Development of a Functional Upper Limb Prosthesis

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Abstract

Upper limb disabilities are defined the absence or severe hypoplasia of upper limb skeletal structures and affect millions of people worldwide, whether it was acquired or originated from a congenital defect. Ever since the early stages of technology patients with these disorders have tried to restore symmetry, appearance and basic function with artificial replacements called prosthesis. Prosthetic devices are in constant evolution and it is now possible to obtain highly sophisticated and complex upper limb bionic prosthesis, that, however, can't be afforded by every patient and may not be suitable for every situation, such as temporary prosthesis for children that are still developing. Additive Manufacturing technology came as a very interesting solution for such prosthetic devices, since it allows high customization and fast production on demand and on site, at particularly low costs. In this work an original, versatile, adaptable and anthropomorphic functional prosthetic hand design was conceived for Additive Manufacturing using flexible filament (TPU), resourcing to Computer Aided Design (CAD). It was made a study on 3D printing with flexible filament, with methodic and documented tests on the key factors in the quality of 3D printed parts and the final recommended slicing parameters for the components of the prosthetic device were presented. A prototype of the designed prosthetic hand was manufactured with positive overall results in terms of appearance and function. Finally, the different actuation methods and some existing devices that could be compatible with the presented concept were described.

Keywords: Upper Limb Disabilities, Computer Aided Design, Functional Prosthesis, Additive Manufacturing, Flexible Filament

1 Introduction

There is a number of people who suffer from Upper Limb Deficiencies that have to face and overcome the challenges of the lack of a hand on a daily basis. The lack of an Upper Limb can have its origin in congenital disorders or it can be acquired at some point of life, as a result of an amputation. With the advance of technology, increasingly sophisticated Upper Limb Prosthetic Devices were developed and there is a continuous need for innovation. Specifically, 3D printing technology came as a very interesting solution for prosthetic devices manufacturing, since it allows high customization, fast production at low costs. Since the beginning of this decade, it is possible to use 3D printing with flexible filament to produce highly resistant and flexible rubber-like parts, a feature that can be very useful to develop realistic and functional prostheses.
2 Problem

2.1 Upper Limb Reduction Defects

An upper limb reduction defect is defined as the absence of severe hypoplasia of upper limb skeletal structures (Sheba, Hashomer, & Gan, 2007). Upper limb deficiencies differ greatly in their anatomy and etiology (Gold, Westgate, & Holmes, 2011) as it can have two main origins: congenital defects and acquired upper limb deficiencies, commonly known as amputations. A congenital limb deficiency is a failure or error to the formation of a limb bud (Atkins et al, 1996) and it is estimated to affect 1 in every 1300 to 2000 births (Wilcox, Coulter, & Schmitz, 2015). The other origin of this problem is acquired upper limb deficiency, which is defined as any surgical amputation as a result of trauma or disease (Beaver, Skelton, & Vogel, 2007).

It is recommended for children with upper limb disorders to be introduced to a passive prosthesis as soon as possible according to the psychomotor development of the case in question, even before the first year of life (Pruitt, Seid, Varni, & Setoguchi, 1999). This procedure is intended to encourage the use of both upper limb for day-to-day activities, to ensure body symmetry through the development of the child and to improve the chances of accepting a more complex prosthetic in the future, as the increase in age of introduction of the first prosthetic device is related to increase in future prosthetic rejection rate (Curran R., B., Curran, & Hambrey, 1991; Kuyper, Breedijk, Mulders, Post, & Prevo, 2001; Scotland & Galway, 1993). It is important to understand that, although patients with upper limb disorders can be highly independent, as approximately 90% of day-to-day activities can be still be performed (Watson, 2000), the use of prosthesis is still recommended to improve motor skills (Jain, 1996; Watson, 2000) and even psychological development (Dlugosz et al., 1986).

The next level of development should be the introduction to a functional prosthesis (Pruitt et al., 1999), when the patient shows a certain level of psychomotor development, although recommended age is not consensual it is in the range of 18 months to 5 years (Curran R. et al., 1991; Egermann, Kasten, & Thomsen, 2009; Kuyper et al., 2001). In order to improve acceptability of a functional prosthetic device, children shall be introduced to regular, intensive training (Davids, Wagner, Meyer, & Blackhurst, 2006; Egermann et al., 2009). To have a functional moving hand is very beneficial for children in the referred ages, however, during child growth it is necessary to change the prosthetic devices as size and complexity may need to be adjusted.

In that regard, 3D printing technology comes as an ideal manufacturing process for this kind of prosthesis, as it allows for high customization, production on-demand and low costs (Zuniga, Peck, Srivastava, Katsavelis, & Carson, 2016). Most existing devices are still very expensive, hard to obtain and not easily adapted to the specific case of a patient.

2.2 Existing Solutions

There are several categories of Upper Limb Prosthesis that can be grouped by the way that the device is controlled.

A passive prosthesis is a non-functional prosthetic device used for cosmetic purposes, for body-symmetry reasons and to ensure proper children development (Amos, Matthew, & Wimhurst, 2013; Plettenburg, 2009). This device has no active function, and therefore no actuation, however, it can largely restore basic non-moving limb function.

A body-powered prosthesis is a functional, mechanical device that allows a person to use the self-strength and movement of the body to actuate a prosthetic hand (Kutz, 2003; Kuyper et al., 2001). These devices usually ensure a grabbing function and typically there is no possibility of individual finger control.

A myoelectric prosthesis is a functional, sophisticated device that uses one or more sensors to read electrical signals sent from muscles in the remaining upper limb, through the skin, and send the collected information into a controller. This controller is
then configurated to, in real time and when certain signals are sent, actuate specific motors. This allows for a trained user to actuate a prosthetic hand with no effort and no body movement restrictions (Egermann et al., 2009; Matrone, Cipriani, Carrozza, & Magenes, 2012; Scott, 1990).

2.3 User Needs

There is a constant need to improve the technological existing devices to better suit the user necessities. It is important to identify these necessities, since the project specifications should be focused in solving those issues.

The user needs considered for this work were:

Affordability – this is a key problem on existing prosthetic devices, as most available options are very costly. Of course, with higher priced solutions comes higher-end technology and consequently best quality and precision. However, only a small fraction of the patients with Upper Limb Deficiencies can afford these prosthetic devices. Also, there is the case of infants, who are still growing and developing, in which a costly prosthetic device would no longer fit in a span of a few years and has higher probability of getting broken or damaged. Therefore, it is crucial to create an affordable functional prosthesis.

Versatility – The need of versatility comes from two sources: different patient and limb sizes, as well as different level of amputation or congenital defect. Therefore, it is essential to create a device that’s scalable for children size and at the same time adaptable to the specific upper limb disorder of a patient.

Improved appearance – although the futuristic bionic aspect of most prosthetic devices may be appreciated by many users, there is a lack of realistic anthropomorphic prosthesis with close-to-human appearance and feel.

Easy to learn and use – It is important for the prosthetic device developed to be easy to use, and not to be overly complicated to learn how to operate.

Comfort – to minimize risk of rejection it is important for the prosthetic device to be comfortable to wear, to actuate and to use in different circumstances.

On demand fast production – It is important for the user to have available a on-demand solution, with a non-overly long development and production.

Customization – not exactly a “user need” but still a user satisfaction boost, as it can be valued for patients (specially, but now exclusively children) to have their own one-of-a-kind prosthesis, customized with special design or, for example, the patient’s name.

3 Concept

3.1 Project Specifications and Methodology

The project specifications for this work are:

- Creation of an original CAD model
- Main process of manufacturing is 3D printing
- Use of flexible filament
- Separate hand body and finger parts
- Adaptable to different actuation devices
- Low-cost material and production
- Light and resistant prosthetic device
- Voluntary closing (VC) device

We can group the project into two main categories: design and manufacturing. This chapter is focused on design although some tests made during design stage will be mentioned since this is a dynamic process, and design is dependent on the behavior of real printed parts. In Figure 3.1 is displayed a schematic of the methodology followed throughout the project.
The design was made in CAD (computer assisted design) using the software SolidWorks 2016. Finger design was created using Lofts defined by sketched profiles and guide lines to resemble actual fingers, as shown as an example in Figure 3.2, with more importance being given to functionality over appearance. The model presented in this work is a fully developed adult hand by default, although it was made to be adapted to different upper limb sizes by an educated scaling procedure, in order to be used by adults and children as well.

The human finger is composed by narrow bones called phalanges, connected and articulated between them by joints and it’s the rotation of phalanges around this joint that induces movement to fingers (Freivalds, 2007).

The geometry of the finger defines the movement that will occur when the non-elastic wire is pulled. The finger part has three inner chambers, each one intended to recreate each of the joints associated with finger movement. Those joints are, starting from the tip of the finger, the proximal interphalangeal joint (PIP) connecting the proximal and medial phalanges, the distal interphalangeal joint (DIP) connecting the medial and distal phalanges and the metacarpophalangeal joint (MCP) connecting the distal joint and the metacarpal bone of the hand (Doyle & Botte, 2002). Figure 3.3 displays the location of bones and joints referred, while Table 3.1 presents the connection between chambers in finger part and the joint that they represent.

The thumb is a very specific and unique finger, as it as a different appearance, function, and even number of joints, since it doesn’t have a medial phalanx. For this reason, a separate part had to be created for the thumb geometry, using all the same features referred throughout this chapter. As there is one interphalangeal joint, it is simply referred by that name (no longer necessary to distinguish between distal or proximal). The connection between chambers in thumb part and the joints they are intended to represented is presented in Table 3.2.
It is possible to observe that the finger part does not only include the phalanges but also the metacarpophalangeal joint (MCP) in order to engulf all joints into the same part as well as improve the overall appearance of the model. This also eliminates the need for additional parts, such as flexible hinges in the metacarpophalangeal joint.

The same design was used for all the three phalanx fingers – index, middle, ring and little – as they are quite similar in shape and movement, as well relative phalanx size. The proximal phalanx represents approximately 48% of finger length while medial and distal phalanges represent 31% and 21% respectively.

Just like a number of 3D printed prosthesis available so far, the finger movement will occur resourcing to wire “tendons”. A wire is threaded through a hole that goes through the posterior side of the finger and tied on the tip of the finger. The geometry of the finger ensures that when the wire is pulled the finger’s phalanges rotate over the articulations and the finger bends. A schematic demonstrating how the wire tendon movement works is displayed in Figure 3.4.

![Figure 3.4: Finger movement schematic](image)

Return of the finger to its initial position is ensured by elasticity, and methods like elastic wires and flexible hinges could be used. However, in this work it was decided to print fingers as one part and position restoration shall be ensured by the elasticity and shape retention of the finger itself, due to the flexible material used to print it, following the idea and general concept of the Flexy Hand, by Gyrobot (Gyrobot, 2015).

The geometry of the inner hollow chambers, presented in Figure 3.5, defines where and how much it will bend. The stiffness is partially defined by the geometry as well. The opening angle of the chamber, represented as θ, is related to the angle of rotation of the respective joint. The rotation of joint is always lower than the opening angle of rotation θ, because of the fold in the outer shell. The depth of the chamber, L, defines the bending stiffness of the joint.

![Figure 3.5: Geometry of the hollow inner chambers in finger part](image)

It is very important to calibrate L and θ to achieve the desired finger movement. If the depth of the inner chambers L isn’t coherent enough fingers will bend completely on one joint before starting to bend the others. The objective is to obtain smooth bending with movement beginning at the same time on all three joints. Likewise, the θ parameter also must be calibrated. The angle should be high enough to assure the desired movement, however, a value too high would results in lower flexion force in the joint and would cause the wire to press against the outer shell and increasing friction to a point that causes movement to block.

These values were iteratively tested and satisfactory results were achieved using the following angle and depth of the inner chambers displayed in Table 3.3:

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Angle (θ) in degrees</th>
<th>Depth (L) in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber 1 (MCP)</td>
<td>60</td>
<td>17.5</td>
</tr>
<tr>
<td>Chamber 2 (DIP)</td>
<td>60</td>
<td>16</td>
</tr>
<tr>
<td>Chamber 3 (PIP)</td>
<td>60</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 3.3: Values of opening angle, θ, and depth, L, for each chamber in finger part
The values of the inner chambers parameters for the thumb are presented in Table 3.4:

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Angle (θ) in degrees</th>
<th>Depth (L) in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber T1 (MCP)</td>
<td>65</td>
<td>15.4</td>
</tr>
<tr>
<td>Chamber T2 (IP)</td>
<td>75</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Table 3.4: Values of opening angle, θ, and depth, L, for each chamber in thumb part

3.3 Hand Body

The final part of the hand assembly is the hand body, which includes the palm of the hand and is where all the finger parts are connected. This part was designed using lofts defined by profiles and guidelines and, much like the fingers, a good deal of organic design was used in order to try to mimic the natural anthropomorphic shape and curves of the human hand.

The finger mating joint were designed to match the ones in the finger parts with a tested geometric tolerance in order to assemble the parts easily and tightly fit them together. Also, the tendon wire holes were also inserted to match the ones in finger parts and the canals run through the anterior side of the hand all the way to the base where each individual wire comes out. The SolidWorks CAD of the hand body part is displayed in Figure 3.6 and in Figure 3.7 as well, with the frontal surface in transparent mode.

3.4 Assembly

The final model assembly was modelled is presented in Figure 3.8:

4 Manufacturing and Implementation

Additive Manufacturing (AM) is the process of creation of a three-dimensional object with material being added sequentially layer-by-layer. It is a computer-assisted technology that as its origin on a
digital 3D model of the object to be manufactured. This unique process, through which object of almost any shape and geometry can be created, is mostly used for rapid prototyping, complex geometries and highly customized objects. Additive Manufacturing is recommended for single unit or small batch productions, since it is a low cost but typically slow and non-scalable (in the sense that increasing number of unit for production doesn’t heavily decrease price per unit) process. These characteristics are a solid match for the needs of this project: fast prototyping, small batches and highly custom.

The material used was FilaFlex®, By Recreus® a thermoplastic elastomer (TPE) called TPU (Thermoplastic Polyurethane). It is a polyurethane plastic with high elasticity, high abrasion resistance and shear strength and an astonishing shape retention. The slicing software used was Ultimaker Cura®.

The final recommended parameters to print the presented prosthesis in Ultimaker Cura® are displayed in Figure 4.1.

![Figure 4.1: Recommended Printing Parameters for the FilaFlex® Parts](image)

When all the parts are printed, it is still necessary to assemble the 3D prosthetic hand.

The final prototype for the prosthetic device developed in this project is presented while not actuated in Figure 4.2 and while actuated in Figure 4.3. It has a temporary PLA hand body part with a still outdated design and it is being actuated with an adaptation of the
wrist-powered actuation device of the *Flexy Hand* (Gyrobot, 2014).

Figure 4.2: Prototype of the presented Prosthetic Device in different views - not actuated

Figure 4.3: Prototype of the presented Prosthetic Device Actuated (Left) and holding a Rubik's Cube (Right)

5 Adaptation and Actuation

The model designed and manufactured is a standard 3D printed hand actuated through wire tendons, but it is still necessary to adapt it to each specific situation in terms of geometry and actuation of the wires to make it an actual useable and functional prosthesis. There are several solutions available depending on the condition of the patient in question and most importantly the movement and functions available, as well as the complexity and detail requested in each case. It also heavily depends on the cost that the patient is willing to support, since the available solutions vary widely in cost and time to produce.

5.1 Motor Powered

Motor-powered actuation devices have the advantage of not relying on the movements or strength of the prosthesis-user, making it a comfortable long-time solution. A very interesting feature that a number of current upper limb protheses have is Myoelectric Control (A Hambrey & Withinshaw, 1990; Egermann et al., 2009; Matrone et al., 2012; Scott, 1990). This process uses one or more sensors to read electrical signals sent from muscles in the remaining upper limb through the skin and send the collected information into a controller. This controller is then configured to, in real time and when certain signals are sent, actuate specific motors. This would allow the use of one motor per prosthetic finger and allow individual movements, a big advantage of other actuation processes.

5.2 Body Powered

A body powered prosthesis is a device in which the user utilizes self-movement and muscle power to actuate it. The concept consists in the use of one of the joints remaining in the upper limb affected, in order to pull the wire tendons that actuate the finger movement. Figure 5.1 displays the physical principle that is behind this mechanism.

![Figure 5.1: Physical principle behind body powered prosthesis with wire tendons](image)

The extra distance the wire has to go through can easily be calculated as a function of D and \( \theta \) as:

\[
x = \theta \times D, \quad \theta \text{ in radians}
\]
Upper Limb deficiencies that can benefit from the use of the presented 3D printed flexible prosthesis and the respective devices that can be used in each case were grouped in different categories, by the functional remaining joints, in Table 5.1.

<table>
<thead>
<tr>
<th>Body-powered device</th>
<th>Upper Limb Deficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder/back powered</td>
<td>Transhumeral (Upper arm), Transradial (Forearm), Hand and finger</td>
</tr>
<tr>
<td>Elbow-powered</td>
<td>Transradial (Forearm), Hand and finger</td>
</tr>
<tr>
<td>Wrist-powered</td>
<td>Hand and finger</td>
</tr>
</tbody>
</table>

Table 5.1: Categorization of body-powered actuation devices by upper limb deficiency

6 Conclusion

It is fair to say that the body is a person’s most valuable possession and it is extremely difficult to overcome the loss of a limb as essential for virtually every aspect of life as the hand. A functional prosthesis can significantly improve the life of a person suffering from an upper limb disability as it can restore a symmetric appearance and basic grabbing function, as well as attenuate the sense of incompletion. Additive Manufacturing technology came as a very interesting solution for prosthetic devices, since it allows high customization and fast production on demand and on site, at particularly low costs. In this work an original functional prosthetic hand design was conceived for Additive Manufacturing using flexible filament, a feature that allow this device to be realistic looking and to avoid moving parts and exposure of the tendon cables that actuate the device. Design sub-problems were individually documented, which can be useful for students and researchers searching for solutions to similar issues.

There were a series of difficulties that were identified and surpassed throughout this work, namely during manufacturing stage, with a tested set of 3D printing parameters for FilaFlex® being recommended. A prototype of the designed prosthetic hand was manufactured, which included a temporary adapted actuation device, and showed promising results with basic function being assured. The objective of creating a low cost, light and functional 3D printed hand using flexible filament prosthesis was met, although there still is room for improvement. Innovation must continue, and the future of upper limb prosthesis will depend on the of the ability prosthetists, doctors and engineers to work together and, with effort and research, to develop devices that will furtherly improve people’s life.

References


