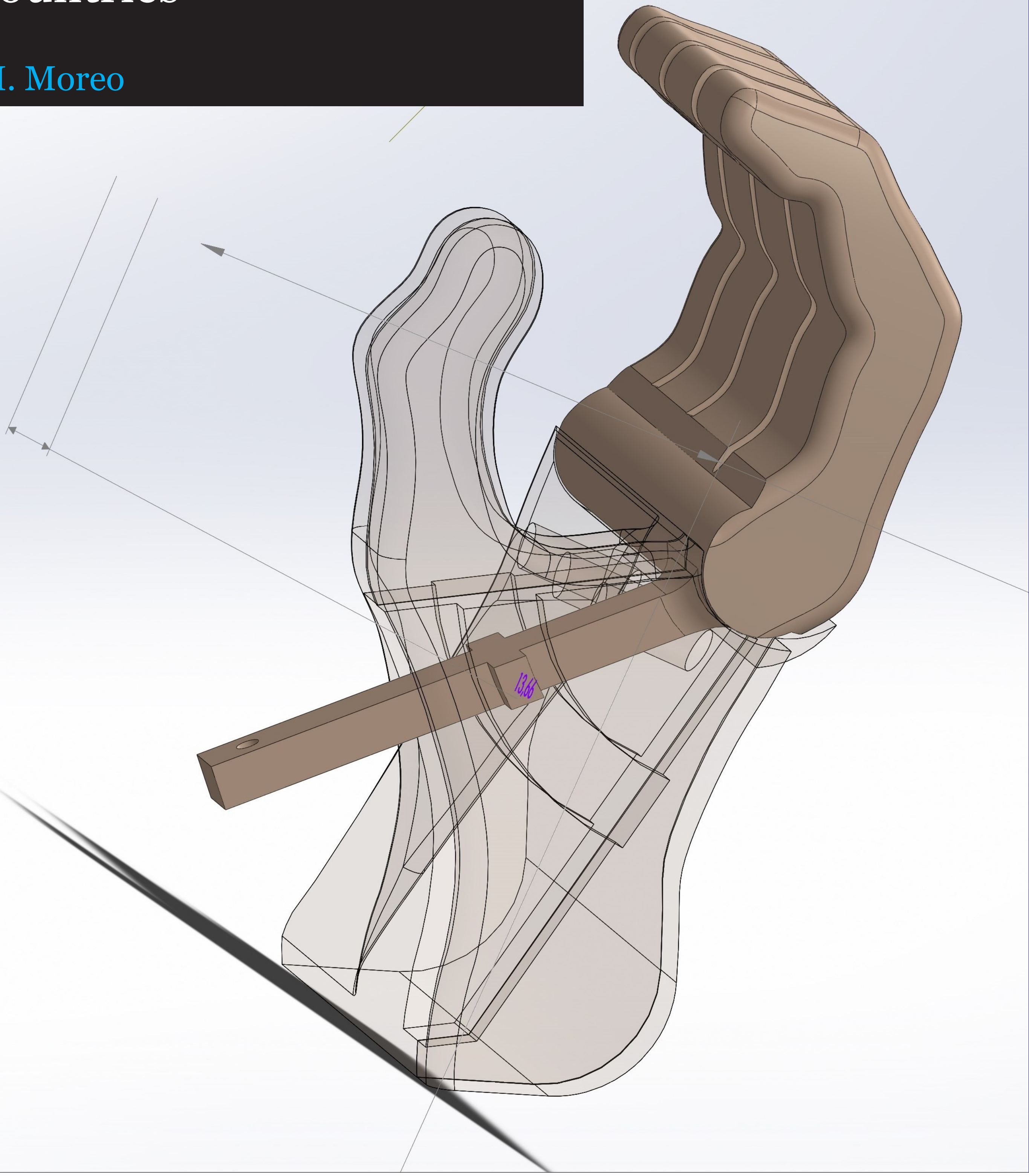
Parametric design of a 3D printable hand prosthesis for children in developing countries

M. Moreo

Technische Universiteit Delft



Delft University of Technology

Challenge the future

Parametric design of a 3D printable hand prosthesis for children in developing countries

by

M. Moreo

in partial fulfillment of the requirements for the degree of

Master of Science
in Biomedical Engineering

at the Delft University of Technology,
to be defended publicly on Firday November 25, 2016 at 10:00 AM.

Student number:	4398661	
Project duration:	April 15, 2016 – November 25, 2016	
Thesis committee:	Prof. dr. ir. P. Breedveld,	TU Delft, supervisor
	Dr. ir. D.H. Plettenburg,	TU Delft, supervisor
	Dr. ir G. Smit,	TU Delft, supervisor
	Ir. J.S Cuellar	TU Delft, supervisor

Preface

I have started biomedical engineering five years ago, with the aim of being able to improve people's lives, helping them to recover from illness and assist them if disabled. I have always felt the need of being supportive for people that are facing difficulties in life, not only during my studies but also with volunteering jobs.

When it was the moment to choose my master thesis I wanted to use the knowledge achieved during my studies to develop something that can support people in needs.

I decided to invest time and knowledge in this project because, after spending one month in Senegal few years ago, I was able to experience first hand the poverty and the problems that citizen of developing countries have to face every day and it is easier for me to imagine how difficult a life of a young amputee in these countries can be.

In developing countries only 5% of the amputees have access to prosthesis due to the high costs and problems in reaching the specialized centers. Amputees are often rejected from society and have little or no access to medical services. They live in poverty and ignorance. Children are excluded from school and marginalized. This can be prevented if everyone has access to prosthetic devices that resemble the human hand. And this is what I wanted to work on.

I am proud of the results achieved during my thesis and I am confident that this can be the starting point of a complete product that can be sold and used in developing countries.

I would like to thank all the people that have supported and helped me during my studies. First all the professors that shared their knowledge with me and made me an engineer, especially Gerwin, Dick and Paul for their time and advice during my thesis. Thank you Juan not only for being my daily supervisor and a nice mentor but also for being a good friend ready to listen whatever it was a problem regarding the thesis or just a private talk. Thanks to all my friends that made my stay in Delft a great life experience. A special thanks goes to my family for supporting me through the entire master and to make it possible for me to study in one of the best universities in Europe. Thank you for believing in me even in the most difficult moments and to push me to always do my best.

Monica Moreo
Delft, November 2016

Abstract

In developing countries amputation surgeries are performed more often than in western countries due to a lack of medical knowledge and the prevalence of illnesses that have been defeated in the developed world. Only 5% of the amputees own a prosthesis because there are distribution and maintenance problems, as well as cultural issues surrounding the reputation of amputees, therefore only a few of the available devices are used. It is very important to have a prosthetic hand that resemble the real human hand to avoid discrimination and exclusion from the society. This is especially an issue for children due to the fast changing anatomy.

The aim of the project is *to develop a generalized 3D printable body-powered prosthetic hand design for children in developing countries that allows parametric design*. The advantages of parametric design is that it can be personalized for every user and every child can be fitted with a prosthesis that most resembles the size of his/her sound hand.

A statistical analysis has been conducted to understand which parameters are the best choice for a parametric design. Starting from 8 parameters, only four were found important to draw a prosthetic hand (grip circumference, palm breadth, thumb breadth and palm length), while the others can be connected to the main ones. It was possible to connect all the parameters, including the four main ones, to a single parameter (palm breadth). The design was done in Solidwork and it was connected to an external file that allows to change and adapt the design without needs to open the CAD file.

The hand is body powered and it is activated with a lever that, when pushed, closes the fingers. Elastic bands reopen the hand when the tension on the lever is released. The connection between the moving part (fingers) and the fixed part (palm and thumb) is a sliding curved joint, considered the best option due to the easiness of printing and similarity with a human hand. It was found that the best printing strategy is to print the device into 3 parts and then connecting it with glue and elastic bends.

The prosthesis was successfully 3D printed and it fulfilled all the requirements concerning price, weight and hand shape. The device is required to support a pinch force of 10 N and mechanical tests proved that it is able to provide force up to 35 N for a child of 13 years old. User testing showed that the hand is as functional as already existing devices and that it can perform daily activities. The main problem of the hand is the durability, which needs to be improved with studies regarding support and printing strategies. Future work is needed to design a 3D printable wrist and socket.

Contents

1

Introduction

1.1. Prostheses in developing countries

People with disabilities have more difficulties in reaching the appropriate care and in being accepted by the society. If this is a problem in developed countries, where technology and medical knowledge make it possible to overcome a lot of disabilities, it is even more problematic in developing countries, where superstitions, lack of material and human resources and limited medical knowledge leave most of the disabled without appropriate care.

Thanks to the advanced level of medical knowledge and technologies in western countries, amputation is rarely performed, while in developing countries it is a practice that is increasing. This is partly due to the increment of population but mostly because of the poor knowledge and experience doctors have, the time that it takes to patients to reach medical centers and the bellicose situation. Violence, traumas, diabetes, polio and the diffuse presence of landmines are considered to be the most common causes of amputations in developing countries [1–3].

The world health organization (WHO) estimated that there are about 40 million amputees in developing countries and that only about 5% of them has access to prosthetic devices [4]. One of the main reason is the difficulty in reaching specialized medical centers. In low-income countries there are only a few big cities and transportation from rural areas to the centers is complicated, expensive and may take many days. For this reason, amputees that come from villages either do not have access to prostheses at all or, if they are able to get one, they rarely go back to the centers for follow-up checks or to repair the prosthesis [5–7]. Furthermore in these centers there is a general lack of trained personnel able to provide the appropriate care [6, 8, 9].

The majority of the prostheses available in developing countries are second-hand prostheses given through non governative organziations (NGOs) from amputees in the developed world [4]. therefore prostheses easily break. Different studies show that up to 50% of the prostheses used needed to be repaired or changed [3, 5], the amputees complained repeatedly about mechanical failures and the high repair prices [6, 10, 11]. another problem related to second-hand prosthesis is the socket, which is not personalized. This creates a high level of discomfort, pain, and in some cases wounds [3, 5].

A limb deficiency in developing countries is often seen as a curse, a sign that the person in question is cursed or deserved to be punished for his/her sins therefore persons with disabilities are rejected from society. [6]. This create a spiral of poverty and ignorance that reduce the amputee's possibilities to have access to rehabilitation centers and/or appropriate care [6, 7, 9]. It is especially important in developing countries to have a prosthesis that looks like a real hand.

All the difficulties showed above are even greater for children. Due to their disability they are often excluded from schools which increases ignorance and prevent them from obtaining the appropriate care [7, 9, 12]. Therefore it is even more important for them to have a hand-shape prosthesis that resembles the sounds hand.

1.2. Problem definition

The challenge in developing countries is to make prostheses that are available, affordable and easy to manufacture, they also have to be accessible to everyone, considering both price and location. They have to be durable and they have to be easy to repair. They also have to be socially acceptable, therefore having a hand shape look, and, if possible, adaptable to local materials.

Most importantly, the design should be able to be adapted to different hand sizes, and to do so it has to be parametric. Parametric design, as defined by Jae Yeol Lee and Kwangsoo Kim, ”*allows designers to make modifications to existing designs by changing parameter values, thus making it possible for them to create shapes without knowing precisely how they will be configured in the final*”[13].

1.2.1. Research question

The question we aim to answer in this report is ”Is it possible to find the right parameters to make a parametric design of a prosthetic hand, that is able to adapt to the size of the child sound hand and that is functional and cheap?”

1.3. Goal

Develop a generalized 3D printable body-powered prosthetic hand design for children in developing countries that allows parametric design.

The age range for children is selected according to results found in literature, and it was chosen to be from 4 to 13 years old. Recent studies suggest that a child should be fitted with the first prosthesis before age of 2, to decrease the rejection rate [14, 15], but children are not usually fitted with an active prosthesis before the age of 4 since the muscle strength is not enough to operate the device [16]. Age of 13 was chosen as an above limit because there are no anthropomorphic data regarding children above 13 years available in literature. Also a study conducted in the Netherlands by Van Lunteren regarding an evaluation of below-elbow prostheses for children uses the same age range [17]. The age range has been defined according to the available data but, since the design is meant to be parametric, the prosthesis can be printed for every age and every hand size.

Since childhood is the time in which the body undergoes the biggest changes, design will be parametric. In this way every child can be fitted with a prosthesis that most resemble the size of his/her sound hand.

The prosthesis has to be body powered because, from a previous literature review it is clear that electric prostheses are not recommended in developing countries due to the high costs and the frequent maintenance required [18]. Myoelectric prostheses can produce a higher pinch force [19], can assure better comfort due to the absence of the harness and usually have a nicer hand-shape, however they are generally heavier, slower and they can produce discomfort in the fitting [19, 20]. Body-powered prostheses are the most commonly prescribed as a first active prosthesis for children [14, 16].

The hand should be 3D printed so that the production costs are limited and the device should be designed in such a way that is easily assembled.

1.4. Thesis project

This thesis is part of a PhD project named ”Access to prosthetics thanks to 3D printing and smartphone app”. The entire project consists in a smartphone app which scans the sound hand of the amputee, elaborates the image and determines the measures of the hand, these data is then sent to a CAD modeling software that automatically design a hand, which will then 3D printed. The project is meant particularly for Colombia. As part of a the project, also this thesis focuses on Colombian children. Therefore, when possible, choices are made considering that the prosthesis will be used in Colombia. No anthropomorphic data or studies about the use of prostheses in Colombia are available in literature, therefore the requirements regarding the prosthesis functions and size are based on Dutch literature.

1.5. Layout of the report

- **Chapter 2** lists the requirements of the project and explains why they have been selected. It is divided into prosthesis design, parametric design and 3D printing.
- **Chapter 3** contains a small literature review regarding already existing 3D printing prosthesis, it summarizes the different concepts that have been analyzed and it explains the final choice.
- **Chapter 4** describes the design process of the final prototype. First the hand parameters have been evaluated and analyzed through statistical analysis, the printers and the materials have been chosen and the the moving principle defined. Eventually the printing strategy has been defined.
- **Chapter 5** explains the set-up and the test approach of the mechanical and user tests, conducted to check durability, pinch and activation force and functionality.
- **Chapter 6** explains how the device has been evaluated according to the requirements defined in Chapter 2. Statistical data have been checked to assure the final measurements of the device are comparable with the one of a real hand. The results from the mechanical and user tests are shown.
- In **chapter 7** the tests results are analyzed and the week points of the project are commented.
- **Chapter 8** presents the conclusions of the project and some recommendations for the future.

2

Design Approach and Requirements

2.1. Methods

Literature regarding child prostheses, 3D printing and parametric design was read in order to find the best requirements the prosthetic hand should have to meet the goal.

2.2. Upper limb prosthesis

A study conducted in the Netherlands by A. van Lunteren has been used as a base to find the best hand requirements [17]. In his research, the researcher evaluated the use of prostheses among Dutch children. He reported all the activities the children perform, the way in which each activity is preformed (with or without prosthesis, in an active or passive way) and he defined some design guidelines for future prostheses. Since no similar studies regarding the use of prostheses in children in Colombia or in developing countries have been found the study of Van Lunteren was used to define the hand requirements.

Prostheses are usually analyzed considering three main aspects: control, cosmetics and comfort [21]. Control and function will be divided into two separate sections.

2.2.1. Functions

Unilateral upper-limb amputees most commonly use the prosthesis in a passive way, meaning that the child uses the sound hand to manipulate the object and the prosthetic device to hold it. Most of the actions done in an active way are bi-manual tasks, as getting dressed or brushing teeth. The most common actions executed by children can be performed in two ways: using cylindrical grip or using tip grip [17]. Cylindrical grip is defined as the grip used in activities that require holding an object and manipulating it, such as moving a bottle of water or riding a bike. Tip grip is related to all the actions where a small object is hold between the index and the thumb, like, for example, using a pencil or tying the shoes. Figure 2.1, (taken from a study of Kita et al. [22]) shows and explains the difference between cylindrical grip and tip grip. In the study they are defined as cylindrical grasp and tip pinch grasp.

The user has to be able to perform these two kind of grips with the device. The third most used type if grip is the hook grip, or the grip used to carry a object for a long time, like a toy or a suitcase. Because, as stated in Van Lunteren study, this grip is used only in few activities, the ability of the prosthesis to perform it is considered additional. The grip force needed for most of the children's daily activities is considered to be 10N [17].

The minimum opening width was found to be 35mm (enough to ride a bike). Some children asked for an opening of 45mm to be able to perform some gymnastic activities like grasp the bars of a climbing frame [17].

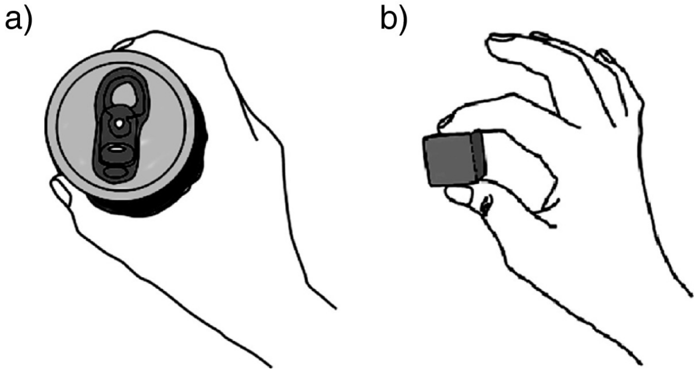


Figure 2.1: *Cylindrical grasp task and tip pinch task. a) The fingers and thumb close and flex around the object in the cylindrical grasp task. b) The tip of the thumb is pressed against the tips of other fingers. In tip pinch training, the patient was asked to pinch a small cube between the tips of the thumb and index finger.* [22]

2.2.2. Control

There are two ways to control a body powered prosthesis: by the elbow or the shoulder. A body-powered prosthesis controlled by the elbow has the advantage of being more comfortable and is easier to wear, but the range of motions of the arm will be reduced and the child will loose one degree of freedom [17, 23, 24]. Van Lunteren indicated that the prehensor functions (number of actions in which the child uses prehension) of a elbow-controlled prosthesis are used less than for a shoulder controlled or a myoelectric prosthesis therefore the prosthesis will be operated with the shoulder. There are different movements that can be used to operate body powered hand prosthesis controlled by the shoulder, including gleno-humeral flexion, bilateral or unilateral scapular abduction and elbow flexion control [25].

Body-powered prostheses can be divided into voluntary-opening (VO) and voluntary-closing (VC) ones. VO hands are normally closed and they open when the cable is pulled; VC prostheses work in the opposite way. Both hands have their own advantages and disadvantages but a study conducted by Shaperman in 1995 proves that VO prostheses are not feasible for young children [26]. Many other studies show the advantages of having a VC prosthesis rather than a VO one: lower energy losses and lower activation force needed and it allows grip force control [17, 27, 28].

The main drawback of a VC body-powered device appears when the user has to carry an object for a long time. While with a VO prosthesis the muscles can relax and the hand will automatically close around the object, for a VC prosthesis the user has to keep the muscle in tension in order not to drop the object. A solution for this problem is the use of a locking mechanism, which will block the cable in tension and the muscles can be relaxed. Even if children do not usually have to carry objects for a long time (there are almost no activities that involve hook grip in the research by Lunteren [17]), having a locking mechanism will improve the device's efficiency. Not having to concentrate on the muscle's contraction while holding an object decrease the risk of breaking it or letting it fall, at the same time it reduces muscle fatigue.

The last feature that a prosthesis can have is the possibility of rotating the wrist. In Lunteren study [17] all the children involved had a passive wrist but most of them did not use it. Therefore a passive wrist is not considered mandatory in the device's design.

2.2.3. Cosmetics

In developing countries it is considered very important to have a device that resembles a human hand to be accepted in the society, even up to the point that some amputees prefer to have a passive hand-looking device rather than an active hook or prehensor. [18]. These are the reason why the prosthesis designed in this project will have a hand shape although hooks are proves to work better than hand devices [19, 27, 28]. The final hand should have measurements included between the 25th and the 75th percentile of the sound hand measurements of the same age group.

2.2.4. Comfort

This study is strictly related to the terminal device and it does not involve the study of a socket. The comfort does not concern the pain related to the prosthesis fitting but the total weight of the prosthesis. A prosthesis is an external body and it will feel heavier even if the weight is the same as a human hand. The main requirement for the prosthesis is to have a weight lower than the child's hand (which is about 5% of the total weight [29]) The ultimate goal is to produce a prosthesis which is lighter than all the other existing devices. The lightest available 3D printed hand prosthesis for children is called Cyborg Beast Hand and it weights 131g for a 3 years old child [30].

2.2.5. Additional requirements

Having a low cost device is a main requirement in order to be used by children in Colombia. Body powered prosthesis for developing countries have a material cost around 50€ [18]. It is the aim of this project to have a device with material costs lower than existing prosthesis. Since only few children would have the opportunity to go to a rehab center for check up visits or rehabilitation, the prosthesis has to be durable, intuitive and very easy to use. To define better the word durable, a study conducted by Kuiper et al, in 2001 has been used as reference [16]. The study shows that a child is usually fitted with 3 prostheses in the first 10 years of life, and each prosthesis is used in average 3.8 years. Therefore the prosthesis should last around 4 years to be competitive with the already existing ones. It has to be as functional as possible, which means that children can do as many tasks as possible, even if the tasks performed by children do not usually require the same precision as the ones performed by adults. Adaptive fingers or additional features which can be useful in Europe, are considered an optional in this case.

2.3. 3D printing

The prosthesis should have little or no assembly, so that it is easier for the user to build it. There are different kinds of technologies that allows 3D printing. A review of 3D printed hand prostheses shows that the 3 most common technologies used are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Selective StereoLithography Apparatus (SLA) [31]. A small comparison has been made between these three technologies. FDM consist in a fused plastic filament deposition. The model is built from bottom up and it only allows to print simple shape objects. In case of a complex geometry support material is needed. FDM printers are the cheapest printers and they are meant to be used by single costumers. SLS is based on a laser which melts powder to build a solid structure. The powder that is not melted is used as structural material and it can be easily removed after printing. SLS printers are significantly more expensive than FDA ones and they are used in professional or industrial environments. SLA uses liquid resins that is solidified layer by layer. When the prototype is ready the rest of the liquid resin can be washed away. The main disadvantages are the price of maintenance of the printer and the material cost. In addition, resins are not easy to handle and be printed. [32–34]. FDM was chosen as the preferred printing technology for the project, mainly for the low price and easiness of use. The printer should be easily available and intuitive, the quality to price relation should be high.

The device material should be easily printable, it should be mechanically resistant and, considering that the device will be used in developing countries, it should resist to temperature up to 45°. The selection will also depend on the printer since different printers are optimized for different materials.

2.4. Parametric design

The hand design will be generated using Solidworks, which allows to relate different parameters thanks to equations and global variables. To facilitate the prosthetist work and to make it easier to modify the solidwork files, if possible, all the parameters used to design the hand should be related to a single one. Statistical analysis should be conducted to check the correlation relationship between parameters.

2.5. Summary

In summary the prosthesis should have the following requirements:

GENERAL

- Target population: Colombian children 4-13 years old
- Body-powered
- 3D printable

UPPER LIMB PROSTHESIS

1. FUNCTION
    - Performing cylindrical and tip grip (optional hook grip)
    - Required grip force 10N (goal 15N)
    - Required opening width 35mm (goal 45mm)
2. CONTROL
    - Operate with a shoulder harness
    - Voluntary closing mechanism
    - Locking cable
    - Optional: passive wrist
3. COSMETICS
    - Hand shape prosthesis
4. COMFORT
    - Weight less than 5% of the child's total weight (goal: weight less than 131g)
5. ADDITIONAL
    - Low price (material costs below 50€)
    - Durable (4 years)
    - Intuitive and easy to operate
    - As functional as possible

3D PRINTING

1. PRINTER
    - FDA technology
    - Easily available
    - Intuitive
    - High quality/price relationship
2. MATERIAL
    - Easily printable
    - Cheap
    - Durable and mechanically resistant
    - Resistant for temperature above 45°

PARAMETRIC DESIGN

- Software: Solidworks
- Parameters: all related to a single one

3

Concepts Design

3.1. Previous design concepts

Already existing 3D printable upper limb prostheses have been studied to see if any of them matches the requirements listed in chapter 2.

A literature review done in TU Delft was used as a starting point to check the already existing devices [35]. 58 3D printable prostheses have been analyzed in the review. Out of these, 32 devices are body-powered 14 of which are meant for below-elbow amputations. As indicated in the requirements, an adaptive fingers is not required for this specific design, therefore there are only 8 prostheses left that meet the main requirements. The prostheses, the way they are controlled and the manufacture companies are listed in Table 3.1. All the designs are operated by cables and they allow the movements of both fingers and the thumb. They all have a hand-looking shape but the design reminds more a bionic arm rather than a natural arm as it can be seen in Figure 3.1.

All the prostheses require high levels of assembly, which goes against the requirements of this project. Most of the prostheses can not produce enough grip force due to the position of the thumb. Flexy arm is built with two different materials, which may produce a difference in color and/or in texture, decreasing the cosmetics of the device. In conclusion none of the already existing devices meets perfectly the requirements.

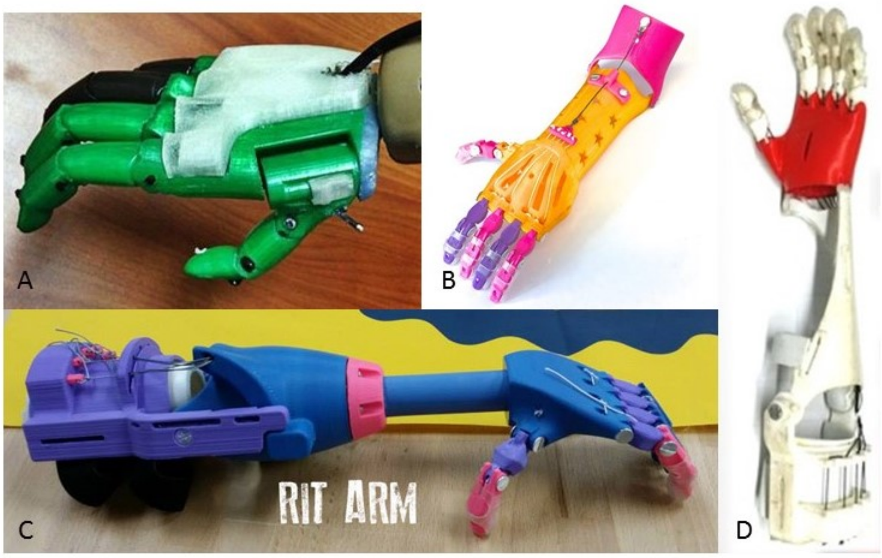


Figure 3.1: Example of already existing devices: A) Galileo Hand [36], B) Cyborg Arm [30], C) Rit Arm [37], D) Flexy Arm [38]

Table 3.1: Available 3D printed, body-powered, below-elbow devices

Name	**Operated by**	**Design by**	**Features**	**Ref**
Cyborg Arm	Elbow	Cyborg beast	Composed by a lot of different parts, assembly required. Thumb and index perpendicular to each other, not enough grip force.	[39]
Flexy Arm	Elbow	Gyrobot, RIT, E-Nable	Printed with different materials, fingers with flexy material, palm and forearm in PLA. Require assemble.	[38]
Flexy Hand	-	Gyrobots	Uses flexible filaments to replace joints. When the hand is closed thumb and index do not touch. It doesn't allow pinch force	[40]
Flexy Hand filaflex remix	Elbow	Gyrobot, RIT, E-Nable	Composed by six parts (fingers+palm) Fingers printed with a flexible material, it allows fingers to bend and adapt to the object. Thumb and index perpendicular to each other, not enough grip force.	[41]
Not impossible	Elbow	Not impossible	High level of assembly, Similar to Cyborg Arm.	[42]
Galileo Hand	Shoulder	-	Requires screw and screwdrivers for assembly. There are no videos that prove the functionality of the hand.	[36]
RIT Arm	Elbow	E-Nable	A lot of assembly required. Thumb and index perpendicular to each other, not enough grip force.	[37]

3.2. Design concepts

Eight new design concepts have been developed. They will all be presented and discussed below. Note that concepts 1 to 3 are design to have a movable thumb but the same working mechanism can be applied to a design with movable fingers. All the concepts are shown in Figure 3.2, a sketch of the prosthetic hand, on the left, and, on the right, a mechanical scheme of the working principle are shown for each concept.

Concept 1: flexible hand

The hand device consists of a single piece made with flexible material with a stiffer lever inside. When the lever is pushed the flexible material bends and the thumb closes. The device will be printed with a flexible material that allows the palm to bend. The flexibility of the material is used to re-open the hand that is closed when the lever is pushed.
ADVANTAGES: The closing mechanism resemble the movement of the real hand thanks to the flexible material that bends in a way similar to the skin.
DISADVANTAGES: The flexible material has a non-linear behavior which is difficult to predict. The entire hand will be printed with flexible material so additional screws or metal pieces are needed to support the lever and the thumb and prevent unwanted movements.

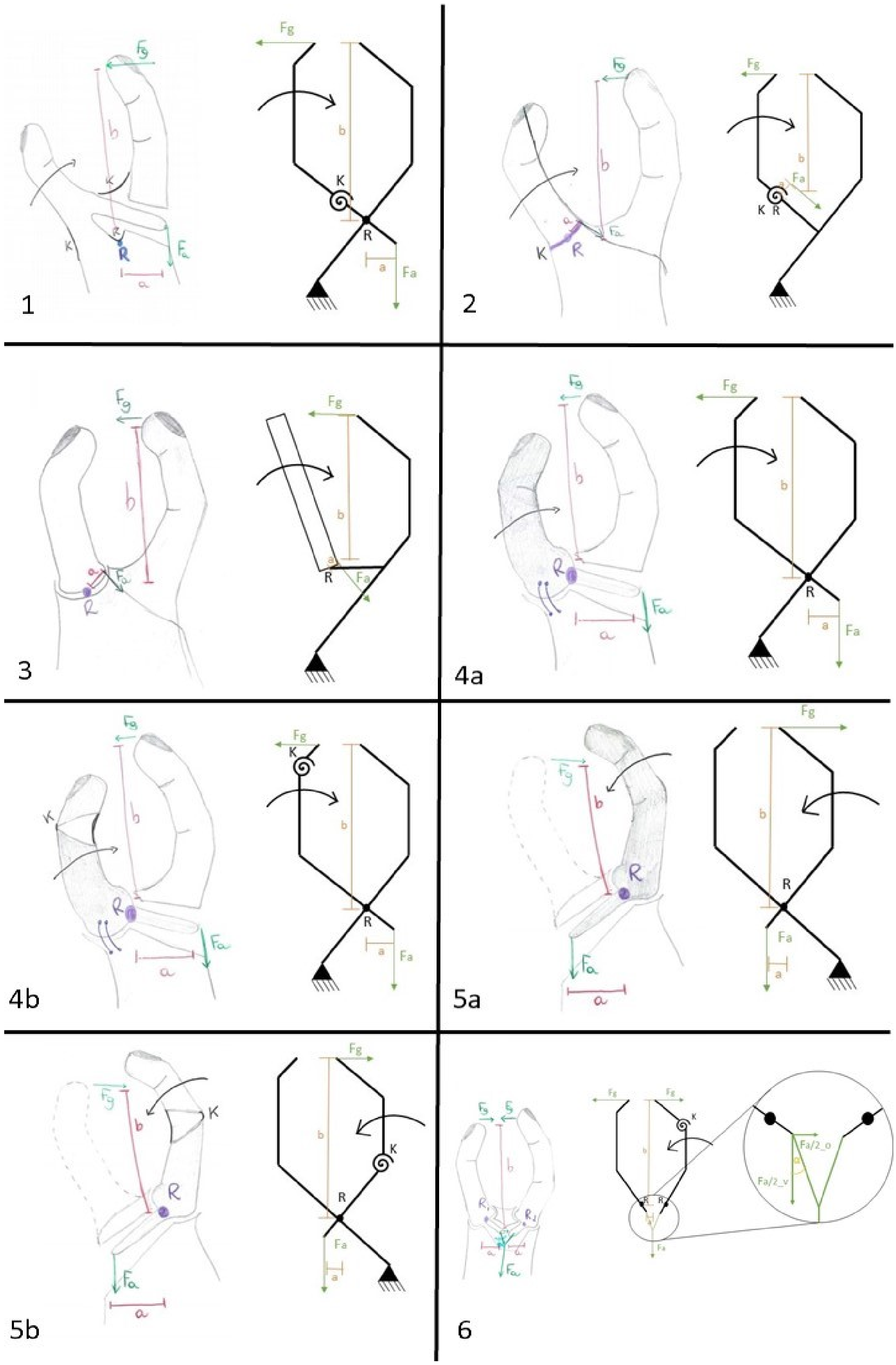


Figure 3.2: **Concept 1**: flexible hand; **Concept 2**: cable flexible hand **Concept 3**: rotational thumb; **Concept 4a**: rotational lever thumb **Concept 4b**: flexible rotational lever thumb; **F** Concept 5a: rotational lever fingers **Concept 5b**: flexible rotational lever fingers; **Concept 6**:rotational thumb and fingers
$\mathbf{F_g}$= grip force, **b**= F_g arm, $\mathbf{F_a}$= activation force, **a**= F_a arm, **R**= rotational point, **K**=stiffness of the flexible material.

Concept 2: cable flexible hand

The hand consists of 3 different parts: the movable part (fingers or thumb), the fix part (the palm) and a connection made by flexible material. The device will be printed with a rigid material, while a flexible material will substitute the thumb join and it will connect the thumb to the palm. The concept remembers the flexible joints of *Flexy Hand* [40]. The thumb is closed with a rope and it opens again thanks to the flexibility of the joint.
ADVANTAGES: the concepts uses a flexible material to reopen the joint, therefore there is no need for elastic bends.
DISADVANTAGES: the hand is printed with two different materials which will increase the time and costs of the hand. The behavior of the flexible material is difficult to predict.

Concept 3: rotational thumb

Concept 3 is similar to concept 2, with the difference that the thumb is attached to the palm thanks to a rotational joint, which allows movements only in the direction of the other fingers (no lateral movements).

A simple force analysis was made to check the functionality of the concept. The design has to be parametric, therefore it should work for all ages between 4 to 13 years and both for males and females. For this preliminary calculation the prosthesis was assumed to be designed for 4 year old girls. This is because they are the users with smaller hands and lower muscle strength. It can be assumed that if the concept works for young users it also work for older and stronger users.

It has been proved in a pilot study by Shaperman in 1992 that children with an amputation have lower force on both limb deficient and sound side [43]. In the study it is shown that for shoulder flexion and abduction none of the children has a strength above the 15th percentile of healthy children. Therefore the force values have been taken from a study conducted specifically on children with arm defects [26]. The force used in the calculation is 50% of the maximum force, which has been calculated to be the maximum force recommend for repetitive actions to avoid fatigue [44] . The measurements of the hand have been taken from DINED, and online database created by TU Delft that contains anthropomorphic data [45]. All the calculations for the following concepts have been made with the same data.

As it can be seen in Figure 3.2 the distance between the rotation point and the force application (the force arm) is limited to a length equal to the thumb width.

Basic calculations have bee performed to test the hand. If we consider the equilibrium of momentum on the thumb taken at the rotational point we obtain the following equations:

$$\mathbf{F_a} * \mathbf{a} = \mathbf{F_g} * \mathbf{b} \rightarrow \frac{\mathbf{F_a} * \mathbf{a}}{\mathbf{b}} = \mathbf{F_g} \tag{3.1}$$

where:
F_a is the available force produced by the shoulder abduction; The force in Shaperman study, expressed in Kg, has been turned into Newton. The force obtained is then divided by 2 as suggested in Monod study [44]

- $\mathbf{F_a}$ = **2.8 kg*9.8 (m/2^2) /2 = 13.7 N**

a is the arm of F_a which is equal to half of the thumb breadth

- **a = 6.5 mm**

F_g is the grip force and it should be at least 10 N as specified in the requirements

- $\mathbf{F_g}$ **= 10 N**

b is F_g arm, which is approximated as the the hand grip diameter

- **b = 24.1 mm**

Solving equation we obtain that $\mathbf{F_g}$ = **3.7 N** which is below the requirements.
ADVANTAGES: the concepts does not use any flexible material, therefore the behavior of the hand is linear and the grip force is directly proportional to the force used to activate the hand.

DISADVANTAGES: due to the geometry of the hand the force the muscles need to exert to obtain a grip force of 10N is too high for children.

Concept 4a: rotational lever thumb

Concept 4a is the evolution of concept 3. In order to be able to produce enough grip force, a larger arm is needed. To assure it, a lever is added to the thumb, and the force is applied at the end of it. The maximum lever size depends on the geometry of the hand. Elastic cords will be used to reopen the hand. A simple force analysis was made to check the functionality of the concept, as it was done for the previous one.

Calculations for this concept are very similar to the one done for concept 3, with the difference that the length of arm a has now increased.

$$\mathbf{F_a * a = F_g * b \rightarrow \frac{F_a * a}{b} = F_g} \tag{3.2}$$

where:

- $\mathbf{F_a}$ **= 2.8 kg∗9.8 (m/2^2) /2 = 13.7 N**

a is the arm of F_a which is equal to the width of the hand when the thumb is positioned in front of the index and middle finger. The value was assumed to be at least as the sum of the hand thickness and the thumb breadth

- $\mathbf{a= (17 + 13)mm = 30\ mm}$
- $\mathbf{F_g}$ **= 10 N**
- **b = 24.1 mm**

Solving the equation we obtain that $\mathbf{F_g = 17N}$ which is higher than the required one. The concept could work.
ADVANTAGES: the user can obtain enough grip force.
DISADVANTAGES: In the natural grasping the fingers move more than the thumb. therefore, the moving principle of this concept does not resemble the one of a real hand.

Concept 4b: flexible rotational lever thumb

Concept 4b uses the same moving principle showed in concept 4a, but a flexible joint is added at the tip of the thumb. This feature will assure a better grip shape when a large object is grasped and it also guarantees a higher opening width. In order to print a flexible joint the entire hand has to be printed with the same flexible material. For the preliminary calculations the material ninjaflex was considered.

Calculations regarding this concept are very approximated due to the limited knowledge about the material mechanical properties. The data has been taken from the material's technical data-sheet [46], but the strength module is given only at the yield and at the breaking points. Since the material is estimated to elongate about 100% of the initial value, the strength value at the yield at the yield point was used.

The final grip force is a combination of the force given by the lever and the force needed to bend the thumb. In order to have a grip force of 10N on the tip of the finger F_a should be at least 7.8N. The force was calculated using the same data as for concept 4a. The force needed to bend the finger is harder to calculate. For a rotational elastic material the force is given by the following formula:

$$F = M * \theta \tag{3.3}$$

where:

- F= force
- M=rotational stiffness
- θ is the angle of rotation

The data available on the material data-sheet does not allow to calculate the value of M. It is possible to calculate the force assuming that the displacement is linear. In this case equation 3.3 will become:

$$F = K * \Delta L \tag{3.4}$$

where:

- F= force
- ΔL is the elongation of the material
- K=linear stiffness

Linear stiffness is calculated with the following formula:

$$k = \frac{E * A}{L} \tag{3.5}$$

where:

- E= material young module
- A= area of the material
- L= initial length

As it can be seen from equation 3.5, the final force needed to bend the thumb is highly dependent on the geometry of the thumb joint. For a preliminary analysis the area of the joint can be estimated to be rectangular with the thumb breadth as a the base (13mm) and a fifth of the thumb breadth as the height. The young module of Ninjaflex is 12MP. The final length of the joint is estimated to be twice the initial length.
Using the data above the stiffness **K** is estimated to be around **52 N/mm**. A young child does not have enough force to bend the thumb.
The calculations show that the gripping force is highly dependent on the joint geometry, and therefore, in order to prove the functionality of this idea a more precise study of the material and a better analysis of the thumb geometry are needed. Even then, due to the high stiffness of the material, the concept will probably not work for young children.
ADVANTAGES: having a flexible thumb assure a higher opening width.
DISADVANTAGES: the force seems to be too high to be operated by children. The moving principle does not look natural, as explained in concept 4a. The entire hand will be printed with flexible material so additional screws or metal pieces are needed to support the lever and the thumb and prevent unwanted movements.

Concept 5a: rotational lever fingers
Concept 5a is the same as concept 4a but instead of a having moving thumb it allows the movements of the fingers.
ADVANTAGES: while grasping an object, moving the fingers gives a more natural impression. In addition a passive moving thumb can be designed, which allows tip and cylindrical grip when it is positioned in front of the fingers, and hook grip if it is positioned next to the index, as when the hand is fully open. The concept calculation is the same as the one showed for concept 4a. Even a small child will have enough force to generate a grip force of 10N
DISADVANTAGES: the concepts does not have adaptive fingers.

Concept 5b: flexible rotational lever fingers
Concept 5b uses the same working principles of concept 4b but the mechanism is shifted to the fingers.
ADVANTAGES: the concept has adaptive fingers, which gives a more natural look at the movements and they can adapt to the shape of the object.
DISADVANTAGES: the force required to bend 4 fingers is about 4 times higher than the one needed to bend the tip of the thumb, therefore the concept is expected not to work. The entire

hand will be printed with flexible material so additional screws or metal pieces are needed to support the lever and the thumb and prevent unwanted movements.

Concept 6: rotational thumb and fingers
In this concept both the fingers and the thumb are movable, using the same mechanism proposed for concept 4 and 5. The two levers are connected with one single rope, therefore they move simultaneously with the same force. The hand re-opens thanks to elastic cords.
ADVANTAGES: since both fingers and thumb are moving the initial opening width can be higher.
DISADVANTAGES: the same force that in the previous concepts is used to operate one single lever is now used to move two levers, therefore the final grip force will be half of the one obtained in the previous concepts.

3.3. Final concept

Eight concepts have been illustrated and explained. The main constrain in the design of the working principle is the device's, which is required to fit inside the measurements of a real hand. All the concepts have the potential to work if the geometry of the working mechanism is changed.

- Concept 1 and concept 2 use as main movable principle a flexible material. Due to the fact that it is difficult to predict the behavior of a non-linear elastic material and to overcome the influence of the non linear stiffness, these concepts are not considered suitable for the thesis purpose [47].
- Concept 3 is not suitable for children due to the high force required to move the thumb.
- Moving the fingers is considered more natural so concepts 4a and 4b have been excluded.
- Concept 5b is not suitable for children due to the high force required to operate the flexible part of the fingers.The hand needs to be fully printed with flexible material there is the need of additional rigid material to prevent unwanted movements in the thumb and in the lever.
- Between concept 5a and concept 6, concept 5a is preferred because it is able to provide higher grip force. Moreover it can allow hook grip if a passive thumb is added. The final concept and the moving principle are shown in Figure 3.3

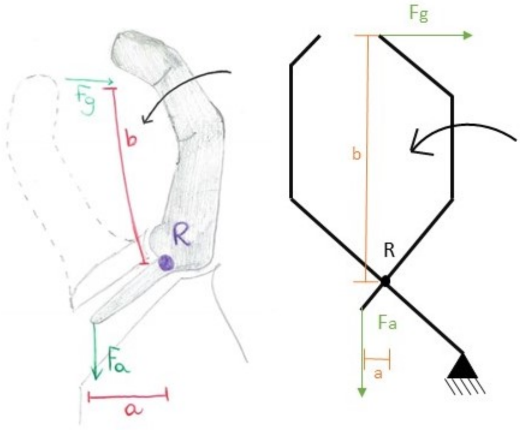


Figure 3.3: Concept 5a: rotational lever fingers

4

Final Design

4.1. Design and Parameters

4.1.1. Parameters choice

The main goal of this project is to develop a hand prosthesis that allows parametric design. The parameters used were taken from a database created at TU Delft from a research project known as KIMA, in which different anthropomorphic measures of 279 dutch children have been collected, among which the following 8 hand parameters have been taken [45, 48]:

1: Middle finger length

2: Hand breadth without thumb

3: Pink breadth

4: Hand length

5: Thumb breadth

6: Hand thickness

7: Grip circumference

8: Hand diameter: *Minimum diameter of the hand, when in its smallest configuration*

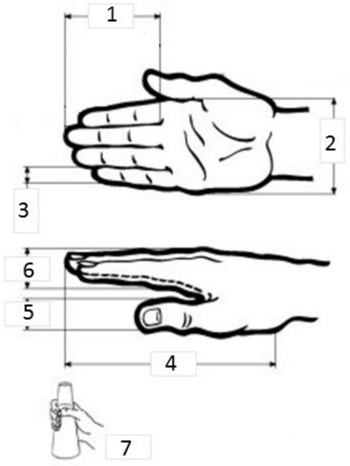


Figure 4.1: Available hand parameters [45]

The first design step was to decide which parameters are really needed to design a prosthetic hand and which ones are redundant. This step is very subjective and depends on how the hand is drawn. Considering that for this specific project the hand is mainly needed to perform tip and cylindrical grip, it was decided to start drawing the hand imagining it while performing a tip grip, so the **grip circumference** was used as the starting parameter. It is important to understand how the fingers close and which is the maximum object size a hand can grasp. The hand was drawn around a circle as shown in Figure 4.2. The circle has the measure of the grip circumference of a 4 years old girl. The hand has been connected to the circle so that when the parameter grip circumference changes also the hand scales according to it. 2 parameters have been related to the grip circumference, as shown in Figure 4.2: the hand thickness and the middle finger length.

The **palm breadth**, or as described in the parameters presented above, the **hand breadth without thumb** was the second parameter used for the hand design. It was needed to define the total breadth of the hand. The breadth of the fingers followed from this parameter. Since

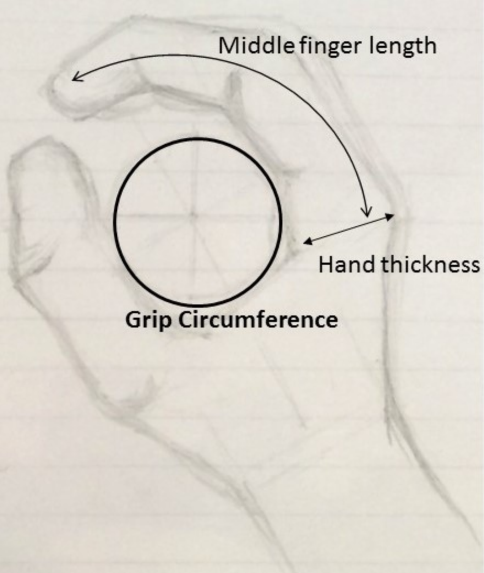


Figure 4.2: This Figure shows the sketch used to design the hand, using the grip diameter measure as starting point and the related parameters

only the value of the pink breadth, or little finger breadth, is available, the other three fingers breadth were estimated considering the total palm breath minus the pink breadth, or little finger breadth. the result was divided by three and adjusted so that the middle finger breadth is slightly larger than the other two fingers. The last two parameters considered important to complete the design are the **thumb breadth**, needed to define the shape of the thumb, and the **palm length**, which is defined as **hand length minus middle finger length**. Figure 4.3 shows how the 3 parameters have been used while sketching the design in Solidworks.

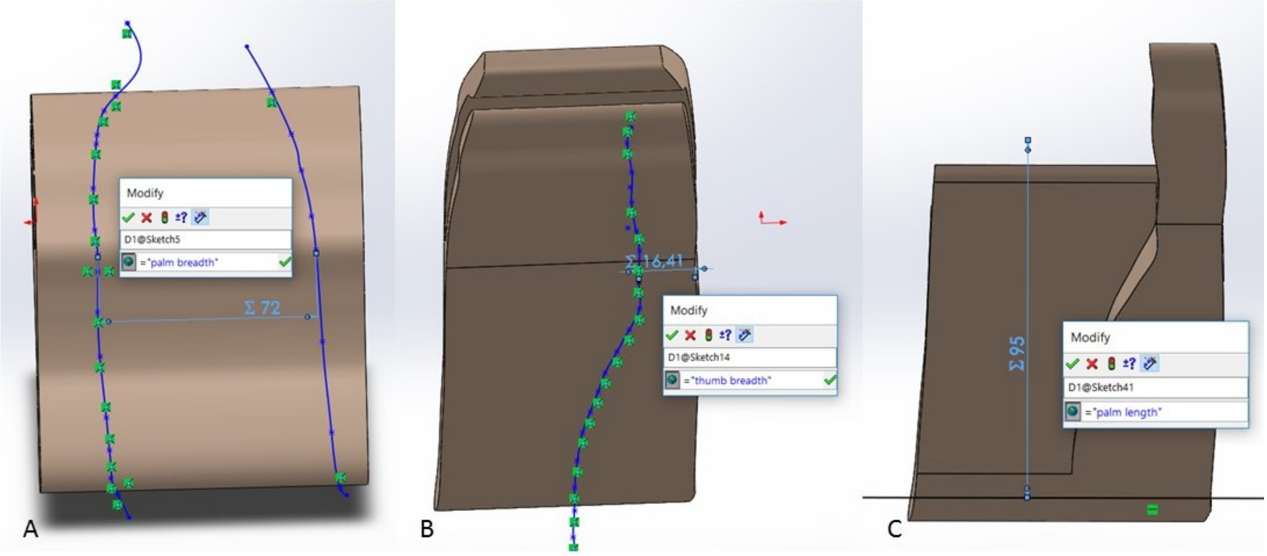


Figure 4.3: **A** profile of the back of the hand using the palm breadth as main parameter. **B** design of the thumb profile using thumb breadth as main parameter. **C** determine the length of the hand using palm length as main parameter

4.1.2. Parametric correlations

Parametric correlation using the grip diameter

A correlation analysis has been conducted, based on the data in the DINED database [45], prove that the grip circumference is related to the middle finger length and to the hand thickness. The correlation coefficient between the middle finger and the grip circumference resulted to be **0.89**, while the correlation coefficient between the hand thickness and the grip circumference resulted to be **0.57**. Figure 4.4 shows the relationship between grip diameter, middle finger length and hand thickness. It is evident that grip diameter and middle finger length have a linear relationship, as it is underlined by the high correlation coefficient. The relationship between the grip diameter and the hand thickness is less linear but the correlation coefficient is still higher than 0.5 so it was considered high enough to assume a linear relationship.

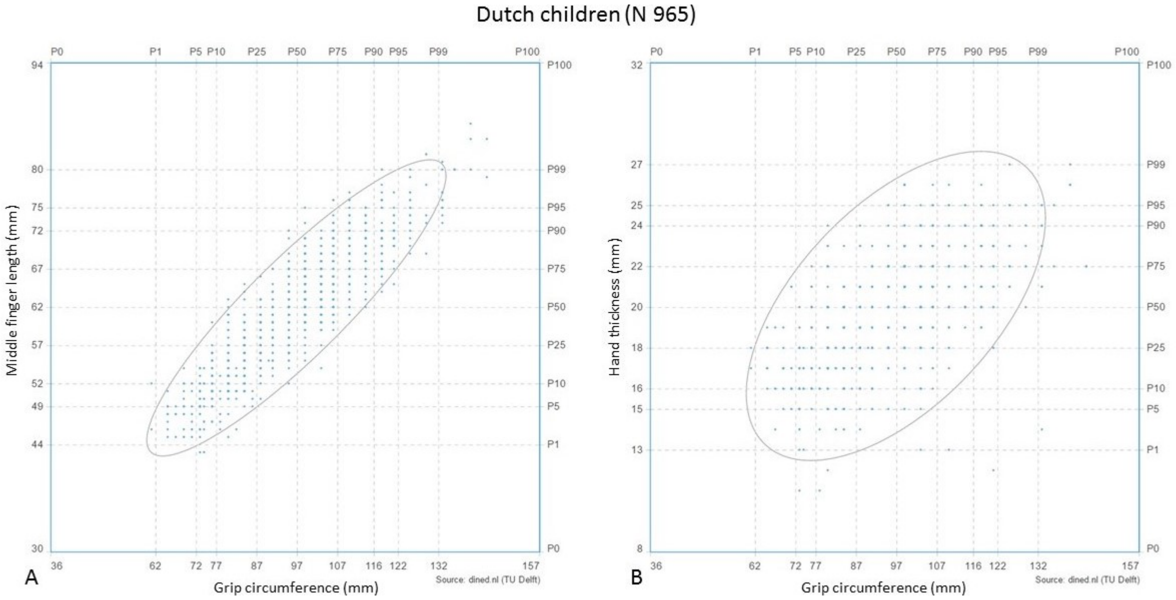


Figure 4.4: Correlations between the grip circumference and middle finger length and hand thickness. It is evident the high linearity between the grip circumference and the middle finger length. The correlation with the hand thickness is lower but it is still higher than 0.5

Parametric correlation using the grip diameter

The same analysis was conducted to investigate the relationship between the palm length and the little finger breadth. The correlation coefficient is only **0.31**, but this may be due to the fact that the instrument used to take the measurements has a sensitivity of $1mm$, which is negligible for measures like the palm breadth or the middle finger length that have a minimum size of $4cm$, but it becomes quite relevant for measure such as the little finger or the thumb breadth which are around $1cm$. In the last two cases an error of $1mm$ is translated in an inaccuracy of 10%. Figure 4.5 shows the relationship between the palm length and the little finger breadth.

Parametric analysis

The main question after deciding the parameters is: how can we obtain these parameters? The target of the project are children in developing countries, and, as it is shown in a review about prostheses in developing countries [18], one of the main problems is reaching the rehabilitation centers. 3D printing a hand may take up to 32 hours (depending on the size) which means that the amputees and their families have to stay in the city for 3 days, paying for hotel and food. This option is too expensive for most of the amputees in small villages, and thus a solution should be found. A possible alternative is using a scanning app from the phone and send the the scan to the rehab center, but since the way the app will work is not known yet it was not possible to make any assumption regarding this hypothesis. Another possibility would be to call the rehab center and give them the information they need and then reach the city only to the prosthesis or the prosthesis can be delivered home. For this hypothesis it is important to ask ourselves how easy it is to take hand measurements for someone that is not trained. A small experiment has been conducted to determine how easy it is to measure specific parameters. The same parameters as the one measured in

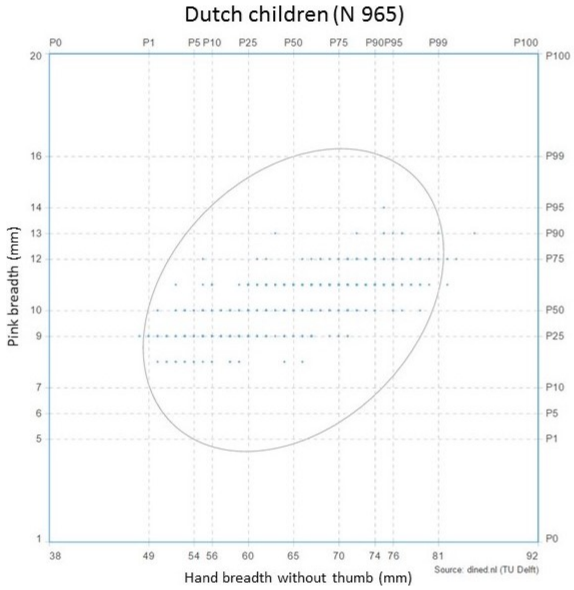


Figure 4.5: low correlation between palm breadth and little finger breadth, most likely due to the low sensitivity of the measurement instrument

DINED database have been measured in 20 adult subjects using a simple measuring tape. It resulted that not all measurements are intuitive, especially the finger and thumb breadth can be complicated due to the anatomy of the fingers and the different stiffness in different points. To measure the grip diameter a special tool with a cone shape is needed. In order to avoid mis-interpretation of the parameters and to avoid the use of extra tools not available to common people, it was decided to connect the four parameters used for the design to a single one.

Three options have been considered to choose the main parameter

- Age
- Stature
- One of the hand parameters

A correlation analysis has been run to check which parameter had the higher correlation coefficient. The results for children are shown in Table 4.1 and in Table 4.2 for adults (20 to 94 years old). Adults are also included in the statistical analysis because, even if the requirements have been thought for children, the design is parametric, and, therefore, it is possible to scale the hand also for adults.

The same experiment mentioned above has been used to choose which hand parameters are suitable to be used as main one. After measuring the hand of 20 adult subjects the two parameters it was found out that it is easier to measure the palm breadth (defined as *the distance from the radial to ulnar side of the hand, measured at the distal extremities of the metacarpals* [45]) and the middle finger length (defined as the *distance from the skin crease at the middle finger to the tip of the middle finger, parallel to the long axis of the middle finger* [45]). The parameter chosen as the main one was the palm breadth due to the higher correlation coefficient with the other 4 parameters used to draw the hand, has shown in Table 4.1. The parameters have higher correlation during childhood than adulthood, so it is better to only use the design for children.

As it can be concluded from Table 4.1 the correlation coefficient of the little finger breadth is low compared to every other parameter. It is considered very difficult for an uneducated person to measure the little finger accurately, due to the shape of the finger and to the sensitivity of the instruments available. Therefore, the little finger breadth was decided to be estimated in relationship with the palm breadth, as explain in paragraph 4.1.1.

Table 4.1: summary of the correlation coefficients of the design parameters with the options for main parameter for children (4-13 years old)

	Middle finger length	**Palm breadth**	**Age**	**Stature**
Palm breadth	0.904	1	0.875	0.921
Palm length	0.970	0.921	0.923	0.968
Thumb breadth	0.787	0.845	0.766	0.816
Grip circumference	0.910	0.832	0.856	0.893
Little finger breadth	0.284	0.310	0.198	-0.036

Table 4.2: summary of the correlation coefficients of the design parameters with the options for main parameter for adults (20-94 years old)

	Middle finger length	**Palm breadth**	**Age**	**Stature**
Palm breadth	NA	1	0.147	0.340
Palm length	NA	0.541	-0.003	0.596
Thumb breadth	NA	0.539	0.345	0.041
Grip circumference	NA	0.197	-0.218	0.517
Little finger breadth	NA	NA	NA	NA

The thumb breadth, the grip circumference and the palm length have been related to the palm breadth using the equation of the straight line that better fits the relation between the parameters. Figure 4.6 shows the correlation between the parameters and the straight line which approximates the correlation. It is easily notable that the relationship between the thumb breadth and the palm breadth is not quite linear but the maximum error is still less than a standard deviation (at least 50% of the predictions of future observations are contained in y ± 0.3mm, the maximum error is less than y ± 0.3mm). In case a perfect fit with the hand is wanted, the real thumb breadth can be inserted in the Solidwork design.

The relationship between the palm breadth (PB) and the grip diameter (GD), the thumb breadth (TB) and the palm length (PL) for girls is expressed by the following equations:

$$GD = 2.141 * PB - 41.880 \tag{4.1}$$

$$TB = 0.182 * PB + 3.264 \tag{4.2}$$

$$PL = 1.679 * PB - 26.747 \tag{4.3}$$

Although the above correlation are related to girls the same approach was applied to data obtained from boys and it lead to the same results. Correlations tables, graphs and relationship equations for boys are shown in Appendix A.

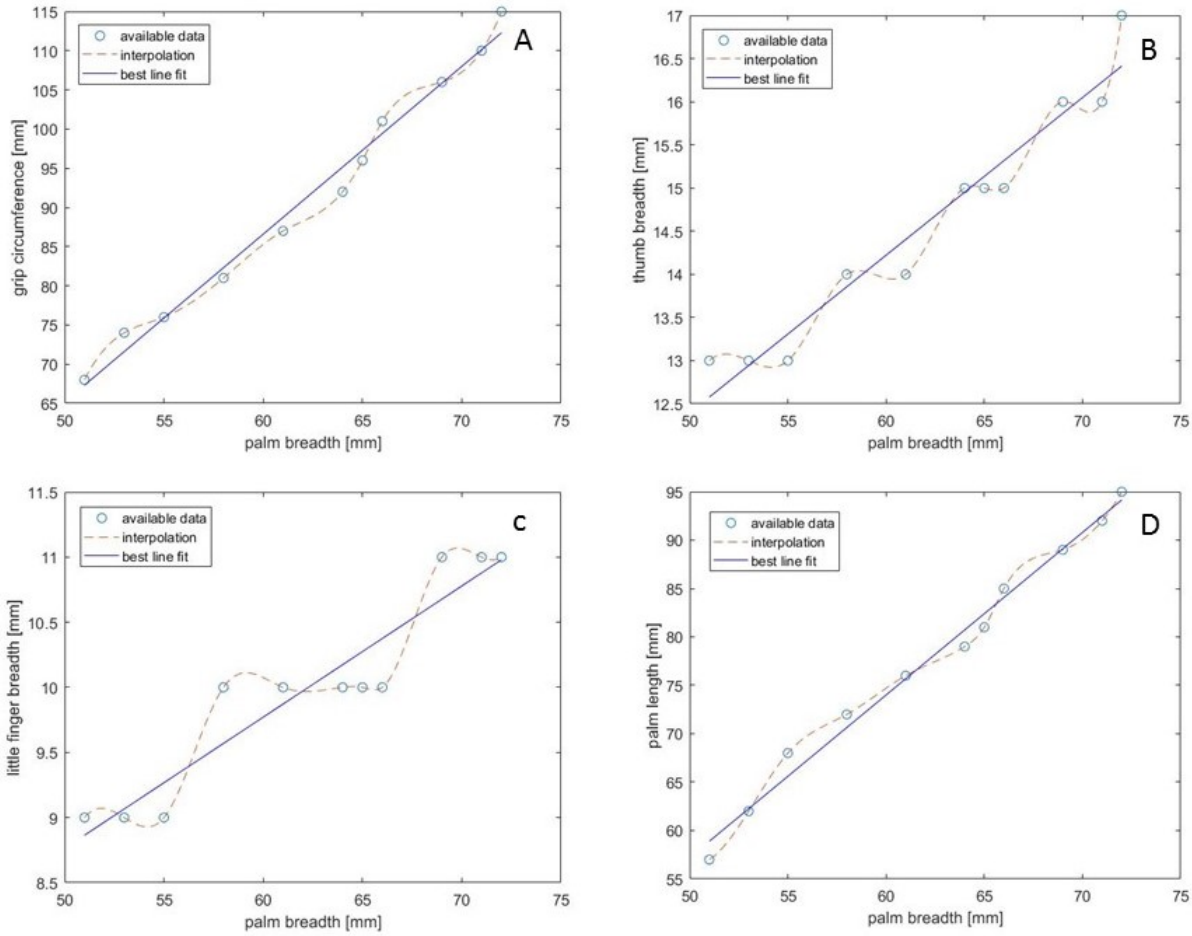


Figure 4.6: **A**: relationship between palm breadth and grip circumference. **B**:relationship between palm breadth and thumb breadth. **C**: relationship between palm breadth and little finger breadth. **D**: relationship between palm breadth and palm length. The dot line are the available data (averaged by age) the dash line is the spline interpolation line and the blue line is the straight line that best fits the data

4.1.3. Design

The hand has been designed in Solidworks, generating one single file for the fingers and two for the palm. They have been assembled in a single file and the parameters of each part have been connected to the parameters of the assembly. Finally, two .txt files have been created, one called ”assembly boys” and one called ”assembly girls”. Changing the values of the parameters in the .txt files automatically changes the Solidworks assembly. The files have been created to simplify the modification process for the user, even if Solidworks is an intuitive program, it can be tricky to use without experience the .txt files allows the user to adapt the design to the child hand size without changing the Solidworks files.

4.2. Printer and materials

4.2.1. Printer

As specified in the requirements the printer should be easily available to most of the population with a high quality to price ratio. Because of a lack of literature regarding 3D printers, different blogs about performances and evaluation of 3D printers have been read (specifically six blogs have been consulted) [49–54]. Each blog had a different opinion about which one is the best printer, but the same printers are mentioned in different blogs. The printers mentioned in more than 3 blogs are listed in Table 4.3, the first column (Cit) contain the number of blogs the printer was cited in. These printers are the ones users like the most. To have an objective comparison, different features have been considered and each of them has been taken from the printer website. The final choice was Ultimaker 2+, since it is the one with the highest speed and resolution even if the price is higher than other printers. The printer was chosen also because it was the most sold printer in Colombia in 2015 [55], which means it is the most common one, and thus the easiest to be found. The hand has a very simple design which does not require high resolution or specific features, and, therefore, also other printers can be used. A list of all the features of Ultimaker 2+ are listed in Appendix B.

Table 4.3: Comparison between the best desktop printers

	Cit	Price	Head travel speed (mm/s)	Nozzle diameter (mm)	Layer resolution (micron)	Ref
LulzBot TAZ 5	6	2200$	200	0.35	75	[56]
Ultimaker 2+	5	1895€ 2087$	30 to 300	from 0.25	from 600 to 20	[57]
MakerGear 2M	4	1825$	80 to 200	from 0.25	50	[58]
MakerBot Replicator+	4	1999$	NA	0.4	100	[59]
Printrbot plus	3	1199$	80	0.4	50	[60]

4.2.2. Hand material

After choosing the printer, a material analysis has been conducted. Ultimaker 2+ is optimized to print PLA, ABS, CPE, CPE+. A comparison between the materials was done as shown in Table 4.4 to select the most appropriate one. The data in the table has been taken from the Ultimaker website [57].

Table 4.4: Comparison between material printable with Ultimaker 2+

	PLA	ABS	CPE and CPE+
Tensile Module	2852Mpa	2030Mpa	1900Mpa
Glass Transition	60-65°	97°	82°
Max reccomanded temperature	50°	85°	70° (CPE) 100° (CPE+)
Price (for 750g)	33€	33€	41.5€(CPE) 54.5€(CPE+)
Note	1) Easy to print 2) Good tensile strength 3)Environmentally friendly: derive form renewable resources and it is biodegradable	1) Excellent mechanical properties 2) Printing temperature: 210-250°	1) Excellent chemical resistant 2) CPE has a higher strength 3) CPE+ is 10 time tougher

CPE and CPE+ are the most expensive materials, so only PLA and ABS have been considered. They are both cheap materials (sold at the same price), available everywhere and easy to find on every on-line material shop. PLA is very easy to print and it has a low environmental impact. It is produced by renewable source and it is biodegradable. However it is not advisable not to expose it to a temperature higher than 50° since it experience deformations. On contrary ABS is a bit more complicate to print and not environmentally sustainable, but it is more resistant and it is suitable for applications up to 80°. Eventually the device will be printed with PLA, mainly because it is easier to print and it has low environmental impact.

4.2.3. Extra materials

Beside the 3D printing material, other two materials are needed to assemble the hand:

Cords

In order to close the hand a cable is needed. The hand could work with normal plastic rope with a diameter of 1mm, which is available in all the ”do-it-yourself” store. Another kind of cord that can be used is a wire cable, which is less flexible and it transfers the force better with lower losses. The disadvantages are that it is more expensive and less easy to find. The wire cable that will be used to test the hand has 0.45mm outside diameter and a resistance of 1770 N/mm^2.

Elastic Cord

Elastic cords are needed to reopen the hand, they need to be strong enough to open the hand but also the force required to stretch them should be as low as possible. The hand will be tested with two different elastic cord. The first is a simple elastic cord that can be bought in any store. The diameter is approximately $2mm$. The second kind of elastic cord, Beadalon Fabric Elastic 1.0mm, is the one suggested from e-nable, a no profit organization which produces 3D printing prostheses for developing countries. It was decided to use that elastic cord so that it will be easier to compare the tests results with already existing devices. Figure 4.7 shows the hand with the two different kind of cords.

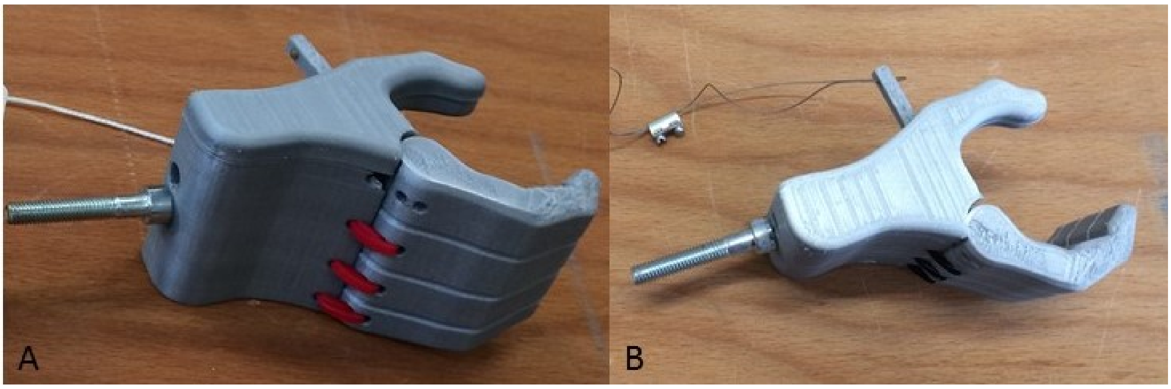


Figure 4.7: A: plastic rope and simple elastics, B: metallic wire and Beadalon Fabric Elastics

4.3. Moving principle

It is proven by different studies that a hook or prehensor device performs better than a hand device [27, 28] The objective of the design was to combine the cosmetics of the device with functionality, therefore it was chosen to design a hand looking device with a hook working mechanism.

The device is divided into two parts:

- Palm and thumb, which is the fix part of the design.
- fingers, which is the movable part of mechanism.

The fixed part consists of the palm and the thumb. The fingers were design as a single part to avoid unwanted lateral movements and to add robustness to the device. To keep the design simple and intuitive, the fingers are not adaptive, which means that they can not change the angle of the distal interphalangeal and proximal interphalangeal joints. For this reason the fingers were designed with an initial angle, so that it is possible to have pinch and cylindrical grip. The relative movement between the fingers and the fixed part is ensured by a joint and a lever. The hand was decided to be VC concept and, therefore, the level is designed in a way that if it is pushed, the fingers close. The final length of the lever is, for a palm of $55mm$, $44mm$. The dimension increases as the hand device's size increases.

4.3.1. Lever connection

The connection point between the lever and the fingers is the weakest point in the design, so the minimum thickness of the lever has been calculated to avoid breaking and to make the design more resistant.

The lever is pushed with a cord in the final point, which creates a rotation of the fingers. Elastic bands are attached to the back of the hand so that the hand can reopen when the force stops. A schematic view of the forces and momentum is shown in Figure 4.8.

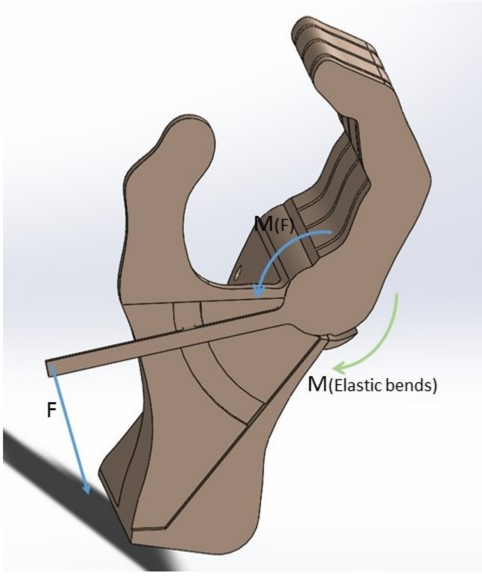


Figure 4.8: Moments acting on the level due to the activation force and the elastic force

The moment in which the lever undergo the higher stress is while the hand device is grasping an object. Therefore, the problem can be seen as the calculation of the maximum bending stress for beams, as shown in Figure 4.9.

Figure 4.9: beam stress calculation scheme

For the calculations it was considered the case of a prosthesis for 13 year old boys, the one in which the highest force is exerted on the prosthesis. The stress on the beam is expressed with the following formulas:

$$\sigma = \frac{FL}{Z} \qquad Z = \frac{bh^2}{6} \qquad \Rightarrow \sigma = 6\frac{FL}{bh^2} \tag{4.4}$$

Rearranging the equation, the minimum thickness of the lever is defined as:

$$h_{min} = \sqrt{\frac{6FL}{b\sigma_{max}}} \tag{4.5}$$

F is the force acting on the beam. The direction of the force is not constant and it will change according to the relative position between the socket and the lever. The maximum momentum is given when the force is perfectly perpendicular to the beam. The force a child uses during everyday tasks is around 10N [17], to overestimate the calculation and consider the worst case scenario, it is suppose that the grip force of the hand on an object is 40N. Using Equation 4.6 it is possible to calculate the theoretical force (F) that the child exert on the lever in order to obtain 40N as a grip force.

$$F * a = F_g * b \frac{F_g * b}{a} = F \tag{4.6}$$

F_g is the gripping force **F_g=40 N**
b is F_g arm, which is approximated as the the hand grip diameter **b = 35.1 mm**
a is the arm of F_a which is equal to half of the thumb breadth **a = 53 mm**
Therefore **F** is **26.6 N**. Since these calculations do not consider the friction between the two parts and the constant of the elastic bands, the force is rounded to 30N

- **F=30 N**

L is the length of the lever

- **L=53 mm**

b is the length of the beam designed to be half of the thumb breadth

- **b=9 mm**

σ is the tensile stress for PLA at the break point [61]

- **σ =42 MPa**

The lever thickness in the top of the lever is calculated to be **5 mm**.

Summarizing:

$$h_{min} = \sqrt{\frac{6FL}{b\sigma_{max}}} = \sqrt{\frac{6 * 30N * 53mm}{9mm * 42MPa}} = 5mm \tag{4.7}$$

To assure a higher hand opening width the lever was designed in a way that has a thickness of 7 mm on the top and it decrease to 4 mm at the bottom of the lever.

4.3.2. Joint

Different joints to connect the two parts have been proposed and compared. Figure 4.10 shows all the possible joints which allows one degree of freedom. The existing joints and properties and the picture shown in Figure 4.10 have been taken from a review done by F. Jelinekin as part of his PhD project in 2015 [62].

- ROLLING FRICTION JOINT: the movement is more difficult to constrain since the fixed part is not surrounding the movable part
- ROLLING TOOTHED JOINT: because of the teeth the movement of the fingers will not be smooth. It will not resemble the natural movement of a hand. It will also be more complicate to print because of the tolerance between the teeth and less resistant, the teeth are more likely to break due to the relative motion between the two parts of the joint.

- ROLLING BELTED JOINT: it requires a flexible material which, as explained in chapter 3, will create non linearity and it requires more force to operate.
- SLIDING CURVED JOINT: it allows smooth movements and it resemble the most the shape of a human hand. It is easy to print and it constrain the movement in only one direction.
- SLIDING HINGED JOINT: it allows smooth movements but it gives a non natural look to the hand.
- ROLLING SLIDING JOINT: very similar to the sliding curving joint, was not chosen mainly because of the shape.
- BENDING FLEXURE JOINT: it requires a flexible material which, as explained in chapter 3, will create non linearity and it requires more force to operate.

The **sliding curved joint** has been considered the best one for this specific project.

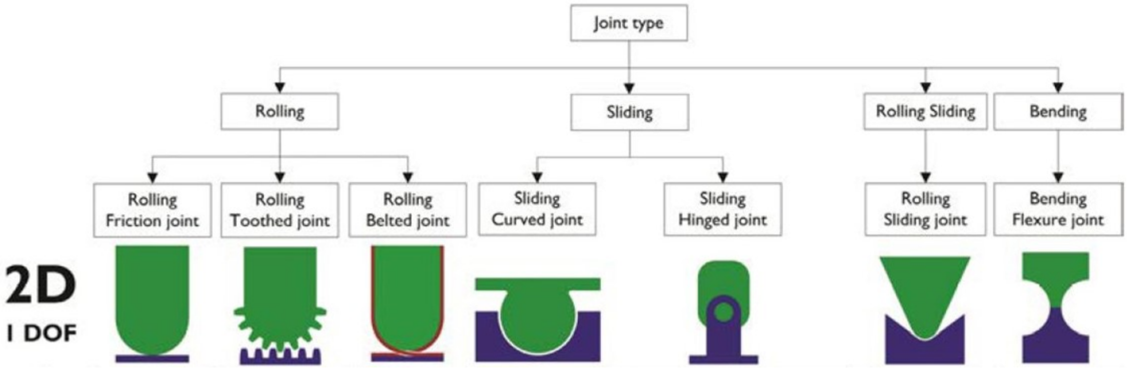
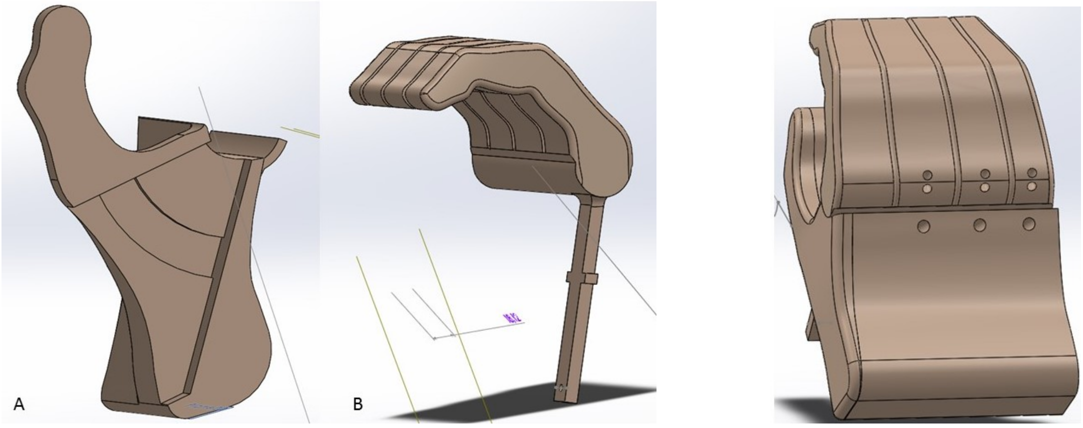


Figure 4.10: summary of joints divided by degree of freedoms and types. Figure taken from the PhD report of F. Jelinekin [62]

The thumb has an empty space inside, where the lever of the finger is free to rotate. To fix better the fingers to the palm, the lever was designed with a "cross-shape" and in the empty space was added a recess where the lever can rotate. The closing mechanism is shown in Figure 4.11a

The hand closes when a cable attached to the lever is put under pressure, and it reopens thanks to the elastic cords attached on the back. The hand was design to support 3 elastic cords, as shown in Figure 4.11b



(a) Solidwrok design A: palm and thumb rotational mechanism B: fingers and lever

(b) Solidwork of the hand, re-opening space

Figure 4.11: Solidwork drawings

4.4. Printing strategy

The technique chosen to print, FDM technique, has as main disadvantage the need to use support material if the design contains holes or geometries with an angle of more than 45°. If the hand is printed in only two parts, the fingers and the palm&thumb, support material will be added inside the hole where the finger should rotate, and, due to the geometry of the design, it will be almost impossible to remove the support material. After few trials it was decided to print the hand in three parts, cutting the thumb in half longitudinally. This way, the support material can be easily removed and the fingers can be inserted inside the palm before closing it. Figure 4.12 shows the solidwork designs of the three parts of the device. To attach the two parts of the thumb it was decided to use plastic glue. Different commercial cyanolit and double components glues have been tried and they all resulted to be strong enough. The best glues are the one with instant attachment, which reduce shifting of the parts while drying.

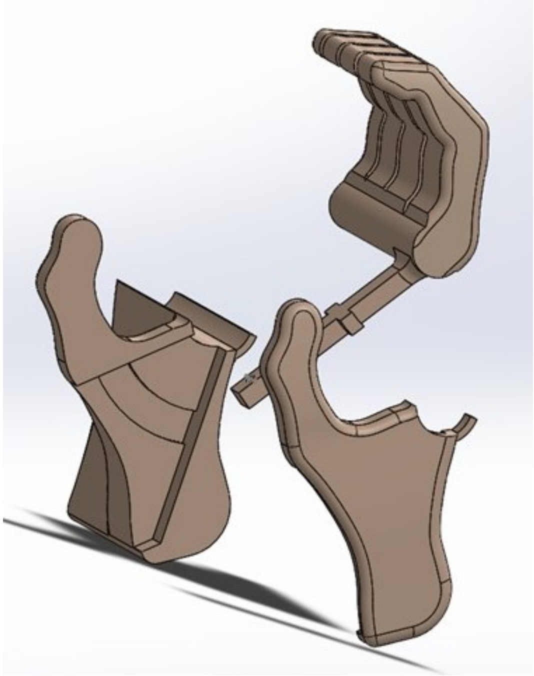


Figure 4.12: Solidwork assembly explosion of the three parts the hand has been printed in

4.5. Extra feature

The project consisted in designing a hand, but in order to be used there are some other features that needs to be considered:

4.5.1. Locking mechanism

In literature is often underlined the need of a locking mechanism if the hand is designed to be voluntary closing. The locking mechanism is needed to block the cable under tension, so that the shoulder or elbow muscles can rest; it is especially needed when a object needs to be hold for a prolonged amount of time. There are four different possible kinds of locking mechanism:

1. Automatic locking mechanisms inserted in the hand, as the one used by Otto Bock or Hosmer [63, 64]. The main disadvantage of this kind of locking mechanism is that it is activated every time the hand is closed, so it is activated also when a object is hold only for a few seconds, and is also proven that the locking mechanism cause a drop of grip force [27].

2. Automatic locking mechanisms in the socket. It was not found any example of this kind of locking mechanisms in literature. It has the same drawback of a automatic loking mechanisms in the hand.
3. Voluntary closing mechanisms inserted in the hand.
4. Voluntary closing mechanisms inserted in socket, as for example the locking mechanism produced by TRS that is shown in Figure 4.13. This specific lock has the advantage that, when activated, the cable can still be pushed more in case the hand is losing gripping force [65].

The advantages of manually activated locking mechanism is that they can be activated only when needed. For this project it is advised to design a voluntary closing locking mechanism, and it seems that a locking mechanism on the socket is more suitable since it does not interfere with the opening mechanism in the hand but further studies are needed.

Figure 4.13: TRS locking mechanism [65]

4.5.2. Wrist

In a study done by Lunteren in 1992 regarding the use of upper limb prostheses among children, it was concluded that a wrist was present in every prosthesis but only two children out of 26 used it, and mostly only in two positions. The main activity they use the wrist for is biking [17]. Since a wrist is not considered priority, it was decided to leave the design of a 3D printed wrist for future work. Most of the already existing wrists for children are connected to the hand using a screw with ½”-20 internal threat, as the wrist sold by TRS in collaboration with Fillauer-Hosmer or with a screw with M12x1,5 threat as the wrist sold by Ottobock [66, 67]. Examples of the wrists are shown in Figure 4.14. Out of the shelf wrists can be used while a 3D printed wrist is under development.

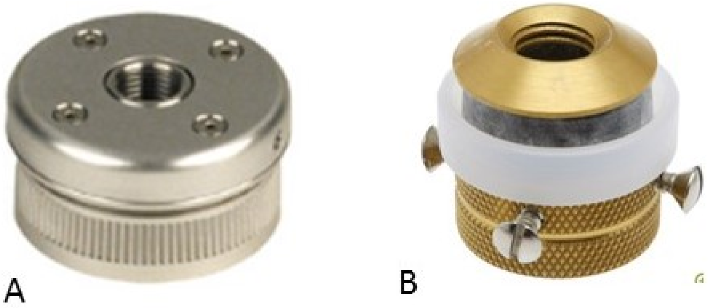


Figure 4.14: A: trs children wrist [66], B: Ottobock children wrist [67]

5

Testing

5.1. Mechanical testing

5.1.1. Test set-up

The test bench already available in the department and adjusted by Gerwin Smit during his PhD has been used for this research project. The bench allows to measure the pinch force thanks to a custom built pinch force load cell with a thickness of 10mm. Moreover, the activation force and the cable displacement are measured with displacement sensors [27]. A sketch of the test set-up is shown in Figure 5.1.

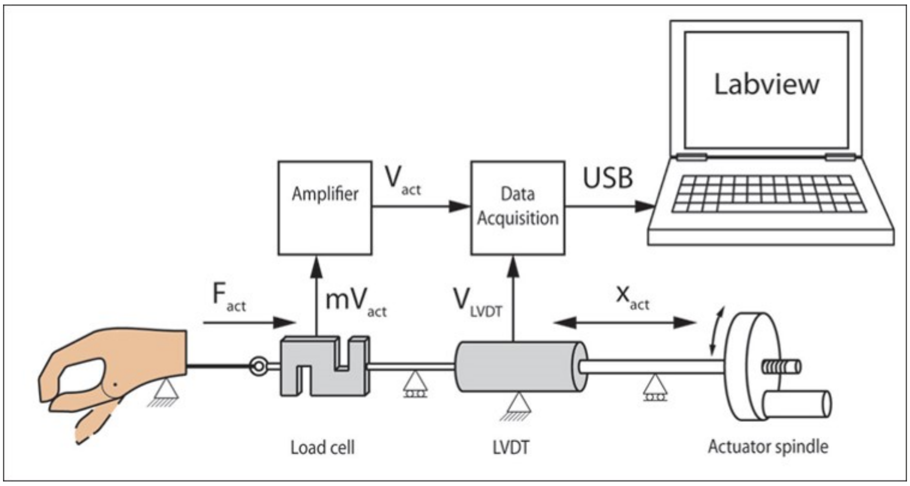


Figure 5.1: Schematic view of the testing set up [27]

Two tests have been performed: the pinch force test, to assure that the hand is able to reach a pinch force of 10 N with a given activation force and an endurance test, to check how durable the hand is. Figure 5.2 shows the set up for the pinch force test.

The endurance test was performed adding two sensors to the test set up; one sensor is used to sense when the hand is completely open and one is used to sense when the hand is closed. A pinch force of 8 N was chosen because it is assumed that not all the action require the maximum pinch force. To assure a pinch force of 8N, a spring was added between the fingers and the thumb; it was calculated that a pinch force of 8N is reached when the spring length is reduced by 5mm. The test set up is shown in Figure 5.3

5.1.2. Testing approach

Two hand devices have been tested: to prove that the parametric design works, the smaller hand device and the bigger hand device have been tested (4 and 13 years). The hands have

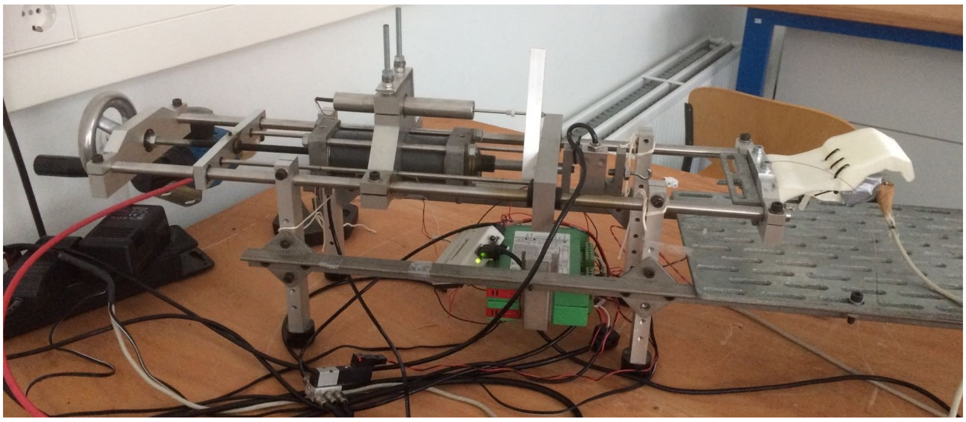


Figure 5.2: Testing set up for the pinch force test. The pinch force sensor is added between the fingers and the thumb to register the maximum pinch force reachable

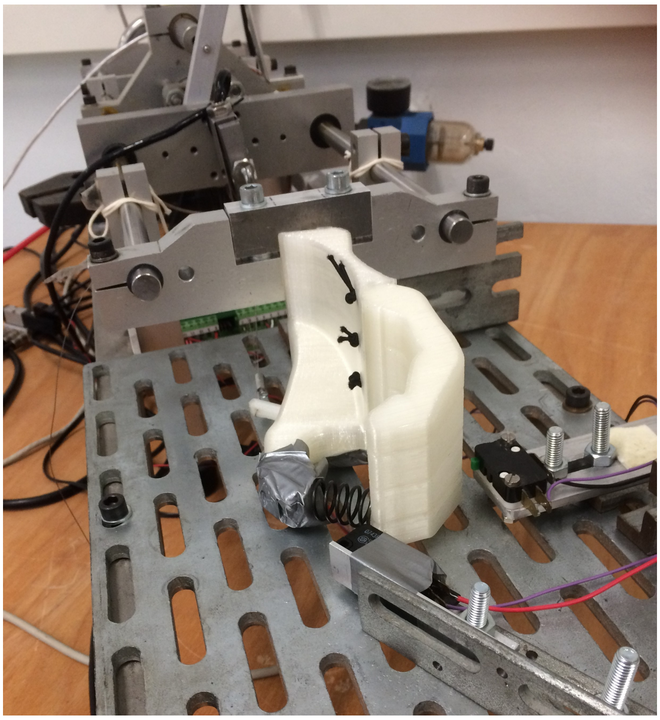


Figure 5.3: Testing set up for the endurance test: two sensors have been added to the previous set up to open and close the hand automatically. The spring has been added to assure a pinch force of 8N

been tested with female measures. The tests are needed to confirm that a pinch force of 10N is reachable considering the available force of the child and the fact that the hand has a duration of about 4 years.

To test the pinch force the hand underwent a full cycle of closing, pinching and opening an object (thickness= 10mm) until the pinch force was around 20N (double the desired pinch force). Each test has been performed 3 times to increase the accuracy of the test. The hand has been tested with different combinations of elastic bands, as shown in Figure 5.4. According to the number of elastics used and if the elastic is single or double the actuation force required to obtain a pinch force of 10N varies.

The maximum force available for a child with arm defect is taken from a pilot study of Shaperman [26]. Half of the available force is considered as advised in a study by Monod [44]. In the Shaperman's only the force of children up to 5 years old is analyzed, but in a different study done few years before she proved that a child with arm defect has usually a

Figure 5.4: Different combinations of elastic bends: A three double elastics, B two double elastics, c three single elastics

force included between the 5th and the 15th percentile of the force that a child of the same age with no arm defect can produce [43]. The study is done on children up to 7 years old. The force that a child with an arm defect above 5 years old can produce is estimated considering the average force of a child of the same age minus 1.5 standard deviation. The force available for children with no arm defect is taken from a study of Beenakker et al [68].

The second test performed is an endurance test. According to van Lunteren, in 35 visits (in each visit only one child was observed, but the same child could have been observed in multiple visits) the children performed 617 actions using the device [17]. An average of 18 action per day were performed with the prosthetic hand, which multiplied by 356 days per year and for 4 years leads to an estimation of 25737 opening and closing cycles. Therefore the endurance test was performed 25.800 times, closing, pinching 8N and opening again.

5.2. User testing

5.2.1. Testing set-up

There are different tests already approved to test a prosthetic device. The only 3D printed hand for developing countries that underwent a user test is the Raptor Reloaded, by e-nable which was tested using the Southampton Hand Assessment Procedure (SHAP) test [69]. The hand designed in this thesis will also be tested using the SHAP so that it is possible to compare the functionality of the device. The test consists in a first part in which objects with different shape and weight have to be manipulated and moved, and a second part in which the user has to perform activities of daily living (ADL).

The objects to manipulate are the following:

1: Spherical

2: Tripod

3: Power

4: Lateral

5: Tip

6: Extension

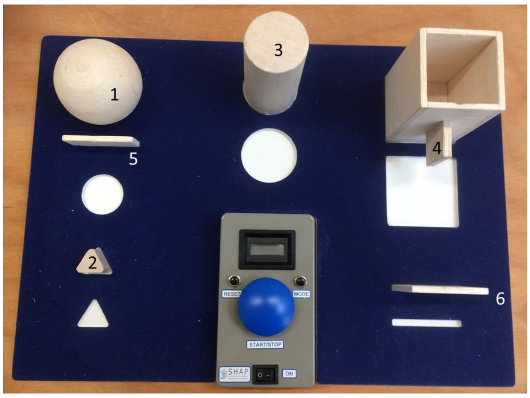


Figure 5.5: Testing set-up: moving objects

The activities of daily living to perform are the following:

1: Pick Up Coins

2: Button Board

3: Simulated Food Cutting

4: Page Turning

5: Jar Lid

6: Glass Jug Pouring

7: Carton Pouring

8: Lifting a Heavy Object

9: Lifting a Light Object

10: Lifting a Tray

11: Rotate Key

12: Open/Close Zip

13: Rotate A Screw

14: Door Handle

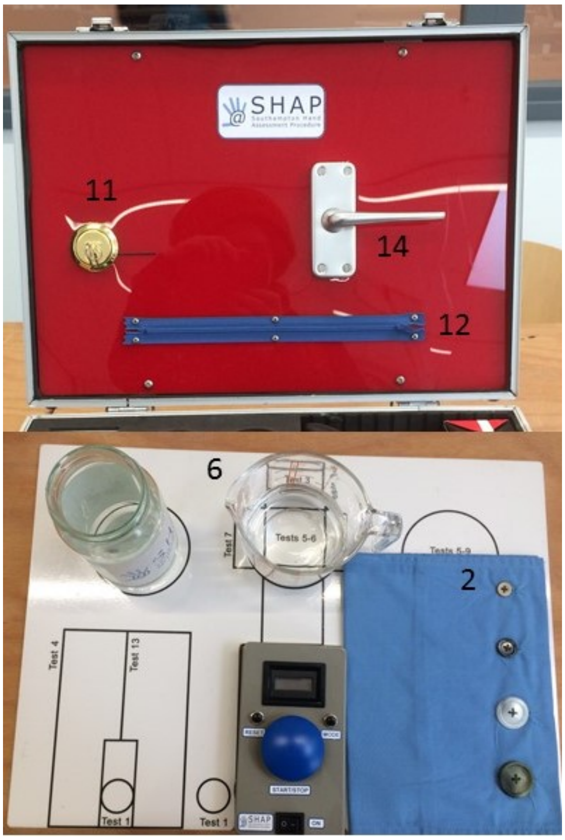


Figure 5.6: Testing set-up: Example of ADLs

5.2.2. Testing approach

The test will be performed with 12 healthy adults, a simulator will be used to simulate the amputation and the hand will be printed in adult size to match the testing target. Figure 5.7 shows one of the subjects who volunteered for the test wearing the prosthetic hand.

Figure 5.7: Healthy subject wearing the simulator and the prosthetic hand for the user testing

Appendix C contain the Assessor's SHAP Protocol with the instruction on how to perform each task while the consent form is shown in Appendix D.

6

Hand Evaluation and Tests Results

6.1. Hand Evaluation

The project will be evaluated comparing the requirements with the final prototype.

Some of the requirements have been considered during the design process, so they are fulfilled without further testing. These requirements are:

- *Target: Body-powered prosthesis for children from 4 to 13 years old with a below-elbow amputation*

  The solidwork design is able to adapt to children from 4 to 13 years old and it can be scaled also on adult size without the need of any further adjustment. It is operated using a cable.

- *3D printable*

  The hand is fully 3D printed with the exception of the cables to open and close the hand which are made of out off shelf items.

- *Voluntary closing design operated by the shoulder*

  The hand closes when the lever is pushed down, this is done by putting pressure over a cable attached to the lever. The cable is operated using shoulder and elbow movements.

- *Performing cylindrical and tip grip, optional hook grip*

  The hand was designed to be able to perform cylindrical and tip grip, the hook grip would need a passive movable thumb to be achieved.

- *Locking cable and passive wrist*

  These two features have not been added to the hand, the locking cable was decided to be added to the socket, while the wrist should be part of a future work.

- *Printer: FDM technology, easily available and high quality to price relation*

  The device has been printed with Ultimaker2+, a printer that uses FDM technology, it is the most sold 3D printer in Colombia in 2015, so also the most available one and, after a comparison with other similar printers, it resulted to be the one with the best quality/price relationship.

- *Material: Cheap, resistant for temperature above 45°*

  The hand has been printed with PLA, the cheapest among the materials supported by Ultimaker2+ and it resist to temperature up to 50°.

- *Parametric design using Solidwork*

  The design has been done using Solidwork and all the parameters used to design the hand have been related with statistical analysis to the length of the palm. In addition, it was possible to connect Solidwork with an external file, specifically a txt file. This way, different files can be made for different children and the design can be modified without making any change in the Solidwork file. Figure 6.1 shows the comparison between two designs, one for girls of 4 year old and one for girls of 13 year old.

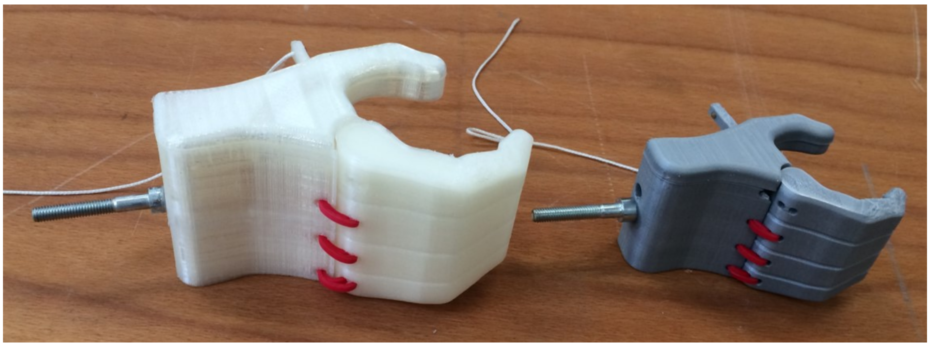


Figure 6.1: Two different hands printed from the same parametric solidwork design. On the left a hand for a 13 years girls, on the right a hand for a 4 years old girl

Different blogs from 3D printer users have been consulted to check the requirements related to the easiness of use of the 3D printer (*3D printer should be intuitive to use and the material easy to print*). The printer and the material have been chosen because considering among the most intuitive.

HAND SHAPE

To check the *hand shape* of the final design the 8 anthropomorphic parameters explained in chapter 4 have been measured in the final hand to see how different they are from the average measures. The hand device has been printed for girls of 4, 7 and 13 years. Table 6.1 shows the value of each parameter and the percentile for the population of the considered age. The hands have been printed considering the length of the palm as the main parameter, and the value chosen was the average length of the palm for the different ages (respectively $55mm$, $64mm$, $72mm$). The hand diameter has not been considered since it is not relevant for our design.

Table 6.1: Measure and percentile of the hand device parameters after printing compared to real hand.
*Hand thickness is measured at the end of the fingers, in our design it is not a reliable measure because it coincide with the joint.

	4 years		**7 years**		**13 years**	
	mm	%	mm	%	mm	%
Thumb breadth	13	P50	15	p50	17	P25
Grip circumference	74	P50	95	p75	114	P40
Hand length	110	P25	135	P50	160	P25
Middle finger length	51	P75	56	P25	77	P75
Hand thickness*	15	P25	18	P25	22	P25
Pink breadth	10	P75	11	P95	13	P95

To have a perfect match with the sound hand, all the measurements should be in the 50th percentile, most of the measurements are included between the 25th and the 75th percentile, which is what stated in the requirements. The parameter which changes the most is the little finger breadth, and this is probably due to the sensitivity of the measurements instrument, as explained in Chapter 4.1.2. Moreover, the difference between the desired value and the obtained one is max $2mm$, which is hardly notable.

OPENING WIDTH

The *opening width* of the hand prototype should be *35mm*. The device has an opening width of $30mm$ for a 4 years old child and it increases up to $42mm$ for a 13 years old child. The requirement is not met for smaller ages but it increase as the child grows. The opening width is larger than 35mm after 6 years and for both boys and girls.

COMFORT

As stated in the requirements, the hand should weight less than 5% of the subject weight. An average girl of 4 years weights $16kg$, while an average boy of 13 years old weight $42kg$, therefore the hand should weight respectively less than $80g$ an $210g$. The final weight of the hands are $49g$ for a 4 years girl and $113g$ for a 13 years old guy. The hand is also lighter than the Cyborg beast which weights 131g for 3 year old children. The requirement is met.

PRICE

The *price* has been calculated considering how much PLA is needed to print each hand and the cost of the elastic and not elastic cords. The elastic cords cost 0.01€ per elastic, and a maximum of 3 elastics are needed per hand, so the elastic price is 0.03€. The elastic cord used by e-nable (Beadalon fabric elastic) costs 16€ per 100 meters (material costs plus shipping), since a mazimum length of 30 cm is needed, the price is limited to 0.05€. The non elastic cord costs 0.25€ per meter. The amount of cord needed depends on how the hand is attached to the harness and to the socket, but it can be estimated that no more than 3 meters are needed. The maximum price for the non elastic cord is 1€. The cost of the wire cable is 0.85€ per meter, therefore the price of the wire needed for the hand is between 0.85 and 2.55€. PLA costs 33€ per 750g, the weight of the prosthesis varies between 49g and 120g which leads to a PLA cost between 2.15€ and 5.30€ The price of the glue depends on which kind of glue is used, it varies from 2€ to 30€ per stuck. A summary of the prices are listed in table 6.2. The maximum price for the hand material is around 10€.

Table 6.2: summary of the price of each component and the total price for the hand material, two total are listed according to which king of cords are used.

Component	**Prize**	
	General	Hand (min-max)
Glue	2-30€	0.1-2€
PLA	33€ per 750g	2.15-5.3€
Normal elastics	0.01€ per elastic	0.3€
Cord	0.25 per meter	0.25-0.75€
TOTAL 1:		**2.80-8.35€**
Beadalon fabric elastic	16€ per 100 meters	0.05
Wire cable	0.85€ per meter	0.85-2.55
TOTAL 2:		**3.15-9.90€**

The *required grip force* and the *durability* will be tested using a mechanical test, as explained in Section 5.1. The *intuitiveness* and the *function* that can be performed by the device will be tested during a user testing as explained in Section 5.2.

6.2. Testing results

6.2.1. Mechanical tests results

The first test performed was a pinch force test with different configurations of elastic bends for a device of a 4 years old girl. For each of the elastic combination explained in Chapter 5.1.2, 3 tests have been made but only one test is shown since the differences between different tests are minimal. According to different elastic combinations, is possible to achieve different grip force. The user can adjust the elastics as he/she prefer, according to his/her strength and daily activities.

The second test performed was a comparison of how the pinch force changes according to the hand measurements. Only female hands have been tested because the same results are expected for boy's hands. Since it is possible to reach the required pinch force with the smaller hand (4 years old girls), then it is also possible to reach 10N with bigger hands. Results show, as expected, the hand pinch force increases with the hand's size.

Finally, the device for 13 years old girls have been tested using first the normal elastic cord and the plastic wire and then using the elastic cords suggested by enable and the wire cable. Figure 6.2 shows the three tests: Graph A shows the results of the pinch force testing with different configurations of elastic bends for a device of a 4 years old girl, a comparison of how the pinch force changes according to the hand measurements is shown in Graph B while Graph C shows the comparison with different cords and it is shown that the second configuration of cords allows higher pinch force with less activation force.

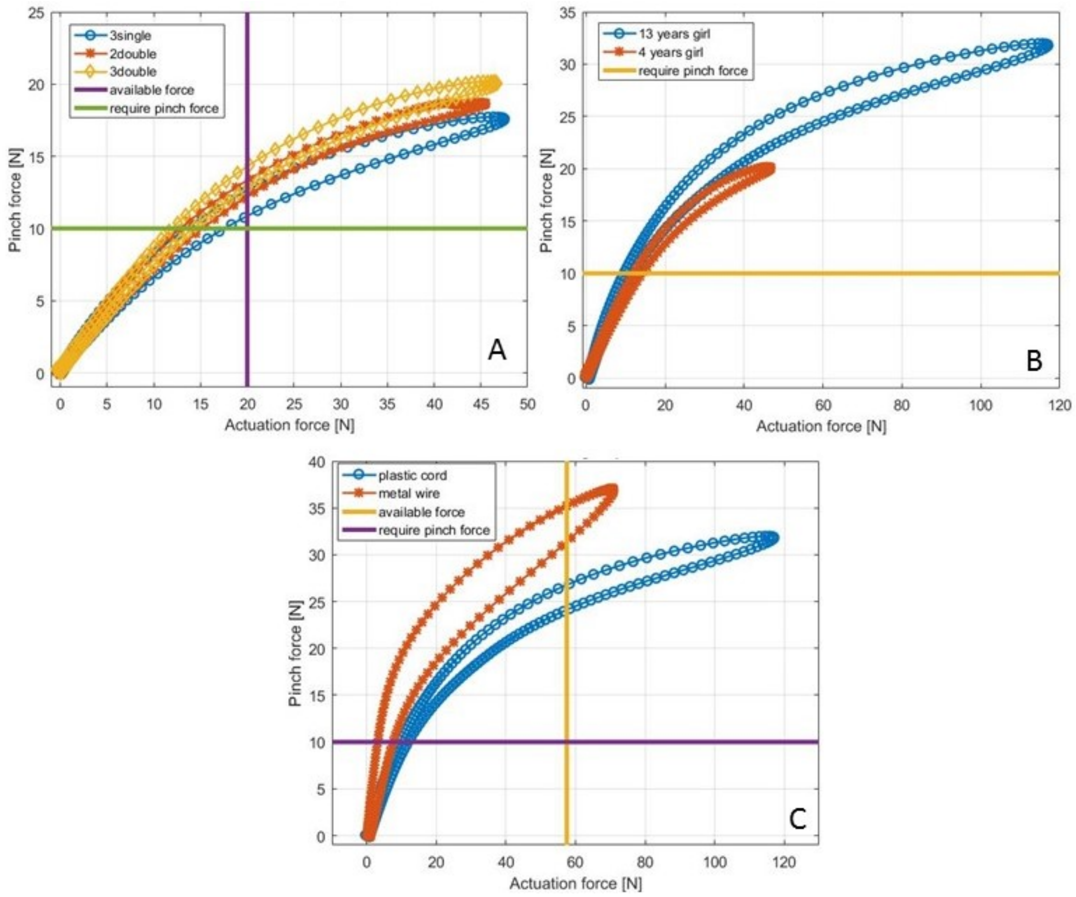


Figure 6.2: A) Pinch force results for a 4 years old girl hand with different elastic combinations B) Pinch force comparison for 4 years and 13 years girls C) Pinch force comparison for a 13 years girl device using different cords

The endurance test proved that the hand prosthesis can open and close 18247 times while pinching 8N. Considering that in average a prosthetic device is opened and closed 18 times, this correspond to almost 2 years and 10 months.

6.2.2. User testing results

The results of the first part of the user testing is shown in Table 6.3. A task was considered a failure if it took the user more than 100s to complete it, as explained in the users SHAP protocol. The test was performed by 12 healthy subjects.

Table 6.3: Results of the user testing part 1, moving objects: percentage of success and time (average time ±SD)

	light objects		**Heavy objects**	
	% yes	***Time [s]***	***% yes***	***Time [s]***
Spherical	0	100 ±0	0	100 ±0
Tripod	100	13.90 ±10.93	100	11.49 ±12.07
Power	100	10.90 ±4.87	100	9.05 ±3.84
Lateral	100	8.07 ±2.45	100	10.15 ±4.52
Tip	100	7.67 ±2.56	100	11.42 ±13.92
Extension	100	8.70 ±2.56	100	9.52 ±4.61

The results of the ADL is shown in Table 6.4. It is stated in the user SHAP protocol that, in case a task is failed, it counts as it took the user 100s to complete it. The test was performed by 12 healthy subjects but only 10 where able to try all the tasks, 2 subjects had to be excluded because the prosthetic device broke and no replacement was available at the moment of the test.

One of the tasks (using a screwdriver) was performed only by one subject but it was shown that it is possible to complete the task if there is enough training. More subjects got closer to succeed when they had the opportunity to try for a longer time.

Table 6.4: Results of the user testing part 2 ADL: percentage of success and time (average time ±SD)

	% yes	**Time [s]**		**% yes**	**Time [s]**
Coins	90	42.48 ±25.07	**Full Jar**	100	8.87 ±3.18
Button Boards	90	58.17 ±32.04	**Empty Tin**	100	9.59 ±4.16
Cutting	0	100 ±0	**Tray Lift**	100	5.63 ±2.15
Page turing	100	8.62 ±2.85	**Key**	100	6.36 ±3.00
Jar Lid	0	100 ±0	**Zip**	100	26.43 ±20.23
Jug Pouring	100	16.78 ±7.93	**Screwdriver**	10	92.44 ±23.97
Cartoon Pouring	90	28.59 ±25. 33	**Door Handle**	100	4.01 ±1.12

6.2.3. User testing experience

During the user testing each subject was able to successfully perform most of the tasks within 15 minutes. No subject complained about difficulties in understanding the prosthetic hand working mechanism.

6.3. Summary

Table 6.5 shows a summary of the device's requirements and results

Table 6.5: Evaluation of the requirements and goals

REQUIREMENTS	**(goal)**	**ACHIEVED**
Function		
Cylindrical and tip grip	hook	yes (no)
Require grip force 10N	15N	Yes
Opening width 35mm	45mm	yes starting from 4 years old girls
Control		
Operated with a shoulder harness		yes
Voluntary closing mechanism		yes
locking cable		No, to incorporate in the socket
	passive wrist	No, possibility to use out of shelf ones
Cosmetics		
Hand shape		yes, comments in Chapter 7
Comfort		
Weight less than 5% of the child weight	**131g**	Lower than 5% of the child weight and lower than already existing devices
Additional		
Low price	50€	yes (max 10€)
Intuitive and easy to operate		yes
As functional as possible		tests results better or as good as existing devices
Durability (4 years)		results 2.8 years. Comments in Chapter 7
3D printer		
FDA technology		yes
Easily available		yes, ultimaker 2+ is the most sold printer in Colombia in 2015
Intuitive		Not possible to determine, more user feedback is needed
High quality/price relationship		yes, considered among the best from different user blogger
Material		
Easily printable		Not possible to determine, more user feedback is needed
Cheap		yes, it is the cheaper material among the one supported by Ultimaker 2+
Durable and mechanically resistant		No, Comments in Chapter 7
Resistant for temperature above 50		yes
Design		
Software: solidwork		yes
Parameters: all could be related to a single one		yes

7

Discussion

7.1. General

The hand is meant for children in developing countries, specifically for children in Colombia but there are no anthropomorphic data available and literature on the tasks and daily activities for the target population. A study similar to the one performed by Van Lunteren [17] should be done in Colombia to confirm that the requirements for a children prosthetic device are the same.

7.2. Upper limb prosthesis

7.2.1. Function

The mechanical testing shows that the hand is able to perform the required gripping force and that it is possible to vary the resistance of the hand depending on the type of elastic band and configuration used, therefore a child would have the opportunity of increasing or decreasing the stiffness of the hand according to his/her preference.

The opening width of the hand reaches 35mm only with a hand device for children of 6 years old. Therefore the position of the fingers and the thumb should be changed to achieve 35mm opening width even at younger ages.

7.2.2. Cosmetics

The shape resembles a hand shape but it is not perfect, the fingers are design in a single block, which decrease the similarity with a real hand. A new design, shown in Figure 7.1 has been made but it is not parametric yet.

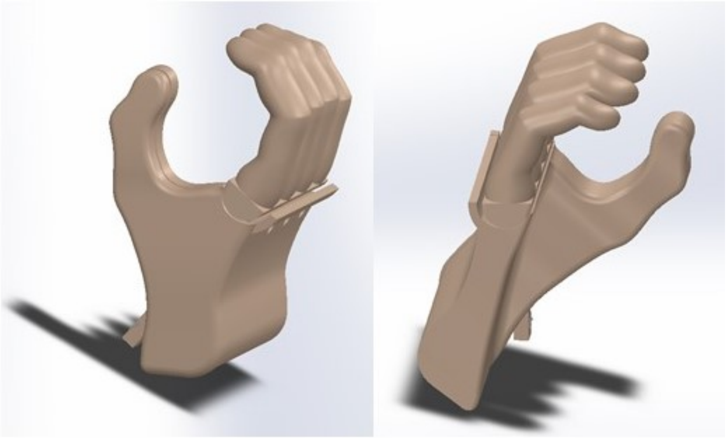


Figure 7.1: Solidwork drawing of a more natural looking fingers. This design still needs to be turn into parametric

In Chapter 6 the final hand devices sizes have been compared with the average values of the measurements obtained from DINED Database [45]. The measurements taken from the prosthetic design approximate due to the shape of the hand. Most of the hand dimensions should be taken when the hand is open and not when the fingers are positioning with an angle. Also the anthropomorphic data in the database are taken using joints as reference, which are not present in the prosthetic design, in consequence it is not easy to determine the limits of some measurements.

7.2.3. Comfort

The weight of the prosthesis depends on the material the device is printed with but also on the printing density of the material. Ultimaker 2+ has a setting that allows the user to decide how dense the material should be inside the device. All the hands have been printed with an inside material density of 35% but changing this setting will change the weight of the hand.

7.2.4. Additional

LOW PRICE

The material price of the prosthetic device has been calculated considering the prices in Europe which is estimated to be less than 10€. The material price in Colombia could be different. Also different printing settings can results in a different amount of PLA used, and therefore the material price could have some variations.

DURABILITY

A endurance test proved that the hand device for a 7 years girl can open and close 18247 times while pinching with a 8 N force, which corresponds to 2.9 years of use. The test run during the night and in the morning after the test set-up was not working; the pneumatic system failed and the device staid for an unknown number of hours under tension. When restarted it run about 500 cycles before the lever broke. The test is not considered reliable and it should be performed again to have a better estimation of the durability of the device.

Even if the mechanical test seemed to prove that the hand device has a durability of almost 3 years, the prosthesis broke 5 times during the user test always in the connection point between the lever and the fingers. Two different lever connection configurations have been used, as shown in Figure 7.2.

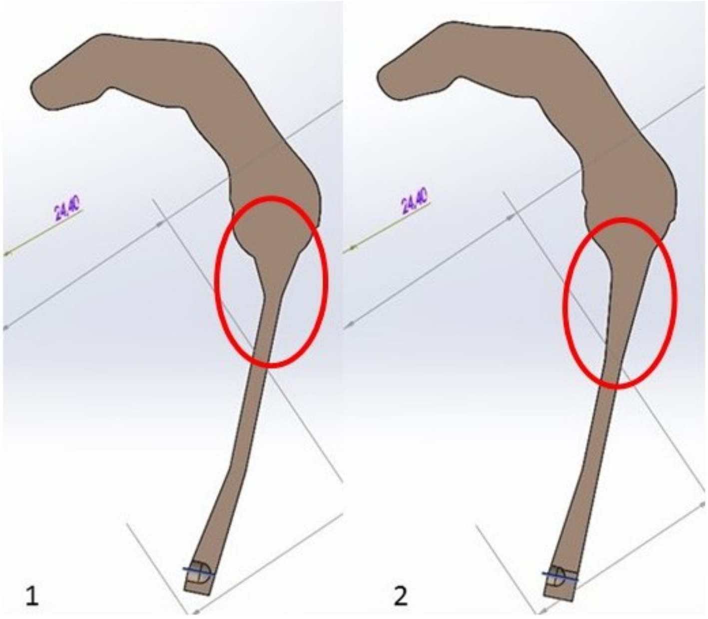


Figure 7.2: Solidwork sections of the 2 hand designs used during testing. Design A) was used 3 times and it lasted respectively 2, 7 and 1 subject. Design B) was used 2 times and it broke both times after 1 subject.

The first hand broke after being used by 2 subjects. When changed, it lasted for the tests performed by 7 users. When changed again it did not last one test sequence. The shape of the three prototypes was exactly the same with the difference that the first one was printed using a different printer with different setting. A fourth hand has been printed but it broke during the first test. The last hand had the same configuration of the first one and it broke after one user. The two different configuration are shown in 7.2.

The hand have been tested on healthy adults, which are able to perform more force then children, so it is not possible to predict how long the same hand will last if used by children. It was found out that the printer settings have a determinant role on the strength of the lever, in fact the second device lasted more than 3 times longer than the first one and the only difference was the printer setting. The third prototype only lasted for less than one subject but it was printed in the same printer with the same settings of the second device. A possible explanation is that 3D printing is never 100% uniform and the density the wall thickness could be different in different points. Additional studies regarding 3D printers settings and lever geometries should be conducted to increase the durability of the prosthetic hand.

7.3. 3D printing

To choose the printer and the material different blogs from 3D printer users have been consulted to check the requirements related to the easiness of use of the 3D printer. These feedback however can not be considered 100% reliable because it is not possible to determine if the opinions expressed are biased, and, therefore an unbiased user feedback is needed to confirm the opinions expressed on-line.

3D printers allow different settings configurations, which change the density of the inside material and the printing quality. Different configurations assure different printing time and they change the strength of the moving mechanism. A study should be conducted on the best printing setting, considering the strength of the material and the printing time.

7.4. Parametric design

The hand design is parametric and it is possible to modify the size from an external file, without changes in the solidwork file. Statistical analyses and evaluations have been conducted with the parameters available online and it was not possible to check the hand device size compared to a child hand.

7.5. Testing

7.5.1. Mechanical testing

The mechanical tests show that the hand is able to perform the require gripping force and that it is possible to vary the resistance of the hand depending on the elastic bands configuration used, so a child has the opportunity of increase or decrease the stiffness of the hand according to his/her preference.

The only study regarding the force that children with arm defect can produce is created on a population of 37 children all from California, with an age between 3 and 5.5 years old. Therefore, the force considered for the testing in children above 5 years is an estimation, new studies should be conducted to have a more reliable result.

7.5.2. User testing

The user test has been performed on healthy adults and the hand was scaled to adult size. The testing are not indicative on the real performance of the device when used by young amputees but it gives a comparison of the functionality between the adult size hand and already existing prostheses. The hand can be compared with two other 3D printable prosthetic hands. The Raptor reloaded, a prosthesis design by E-Nable meant for children in Developing countries [69], and FA3D, a 3D printable hand for adult with flexible fingers designed by a colleague in Delft [70]. The comparison between hands have been done only on ADL since there is no indication of the timing and percentage of success of the raptor reloaded hand regarding the first part of SHAP test. Table 7.1 shows the results of the 3 prosthetic devices.

Table 7.1: Comparison between different 3D printable prosthetic devices

	RAPTOR [69]	FA3D		HAND DEVICE	
	% yes (30s)	**% yes (30s)**	**% yes (100s)**	**%yes (30s)**	**% yes (100s)**
Coins	30	30	100	50	90
Button Boards	100	10	90	20	90
Cutting	25	0	0	0	0
Page turning	100	30	100	100	100
Jar Lid	80	20	70	0	0
Jug Pouring	45	90	100	90	100
Cartoon Pouring	40	70	100	90	90
Full Jar	100	100	100	100	100
Empty Tin	100	100	100	100	100
Tray Lift	35	100	100	100	100
Key	0	90	100	100	100
Zip	10	40	40	50	100
Screwdriver	0	10	10	10	10
Door Handle	70	100	100	100	100

The Raptor reloaded hand has been tested by 20 amputees with a small size prosthesis and by 20 amputees with a adult size prosthesis, only the results of the tests with the adult size prosthesis have been considered. Also only the results of the tasks completed under 30 seconds are listed, while it is not known how many participants completed the tasks in 100s [69]. The FA3D has been tested by 10 healthy subjects and one amputee. Only the results of the 10 healthy subjects have been considered to have a better comparison between the devices. The Hand device is the device designed and tested in this thesis project. Since the opening width of the hand device was not enough to grasp the empty tin and the full jar, the empty tin and the full jar tasks have been done with a smaller container than the one available in the test.

During testing it was noticed that the opening width of the hand should be lager to be able to perform all the tasks and the grip force should be higher to be able to perform tasks which require high pinch force, like cutting food or opening a jar.

The hand was found to provide comparable results with respect to the other devices. It seems to perform better than the Raptor reloaded, probably due to the relative position of the thumb compared to the position of the fingers. While in the raptor reloaded hand the thumb and the fingers, when the hand is closes, are perpendicular to each other, in the hand device studied in this project the thumb and the fingers are parallel to each other.

8

Conclusions

8.1. Conclusions

The aim of the project is:
Develop a generalized 3D printable body-powered prosthetic hand design for children in developing countries that allows parametric design.

The goal was successfully met. This design is the only known prosthetic design which is parametric. The advantages of a parametric design are that it can perfectly match the sound hand size and it is easily adjustable for different ages and hand shapes. A statistical analysis has been conducted to determine the best parameters to use in a prosthetic design. The parameters used are: grip diameter, palm length and breadth and thumb breadth. Lastly, all the parameters have been related to the palm breadth.

The prosthesis is manufactured with 3D printing technology in order to keep the price low and to allow customized products. It is printed with FDM technology, using Ultimaker 2+ and the material chosen is PLA, which is cheap, easy to print and with a low environmental impact. Differently from all the other 3D printable hand devices available, the structure of the prosthesis it is 100% printable and it does not require any additional metallic part. The only extra components are elastic cords to reopen the fingers and a wire cable to attach the hand to the socket. Both materials are easily available in every do-it-yourself shop. It has a total weight under 115g and a final material price under 10€. Mechanical tests proved that the hand is able to provide the require pinch force and user tests showed the functionality of the hand, which is as good as or better than already existing 3D printable hand prostheses.

8.2. Future work

The main disadvantage of the hand is the durability, which needs to be improved with studies on 3D printing techniques and a better connection between the lever and the fingers. The hand should be tested with different materials to check the resistance. Even if the required opening width for children has been reached, the user tests pointed out the need of a larger opening width to be able to grasp every day objects. Also the grip force was proved not to be enough for some specific tasks like opening a jar or turning a screwdriver. Opening width and grip force need improvements and a user test with amputees should be done to have a better prove of the functionality of the device and to improve it with their feedback.It is the personal opinion of the researcher that the shape of the prosthesis can be improved in order to have a higher resemblance with a real hand. A suggestion have been made in Chapter 7.2.2 but it needs to be implemented into parametric design. Finally, it is important to remember that this research project is just a part of a bigger project and that the device needs to be connected to the stump with a 3D printed wrist and socket that will need to be design in further studies.

Bibliography

[1] Amene Sabzi Sarvestani and Afshin Taheri Azam. Amputation: A ten-year survey. *Trauma monthly*, 18(3):126, 2013.

[2] Nicolas E Walsh and Wendy S Walsh. Rehabilitation of landmine victims: the ultimate challenge. *Bulletin of the World Health Organization*, 81(9):665–670, 2003.

[3] Lina Magnusson, Nerrolyn Ramstrand, Eleonor I Fransson, and Gerd Ahlström. Mobility and satisfaction with lower-limb prostheses and orthoses among users in sierra leone: A cross-sectional study. *Journal of rehabilitation medicine*, 46(5):438–446, 2014.

[4] Martin Marino, Shaan Pattni, Max Greenberg, Alex Miller, Emma Hocker, Sarah Ritter, and Khanjan Mehta. Access to prosthetic devices in developing countries: Pathways and challenges. In *Global Humanitarian Technology Conference (GHTC), 2015 IEEE*, pages 45–51. IEEE, 2015.

[5] Lina Magnusson, Gerd Ahlström, Nerrolyn Ramstrand, and Eleonor I Fransson. Malawian prosthetic and orthotic users' mobility and satisfaction with their lower limb assistive device. *Journal of rehabilitation medicine*, 45(4):385–391, 2013.

[6] Lina Magnusson and Gerd Ahlstrom. Experiences of providing prosthetic and orthotic services in sierra leone–the local staff's perspective. *Disability and rehabilitation*, 34(24):2111–2118, 2012.

[7] Richard A Gosselin. The increasing burden of injuries in developing countries: direct and indirect consequences. *Techniques in Orthopaedics*, 24(4):230–232, 2009.

[8] Ilzé Grobler, Gertina J Van Schalkwyk, and Claire Wagner. The application of critical psychology to facilitate reflective clinical practice in orthotics/prosthetics. *Prosthetics and orthotics international*, 30(3):237–245, 2006.

[9] Dominik Wyss, Sally Lindsay, William L Cleghorn, and Jan Andrysek. Priorities in lower limb prosthetic service delivery based on an international survey of prosthetists in low-and high-income countries. *Prosthetics and orthotics international*, page 0309364613513824, 2013.

[10] Kumar Bhaskaranand, Anil K Bhat, and K Narayana Acharya. Prosthetic rehabilitation in traumatic upper limb amputees (an indian perspective). *Archives of orthopaedic and trauma surgery*, 123(7):363–366, 2003.

[11] Colette S Harkins, Anthony McGarry, and Arjan Buis. Provision of prosthetic and orthotic services in low-income countries: A review of the literature. *Prosthetics and orthotics international*, 37(5):353–361, 2013.

[12] Johan Borg, Anna Lindström, and Stig Larsson. Assistive technology in developing countries: national and international responsibilities to implement the convention on the rights of persons with disabilities. *The Lancet*, 374(9704):1863–1865, 2009.

[13] Jae Yeol Lee and Kwangsoo Kim. Geometric reasoning for knowledge-based parametric design using graph representation. *Computer-Aided Design*, 28(10):831–841, 1996.

[14] Julie Shaperman, Samuel E Landsberger, and Yoshio Setoguchi. Early upper limb prosthesis fitting: when and what do we fit. *JPO: Journal of Prosthetics and Orthotics*, 15(1):11–17, 2003.

[15] Michelle A James, Anita M Bagley, Katherine Brasington, Cheryl Lutz, Sharon McConnell, and Fred Molitor. Impact of prostheses on function and quality of life for children with unilateral congenital below-the-elbow deficiency. *The Journal of Bone & Joint Surgery*, 88(11):2356–2365, 2006.

[16] MA Kuyper, M Breedijk, AHM Mulders, MWM Post, and AJH Prevo. Prosthetic management of children in the netherlands with upper limb deficiencies. *Prosthetics and orthotics international*, 25(3):228–234, 2001.

[17] A. van Lunteren G.H.M van Lunteren-Gerritsen. Field evaluation of below-elbow prostheses for children. report No: N-400, 1992.

[18] Monica Moreo. Use of prostheses in developing countries. Delft university of technology, Delft the Netherlands, April 2016.

[19] Shirley A Weaver, Lawrence R Lange, and Virginia M Vogts. Comparison of myoelectric and conventional prostheses for adolescent amputees. *American Journal of Occupational Therapy*, 42(2):87–91, 1988.

[20] DH Plettenburg. Electric versus pneumatic power in hand prostheses for children. *Journal of medical engineering & technology*, 13(1-2):124–128, 1989.

[21] Dick H Plettenburg. Basic requirements for upper extremity prostheses: The wilmer approach. In *Engineering in Medicine and Biology Society, 1998. Proceedings of the 20th Annual International Conference of the IEEE*, volume 5, pages 2276–2281. IEEE, 1998.

[22] Kahori Kita, Yohei Otaka, Kotaro Takeda, Sachiko Sakata, Junichi Ushiba, Kunitsugu Kondo, Meigen Liu, and Rieko Osu. A pilot study of sensory feedback by transcutaneous electrical nerve stimulation to improve manipulation deficit caused by severe sensory loss after stroke. *Journal of neuroengineering and rehabilitation*, 10(1):1, 2013.

[23] Dick H Plettenburg and Just L Herder. Voluntary closing: A promising opening in hand prosthetics. *Technology and disability*, 15(2):85–94, 2003.

[24] J Kruit and JC Cool. Body-powered hand prosthesis with low operating power for children. *Journal of medical engineering & technology*, 13(1-2):129–133, 1989.

[25] Bob Radocy. Introduction to high performance prosthetics. `https://www.youtube.com/watch?v=uKDNkeYFhR4`, October 2013. Accessed: 2016-10-23.

[26] J Shaperman, M Leblanc, Y Setoguchi, and DR McNeal. Is body powered operation of upper limb prostheses feasible for young limb deficient children? *Prosthetics and orthotics international*, 19(3):165–175, 1995.

[27] Gerwin Smit and Dick H Plettenburg. Efficiency of voluntary closing hand and hook prostheses. *Prosthetics and orthotics international*, 34(4):411–427, 2010.

[28] M LeBlanc, Y Setoguchi, J Shaperman, and L Carlson. Mechanical work efficiencies of body-powered prehensors for young children. *Child. Prosthet Orthot Clin*, 27(3):70–75, 1992.

[29] Stanley Plagenhoef, F Gaynor Evans, and Thomas Abdelnour. Anatomical data for analyzing human motion. *Research quarterly for exercise and sport*, 54(2):169–178, 1983.

[30] E-Nable. Cyborg beast. http://enablingthefuture.org/upper-limb-prosthetics/cyborg-beast/. Last open on March 2016.

[31] J ten Kate. 3d-printed upper limb prostheses: an overview and potential improvements. Delft university of technology, Delft the Netherlands, 2016.

[32] Steve Upcraft and Richard Fletcher. The rapid prototyping technologies. *Assembly Automation*, 23(4):318–330, 2003.

[33] ALL3DP. Fdm vs sla: 3d printing explained and compared. https://all3dp.com/fdm-vs-sla/. Accessed: 2016-09-28.

[34] Sculpteo. Fdm vs. sls 3d printing - what they mean and when to use them. https://www.sculpteo.com/en/3d-printing/fdm-vs-sls-3d-printing-technologies/. Accessed: 2016-09-28.

[35] J. ten Kate. 3d-printed upper limb prostheses: A review. *Disability and Rehabilitation: Assistive Technology (IIDT)*, 2016.

[36] Dlacrur. Galileo hand. http://www.thingiverse.com/thing:655432. Accessed: 2016-10-23.

[37] e Nable. Rit arm. http://enablingthefuture.org/upper-limb-prosthetics/rit-arm/. Accessed: 2016-10-23.

[38] Steve Wood. Flexy arm. http://www.thingiverse.com/thing:894705. Accessed: 2016-10-23.

[39] Jorge Zuniga. Cyborg arm. http://www.cyborgbeast.org/#/devices. Accessed: 2016-10-23.

[40] Gyrobot. Flexy hand. http://www.thingiverse.com/thing:242639. Accessed: 2016-09-18.

[41] Steve Wood. Flexy hand - filaflex remix. http://www.thingiverse.com/thing:754513. Accessed: 2016-10-23.

[42] NotImpossible. Project daniel. http://www.notimpossible.com/#notimpossible. Accessed: 2016-10-23.

[43] J Shaperman, Y Setoguchi, and M LeBlanc. Upper limb strength of young limb deficient children as a factor in using body powered terminal devices: A pilot study. *J Assoc Child Prosthet Orthot Clin*, 27(3):89–96, 1992.

[44] HUGUES MONOD. Contractility of muscle during prolonged static and repetitive dynamic activity. *Ergonomics*, 28(1):81–89, 1985.

[45] TU Delft. Dined. http://dined.io.tudelft.nl/en/database/tool. Accessed: 2016-09-18.

[46] NinjaTex. Ninjaflex 3d printing filament technical specifications. https://ninjatek.com/wp-content/uploads/2016/05/NinjaFlex-TDS.pdf. Accessed: 2016-09-18.

[47] Just L Herder, Jan C Cool, and Dick H Plettenburg. Methods for reducing energy dissipation in cosmetic gloves. *Journal of rehabilitation research and development*, 35(2):201, 1998.

[48] PCM Donkers, Huub M Toussaint, JFM Molenbroek, and LPA Steenbekkers. Recommendations for the assessment and design of young children's bicycles on the basis of anthropometric data. *Applied ergonomics*, 24(2):109–118, 1993.

[49] 3DHubs. 3d printer guide 2016. https://www.3dhubs.com/best-3d-printer-guide. Accessed: 2016-10-23.

[50] toptenreviews. 3d printers review. http://www.toptenreviews.com/computers/3d-printers/best-3d-printers/. Accessed: 2016-10-23.

[51] markershed. 3d printer comparison. http://www.makershed.com/pages/3d-printer-comparison. Accessed: 2016-10-23.

[52] Bulent Yusuf. 20 best 3d printers in fall 2016. https://all3dp.com/best-3d-printer/, October 2016. Accessed: 2016-10-23.

[53] Kira. Best 3d printer 2016: the 3d printer buyer's guide. http://www.3ders.org/articles/20160608-best-3d-printer-2016-the-3d-printer-buyers-guide.html, June 2016. Accessed: 2016-10-23.

[54] Brent Hale. The best 3d printers for 2016. https://3dforged.com/best-3d-printers/, October 2016. Accessed: 2016-10-23.

[55] Print3DColombia. Ultimaker 2+. http://www.print3dcolombia.com/2015/01/ultimaker2.html. Accessed: 2016-09-15.

[56] LulzBot. Lulzbot taz 5. https://www.lulzbot.com/store/printers/lulzbot-taz-5. Accessed: 2016-10-23.

[57] Ultimaker. Ultiamker 2+. https://ultimaker.com/en/products/ultimaker-2-plus. Accessed: 2016-10-23.

[58] MakerGear. Makergear m2. http://www.makergear.com/products/m2. Accessed: 2016-10-23.

[59] MakerBot. Makerbot replicator +. https://www.makerbot.com/replicator/. Accessed: 2016-10-23.

[60] printrbot. printrbot plus. https://printrbot.com/compare-printers/. Accessed: 2016-10-23.

[61] Enno Ebel and Thorsten Sinnemann. Fabrication of fdm 3d objects with abs and pla and determination of their mechanical properties. *Navigation*, 1:2, 2014.

[62] Filip Jelínek. *Steering and Harvesting Technology for Minimally Invasive Biopsy*. TU Delft, Delft University of Technology, 2015.

[63] Ottobock. Otto bock system hand -voluntary closing. https://professionals.ottobockus.com/Prosthetics/Upper-Limb-Prosthetics/Body-Powered-Systems/Ottobock-System-Hands/Otto-Bock-System-Hand-voluntary-closing/p/8K27. Accessed: 2016-10-23.

[64] Hosmer. Product and features. http://hosmer.com/products/hands/#male. Accessed: 2016-10-23.

[65] Bob Radocy. Trs prosthetics. http://www.trsprosthetics.com/. Accessed: 2016-10-23.

[66] Bob Radocy. Catalog 2016. http://www.trsprosthetics.com/wp-content/uploads/2016/01/Catalog-2016-28.pdf. Accessed: 2016-10-23.

[67] Ottobock. Wrist units. https://professionals.ottobockus.com/Prosthetics/Upper-Limb-Prosthetics/Body-Powered-Systems/Movo-Wrist-Units/Wrist-Units/c/5166. Accessed: 2016-10-23.

[68] EAC Beenakker, JH Van der Hoeven, JM Fock, and NM Maurits. Reference values of maximum isometric muscle force obtained in 270 children aged 4–16 years by hand-held dynamometry. *Neuromuscular disorders*, 11(5):441–446, 2001.

[69] Corinne Dally, Daniel Johnson, Moriah Canon, Sarah Ritter, and Khanjan Mehta. Characteristics of a 3d-printed prosthetic hand for use in developing countries. In *Global Humanitarian Technology Conference (GHTC), 2015 IEEE*, pages 66–70. IEEE, 2015.

[70] J.D. Ten Kate. The fa3d hand: Design and evaluation of a functional and anthropomorphic hand prosthesis using the advantages of 3d-printing. master thesis, TU Delft, Mechanical, Maritime and Materials Engineering, August 2016.

A

Boys parametric correlation

A.1. Parameters choice

The same correlation analysis conducted in Chapter 4.1.2 for girls hand parameters, has been conducted considering boys hand parameters.

A.1.1. Parametric correlation using the grip diameter

The correlation coefficient between the middle finger and the grip circumference resulted to be **0.84**, while the correlation coefficient between the hand thickness and the grip circumference resulted to be **0.63**. Figure A.1 shows the relationship between grip diameter, middle finger length and hand thickness. It is evident that grip diameter and middle finger length have a linear relationship, as it is underlined by the high correlation coefficient. The relationship between the grip diameter and the hand thickness is less linear but the correlation coefficient is still higher than 0.5 so it was considered high enough to assume a linear relationship. The correlation coefficients are very similar to the ones founded for girls (respectively 0.98 and 0.57)

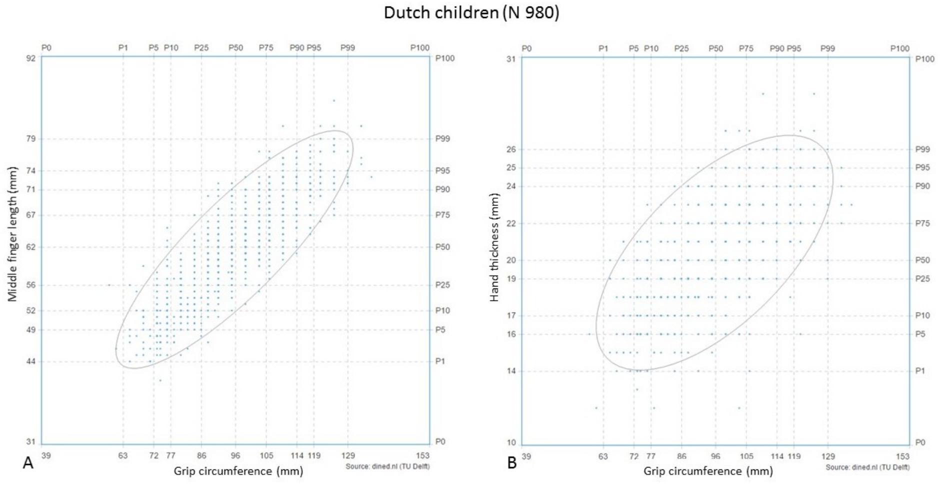


Figure A.1: Correlations between the grip circumference and middle finger length and hand thickness. It is evident the high linearity between the grip circumference and the middle finger length. The correlation with the hand thickness is lower but it is still higher than 0.5

A.1.2. Parametric correlation using the grip diameter

The same analysis was conducted to investigate the relationship between the palm length and the little finger breadth. The correlation coefficient is only **0.71**, This correlation coefficient is much higher than the one founded for girls (0.31). The reason for such a big change are not clear. Figure A.2 shows the relationship between the palm length and the little finger breadth.

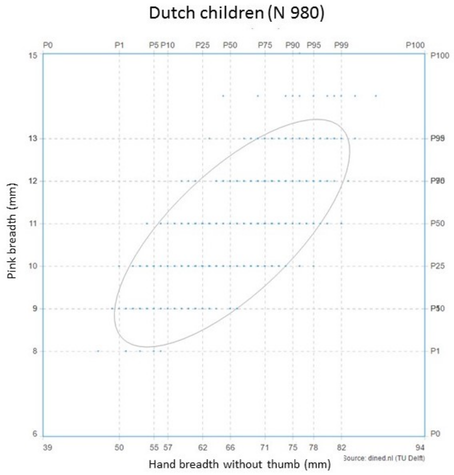


Figure A.2: between palm breadth and little finger breadth, much higher than the same relationship found in girls

A.1.3. Parametric analysis

The same parametric analysis was performed on boys measurements, using the same options as main parameter.

- Age
- Stature
- Palm Breadth
- Middle finger length

The results of the correlation analysis for children are shown in Table A.1 and in Table A.2 for adults (20 to 94 years old).

Table A.1: summary of the correlation coefficients of the design parameters with the options for main parameter for children (4-13 years old)

	Middle finger length	**Palm breadth**	**Age**	**Stature**
Palm breadth	0.887	1	0.887	0.951
Palm length	0.956	0.908	0.923	0.968
Thumb breadth	0.753	0.819	0.732	0.791
Grip circumference	0.848	0.798	0.800	0.852
Little finger breadth	0.642	0.721	0.621	0.670

The results of the correlation analysis are very similar to the one conducted for girls (apart from the little finger ones), therefore they lead to the same results and the palm length as been considered the main parameters also for boys.

Table A.2: summary of the correlation coefficients of the design parameters with the options for main parameter for adults (20-94 years old)

	Middle finger length	**Palm breadth**	**Age**	**Stature**
Palm breadth	NA	1	-0.119	0.458
Palm length	NA	0.559	-0.240	0.650
Thumb breadth	NA	0.543	0.152	0.107
Grip circumference	NA	0.192	-0.253	0.466
Little finger breadth	NA	NA	NA	NA

The relationship between the palm breadth (PB) and the grip diameter (GD), the thumb breadth (TB) and the palm length (PL) for boys is expressed by the following equations:

$$GD = 1.913 * PB - 31.040 \tag{A.1}$$

$$TB = 0.201 * PB + 2.817 \tag{A.2}$$

$$PL = 1.573 * PB - 21.528 \tag{A.3}$$

Figure A.3 shows the correlation between the parameters and the straight line which approximates the correlation.

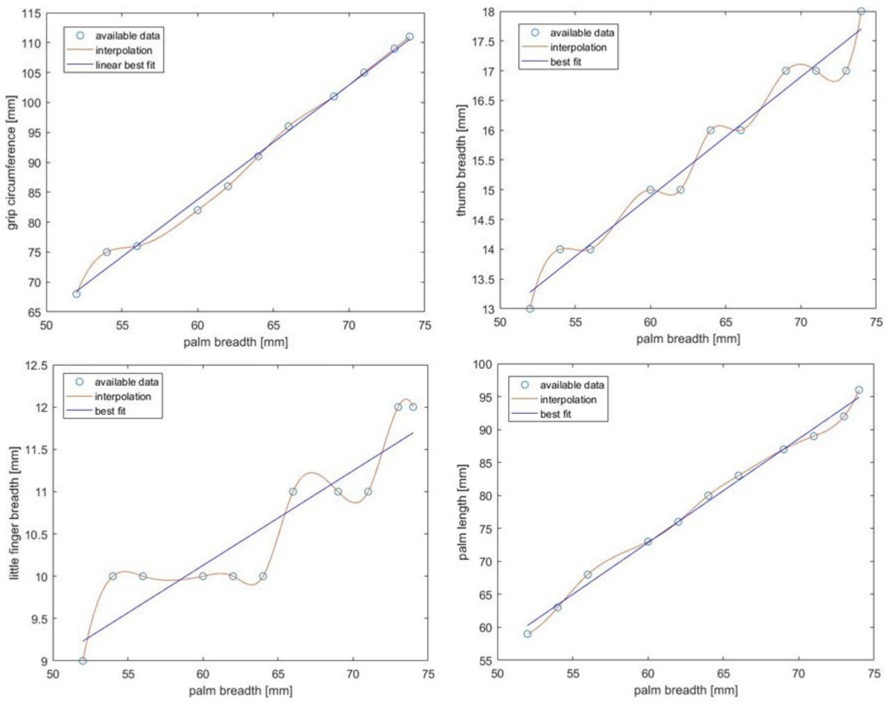


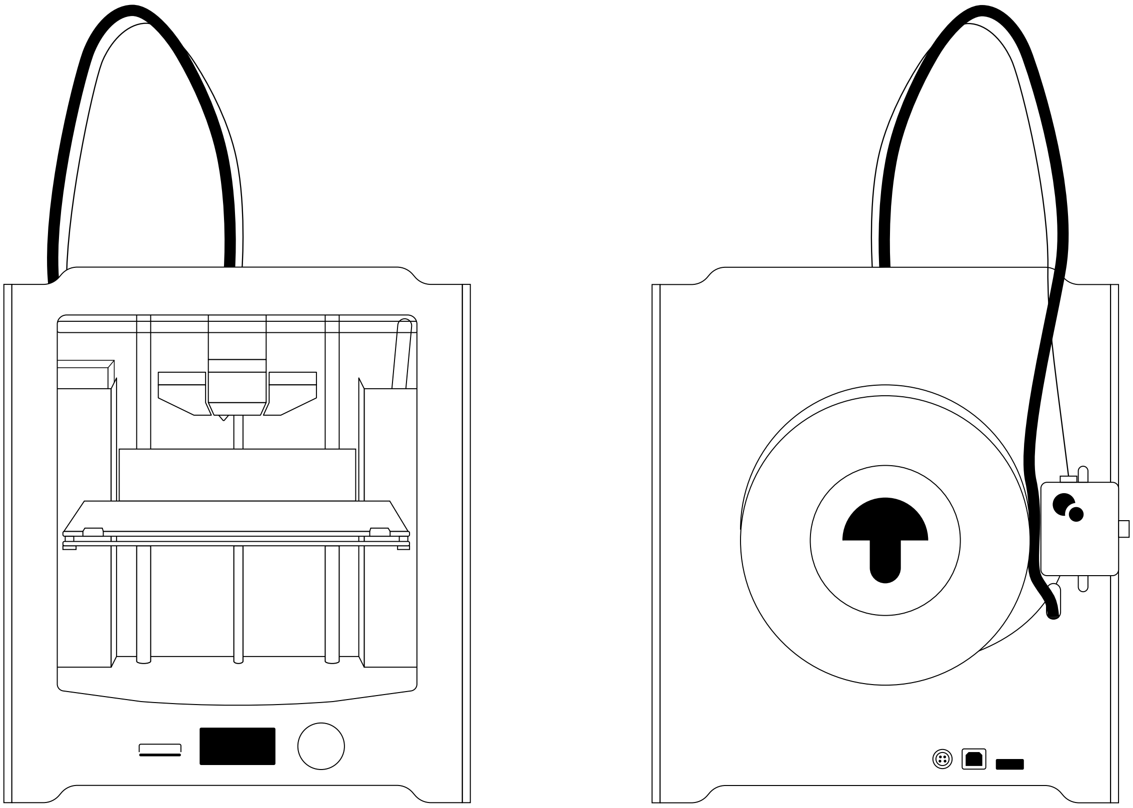
Figure A.3: **A**: relationship between palm breadth and grip circumference. **B**:relationship between palm breadth and thumb breadth. **C**: relationship between palm breadth and little finger breadth. **D**: relationship between palm breadth and palm length. The dot line are the available data (averaged by age) the dash line is the spline interpolation line and the blue line is the straight line that best fits the data

B

Utimaker 2+ features

Ultimaker 2+

Specification sheet



Specifications

Printer and printing properties

Technology	Fused Deposition Modeling (FDM)
Print head	Swappable nozzle
Build volume	223 x 223 x 205 mm
Filament diameter	2.85 mm
Layer resolution	0.25 mm nozzle: 150 to 60 micron 0.40 mm nozzle: 200 to 20 micron 0.60 mm nozzle: 400 to 20 micron 0.80 mm nozzle: 600 to 20 micron
XYZ accuracy	12.5, 12.5, 5 micron
Print head travel speed	30 to 300 mm/s
Build speed	0.25 mm nozzle: up to 8 mm^3/s 0.40 mm nozzle: up to 16 mm^3/s 0.60 mm nozzle: up to 23 mm^3/s 0.80 mm nozzle: up to 24 mm^3/s
Build plate	Heated glass build plate
Build plate temperature	50 to 100 °C
Build plate leveling	Assisted leveling process
Supported materials	PLA, ABS, CPE, CPE+, PC, Nylon, TPU 95A
Nozzle diameter	Included are 0.25, 0.4, 0.6 and 0.8 mm nozzles
Nozzle temperature	180 to 260 °C
Nozzle heat up time	~ 1 minute
Build plate heat up time	< 4 minutes
Operating sound	50 dBA
Connectivity	Standalone 3D printing from SD card (included)

Physical dimensions

Dimensions	342 x 357 x 388 mm
Dimensions (with bowden tube and spool holder)	342 x 493 x 588 mm
Nett weight	11,3 kg
Shipping weight	18,5 kg
Shipping box dimensions	390 x 400 x 565 mm

Power requirements

Input	100 - 240V 4A, 50-60Hz 221 W max.
Output	24 V DC, 9.2 A

Ambient conditions

Operating ambient temperature	15 - 32 ºC See material specifications for optimal conditions
Nonoperating temperature	0 - 32 ºC

Software

Supplied software	Cura, our free print preparation software
Supported OS	macOS, Windows and Linux
File types	STL, OBJ and AMF

C

Shap Protocol

SHAP

Southampton Hand
Assessment Procedure

Assessor's

SHAP

Protocol

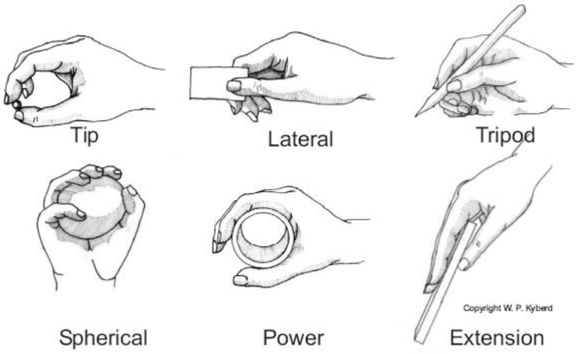
General Information

The Southampton Hand Assessment Procedure (SHAP) has been formed based on the analysis of grip patterns, and their frequency of use in Activities of Daily Living (ADL) tasks. Therefore it is considered to cover the wide range of prehensile tasks the hand usually undertakes (with the omission of specific occupational or recreational requirements).

The test consists of the manipulation of a series of both lightweight and heavyweight abstract objects. These are intended to directly reflect specific grip patterns, whilst also assessing the strength and compliance of the grip. This is followed by 14 ADL tasks. To ensure standardisation, the assessor's test procedure must be followed, whilst objectivity is maintained by participant self-timing. A complete assessment is expected to take around 20 minutes to complete (including all of the relevant explanations to the subject).

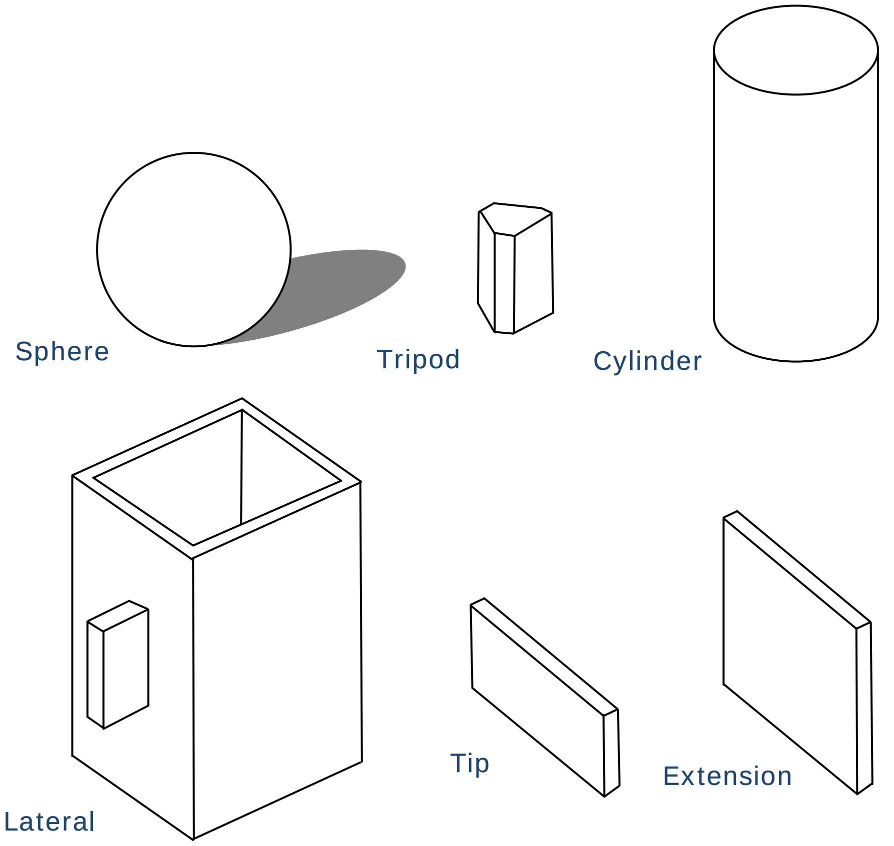
The procedure is designed to provide a score of functionality, which can be equated with a percentage; hence on completion of the test a score of optimum hand function is obtained. This score provides a tangible result describing the level of hand impairment, e.g. the participant has 75% of optimum hand function. As the procedure has been designed to be standardised and objective, this score cannot only be used for comparative assessments of a participant's performance throughout a course of treatment, but also provides information on their level of function (this is with respect to the benchmark of an unimpaired participant).

The protocol outlined in the following pages provides details for the assessor concerning the setup and execution of the test. The assessor is required to demonstrate each task to the descriptions given. The following diagram may help identify the appropriate grip patterns.



Contents of SHAP Test

Quantity	Item
1	Test case containing all SHAP equipment
1	Backboard mounted in case with lock & key, door hand and zip
1	SHAP form-board
1	Foam insert containing all objects
1	Timer unit
6	Lightweight abstract objects (see figure below)
6	Heavyweight abstract objects (see figure below)
1	Lock and key mounted on backboard
1	Zip mounted on backboard
4	Coins (2 x 1p and 2 x 2p)
1	Button board with 4 buttons attached
1	Plasticine block
1	Knife
1	Note card
1	Glass jar with lid
1	Glass jug
1	Cardboard juice carton
1	Empty tin with plastic lid
1	Door handle mounted on backboard
1	Metal arrow unit
1	Screwdriver



SHAP Abstract Object Tasks

Assessor’s SHAP Protocol

Setting up the SHAP

The participant should be seated at a table with arms resting on the table. The participant’s elbows should be at a 90° angle.

Place the SHAP form-board in front of the participant blue side facing upward, approximately 8cm from the front edge of the table. Fit the timer unit into the space provided in the front of the board. For each of the SHAP abstract object tasks, the board should be moved from left to right so that each task is directly in front of the participant, thereby ensuring no bias toward either hand dominance. The SHAP case and all ADL objects can be removed from the table during this first phase of the assessment.

Procedural Notes

Each task should be demonstrated to the participant using slow, clear movements, ensuring that the participant is aware of the appropriate grip for completion of the abstract object tasks.

It is important to note that the demonstration should be carried out using the corresponding hand under assessment, to avoid any confusion for the participant.

Prosthesis users should be encouraged to practice each task, prior to timing it, in order to determine the most appropriate technique as many users usually carry out tasks with the natural hand alone. Due to the difficulties associated with myoelectric prostheses, if it is apparent that the device has failed to respond to user demand, then a note should be made, and a retest allowed. If the device is similarly unresponsive during the second task, a note should be made of the difficulties encountered.

In other circumstances, the participant should be given only one chance to carry out the timed task. The time taken to complete each task, the appropriate grip pattern if identifiable should be recorded, as well as any relevant notes.

When establishing any form of normative data, it is imperative that the task is carried out fully. Due to the need to complete a task in the minimum amount of time there is often a temptation to ‘rush’ the task without actually fulfilling the exact requirements. Under these circumstances the task should be repeated.

Completing the SHAP Test

In the forthcoming document, normal text denotes instructions for assessors. *Text in italic text denotes instructions to be read to participants.* The SHAP website contains video demonstrations to help with accurate placement of the ADL tasks on the form board (please refer to http://www.shap.ecs.soton.ac.uk/about-usage.php for further guidance on completing the SHAP tasks).

SHAP Abstract Object Tasks

The 6 lightweight objects are to be completed first. If a participant cannot complete a task, this could be recorded as C/C (Cannot Complete) on the supplied SHAP test data sheet. All lightweight abstract objects are completed, followed by all heavyweight abstract objects.

"A series of objects will be placed on the board. The task involves moving the object from the rear slot on the board to the front slot. Only the hand under assessment (dominant hand) should be used for any of these tasks, including the starting and stopping of the timer."

Spherical Place the 'spherical object' in the appropriate rear slot. Place the 'tip object' in the slot between the rear and front 'spherical object' slots to create a small barrier. Move the board so that these slots are directly in front of the participant whilst maintaining the approximate 8cm distance from the front of the table. Using the spherical grip move the object over the barrier and place it in the front slot.

"Start the timer, pick up and move the object as demonstrated with as few mistakes as possible, and <u>as quickly as possible</u>, to the front slot. Complete the task by depressing the blue button on the timer again."

Tripod Place the 'tripod object' in the appropriate rear slot. Using a tripod grip, move the object to the front slot.

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot and then stop the timer."

Power Place the 'power object' in the appropriate rear slot. Move the board so that these slots are directly in front of the participant whilst maintaining the approximate 8cm distance of the board from the front of the table. Using the power grip, pick up the object and move it to the front slot.

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot and then stop the timer."

Lateral Place the 'lateral object' in the appropriate rear slot with the handle facing toward the participant. Move the board so that these slots are directly in front of the participant whilst maintaining the approximate 8cm distance from the front of the table. Using the lateral grip, pick up the object by the handle and move it to the front slot.

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot and then stop the timer."

Tip Place the 'tip object' in the appropriate rear slot. Using a tip grip, move the object to the front slot.

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot and then stop the timer."

Extension Place the 'extension object' in the appropriate rear slot. Using an extension grip, move the object to the front slot.

"Start the timer, move the object as demonstrated and as quickly as possible to the front slot and then stop the timer."

The procedure above should now be repeated, in the same order using the heavyweight abstract objects.

Once completed, remove all the abstract objects from the table and turn over the form-board. Place the board directly in front of the participant for <u>all</u> ADL tasks at approximately 8cm from the front of the table.

Activities of Daily Living

As before, each task should be demonstrated to the participant using slow, clear movements, ensuring that the participant is aware of the appropriate procedure.

The 'Optional' instructions should be used when the assessor feels that the participant would be unable, is uncomfortable, or unnatural in using the demonstrated grip.

To avoid repetitive filling/emptying of objects with water for the pouring tasks (jug, carton and full jar tasks), it is advisable to fill a separate container with approximately 1 litre of water. It may also be advisable to have a towel nearby to clear any spillage.

"The second stage of this assessment consists of 14 everyday activities, which should be timed in the same manner by pressing the blue button to start and stop the timer. Again tasks should be completed as quickly as possible, with as few mistakes as possible, using only the appropriate hand unless otherwise stated."

Pick Up Coins Arrange the two 2p and two 1p coins in the designated areas on the board. Place the glass jar in the designated spot for this task with the lid removed. Pick up each coin in turn by sliding the coin to the edge of the board using a tip or tripod grip and drop each coin into the glass jar. Move from right to left. Reset the task for the participant.

"Start the timer, lift each coin in turn as quickly as possible, and drop it in the jar as demonstrated. Repeat that for all the coins and then stop the timer."

[OPTIONAL: If you feel unable to pick up the coins as demonstrated, you may use any method you wish, whilst only using one hand.]

Button Board Place the button board to the right of the timer unit if assessing the right hand, and to the left if assessing the left hand. The buttons should be farthest from the timer unit. Undo each button in turn, using only the assessed hand in a tripod grip. The other hand may be used to steady the board, but may not assist in the task. The button board should remain on the form-board at all times. Reset the task for the participant.

“Start the timer and using only the appropriate hand, undo all four buttons in any order as demonstrated and as quickly as possible. You may steady the button board with your other hand so that it remains on the form-board throughout the task. Then stop the timer using only the appropriate hand.”

Simulated Food Cutting Place the knife to the side of the timer unit (right side for right-handed assessments, left side for left-handed assessments). Place the plasticine ‘food item’ in the designated area on the form board (mould to look like a sausage and fit approximately the area on the form board). Pick up the knife, using the other hand to steady the plasticine. Cut it clearly into two sections. Then replace the knife on the form board. Reset the task by remoulding the plasticine for the participant.

“Start the timer, use the knife provided to cut the plasticine clearly into two pieces, as demonstrated and as quickly as possible. You may use the other hand to steady the plasticine. Return the knife to its starting position on the board and the stop the timer.”

Page Turning Place the piece of card in the designated area on the opposite side of the platform to the hand under assessment. Using an extension or tripod grip, pick up the card, turn it over as if turning the pages of a book and place it on the opposite side of the form board (on the side under assessment). Reset the task for the participant.

“Start the timer lift and turn over the card as if you were turning the pages of a book and place the card on the opposite side of the board as demonstrated and as quickly as possible. Then stop the timer.”

Jar Lid The lid should be placed on the empty glass jar and tightened only with sufficient force as would be expected for everyday use/self storage. The jar should be placed in the designated area on the form board. Both hands should be used for this task. Pick up the jar using a power grip with the non-dominant hand, undo the lid and return both the jar and the lid to the designated areas on the platform. Reset the task for the participant.

“Start the timer, pick up the jar and undo the lid with the hand under assessment as demonstrated and as quickly as possible. Return the jar and lid to the platform as demonstrated and stop the timer.”

Glass Jug Pouring Fill the glass jug with 100ml of water (100ml is marked on the jug). Place the jug in the designated area of the form board with the handle of the glass jug pointing the right for right-handed participants, and to the left for left-handed participants. Place the glass jar (without the lid) on the designated left area for right-handed participants and the right for left-handed participants. Lift the glass jug by the handle using a lateral grip and show how to pour the water into the glass jar. Reset the task for the participant.

"Start the timer and whilst ensuring as little spillage as possible, pour the water from the jug into the jar as demonstrated and as quickly as possible. Replace the jug on the board and then stop the timer."

Carton Pouring Empty the glass jar from the previous task and replace the jar in the same position on the form board. Fill the carton with 200ml of water (measured out in the glass jug). Place the carton in the designated area on the form board with the spout of the carton pointing toward to glass jar (according to the handedness defined for the previous task). Pick up the carton using a power grip and show how to pour the water into the glass jar. Reset the task for the participant.

"Start the timer and whilst ensuring as little spillage as possible, pour the water from the carton into the jar as demonstrated and as quickly as possible. Replace the carton on the board and then stop the timer."

Lifting a Heavy Object Fill the glass jar with water to the top of the label and tighten the lid. Place the jar in the designated area on the form board, on the left side of the board for right-handed participants and the right side of the board for left-handed participants. Place the empty carton lengthways along the middle of the form board (without obstructing the timer unit) to create a barrier. Lift the jar over the carton using a power grip and place on the opposite side of the form board in the designated area. Reset the task for the participant.

"Start the timer, move the jar over the carton to the other side of the board as demonstrated and as quickly as possible. Then stop the timer."

[THE WATER CAN NOW BE DISPOSED OF AND WILL FORM NO FURTHER PART IN THE ASSESSMENT.]

Lifting a Light Object Place the empty tin (with the plastic lid on) in the same position on the board as defined for the jar in the previous task and keep the carton in the same position on the form board creating a barrier. Lift the tin over the carton using the power grip and place on the opposite side of the form board in the designated area. Reset the task for the participant.

"Start the timer, move the tin over the carton to the other side of the board as demonstrated and as quickly as possible. Then stop the timer."

[PLACE THE SHAP CASE ON THE TABLE DIRECTLY INFRONT OF THE PARTICIPANT AND APPROXIMATELY 8cm FROM THE FRONT EDGE OF THE TABLE. PUT THE FOAM INSIDE THE CASE AND KEEP THE LID OF THE CASE OPEN. PLACE THE TIMER UNIT IN THE CASE ON THE FOAM INSERT IN THE APPROPRIATE POSITION. THE FINAL 5 TASKS WILL INVOLVE THE USE OF THE CASE.]

Lifting a Tray Place the form board ADL side up, on the table to the left of the case for right-handed participants and to the right for left-handed participants. Place the form board slightly overhanging the edge of the table with the long edge facing forwards. The timer unit should remain in the case. Both hands should be used to pick up the form board using a lateral or extension grip. Assuming a right-handed participant: lift the form board from the left side, over the case whilst remaining seated and place it on the table to the right side of the case. Reset the task for the participant.

"Start the timer, move the tray from the left/right to the right/left hand side of the case as demonstrated and as quickly as possible. Then stop the timer."

Rotate Key Return the form board to the case ADL side up, placing in on top of the foam insert (the timer unit should fit neatly in its original position on the board without moving it from the foam). Turn the key to the white mark using the lateral grip.

"Start the timer, rotate the key as demonstrated and as quickly as possible to the white mark and release the key (at which time the key will spring back to its start position) and then stop the timer."

Open/Close Zip Ensure the zip is closed. Open and close the zip using a lateral or tip grip.

"Start the timer, open and close the zip as demonstrated and as quickly as possible and then stop the timer."

Rotate a Screw Place the screwdriver in the designated area on the form board on the right side for right-handed participants and the left for left-handed participants. The arrow unit is mounted on a clip, which should be attached to the front of the case (again, the right side for right-handed participants and the left for left-handed participants). Use the area directly in front of the screwdriver between the lock and the handle on the case. Ensure the arrow is pointing upward. Use two hands to guide the screwdriver to the screw and rotate it 90° clockwise to the mark on the clip using one hand only. Hold the screwdriver in a power grip. You may hold the clip on the top of the case to keep it stable with your other hand. Reset the task for the participant.

“Start the timer and use the screwdriver to rotate the screw a quarter turn clockwise to, or beyond the white mark as demonstrated and as quickly as possible. Once completed, the screwdriver should be replaced on the platform and the timer stopped. Two hands may be used to guide the screwdriver to the screw, but only the appropriate hand should be used for turning the screw. Your other hand can be used to steady the top of the arrow unit.”

Door Handle Rotate the door handle using a power grip until it is fully open, then release the handle.

“Start the timer, rotate the door handle until it is fully open and then release it as demonstrated and as quickly as possible. Then stop the timer.”

D

User test consent form

Consent Form

Goal of this research project:

To validate the hand function of the 3D-printed hand prostheses developed by Monica Moreo.

Outline of the experiment:

This experiment consists of two parts. The first part consists of the manipulation of a series of both lightweight and heavyweight abstract objects. Objects have to be placed from one side to the other side of the form-board. In the second part you will use the 3D-printed hand prostheses to perform 14 activities in daily life, which consist of the following tasks:

- Pick Up Coins,
- Page Turning,
- Carton Pouring,
- Lifting a Tray,
- Rotate A Screw,
- Button Board,
- Jar Lid,
- Lifting a Heavy Object,
- Rotate Key,
- Door Handle
- Simulated Food Cutting
- Glass Jug Pouring
- Lifting a Light Object
- Open/Close Zip

Each task will be demonstrated using slow, clear movements, ensuring that you are aware of the appropriate grip for completion of the abstract object tasks. You are allowed to practice the task only once. The second task will be timed. The time taken to complete each task, the appropriate grip pattern will be recorded, as well as any relevant notes.

Time of experiment:

Maximum 45 minutes

Privacy:

Your name will only be used on this form and will not be used any further in this research.

Voluntary participation

Your participation in this research is entirely voluntary. You can stop at any moment.

Contact researcher:

Monica Moreo 0623430531

Agreement:

I have read the terms of conditions and agree to voluntary participate in this experiment.

Participant: ____ Date: __________________

Researcher: ____ Date: __________________