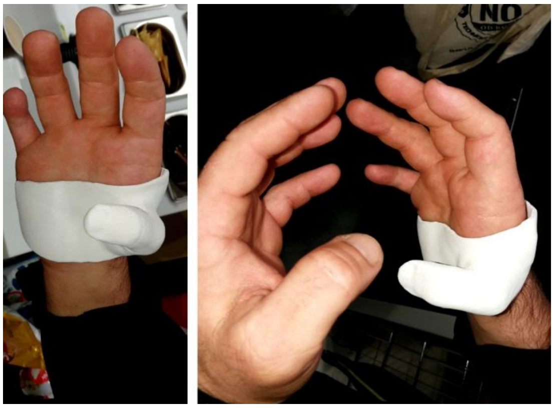

Figure 7: Testing the prototype of the thumb prosthesis.

The necessary correction of the thumb was achieved by re-editing in Autodesk Meshmixer, where the prosthetic thumb was rotated to the desired position according to the testing of the previous model.

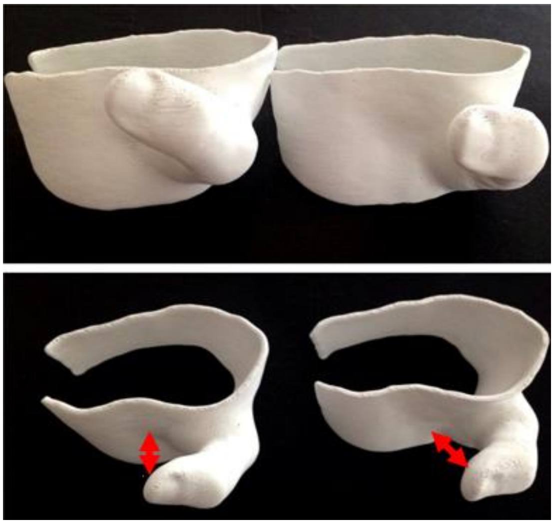

Figure 8: Modified prosthesis (left) compared to the first (right).

3.2 Resulting models

Figure 9: Printed design models with and without padding.

Two design variants were also printed, with a filled and an unfilled socket (Fig. 9). The total material usage and price calculation is in Table 2.

The final prosthesis was sufficiently fixated and corresponded to the shape of the healthy hand. The modified prosthetic thumb, in opposition to the fingers of the hand, was directed upwards, thereby enabling the touch of the distal part of the thumb and index finger. Small cylindrical objects could be grasped in the space created between the palmar side of the hand and the prosthetic thumb.

Figure 10: Testing the functionality of the cylindrical grip of the prosthesis.

Table 2: Price calculation of a design prosthesis with and without socket filling.

Type	Quantity [pcs.]	Material ASA [cm3]	Support [cm3]	Printing time [hour:min]	Price [€]
Prosthesis without filled socket	1	35.21	41.24	9:04	84.78
Prosthesis with filled socket	1	44.33	36.89	6:32	70.58

4. Discussion

The aim of the work was to design and manufacture a thumb prosthesis for a subject with a congenital deformity using progressive methods. Part of the work also includes the creation of various design proposals which differ from classic prostheses in appearance and can only be produced using 3D printing technology. [6]

When designing the prosthesis, it was important to consider the absent metacarpal bone, and therefore it was necessary to choose a socket that had to meet attributes such as shape accuracy and sufficient adhesion to prevent the prosthesis from slipping from the hand. This was achieved by the shape of the socket created using CAD modeling and 3D scanning, which provided the actual dimensions of the hand, which contributed to the creation of a suitable socket. This way, it was possible to continue working on the design of the prosthetic thumb. The combination of a 3D scanner and CAD software made it possible to create individual variants of the prosthesis. [6][7]

During the testing of the first printed model, an inappropriate placement of the thumb was indicated, which resulted in the impossibility of performing a cylindrical grip. There was insufficient space between the thumb and the socket, which prevented the grasping of objects and therefore the thumb was unusable. During the subsequent adjustment of the prosthetic thumb, it was considered that it would be more appropriate to position the thumb higher, which would increase the distance of the thumb from the socket and thus bringing it closer to the healthy hand surface. After the modification, the prosthesis was reprinted and submitted for testing on the subject. The final shape and design of the prosthetic thumb was satisfactory from both functional and aesthetical point of view. Using 3D printing technology, it is possible to reduce weight and ensure ventilation by creating small holes on the surface of the model. The patient noted the comfort and lightness of the manufactured thumb prosthesis. [7][8]

From an overall point of view, the designed prosthesis met the following attributes:

– *the socket appropriately copies the morphology of the hand*
– *the prosthesis does not limit the range of movement*
– *the prosthesis enables adequate cylindrical grip as well as pincer grip*
– *aesthetic idea of the patient*

5. Conclusions

Over the past decade, 3D printed prosthetics have made significant advances due to their light weight, low cost, rapid production, and ease of customization. Our study suggests that for patients with hand amputations, 3D printed thumb prostheses have high potential as an additional prosthetic option to existing passive cosmetic prostheses.

Among the advantages of 3D printing in prosthetics is the speed of production compared to conventional methods, as well as the possibility to create a prosthesis with surface-accurate dimensions through a given modeling software and to create structures that are difficult to realize by hand.

However, innovative methods of design and production in prosthetics also have their drawbacks, for example, when making a 3D scan, complications may arise due to incorrect positioning or constant movement of the patient. In this case, it is necessary to align and adjust the scans, which requires deeper knowledge and experience of the orthopedic technician with the 3D scanner and the relevant scan editing software. Also, for 3D printing technology to be actively used in the production of prostheses, the knowledge and skill of orthopedic technicians in the use of CAD/CAM software and manufacturing through 3D printing is required.

The goal of further development is to modify the design and propose a mechanism that would ensure active control of the prosthesis and achieve mobility of the prosthetic thumb, which would allow multiple types of grips to be performed. It would also be possible to create low-cost passive models of a thumb prosthesis in different grips adapted to different patient activities.

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