Bachelor Degree Project

UNIVERSITY OF SKÖVDE

EXOSKELETON FOR HAND REHABILITATION

Bachelor Degree Project in Mechanical Engineering
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Abstract

This document presents the development of a first proposal prototype of a rehabilitation exoskeleton hand. The idea was to create a lighter, less complex and cheaper exoskeleton than the existing models in the market but efficient enough to carry out rehabilitation therapies.

The methodology implemented consists of an initial literature review followed by data collection resulting in a pre-design in two dimensions using two different software packages, MUMSA and WinmecC. First, MUMSA provides the parameters data of the movement of the hand to be done accurately. With these parameters, the mechanisms of each finger are designed using WinmecC. Once the errors were solved and the mechanism was achieved, the 3D model was designed.

The final result is presented in two printed 3D models with different materials. The models perform a great accurate level on the motion replica of the fingers by using rotary servos. The properties of the model can change depending on the used material. ABS material gives a flexible prototype, and PLA material does not achieve it. The use of distinct methods to print has a high importance on the difficulties of development throughout the entire process of production. Despite found difficulties in the production, the model was printed successfully, obtaining a compact, strong, lightweight and eco-friendly with the environment prototype.

Certification

This thesis has been submitted by Sergio Martínez Conde to the University of Skövde as a requirement for the degree of Bachelor of Science in Mechanical Engineering. The undersigned certifies that all the material in this thesis that is not my own has been properly acknowledged using accepted referencing practices and, further, that the thesis includes no material for which I have previously received academic credit.

Sergio Martínez Conde

Skövde 2018-05-05
Institutionen för Ingenjörsvetenskap/Department of Engineering Science

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Estela Pérez Luque

Skövde 2018-05-05
Institutionen för Ingenjörsvetenskap/Department of Engineering Science

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List of Symbols

Variable	**Description**
θ_0	Angular position of link 1
r1	Length of link 1 (O_2O_4)
r2	Length of link 2 (O_2A)
r3	Length of link 3 (AB)
r4	Length of link 4 (O_4B)
θ_{AC}	Angle $\widehat{AO_2C}$
r_D	Length of O4D

θ_{BD}	Angle $\widehat{BO_4D}$
r5	Length of link 5 (DE)
r6	Length of link 6 (CE)
r_{DF}	Length of DF
θ_{EF}	Angle $\widehat{EDF}$
θ_{EG}	Angle $\widehat{ECG}$
r7	Length of link 7 (FH)
r8	Length of link 8 (GH)
θ_{HI}	Angle $\widehat{HGI}$
θPH1	Angular position of proximal phalanx
θPH2	Angular position of middle phalanx
θPH3	Angular position of distal phalanx
L1	Length of proximal phalanx
L2	Length of middle phalanx
L3	Length of distal phalanx

1. Introduction

In recent years, technology has improved healthcare, which means that the life expectancy of patients has increased. Despite this, some patients can live with functional dependencies, which implies a limitation or decrease in their welfare, it is at this point, where the rehabilitation appears. Technology is a branch, which is constantly advancing and developing. It is involved in almost all fields of work, such as military, social, among others. Throughout the last decades, medicine and engineering have worked together in order to develop new systems of rehabilitation, studies of the human body and its limits. In this way, patients could use the new technologies to recover mobility affected or lost due to illness or accidents. As it was indicated by M. Mulas, M. Folgheraiter and G. Gini (2005) only "in the United States, stroke represents the main cause for the motor disability, approximately three million of persons have a permanent motor deficit due to this disease". With all that, the rehabilitation, known as the therapy with the purpose to regain totally or partially the basic motor abilities or tasks, has become increasingly important.

According to the webpage Exoskeleton Report: "*The field of exoskeleton systems is continuously evolving and re-inventing itself, so it is still difficult to create a singular definition.*

In general:

- *Exoskeletons are wearable devices that work in tandem with the user. The opposite of an exoskeleton device would be an autonomous robot that works instead of the operator.*
- *Exoskeletons are placed on the user's body and act as amplifiers that augment, reinforce or restore human performance. The opposite would be a mechanical prosthetic, such as a robotic arm or leg that replaces the original body part.*
- *Exoskeletons can be made out of rigid materials such as metal or carbon fiber, or they can be made entirely out of soft and elastic parts.*
- *Exoskeletons can be powered and equipped with sensors and actuators, or they can be entirely passive.*
- *Exoskeletons can be mobile or fixed/suspended (usually for rehabilitation or teleoperation).*
- *Exoskeletons can cover the entire body, just the upper or lower extremities, or even a specific body segment such as the ankle or the hip.*

In summary, robotics is the application of engineering towards replacing humans from menial tasks, while exoskeletons are the application of robotics and biomechatronics towards the augmentation of humans in the performance of a variety of tasks."

Therefore, in biomedicine the **exoskeletons** are one of the tools which have been created to improve both the rehabilitation and to discover the new limits of the human body. To explain this in easier words, an exoskeleton is basically a "wearable mechanic device".

The present thesis consists of the design of an exoskeleton especially developed for the fingers rehabilitation with passive motion, in order to help people with limited mobility in their hands. In this thesis, the whole development process is explained, from the synthesis of the mechanism adapted to the characteristics of a patient up to the production by a 3D printer.

1.1 Background

Several studies have demonstrated that the use of these rehabilitation exoskeletons, either with active or passive movement, give benefits to the patients. The majority of them have been produced focusing on solving problems regarding the inferior extremities of the human body. Given that, the hand movements are extremely complex to simulate by a device and expensive to be developed and commercialised. However, other models focus solely on hand injuries. The main difference between the mechanisms are the degrees of freedom (DOF), type of sensors or user control, and used materials. In the following lines, some studies performed in this area will be described.

Concerning the fingers, the article "*Evolutionary synthesis of mechanisms applied to the design of an exoskeleton for finger rehabilitation*" by A. Bataller, J.A. Cabrera and J.J. Castillo (2006) has been the main literature review to carry out this project. The device was designed for the index finger with 4 DOF, and by a developed algorithmic system, the authors from the University of Málaga recreated in an accurate way the natural hand-finger movement. Also, J. Wang, J. Li, Y. Zhang, S. Wang (2009) developed another exoskeleton for the index finger. It has 4 DOF, can generate bidirectional movement and it is adjustable to different measurements of patients. It also uses different sensors to determine the angular position of the finger, and in this way to control, analyse and evaluate the effects of the physical therapy.

Also focused on rehabilitation, A. Wege, K. Kondak, and G. Hommel (2005) worked in a hand exoskeleton. This mechanism has 4 DOF, it is moved by a linear actuator, and it receives information by sensors of Hall Effect in each structure articulation. After that, by trigonometric calculus, the angles of each phalange are known. The model can be observed in Figure 1.

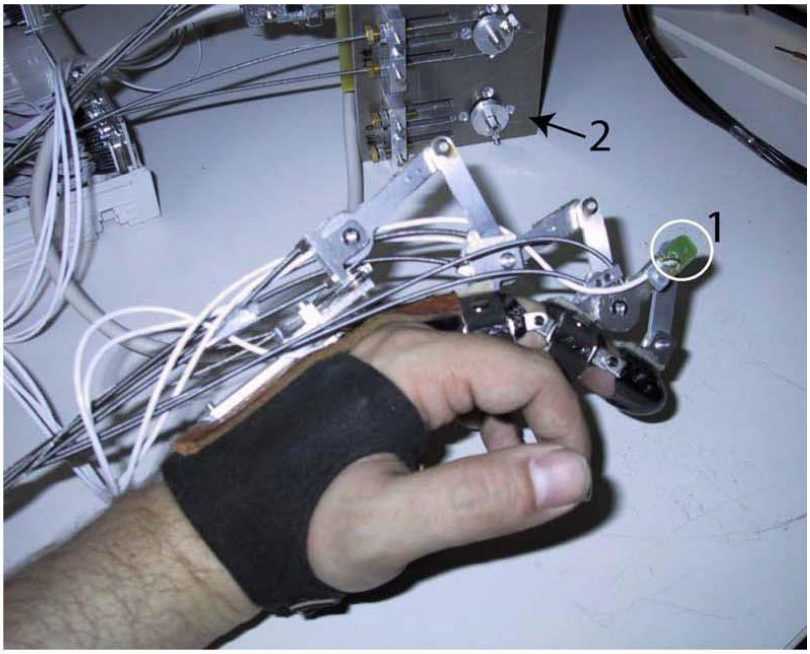

Figure 1. One finger prototype. 1: Hall Effect sensor. 2: Actuator. (Wege, Kondak & Hommel, 2005)

A variation with medical purposes but with a preventive view can be found in "An anthropomorphic hand exoskeleton to prevent astronaut hand fatigue during extravehicular activities" by B.L. Shields, J.A. Main, S.W. Peterson, and A.M. Strauss (1997). This model tries to reduce the hardness of the space suit by movements monitored with pressure sensors localized between the exoskeleton and the hand.

Current exoskeletons used in rehabilitation processes are made from steel and other heavy and difficult to manufacture plastics. A clear example of current exoskeleton made of steel can be seen in Figure 2. The “hand of hope” is a device constructed by Rehab Robotics (Rehab-robotics.com, 2018), which is a company that operates in partnership with the Polytechnic University of Hong Kong. They work developing new technologies in rehabilitation area in order to help patients with reduced mobility and to improve maximum recovery outcomes. It uses steel material and linear servo to achieve the movement. This structure is complex and includes several sensors that use the patient's own muscle signals to activate their desired movement. The “hand of hope” needs a personal computer with specific programs and professionals to manage the program and help the patient if necessary.

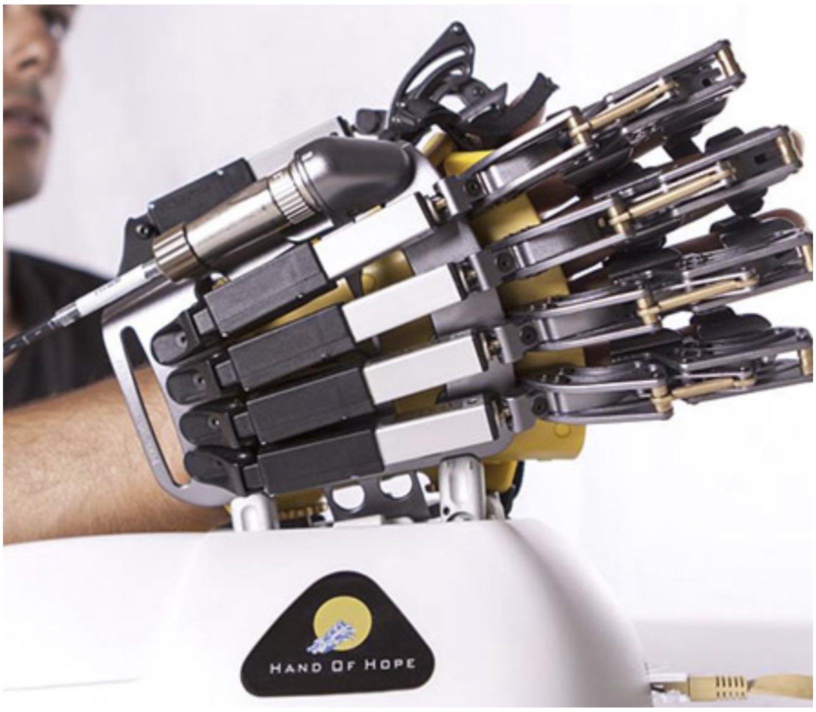

Figure 2. Exoskeleton comparison. (Rehab-Robots 2018)

Surely, there are exoskeletons printed in 3D. ZMorph (ZMorph Blog, 2018) created the first example, Figure 3 shows it. ZMorph is a company developed with the aim of introducing the 3D printing technology to all type of users, even not familiar with electronics, mechanics or engineering. They use a multitool 3D printer with different fabrication methods and materials (ZMorph3d.com, 2018). This device was designed by Eliza Wrobel in the University of Wroclaw; it has a mechanism for each finger including the thumb. It does not use any actuator or motor to move the exoskeleton, it uses a manual mechanism. With this exoskeleton, the rehabilitation is performed for all the fingers at the same time, which is a limitation in order to make the therapy for just one finger. This prototype was created to facilitate to a particular patient grab objects and perform physical activities, on balance the rehabilitation of a patient with reduced mobility in their hands.

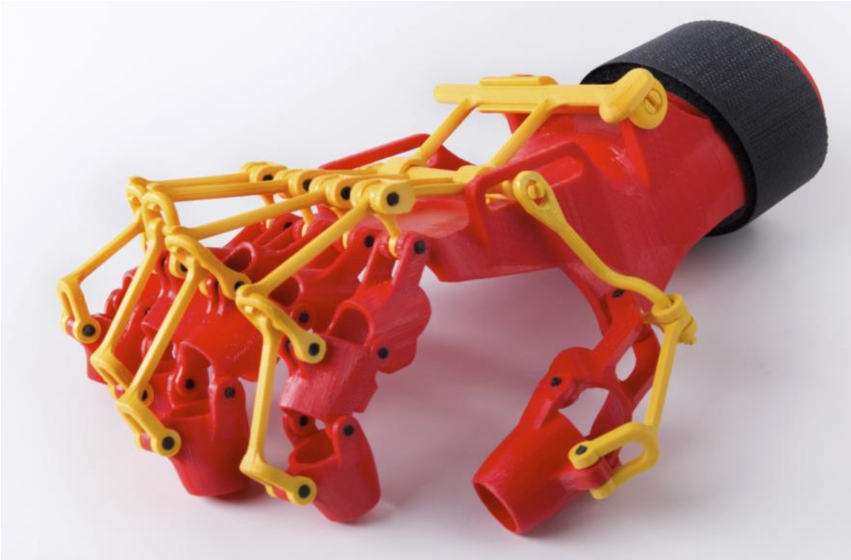

Figure 3.Exoskeleton printed by 3D printer 1. (ZMorph Blog, 2018)

Another example of 3D printed exoskeleton is shown in Figure 4. Lei Cui in the University of Curtin, Australia, (Curtinnovation.com, 2017) created a prototype for one finger rehabilitation; however, it can only perform the downward movement of the finger since the design does not have any type of adjustment to enable an upward movement. As well as the device created by Rehab Robotics named previously, this exoskeleton uses a linear actuator.

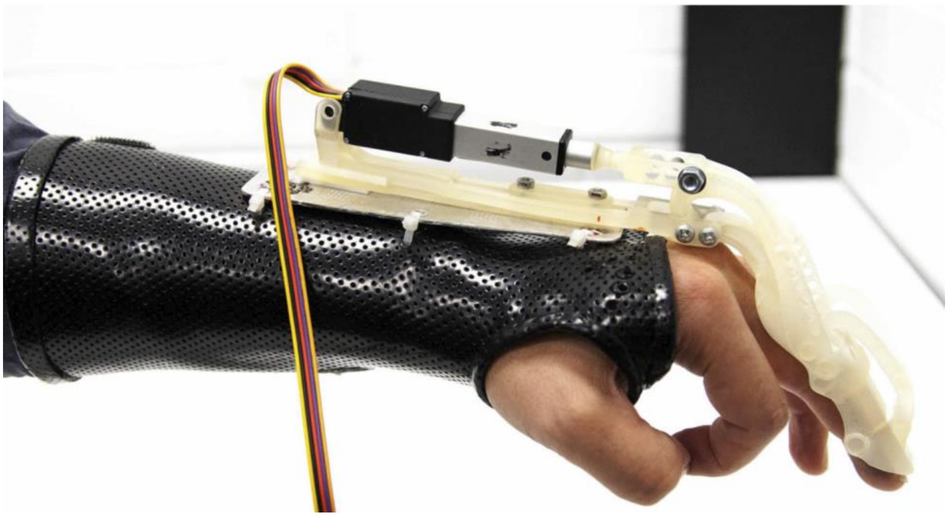

Figure 4. Exoskeleton printed by 3D printer 2. (Curtinnovation.com, 2017)

Furthermore, most of the hand prototypes were design with other objectives, the main applications of them are to create virtual environments with haptic interaction. In this area, M. Bouzit, G. Burdea and G.P. Rares Boian (2002), describe the construction of a glove-exoskeleton that interacts with a 3D virtual environment in real time by pneumatic sensors, infrared sensors and Hall Effect sensors to measure the angle. Also, B.H. Choi and H.R. Choi in the article "A semi-direct Drive Hand Exoskeleton Using Ultrasonic Motor" describe this procedure. This device consists of a glove to sense objects in virtual environments using ultrasonic motors and sensors.

To perform this project many different types of articles have been taken into account. The devices mentioned before were analysed in order to identify their drawbacks and figure out a way to improve them.

On the following table, the features of the previously mentioned exoskeletons are shown:

Table 1. Exoskeleton features

	Rehab Robotics	ZMorph Blog	Curtinnovation
Material	Steel	ABS	ABS
Complexity	High	Low	Medium
Weight	High	Low	Low
Size	Large	Large	Small
Individual finger rehabilitation	YES	NO	YES
Multiple fingers rehabilitation	YES	YES	NO
5 Fingers rehabilitation	YES	YES	NO
Portable	NO	YES	YES
Handling by professionals	YES	YES/NO	YES/NO
Requires a computer	YES	NO	NO
Actuator	Linear	Manual	Linear
Design modifications	NO	YES	YES
Multiples patients	YES	NO	NO
Control by sensor	YES	NO	NO
Nail control (Blood flow cut)	NO	NO	NO
Easy manufacturing	NO	YES	YES
Price	Expensive	Cheap	Cheap

The features in the table 1 are highlighted, for they are to be improved in the development of this thesis.

The main characteristics to improve in the first model (Rehab Robotics) are the use of an alternative material and less complexity (the necessary software to use it, reduce the number of servos, and so on). These two points will make the device cheaper and easier to use in hospitals and physiotherapy centres. The portability is important in the development of a proposal since the resulting device is expected to facilitate its use in patient´s houses or different specific centres.

According to the second exoskeleton (ZMorph) which follows the idea to achieve in this thesis, it is the 3D printing. However, that model has some shortcomings to improve, such as the lack of actuators to perform the movement since this model uses a manual system. In this way, that model cannot rehabilitate the fingers individually. Finally, the last model described on table 1 (Curtinnovation) uses, also, the 3D printing technology but, in this case, this device rehabs only one finger and the downwards movement of the finger since it does not have any adjustment system to the finger in order to enable an upward movement.

The prototype to be developed in this thesis will aim to solve all shortcoming of the models above-mentioned (Statements).

1.2 Problem Statement

After the literature review, observing the advantages and disadvantages of the different exoskeletons on the market, exposed in the Background section, the different characteristics to be developed in this document were defined.

The present project consists of the development of a rehabilitation system in order to improve the mobility in affected fingers, through the use of exoskeletons with CPM (Continuous Passive Motion) by servos. Specifically, the rehabilitation will focus on the flexor tendons; they are responsible for the movement of the closing of the hand. These tendons, normally, are the first affected when the patients suffer any type of accident limiting the movement of the hands; therefore, the tendons suffer atrophy. Thereby, the exoskeleton will work reducing the tension of the tendons enabling an easier rehabilitation process on the patient. The most benefited people are the ones that have suffered any type of accident or illness that affect hand mobility, as well as the respective centres or companies that need a new method to treat these types of problems, such as hospitals or physiotherapy centres. In addition, the device represents an easy and low-cost production that make it more attractive regarding a future commercialization, which will be explained in detail in the following sections.

The organization where the project has been carried out is called "UPACE", Figure 5. UPACE is a Spanish non-profit organization which is dedicated to attend disabled people, especially people affected with cerebral palsy and other disorders. The organization works giving the patients physical therapies to improve their own mobility, and in this way, increase their welfare.

upacesur
Por la discapacidad

Figure 5. Company logotype. (www.upacesur.org)

The thesis is developed for a patient supplied by UPACE. The patient is a 30 years old male suffering from cerebral palsy, which has caused the loss of his hands' mobility. As it was mentioned previously, the main objective of the project is to design the hand exoskeleton with the special characteristics of the patient to execute the rehabilitation. The whole device will only have one degree of freedom, which means it will make just one movement such as being, the natural closing movement of the hand. It could be seen as a limitation; however, it will reduce the complexity and therefore, the costs of production making it more interesting in a supposed commercialisation of the product. On the other hand, a 3D printer will manufacture the model.

The natural closing movement of the hand is the therapy that has been chosen and recommended by the physical therapist of the company for this particular patient, firstly to help the strength and mobility of flexor tendons and to prevent joint stiffness and oedemas, as well as to avoid possible future surgeries. The treatment will consist of the application of the continuous passive motion in the articulations with repetitive and slow exercises. In the first sessions, it will start with a small range of motion that will progressively increase until the full range is achieved. A professional, such as a physiotherapist or the patient himself, can perform this therapy. As it was mentioned, the range of movement will be incremented progressively. The different range is modified changing the angles of movement in the servos; it is explained in Appendix 2.

1.3 Objectives

As previously mentioned, the main objective of this project is to develop an initial rehabilitation prototype of a hand exoskeleton with the following characteristics:

- Recreate the natural closing hand movement (rehabilitation movement) in order to avoid atrophy of the tendons.
- As a mandatory requirement by the physiotherapist, the model must allow the possibility to check the nail of the user, since the nails show a different colour in case the patient suffers a cut-off blood supply.
- Individual rehabilitation for each finger, and complete rehabilitation for all the fingers at the same time.
- A lighter device than current exoskeletons in the market.
- Eco-friendly materials.
- Low cost.
- Installation of servos to perform the passive motion.
- Easy manufacture with ABS (Acrylonitrile Butadiene Styrene).
- Easy manufacture with PLA (Polylactic Acid).
- Testing the device on the patient.

1.4 Overview

The next section will describe the full method carried out in the project, from the data collection of the patient in the Spanish company, up to the 3D printing. In Section 3, the obtained results are presented. Next, a discussion will be performed regarding the results and the entirety of the project. Finally, Section 5 and 6 provides the conclusions and future work.

2. Method

Once the background information was collected, a visit to the patient of the company was made to collect the necessary measurements. With the dimensions of the hand, the different parameters to design the mechanisms that recreate the natural movement of the fingers would be obtained by MUMSA (Malaga University Mechanism Synthesis Algorithm).

The mechanism of each finger was made with WinmecC, a mechanism software for one degree of freedom (Universidad de Málaga, 2018). With this program, the different mechanisms of each finger have been designed with the parameters previously obtained by MUMSA.

After that, Solid Works was the software used to design the CAD model of the exoskeleton, and the main materials for 3D printing were checked to ensure a sustainable development of the project. In addition, a comparison of the environmental effects caused by each material was made with the program CES Edupack 2018.

Following, different actuators were studied to be installed on the CAD Model to ensure they would move the exoskeleton, this evaluation also showed if the weight and dimensional requirements were met, as well as to see the simulation of the therapy movement.

Finally, the prototype was printed by different 3D printers. The University of Málaga uses ABS (Acrylonitrile Butadiene Styrene) plastic to print and the University of Skövde uses PLA (Polylactic Acid) material. The differences among them will be discussed in the results and discussion sections.

The next image describes the method of the project in a visual way, Figure 6. All the process is described, in detail, in the following sections.

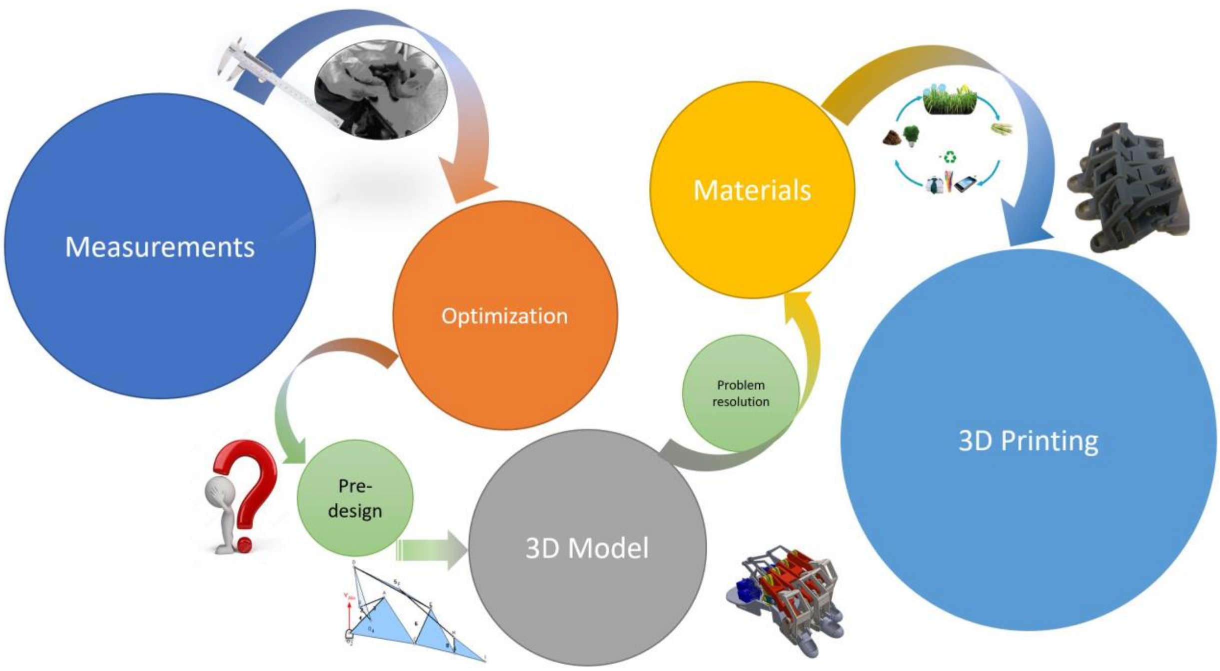

Figure 6. Method.

2.1 Measurements

Sergio Martínez visited UPACE to obtain the measurements of the patients. Three patients were selected by the physiotherapist of the organization, those three patients could see an improvement using the exoskeleton. They cannot move their hands due to cerebral palsy and other disorders. These patients have a daily rehabilitation routine, which consists in performing the closing movement of the hand by the physiotherapist manually operating the patient’s hand, in other words, the passive motion applied on the patient hand is done by the physiotherapist themselves. With the exoskeleton, the physiotherapist could do other activities while the rehabilitation process is being performed, since the exoskeleton would apply this continuous passive motion by servos.

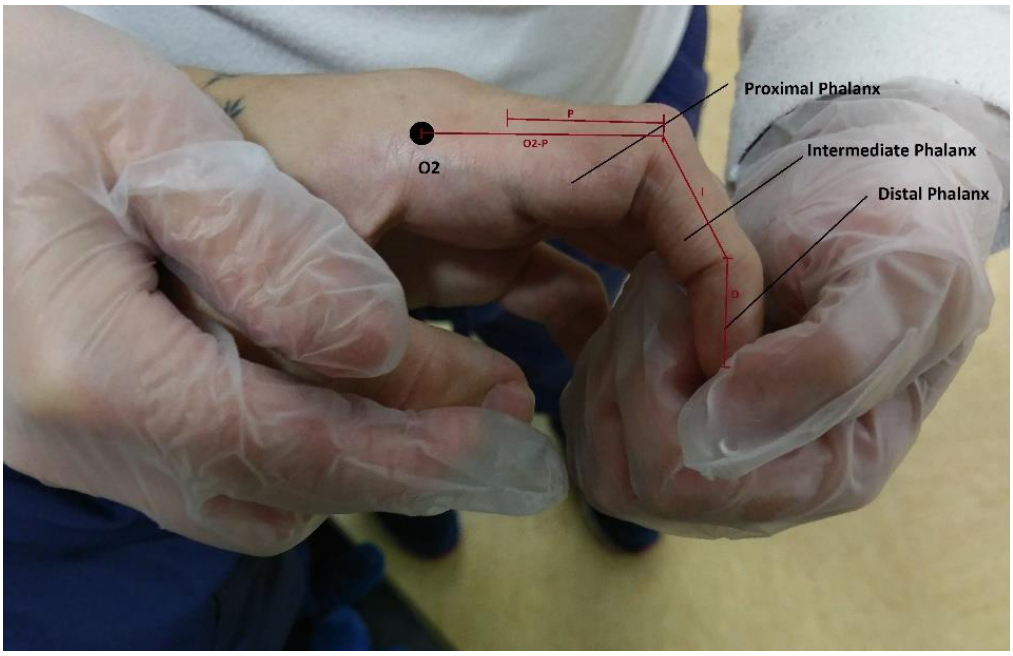

Figure 7. Principal measurements.

Figure 7 shows the principal measures taken. Also, the width of each phalanx and the hand was measured as well as the phalanx angles. All the measurements were taken by a sequence of photos of the closing natural movement of the hand from different perspectives, besides taking the measurements of each phalanx, width of the hand and width of the fingers making use of a calliper. Table 3 and Figure 8 show the phalanx angles obtained in the different photos, which were measured using AutoCAD. Of those three patients, one was selected, in this case, the exoskeleton will be appropriate for the patient number 3. This patient was selected give the bigger hand measurements than the other patients, this condition was an essential and determining factor since it is a first proposal and it will be easier to work with these larger dimensions. Also, a bigger prototype offers facilities to look for problems in the 3D model, in addition to obtain stronger pieces in case of problems are found with the material.

The following tables show the measure results of the selected patient (in mm):

Table 2. Phalanx measurements.

	Index	Middle	Ring	Pinkie
O2-P	48			
Proximal	35	40	35	22
Intermediate	28	33	25	18,5
Distal	24	25	22	20

Table 3. Widths.

Width			Proximal	Intermediate	Distal
Hand	69	Index	20,2	15,5	14
		Middle	17,5	19	16
		Ring	14	14,9	15
		Pinkie	15	13	14

Table 4. Phalanx angles.

Angles (^{o}) / Photo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Proximal	10,4	18,8	21,3	22,3	23	25	28,7	34,2	36,1	48,9	52,8	60,6	62,4	67,1	68,1
Intermediate	24	35,8	41	63,3	76	85,4	102,7	112,4	113,2	116,8	117,7	134,7	138,3	151,3	158,4
Distal	28,4	47,8	57,2	89,1	95	114,3	138,9	152,4	153,6	154,1	157,7	168,9	170	172	174,4

Figure 8. Angle measurement on the hand.

In Table 4, it can be seen the obtained angles in degrees of each finger in the sequence of photos. A number of 15 photos were taken on the hand to collect the necessary data and simulate the patient's movement of the hand. Once the different angles were obtained, they were introduced to a graph, as shown in Figure 9. Some data was modified to follow a movement as natural and soft as possible, as well as to control possible measurements errors. The errors are obtained due to the closing movement of the hand is produced helped by a physiotherapist and it is impossible follow a soft movement. These lines represent a grade 3 polynomial function, with that, the lines are accurate enough with a high level of smoothness and continuity. The solid line represents the taken data and the dotted the most accurate movement that should follow the hand. Then, finally, the measured movement is sufficiently captured by these fitted curves.

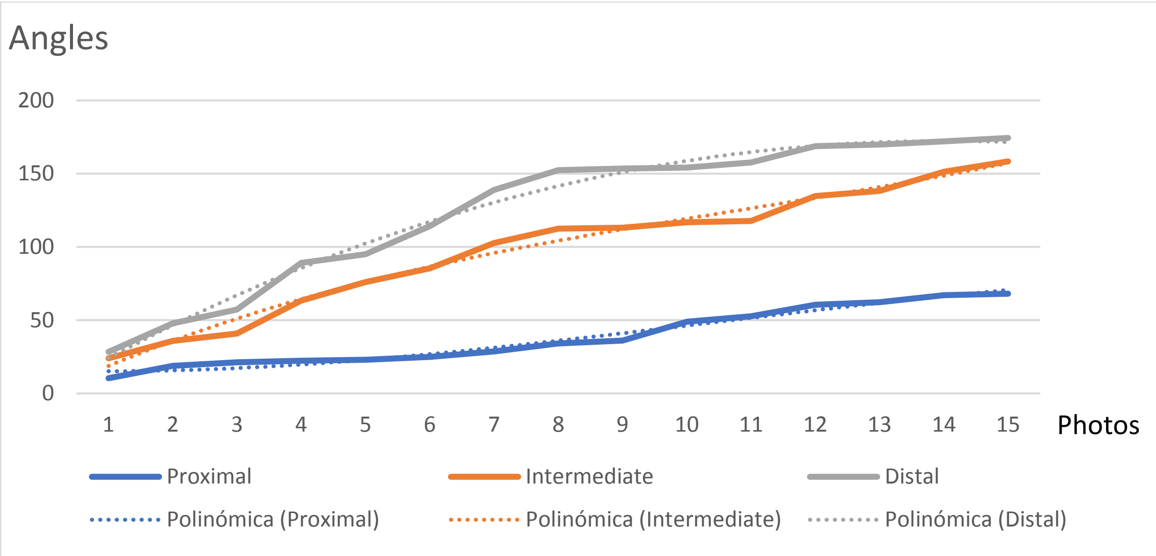

Figure 9. Angles distribution.

2.2 MUMSA

The University of Málaga works in the development of an evolutionary algorithm system called MUMSA. This algorithm works with MATLAB using the equations collected in Appendix 2 and uses the mechanisms shown in Figure 10 as a base.

The variables used by the algorithm are the angles and the length of each phalanx, this data is collected in the tables 2, 3 and 4. With such data, MUMSA provides different values to create a mechanism that simulates the real (or with the least possible error) movement of the fingers. Following, the problems with the use of MUMSA will be exposed, and the solution found as well.

The different data offered by the program are in the Figure 10, and the different output and input data of MUMSA are showed in table 5.

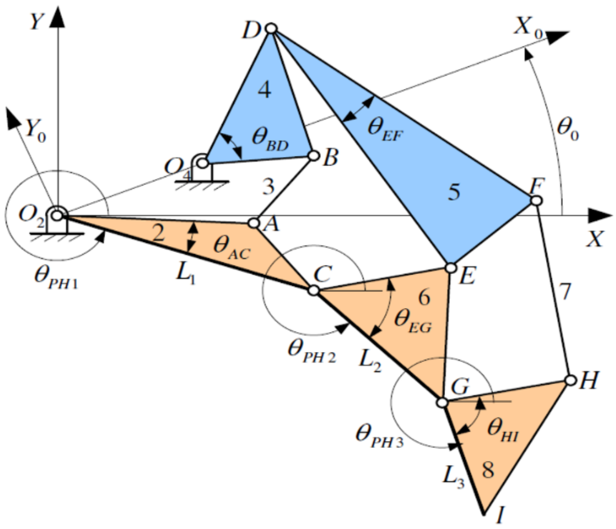

Figure 10. Mechanism parameters. (Bataller, A., Cabrera, J., Castillo, J. and Nadal, F. 2017)

The different parameters of the picture above are explained in the following table.

Table 5. Input and output MUMSA parameters.

Variable	**Description**
θ_0	Angular position of link 1
r1	Length of link 1 (O_2O_4)
r2	Length of link 2 (O_2A)
r3	Length of link 3 (AB)
r4	Length of link 4 (O_4B)
θ_{AC}	Angle $\widehat{AO_2C}$
r_D	Length of O4D
θ_{BD}	Angle $\widehat{BO_4D}$
r5	Length of link 5 (DE)
r6	Length of link 6 (CE)
r_{DF}	Length of DF
θ_{EF}	Angle $\widehat{EDF}$
θ_{EG}	Angle $\widehat{ECG}$
r7	Length of link 7 (FH)
r8	Length of link 8 (GH)
θ_{HI}	Angle $\widehat{HGI}$
Input variables	**Description**
θPH1	Angular position of proximal phalanx
θPH2	Angular position of middle phalanx
θPH3	Angular position of distal phalanx
L1	Length of proximal phalanx
L2	Length of middle phalanx
L3	Length of distal phalanx

Each input parameter of length and the angle corresponding to the length and angle of each finger and phalanx shown and explained in the tables 2 and 4. The obtained output data by MUMSA is necessary to create the mechanism that simulates the most accurate movement of the hand.

As it was mentioned previously, MUMSA offers the parameters to achieve a mechanism with a more accurate movement of the real human hand. This does not mean that the first result offered by MUMSA is adequate, as it can be seen in Figure 11, the points 02 and 04 are really close to each other.

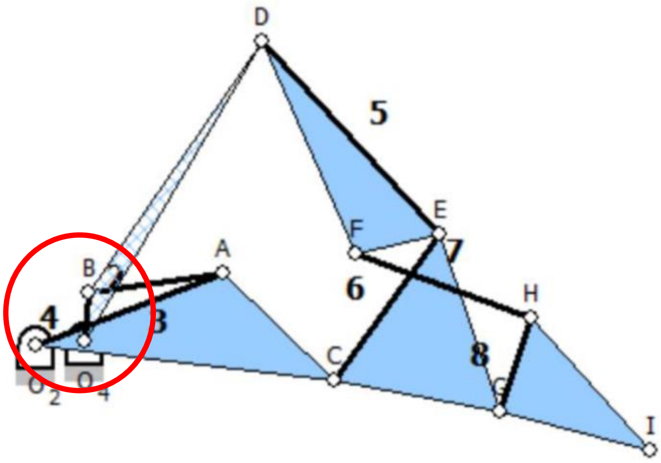

Figure 11. First mechanism result with MUMSA parameters.

The O2 point would be the rotation point of the finger (shown in Figure 12) and the 04 point is the first rotation point of the exoskeleton to carry out the movement. To facility the explanation, the following Figure 12 shows a recreation of a hand with an exoskeleton. Here can be seen the referent points 02 and 04.

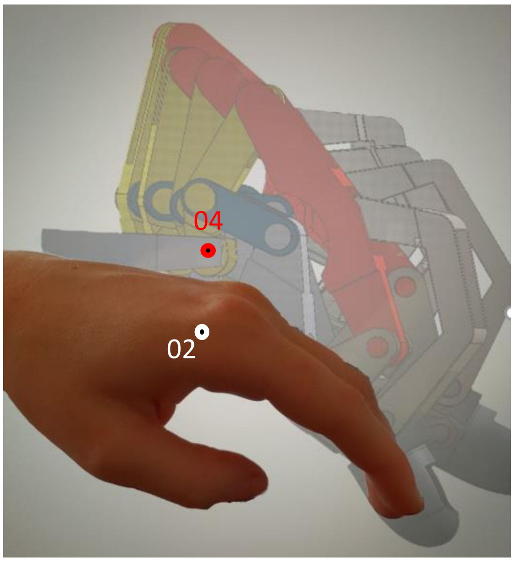

Figure 12. Representation of 02 and 04 points.

The first restriction was to control the angle between 02 and 04. As it can be seen in Figure 11 the angle between 02-04 is too small, that means the mechanism would start “into” the finger which is not

a valid option. On the other hand, if 04 is placed behind 02 (angle > 90°), the space for servos would be limited since an area of the hand-support would be used to place the mechanism. It should be required to have the maximum space possible, in the hand-support, to install the servos. With this restriction, another result was obtained in MUMSA and the resulting mechanism is shown in Figure 13. It will be created with a restriction of 30 and 90 degrees.

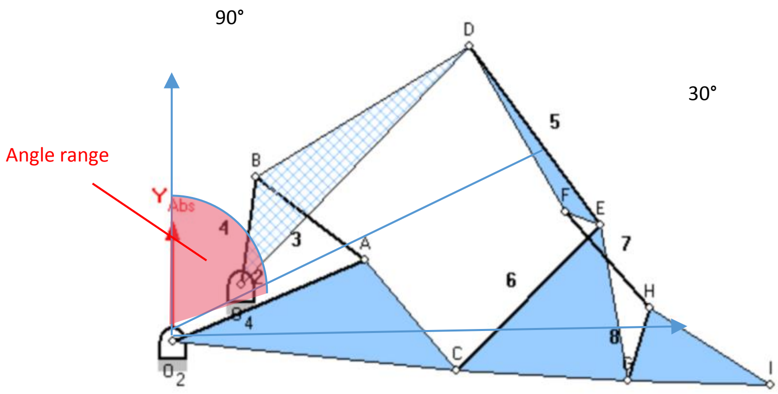

Figure 13. Resulting mechanism with angle restriction.

As it can be observed in Figure 12, the point 04 needs a minimal distance of the hand and from point 02. In the mechanism created from the parameters offered by MUMSA, the point 04 would be over the finger, meaning it would not result in a comfortable and workable final exoskeleton. Because of this, a restriction among these points will be assumed for the following analysis by MUMSA.

In addition, this mechanism does not work properly since other restrictions were not considered, such as the linear distance between 02 and 04. With a short distance between these two points the space needed for the hand knuckles is lower than the required to insert the hand into the exoskeleton. For that, this time a 20 mm restriction, between 02-04, was taken. With these two restrictions another analysis was carried out in MUMSA and it offered a valid mechanism. It is shown in Figure 14.

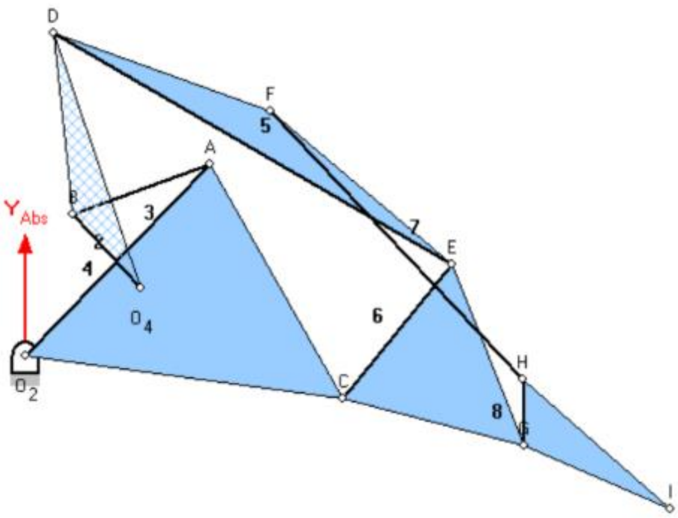

Figure 14. Final mechanism.

To facilitate the understanding of these mechanisms, Figure 15 is shown below. The figure shows the different parts of the mechanism that correspond with the hand as well as with the exoskeleton.

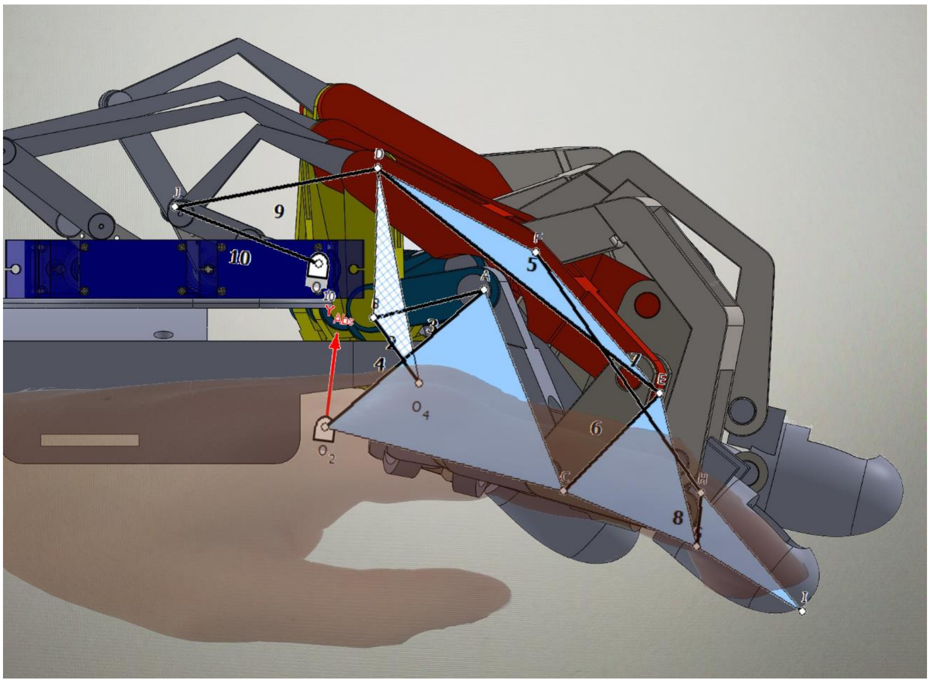

Figure 15. Explanation of the final mechanism.

All the previous analyses were made for the index finger. Once the final mechanism was found, the corresponding analyses, for the rest of the fingers were performed using the same angle and length restrictions. The results for each finger are shown in the following Table 6, on the next page:

Table 6. Results of each finger.

Index	Value	**Intermediate**	Value	**Ring**	Value	**Pinkie**	Value
L1 [mm]	48	L1 [mm]	40	L1 [mm]	35	L1 [mm]	22
L2 [mm]	28	L2 [mm]	33	L2 [mm]	25	L2 [mm]	18,5
L3 [mm]	24	L3 [mm]	25	L3 [mm]	22	L3 [mm]	20
Θ_{PH1} [º]	306,04	Θ_{PH1} [º]	305,36	Θ_{PH1} [º]	305,27	Θ_{PH1} [º]	302,84
Θ_{PH2} [º]	294,64	Θ_{PH2} [º]	281,97	Θ_{PH2} [º]	289,16	Θ_{PH2} [º]	287,37
Θ_{PH3} [º]	244,93	Θ_{PH3} [º]	252,44	Θ_{PH3} [º]	254,27	Θ_{PH3} [º]	267,88
Θ_{BD} [º]	142,74	Θ_{BD} [º]	147,96	Θ_{BD} [º]	152,44	Θ_{BD} [º]	151,09
Θ_{EF} [º]	349,92	Θ_{EF} [º]	356,76	Θ_{EF} [º]	355,68	Θ_{EF} [º]	346,60
Θ_{AC} [º]	75,34	Θ_{AC} [º]	78,81	Θ_{AC} [º]	70,46	Θ_{AC} [º]	55,36
Θ_{EG} [º]	60,68	Θ_{EG} [º]	52,51	Θ_{EG} [º]	47,96	Θ_{EG} [º]	33,61
Θ_{HI} [º]	48,37	Θ_{HI} [º]	50,81	Θ_{HI} [º]	51,57	Θ_{HI} [º]	59,61
Link 2 [mm]	39,99	Link 2 [mm]	39,96	Link 2 [mm]	39,89	Link 2 [mm]	39,29
Link 3 [mm]	22,03	Link 3 [mm]	21,17	Link 3 [mm]	20,00	Link 3 [mm]	18,46
Link 4 [mm]	14,94	Link 4 [mm]	13,84	Link 4 [mm]	14,39	Link 4 [mm]	13,98
Link 5 [mm]	69,19	Link 5 [mm]	69,97	Link 5 [mm]	66,65	Link 5 [mm]	58,23
Link 6 [mm]	25,97	Link 6 [mm]	30,65	Link 6 [mm]	31,86	Link 6 [mm]	38,16
Link 7 [mm]	55,29	Link 7 [mm]	58,09	Link 7 [mm]	51,36	Link 7 [mm]	53,58
Link 8 [mm]	9,91	Link 8 [mm]	12,84	Link 8 [mm]	12,31	Link 8 [mm]	12,08

2.3 Mechanisms

As it was mentioned in section 2.2, the mechanisms of each finger were made taking into account both limitations, angle and length restriction. The following Figures show the mechanisms made with the parameters offered by MUMSA collected in table 5 for the specific mechanism of each finger. WinmecC was the software chosen to make the different mechanisms since it allows working with structures with one degree of freedom and it is perfect to obtain a first view of the movement simulation.

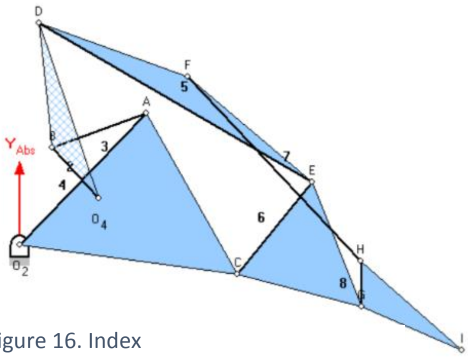

Figure 16. Index

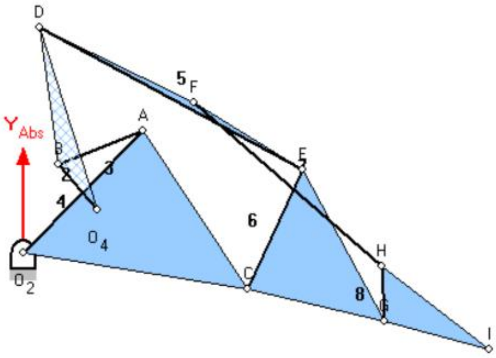

Figure 17. Intermediate.

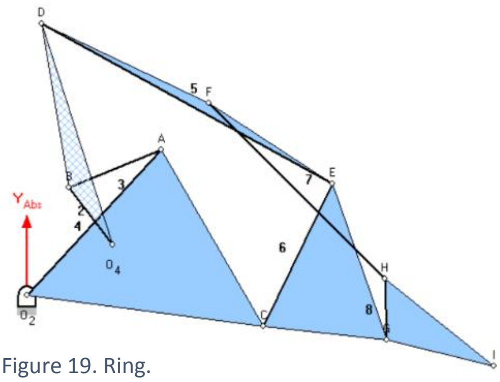

Figure 19. Ring.

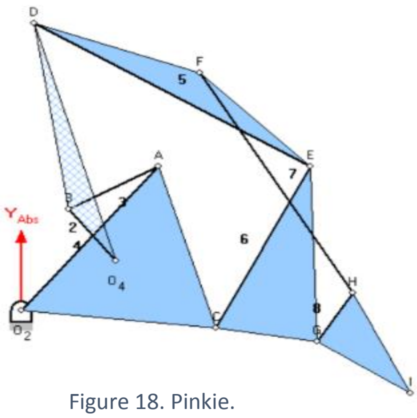

Figure 18. Pinkie.

2.4 Servos

Having reached this point, the question was *“What type of actuator should we use?”*

Different servos were researched in several catalogues, for there is a wide range of existing models. Finally, due to weight and size conditions, two workable solutions were found to achieve the correct move of the exoskeleton. Next, these solutions are exposed and how they would work is plotted using WinmecC.

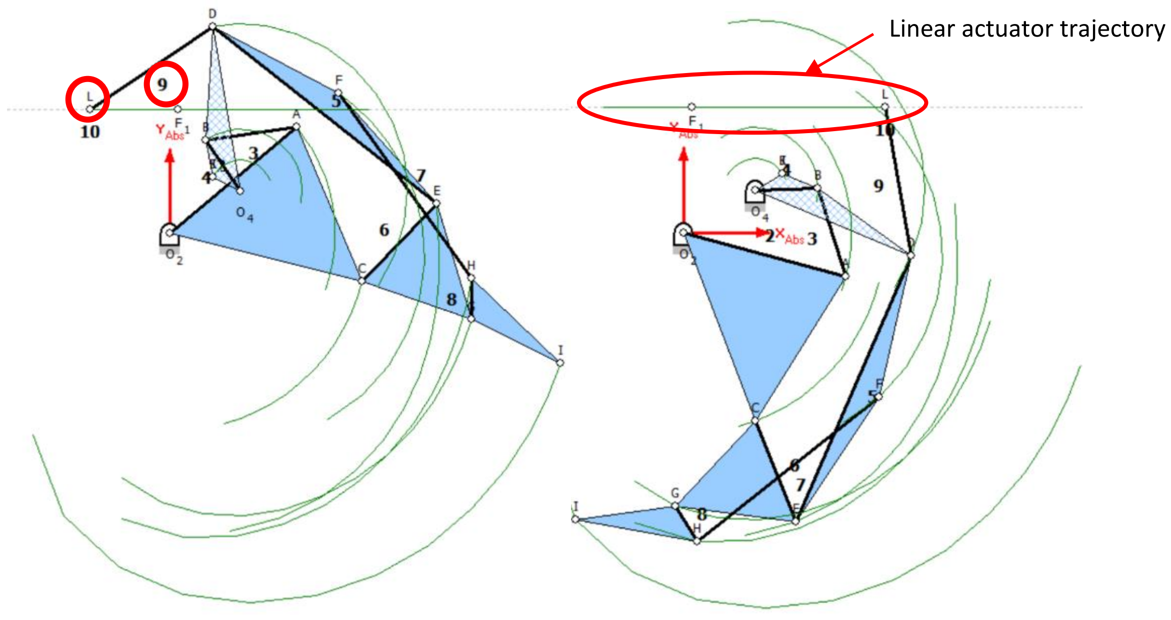

Figure 20. Linear Actuator.

Each green-line represents the displacements of each joint. In this case, green-line printed by the point "L" in Figure 20 would represent a linear actuator. This solution is theoretically correct because by adding the bar 9 it is possible to realize the movement with a great torque, and without dead points. However, there are not commercial actuators with a good relation length-width acceptable to use in a little space such as the hand. The best option found was to use an actuator with 10 centimetres length, but it was discarded because it would use a lot of space on the hand and arm.

The second option would use a rotary actuator. The simulation in WinmecC is represented in Figure 21 below:

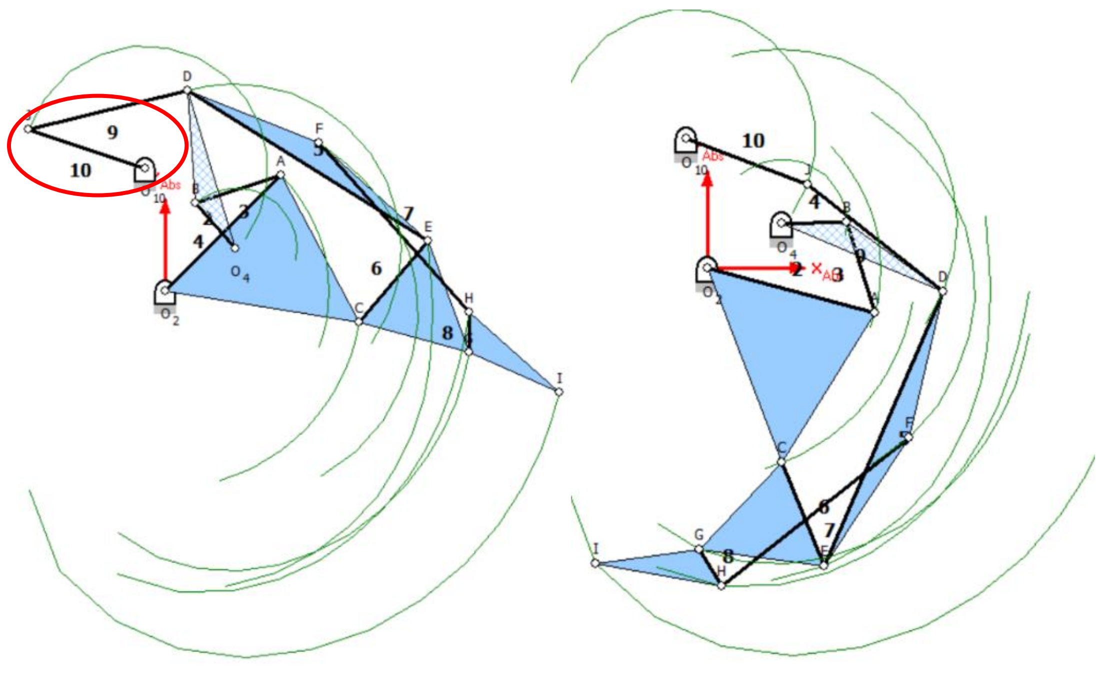

Figure 21. Rotary Actuator.

Using this option, it is possible to find a commercial actuator available in electronic shops. In this case, the actuator used is "Micro 9G SG90 TowerPro", shown in Figure 22, it costs around 70 SEK, and it is one of the least expensive 4.8v servos on the market. This one is selected considering the weight and size of this type of servos. It produces a 180° movement, which allows the complete movement of the fingers in this exoskeleton, it also has a great force to make the continuous passive motion. Another point taken into account was the power of the actuator. In this thesis the patient does not have any stark or strength in the hands, therefore with a minimum torque, the movement would be made. If the patient would have any strength or stark this point should be analysed to consider if the power of the actuator is adequate.

The most important specifications are the following, Table 7:

Table 7. Actuator Specifications.

	Dimensions
Wire length	200 mm
Size	23.2 x 12.5 x 22.0 mm
Weight	9 g

	Specifications
Torque	0.1274 N·m
Voltage	4.8V / 6V
Speed	0.12 sec/60 degree

Figure 22. Selected Actuator. (Electronilab, 2018)

2.5 3D Model

With the mechanism information, the 3D modelling can begin. Different models were created following the mechanisms obtained previously by WinmecC and finding several problems. The software chosen to create the 3D model was SolidWorks, a powerful software package to create and simulate either pieces or assemblies. With this program, each part of the exoskeleton was created as well as the assembly of them and the movement analysis.

There is a limited freedom to create each piece, which must be robust enough to resist rough handling. Between moving parts, there must exist a 0.2 mm gap because to reduce the possibility of parts sticking together when they are printed. Of course, the distances between joints must be respected.

Some problems were already mentioned in section 2.3. The first of them being the angles according to 02-04 points. With the first mechanism made with WinmecC (Figure 11) the designed model is shown in Figure 23. As it was mentioned, the model is not suitable for a comfortable rehabilitation due to the position of point 04 located directly on the real finger.

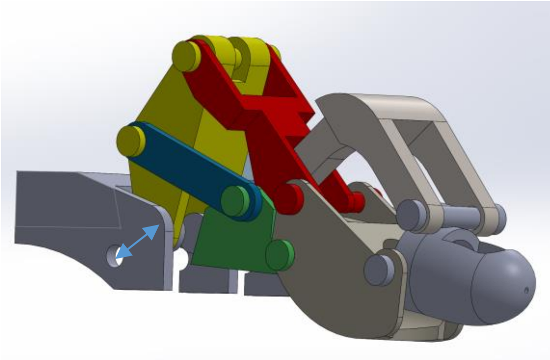

Figure 23. Wrong CAD model.

Once the 3D model was studied, another problem was found since by only changing the angle restriction the knuckle space required is not met. Then the second restriction, 20 mm length between the points, mentioned previously became necessary. The CAD model was created once the final mechanism was made by WinmecC with both restrictions (Figure 24).

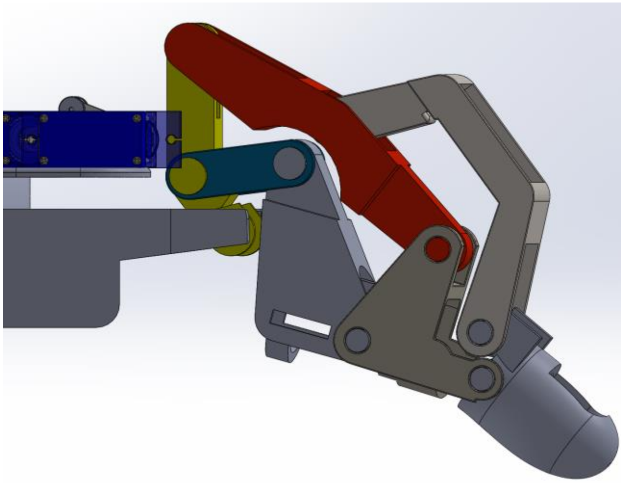

Figure 24. Final finger CAD model.

Once the index finger was made, the CAD model of each finger were also created. The final model of all the fingers can be seen in the Figure 25 below:

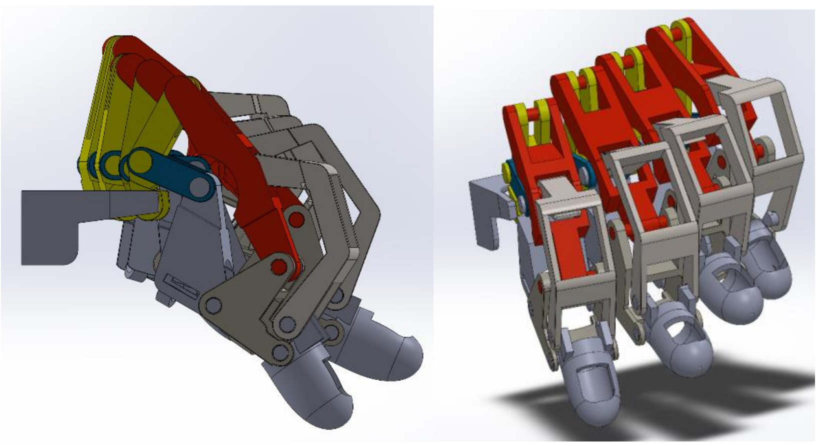

Figure 25. 3D Model.

On the following Figure 26, the 0.2 mm gap explained above is shown. These gaps are necessary to enable movement between the parts.

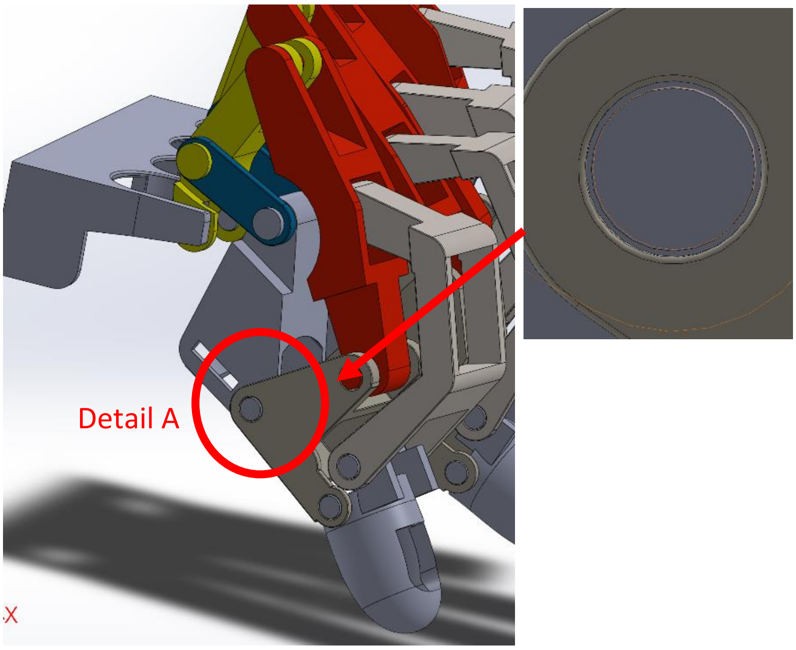

Figure 26. Detail A – 0.2 mm gap.

All the separations between parts must be taken into account because the 3D printer will reproduce the exact blueprint, Figure 27.

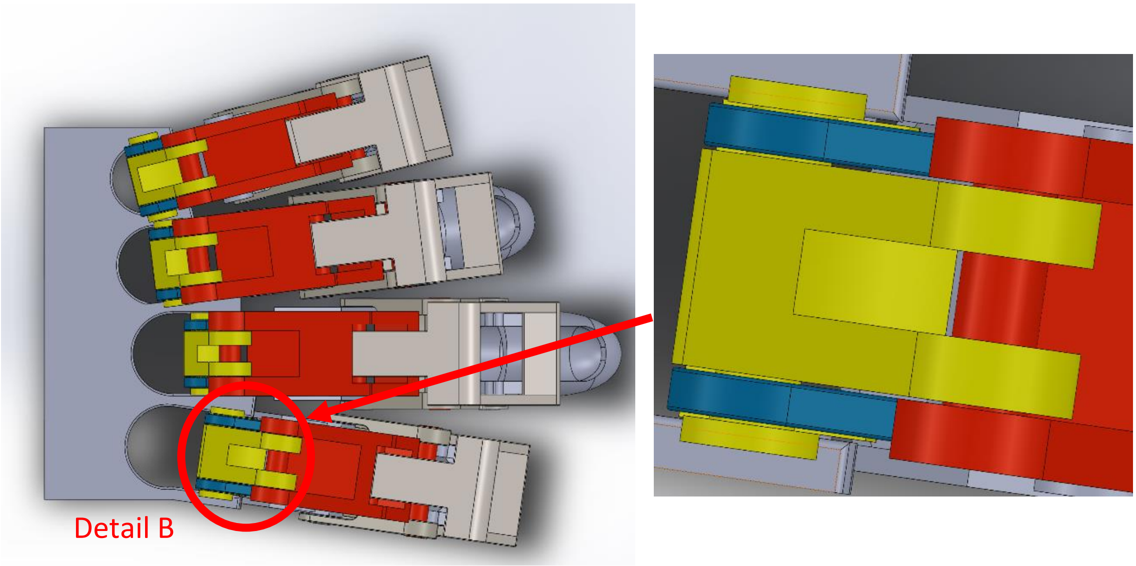

Figure 27. Detail B – 0.2 mm gap.

The following Figure 28 shows the movement sequence using the actuator simulation. As it can be seen, the actuator-support does not exist, the reason being to simplify the hand-support to perform the simulation quickly.

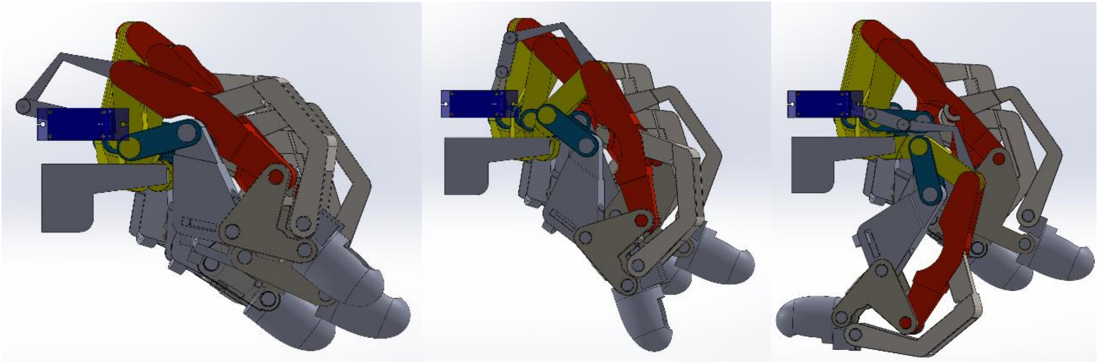

Figure 28. Movement Sequence.

2.5 Material Selection and Sustainable Development.

3D printers are part of the additive manufacturing process. These processes can fabricate a broad range of objects in three dimensions with very complex geometries. The printing starts from the bottom layer creating a superficial plane on the base to later allow the separation of the piece. 3D printers use a fine plastic filament, which is heated when it is pushed through the extruder. The extruder is basically a device that warms the material until its melting point. Once the bottom layer is made, the process consists of printing layers of material on top of each other until the piece is completed. Finally, the material cools down and therefore, it is solidified.

Currently, 3D printers can use a wide range of materials, such as polymers, metals, concrete or ceramics. However, the most used and developed ones are thermoplastic polymers, especially ABS and PLA.

ABS (Acrylonitrile Butadiene Styrene), whose composition is approximately 15-35% acrylonitrile, 5-30% butadiene, and 40-60% styrene, is the main material used in 3D printing. This material is extremely rigid, resilient, and easily moulded. It is usually opaque, although depending on the grade, it can also accept colours or be transparent. ABS has to be extruded in a range of temperatures between 220˚ and 240˚ Celsius degrees, and it should be printed using printers with a heated print bed to avoid the thermal shock and possible deformations. When the melting point is reached, ABS material releases gases that in high concentrations that can be harmful. It also has the advantage that can be mechanised easily and has a smooth surface finish. The main properties of the material are shown in Table 8.

Table 8. ABS Properties.

General Properties ABS				
Density	1,01E+03	-	1,21E+03	kg/m^3
Price	20,6	-	24,3	SEK/kg

Mechanical Properties ABS				
Young´s Modulus	1,1	-	2,9	GPa
Yield strength (elastic limit)	18,5	-	51	MPa
Tensile strength	27,6	-	55,2	MPa
Compressive strength	31	-	86,2	MPa
Elongation	1,5	-	100	% strain
Hardness (Vickers)	5,6	-	15,3	HV

Thermal Properties ABS				
Glass temperature	87	-	128	°C
Maximum service temperature	61	-	76	°C
Minimum service temperature	-123	-	-73	°C

Optical Properties ABS	
Transparency	Opaque

Process Ability ABS			
Castability	1	-	2
Moldability	4	-	5
Machinability	3	-	4
Weldability	5	-	

Scale: 1→Excellent; 5→Not recommended

ECO Properties ABS				
Embodied energy, primary production	90,3	-	99,9	MJ/kg
CO^2 footprint, primary production	3,64	-	4,03	kg/kg
Recyclable	YES			

PLA (Polylactic Acid) is the second most popular material used in 3D printing. PLA is a biodegradable thermoplastic derived primarily from renewable resources, such as corn, milk or maize. It can be available with different compositions due to their chiral nature, which means their properties can change. This material has mechanic properties similar to PET (Polyethylene terephthalate), with the difference of it is biodegradable, therefore, it is more expensive, yet it provides good aesthetics, and it can accept a higher number of colours than ABS, with a glossy and clear finish. PLA is a rigid material but also brittle, that is the reason why the post-process (mechanize, paint or paste) is more complex. This material works with a melting point in a range of temperature between 165˚ and 170˚ Celsius; however, it does not resist high temperatures, when it achieves 50˚- 60˚ (the glass transition temperature) it starts to decompose. This material can be 3D printed, it does not need a heated print bed, and during the printing process, there are no gas emissions. The main properties of PLA are as shown in Table 9.

Table 9. PLA Properties.

General Properties PLA				
Density	1,24E+03			kg/m^3
Price	22,4	-	30,6	SEK/kg

Mechanical Properties PLA				
Young´s Modulus	3,3	-	3,6	GPa
Yield strength (elastic limit)	55	-	72	MPa
Tensile strength	47	-	70	MPa
Compressive strength	66	-	86	MPa
Elongation	3	-	6	% strain
Hardness (Vickers)	17	-	22	HV

Thermal Properties PLA				
Melting point	145	-	177	
Glass temperature	52	-	60	°C
Maximum service temperature	45	-	55	°C
Minimum service temperature	-20	-	-10	°C

Optical Properties PLA	
Transparency	Transparent

Process Ability PLA			
Moldability	4	-	5
Formability	4	-	5
Machinability	4	-	5
Weldability	3	-	4

Scale: 1→Excellent; 5→ Not recommended

ECO Properties PLA				
Embodied energy, primary production	49	-	54,2	MJ/kg
CO^2 footprint, primary production	3,43	-	3,79	kg/kg
Recyclable	YES			

The properties of both materials have been obtained from CES EduPack 2017, software provided by the University of Cambridge. Using this program, a comparison of both materials is performed in order to know the environmental effects caused by each one. The study was done supposing 1kg of virgin material mass and a product life of 1 year. The obtained results are as follows, Figure 29 and Figure 30:

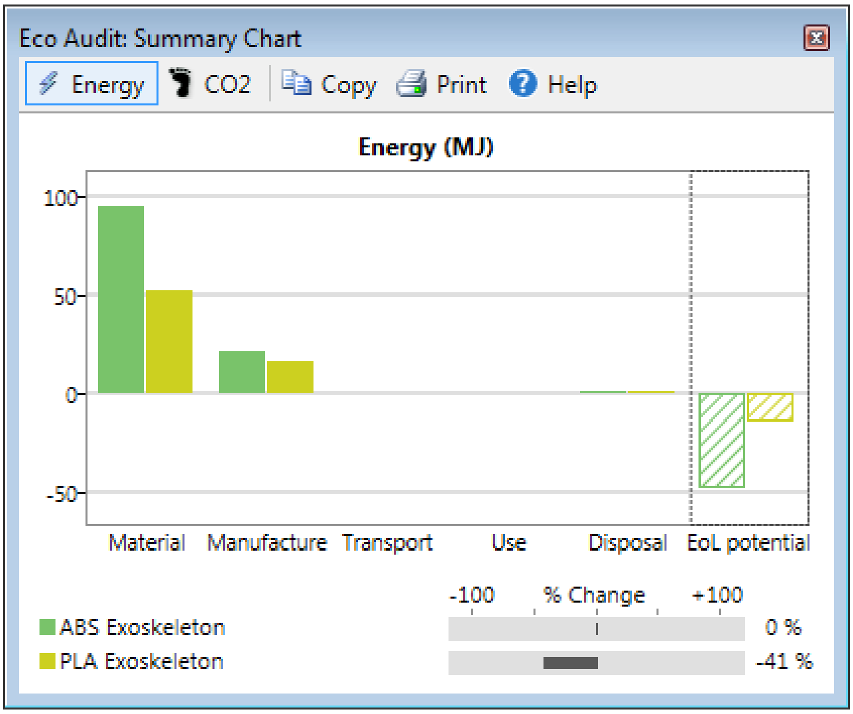

Figure 29. Summary Chart of Energy. (CES EduPack 2017)

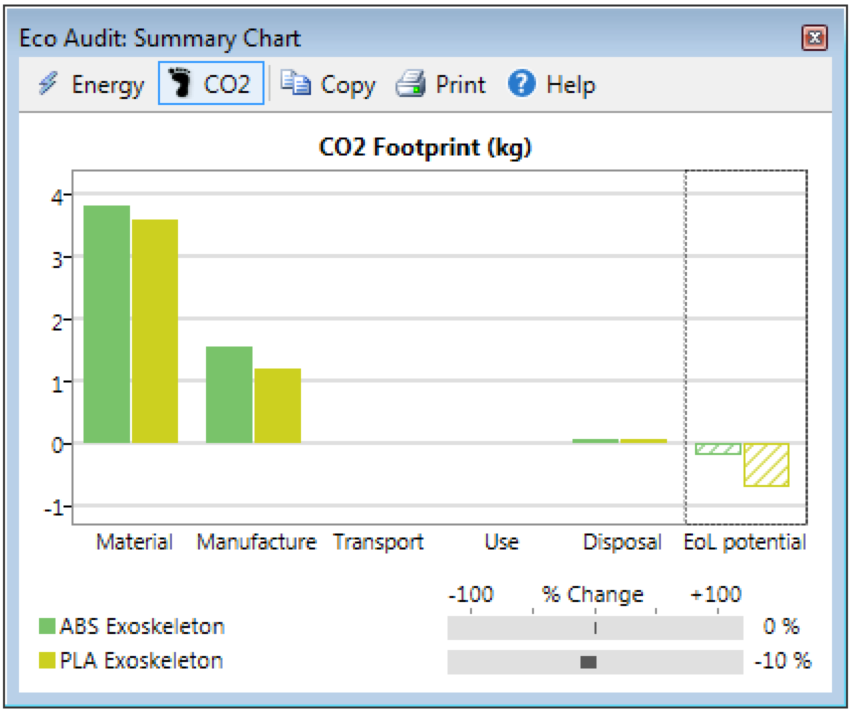

Figure 30. Summary Chart of CO^2 emissions. (CES EduPack 2017)

Firstly, both materials are recyclable, it can be observed in the above properties tables, Table 8 and Table 9. In the case of ABS, the excess material can directly be reused by re-melting it. On the other hand, PLA cannot be reused with the same heating process, it must experiment with the complete recycle process to be used again. Figure 31 describes the lifecycle of both materials.

Figure 31. Lifecycle of the Materials.

Observing the summary chart of the comparison of the environmental effects caused by each material, PLA needs less energy to be produced, as it can be seen, Figure 29. Regarding CO^2 emissions, Figure 30, the amount is quite similar between the materials, being again the PLA material, the one with lower emissions. However, observing the End of Life, ABS material is the one that requires more energy to be produced; but it also has a higher afterlife potential. On the other hand, the price of both materials are rather similar and it is possible to work with any of them.

Taking into account all the mentioned factors, mechanical, post-processing, price and environmental effects, it can be concluded that it would be possible to carry out the present work with any material, due to both materials have similar properties. While keeping in mind that it is a rehabilitation project, it is especially required flexibility to adapt the exoskeleton on the patient´s hand in order to execute a proper therapy. ABS is much more flexible than PLA, it can be seen in Elongation property in Table 7, and therefore ABS is much better adapted to a therapy project.

2.6 Installation of the actuator.

The final solution to perform the passive motion in the rehabilitation was to use a rotary actuator as was mentioned in section 2.4. The trajectory was described in Figure 16. To make the movement possible, it has been necessary to add a new piece connecting the motor (blue devices) to each finger-mechanism, the green bars shown in Figure 32.

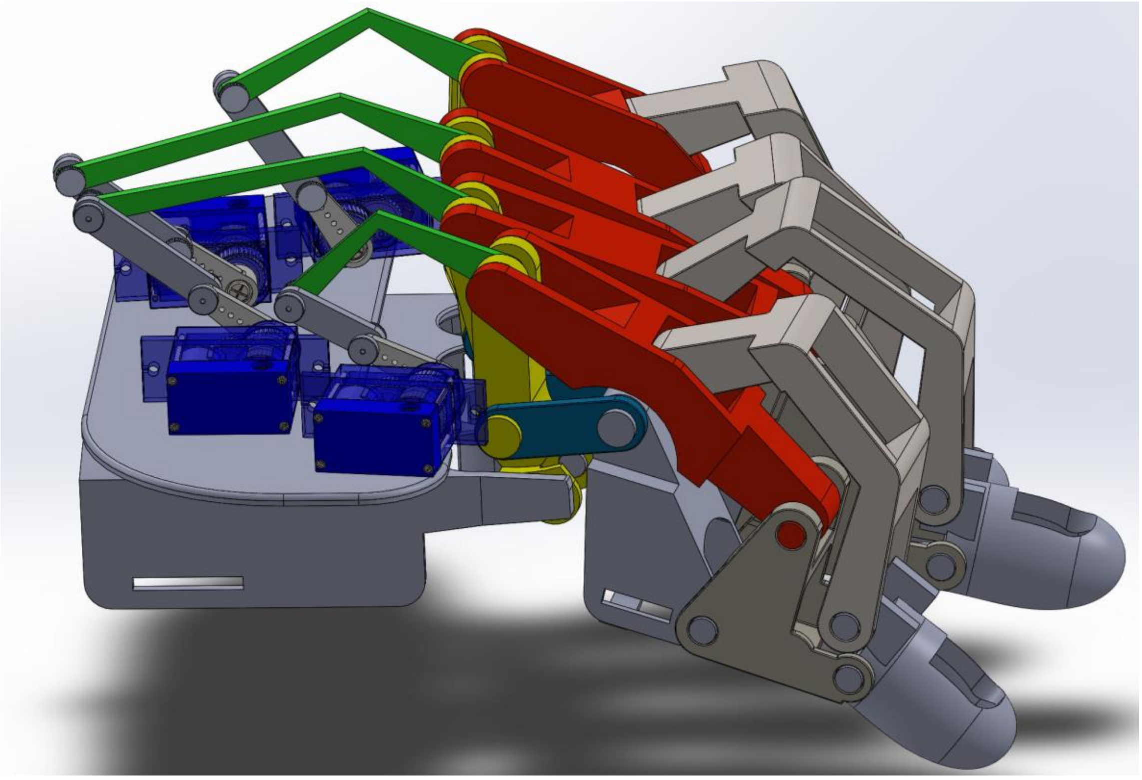

Figure 32. Necessary added bar.

The therapy can be conducted for only one finger or for the four fingers at the same time. To perform the first one, it is necessary one actuator and it can be changed depending on the disabled finger. To get a rehabilitation for the complete hand, the four fingers at the same time, it is necessary to use four rotary actuators, one for each finger. The layout installation of them can be seen in the next Figure 28 and in the Results Chapter. It has been required to design a support in order to attach the motors in the model. This bracket has been designed with the possibility to dock only one servo for the individual finger rehabilitation, or the four motors simultaneously.

The extra-support can be seen in the next Figure 33. The Arduino code to recreate the movement is collected in the Appendix 3 (del Valle, 2018).

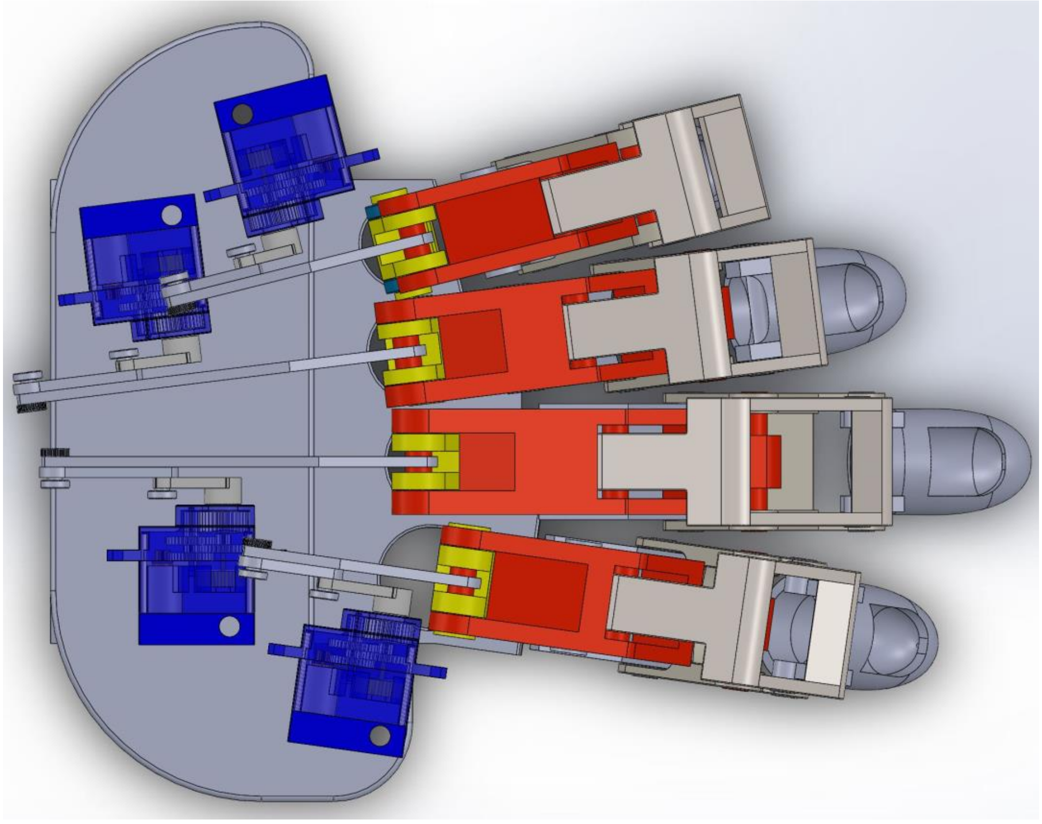

Figure 33. Modified support.

2.7 3D Printing

With the model totally adjusted, the printing process can then begin. The initial idea was to use ABS material to print in 3D due to material flexibility, as it was explained in the previous section, but Maker Space does not have the necessary printers (with heat print bed) for this material, and they only use PLA.

Nevertheless, to have two different points of view and observe possible problems that depend exclusively on the printer and not on the authors of this project, the model was printed in Málaga and Skövde, being printed in Málaga with ABS (Acrylonitrile Butadiene Styrene) and in Skövde with PLA (Polylactic Acid).

The results are collected in the results section. The print was done without the actuator support to easily manipulate and tested on the patient.

3. Results

3.1 Goals

Considering the objectives list explained in the Introduction section, and after performing the project, the obtained results as well as the contributions of the proposed model regarding with some current devices are shown as follows.

1) The natural closing movement of the hand → DONE
   The natural closing movement is achieved using MUMSA and mechanisms created with WinmecC. It is an important point since the device must have an movement equal to the real hand.
2) Perforation in the design which allows to check the nails of the patient → DONE
   This point will offer the opportunity to see the nails state in case of blood cut.
3) Individual and multiple finger rehabilitation → DONE
   This is possible using different actuators for each finger.
4) Light device → DONE
   A light exoskeleton is achieved thanks to the materials and the manufacture process used.
5) Eco-friendly materials → DONE
   A large information about the materials used is explained in section 2.5. The materials used are friendly with the environment.
6) Low cost → DONE
   Due to materials and processes used the cost is low. In following sections, it will be explained in more details.
7) Installation of servos to perform the passive motion → DONE
   Using actuators is possible to perform the movement in each finger. Light and strong servos were founded in the market.
8) Easy manufacturing with ABS → DONE
   It has been tested printing the model using a 3D printer with ABS material. The process has been achieved in just one step, printing the complete model in one step.
9) Easy manufacturing with PLA → NOT DONE
   PLA model was printed. With this material is possible to find more problems than ABS. It is explained in more details in section 3.3.
10) Testing on the patient → NOT DONE
    The prototype has not tested in the patient hand due to a meeting with the company (UPACE) has not concerted yet.

In order to compare several current devices in the market with the proposed model, the following Table 10 was made using the next points system. The points go from 0 to 10, being 10 the maximum points possible. The maximum total points possible are 160.

Points System	Red	Yellow	Green
	0	5	10

Table 10. Comparison of current devices.

	Rehab Robotics	ZMorph Blog	Curtinnovation	Proposed model
Material	Steel	ABS	ABS	PLA and ABS
Complexity	High	Low	Medium	Medium
Weigh	High	Low	Low	Low
Size	Large	Large	Small	Medium
Individual finger rehabilitation	YES	NO	YES	YES
Multiple fingers rehabilitation	YES	YES	NO	YES
5 Fingers rehabilitation	YES	YES	NO	NO
Portable	NO	YES	YES	YES
Handling by professionals	YES	YES/NO	YES/NO	YES/NO
Requires a computer	YES	NO	NO	NO
Actuator	Linear	Manual	Linear	Rotary
Design modifications	NO	YES	YES	YES
Multiples patients	YES	NO	NO	NO
Control by sensor	YES	NO	NO	NO
Nail control (Blood flow cut)	NO	NO	NO	YES
Easy manufacturing	NO	YES	YES	YES
Price	Expensive	Cheap	Cheap	Cheap
TOTAL POINTS	55/160	105/160	105/160	**125/160**

The scoring system has been selected according to the characteristics of the model defined in the Introduction. The objective is to design an easily handled, portable and low-cost prototype.

3.2 Final design

The result is obtained once the model is completely designed by the software Solid Works, with the motors attached and simulating the natural closing movement of the hand. The full movement is shown in the following sequence of photos, Figure 34.

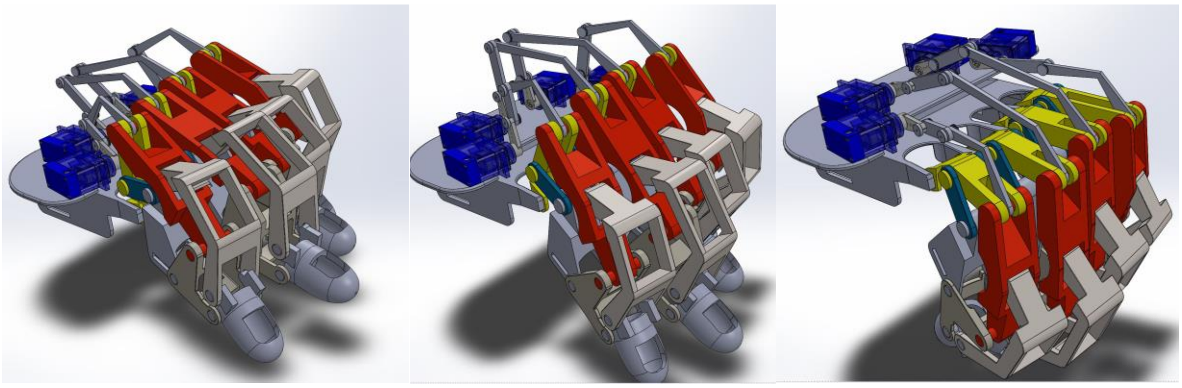

Figure 34. Photo sequence with the rotary actuators.

Different colours were applied to differentiate the parts in the 3D model in order to facilitate a visual analysis to detect contact between parts and correct the spacing between the parts.

In the design, a special requirement, asked by the physiotherapist, was to design the distal phalanx piece with a perforation on the top in order to allow the physiotherapist to check the nails state of the user. This is important since the blood supply can be stopped by the exoskeleton if used during long periods because it is adjusted to the hand.

On the other hand, the natural closing movement of the hand is achieved, however, something to consider is the characteristic morphology of the hand. When the hand is closed it is unavoidable for the fingers to touch each other, therefore on the model is also unavoidable the contact between them. This contact could create tensions in the model, with the hand closed, resulting in the model breaking. The flexibility of ABS material can help to solve this problem and to avoid potential problems in a continuous use. With PLA material would have to be used a post-processing such as a silicone grease or other lubricant to reduce the friction between pieces in the contact during the movement of the fingers.

Finally, the hand-support was redesigned to make possible the addition of servos, Figure 33. It was rounded to improve aesthetically as well as to prevent possible injuries when it is handled by the professional or used by the patient. In addition, in this new design, two new slots were added to insert a strap and have a better adjustment to the hand. Moreover, the zone in contact with the hand has a curve to make the hand-support more comfortable for the patient.

3.2 Servos distribution

As it was mentioned in the method section, to perform the rehabilitation of fingers at the same time four servos were needed. These servos were placed on the top of redesign hand-support, previously mentioned. Each servo is situated in the line direction of each finger. Because of reducing dimensions of the hand-support (keep in mind normal dimensions of a hand) was not possible to place all the servos in the same axle. As it can be seen in Figure 28, the two servos responsible for the index and pinkie finger movement are placed nearest of the finger’s mechanism, and the other servos, for intermediate and ring fingers, are placed behind the first mentioned servos.

Due to the distance between each servo, the new bars added have different lengths. These bars are shown in Figure 27 in colour green. In addition, the length of servo´s torque arm was not enough; therefore, the addition of a new bar was needed to apply the maximum torque possible.

The used rotary actuators are “Micro 9G SG90 TowerPro”, the main characteristics were numbered in method section 2.4 “servos”, also Appendix 3 includes the data and the Arduino code to use (del Valle, 2018).

3.3 Materials and print

As it was mentioned in the method, the model will be printed in two different 3D printers with two different materials. The University of Skövde, in particular, MakerSpace does not work with ABS material which is the material with better properties (more flexibility) to perform this rehabilitation project.

On one hand, the CAD model was printed in the University of Málaga since they have the necessary printer with the heat print bed to use ABS material. The printed CAD model is shown in Figure 35.

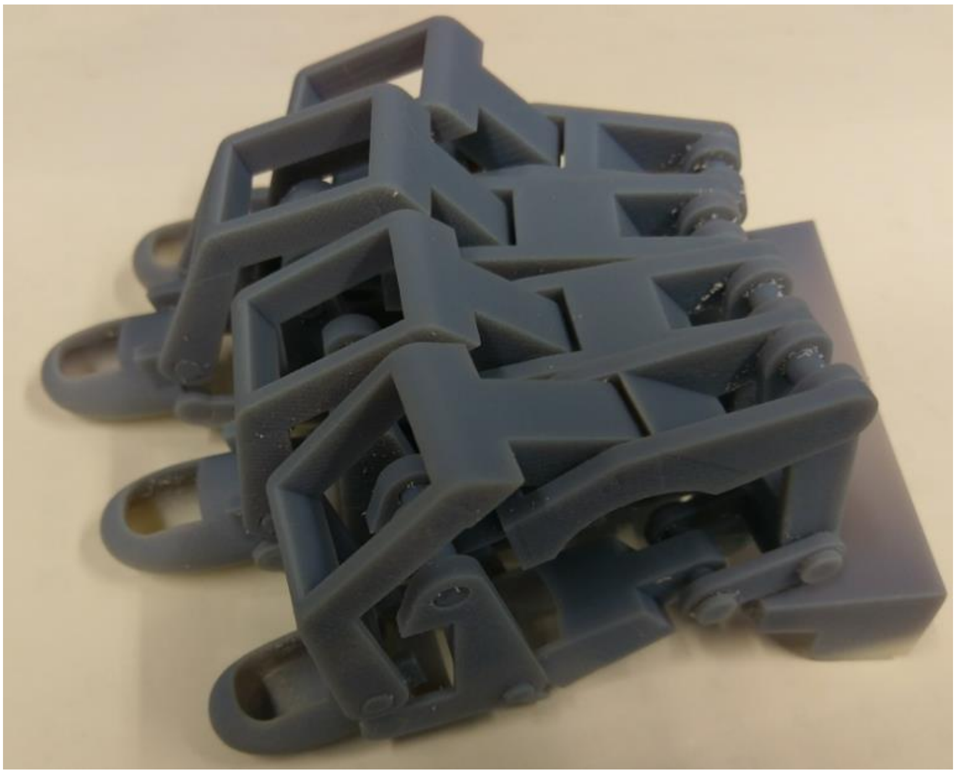

Figure 35. Printed Model in ABS.

It can be seen in the above Figure 30 that the quality of the printout is quite high. The 3D printer has done an accurate replica of the model. The CAD model consists of various parts already joined, and this does not represent any problem to be printed. Regarding the surface finish, it can be observed even some parts show roughness due to excess material during the printing, it is clean and smooth enough. Regarding the material, the prototype does not suffer any breaks, which shows the flexibility of the material. The 3D printer took 19 hours the whole exoskeleton.

On the other hand, the model was also printed in Maker Space, using PLA material. In this case, the quality of the printer is lower and the CAD model had to be slightly modified in order to avoid errors during the printing, particularly regarding the narrowness between parts. The obtained model is shown in Figure 36:

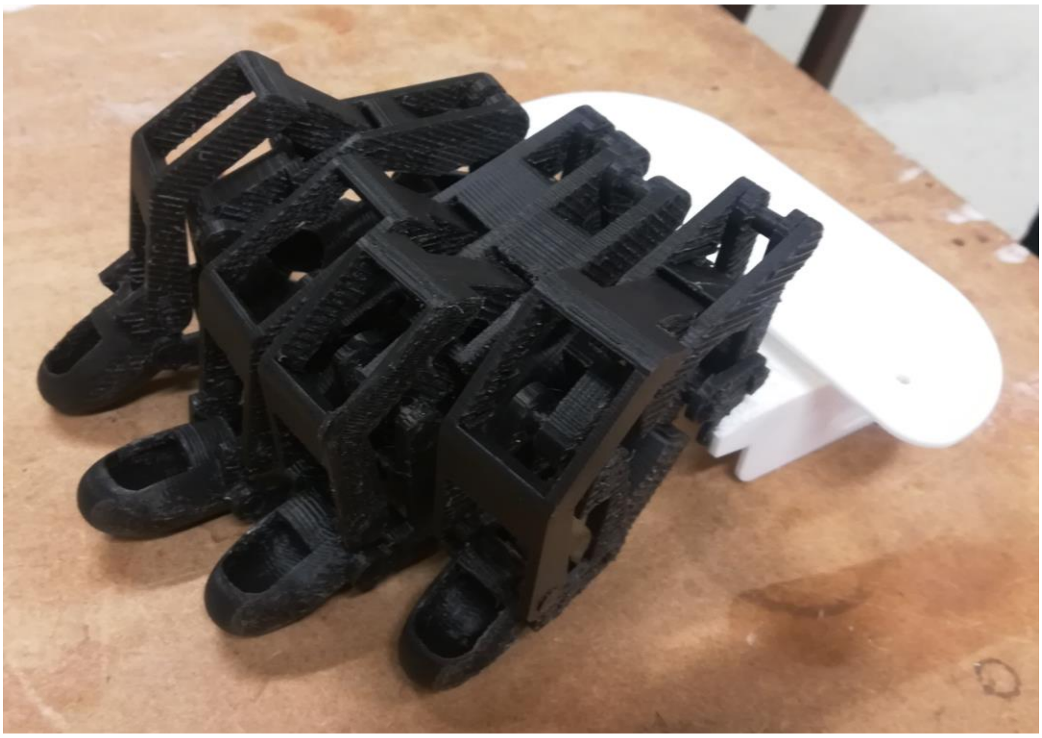

Figure 36. Printed Model in PLA.

This time, the printed model required the removal of the support material given that PLA printers cannot print material suspend in the air. This process of removing material caused roughness and a low quality surface finish. In this case, the 3D printer took around 7 hours to print each finger and the hand-support.

3.4 Costs

As it was mentioned in the background and emphasized in table 11, the costs in the proposed exoskeleton are lower than others current exoskeletons used nowadays. For example, the use of steel and the addition of different sensors increase the features of the model, however, at the same time, increasing the costs and complexity to use it. Only the necessary machines to manufacture and produce the steel are more expensive than the use of a 3D printer as the main manufacturing process.

The costs of the device developed in this thesis are:

Table 11. Price list

PRICE (SEK)	ABS	PLA
Finger 1 (Index)	-	12,1
Finger 2 (Intermediate)	-	13,2
Finger 3 (Ring)	-	12,2
Finger 4 (Pinkie)	-	11,4
Hand-support	-	21,2
Total Printed	80	70,1
Actuators (x4) [1 per finger]	70 (price per unit) x 4 = 280	70 (price per unit) x 4 = 280
COMPLETE HAND	**360**	**350,1**
Discarded parts*	-	36

The discarded parts have been included in the price list. The reason of this discarded parts is the possibility of break parts in the cleaning process or problems in the printing process with the 3D printer.

As it can be seen the total price including the actuators is 360 SEK using ABS and 350.1 SEK using PLA.

4. Discussion

The project presents a new solution for hand rehabilitation methods. Although the device has been carried out assuming simplifications, it has found some difficulties in the method process, said difficulties are described as follow.

Given the social nature of the project, aiming to improve the welfare of the patients, a direct contact with the stakeholders was necessary for the proper development of the device. This contact with the users represented a challenge for the authors of the project, especially regarding data collection, given that working with disabled users also means taking into consideration other health factors such as involuntary movements, muscle stiffness caused by illness, or pain during specific hand movements. It was difficult to collect measurements given the inexperience in these types of projects. For example, the first patient suffered involuntary movement and was difficult to take the sequence of photos of the closing movement of the hand as well as to take the necessary measurements using the calliper. The second one has a small hand and was difficult to take the photos given that she had an accident in her hand, each time that she performed the closing movement she suffered pain. The last patient (the selected one) did not have involuntary movements or pain, being this the reason why it was easier to work with him.

The method used to take the measurement was not the best, maybe using fixed cameras, good illumination, assistance from specialists or a machine to immobilize the patient's hands would improve the data accuracy.

Another challenge was the incorporations of the motors. The selected servo was the smallest found in the market with a competitive price, but even being the smaller possible solution, it supposed to be an obstacle. Because of the space in the palm of the hand is reduced, it had to be chosen between performing just an individual finger therapy or also to have the possibility of performing the rehabilitation with the four fingers at the same time. The second option was the most attractive to get the complete rehabilitation method. In order to achieve this, the piece had to be readjusted (the extra support), as it was explained previously. In addition, it was considered to move all the fingers with just a motor, but this option was ruled out almost immediately because it meant to work with several shafts and gears, which will increase the complexity of the device considerably.

The use of linear actuators was considered, however nowadays the market does not offer telescopic small servos, resulting in the use of normal linear servos. Linear servos require extensive space meaning the hand support would probably extend to the user's arm. Given these problematics, the rotary actuator was selected.

According to the design, the materials require a robust design of the pieces. As discussed in previous sections the differences in flexibility and hardness in the materials required the design to be modified to supply the deficiencies of each material. Even so, the complete exoskeleton is light and resistant enough to comply with requirements. The current exoskeletons used in rehabilitation processes are made from steel and other plastics.

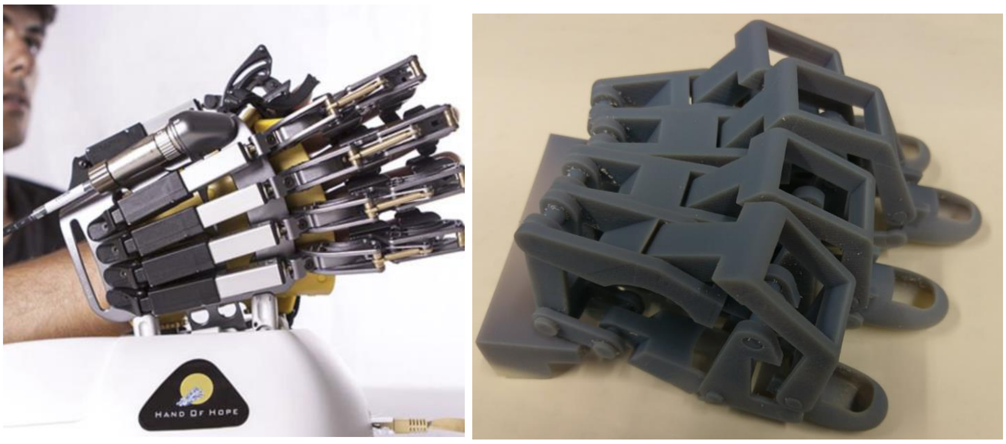

Figure 37. Exoskeleton comparison.

As it can be seen on the left of Figure 37, the material used is steel and the motors used are linear servos. It is a clear example to show the main differences between the mostly exoskeletons in the market and the solution suggested in this thesis. The solution offered by Rehab Robotics “Hand of Hope” (Rehab-robotics.com, 2018) is more complex and include several sensors. In this thesis, the idea is to design and manufacture an exoskeleton in the easiest way possible to help companies and patients with fewer resources. For example, the “hand of hope” (Rehab-robotics.com, 2018) needs a personal computer with specific programs and professionals. In comparison, the device developed in this document does not require such assistance. The rehabilitation can be done even by the own patient. Moreover, unlike other exoskeletons, it is portable, that means the device, for example, can be moved to patient`s houses if they could not go to the hospital or rehabilitation centres.

Regarding with the other exoskeletons made from 3D printers, the present prototype incorporates the possibility to carry out the rehabilitation for just one finger, and all the fingers at the same time allowed using several rotary actuators. As well as, this device can perform the down and up rehabilitation movement of the hand, it was not possible for one of the models describes in the Background.

The movement study performed by the software Solid Works resulted in a time drawback in the work timeline, due to the high number of assembled pieces needed.

As a result of the low quality of one of the 3D printers, it was necessary to print each finger individually, and joining all the model afterwards. Also, taking into account the reduced flexibility of the PLA material, the thickness of the joints finger-support was modified and rounded to facilitate the union of parts. The model, to be printed by PLA, needs a support for the parts suspended in the air resulting in the removal of excess material. To remove said support was a challenging task, due to the material strength accompanies by the fact that most parts of each finger are significantly weaker. This process caused many hours of arduous work and caused some parts of the structure to break, and the necessity to re-print some fingers, which consume more time than expected.

These factors have been the main found obstacles developing the hand exoskeleton, however, all of them were solved. This project has offered knowledge in new areas of the engineering such as the 3D printing.

In relation to the materials, it has been verified that PLA or ABS are materials sufficiently strength and hard to carry out a rehabilitation program using an exoskeleton made with these materials. With the first test of the prototype (PLA model) on a real hand, the material behaviour was good and it endured the handling of the device by different people without knowledge about the correct use of the exoskeleton. The use of other materials was not contemplated due to the 3D printers used just worked with PLA or ABS, other materials can be printed as graphene but nowadays is difficult/expensive to achieve.

The use of other manufacture methods as injection moulding is discarded since with these methods are impossible to obtain the complete exoskeleton in one step. Nowadays, only a 3D printer offers a solution since it is capable of print movable parts also with its joints and “screws” also printed in the model.

On the other hand, the costs could be significantly lower purchasing a 3D printer since the workforce for one hour of printing costs 300 SEK, therefore the cost of one finger is around 2100 SEK (7 hours printing). The table below (table 12) shows the comparative prices between using your own printer and using a printing service.

Table 12. Comparison printing prices.

	By yourself	Printing Service
Cost of 3D printer	3000 – 4000 SEK	-
Price per hour	-	79 SEK
Approx. price of one finger	12,50 SEK	474 SEK
Complete hand	70,10 SEK	2765 SEK (35 hours)
Final Cost	3082,60 – 4082,60 SEK	2765 SEK

Once a 3D printer is bought (the highest cost 3000 – 4000 SEK), a complete hand would be obtained with a cost of 70,10 SEK approximately. This is relevant in relation to costs since the following pieces will cost around 70 – 80 SEK (depends on hand dimensions: big hands need more material) while in a printing service will be necessary to pay 2765 SEK per hand exoskeleton. It can be explained with an easy example, 100 complete exoskeletons printed in a printing service will cost 276500 SEK while using a 3D printer by yourself is possible to print 100 exoskeletons for only 7010 SEK. In others words, to buy a 3D printer to print a high number of exoskeletons is recommended.

As it can be seen, the price of printing by yourself is higher but it would be interesting to invest in a 3D printer if the purpose is printing more than one exoskeleton. Figure 38 shows an estimation of prices per hour in a printing service, it has been obtained using the software “Print 3D” included in Windows 10 Home, Figure 38.

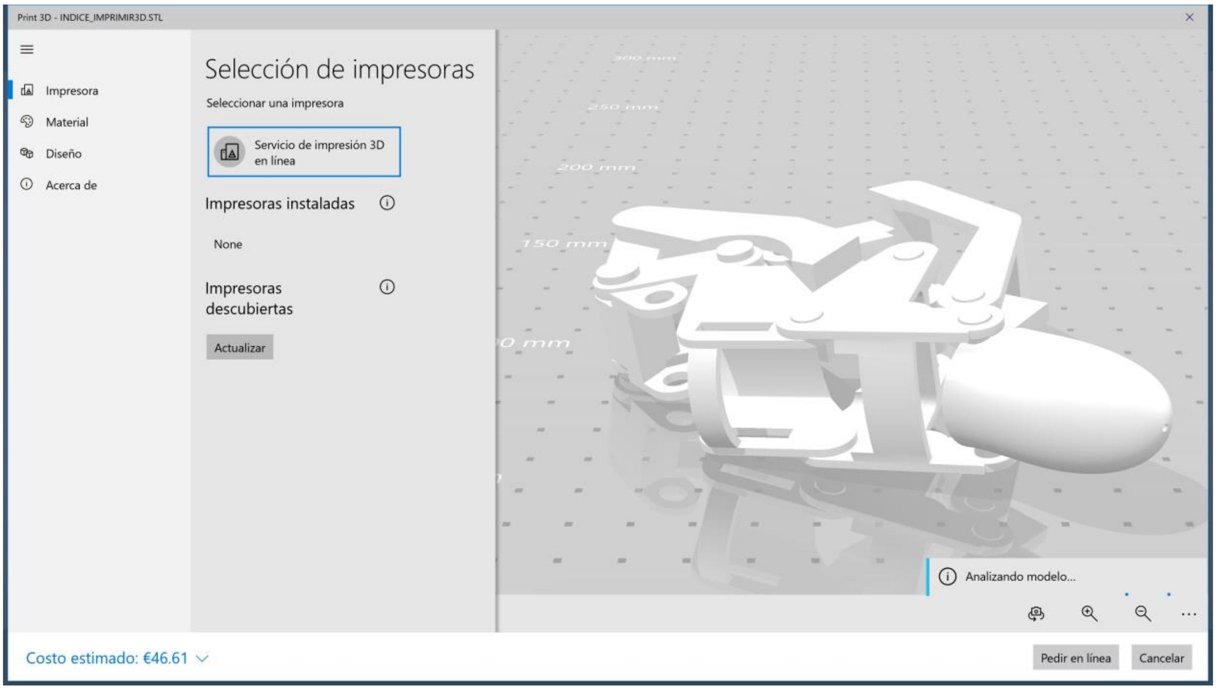

Figure 38. Price estimated

4.1 Technology, Society and the Environment

Current devices have a different type of sensors and 4 DOF, which means they have a wide range of movement possibilities, but as an inconvenience, they are complex, heavy, bulky and expensive. In contrast, the present exoskeleton designed in this project is a new approach to rehabilitation methods regarding hand or finger injuries. This prototype can perform just one rehabilitation movement (one degree of freedom) by passive control motion (PCM), but the device is easier to manipulate, lighter and cheaper. It is achieved due to the use of 3D printer technology, as well as the materials, such as ABS or PLA.

The characteristics of the proposed exoskeleton could positively affect society. The device could be used by centres or companies working with rehabilitation methods helping disabled people, and improving the work of the professionals. Also, given the ease of use, the rehabilitation could be carried out from home by the patients.

Regarding the environmental effect, the used materials are eco-friendly and can be reused and recycle, without emitting a high amount of gases.

The technology of 3D printers is continuously advancing and developing, as well as the materials that they use. Meaning, the properties of the materials and the quality of the printer will improve increasingly, obtaining more resistant, and flexible devices, perfect to be adapted to the patients.

5. Conclusions

The main purpose of the project consisted of designing and manufacturing an exoskeleton to rehabilitation for patients who suffer any type of limitation movements in their hands, caused by an accident or illness. The model including all the fingers (except the thumb) in a natural position has been found by measuring enough data by photo sequences from different angles, in order to achieve an accurate natural closing movement in the most comfortable way as possible.

Also, the prototype has a compact, strong and lightweight design, it allows for the possibility of handling it with safety and simplicity. The materials used, ABS and PLA, stand out especially in the lightness, and the flexibility of the ABS. The physiotherapist recommended a perforation in the piece that it is attached to the distal phalanx, as it is necessary to see the condition of the nail and check that there are no problems related to blood flow.

The use of the rotary motors and the addition of an extra piece make it possible to perform the complete range of movement. Also, the installation of one motor for each finger has been achieved, due to the motor dimensions and modification of the hand support. To secure the device to the user’s hand, a strap has been implemented, covering the entire palm and making a complete, adjustable and comfortable support.

Printing the model in one piece saves assembly time and money. The low cost is essential to produce the exoskeleton, by measuring the cost of production; the personnel needed for patient’s rehabilitation would be reduced.

Finally, and concerning the environment, the used and wasted materials in 3D printing can be completely recycled and can be used to produce new printing filaments.

6. Future Work

Since this first prototype is being described, there are many possible improvements. In respect to the mechanical structure, the movement of the thumb could be included, which means more degrees of freedom. That would make the prototype more complex, however, at the same time, the range of movements and possible therapies to carry out would increase considerably. Incorporating these changes would also require reconsidering the motor's behaviour, as well as the possibility to add more of them.

Concerning the production, an interesting idea to develop is to make a modular structure, which presents a difficulty to join the different parts given the small fixing screws needed for assembly. However, it would allow the possibility of using the same exoskeleton with several patients by easily changing pieces of the device. Also, whether any of the components need to be replaced because of breaking, it would not be required to print the complete model again.

On the other hand, to check the device is performing the therapy in a proper manner, and it is benefiting the patients, it would be essential to develop a test series with several patients, not only with a unique patient. In this way, the effectiveness would be really tested.

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Appendices

Appendix 1 Time Plan

In this Appendix, the previous Gantt Chart (Table 13 in next page) will be compared with the new one created while the project was being performed (Table 14). The literature review was done in the predetermined time using seven weeks to read and study the different articles and news of all types of exoskeleton used nowadays and the future ones. Although some articles were reviewed while the design process was made, this was because in the design process three programs were used simultaneously (the evolutive algorithm MUMSA from Málaga, SolidWorks and WinmecC).

The evolutive algorithm needed some measurements to obtain the necessary parameters to be able to create the mechanism in two dimensions. It took time because a student had to go to Spain to take the measurements. Once the measurements were taken, the predesign 2D with MUMSA was not correct. The mechanism done with that parameters had good aesthetic and performed the movement perfectly but transforming the model from 2D to 3D was impossible in some cases. The model 3D could be done but, for example, it would not adapt to the patient hand.
Those problems were solved on the third try but it consumed more time than expected.

Table 13. Initial Gantt Chart

Activity	Resources	v4	v5	v6	v7	v8	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20	v21	v22	v23	v24
Specification and planning	Supervisor and client																					
Presentation 1: Specification and time plan	Supervisor and examinator			Thursday Feb 8th																		
Literature and 1st part of thesis (background, literature review and method)	Supervisor																					
Finalisation	Supervisor																					
Presentation 2: Introduction, literature review and method	Examiner and supervisor								Wednesday March 14													
Analysis, design, etc	Supervisor																					
Result and discussion	Supervisor																					
Peer review	Partner Group																					
Finalisation of presentation	Supervisor																					
Presentation 3: Final presentation of complete project and opposition	Examiner, supervisor, partner group																					
Finalisation of report	Supervisor																					
Report to supervisor	Supervisor																					
Supervisor reviews report	Supervisor																					
Correction of report	Supervisor																					
Submission of report to examiner																						
Examiners report review	Examiner																					

Table 14. Updated Gantt Chart

Activity	Resources	v4	v5	v6	v7	v8	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20	v21	v22	v23	v24
Specification and planning	Supervisor and client																					
Presentation 1: Specification and time plan	Supervisor and examinator			Thursday Feb 8th																		
Literature and 1st part of thesis (background, literature review and method)	Supervisor																					
Finalisation	Supervisor																					
Presentation 2: Introduction, literature review and method	Examiner and supervisor								Wednesday March 14													
Analysis, design, etc	Supervisor																					
Result and discussion	Supervisor																					
Peer review	Partner Group																					
Finalisation of presentation	Supervisor																					
Presentation 3: Final presentation of complete project and opposition	Examiner, supervisor, partner group																		Wednesday May 23			
Finalisation of report	Supervisor																					
Report to supervisor	Supervisor																					
Supervisor reviews report	Supervisor																					
Correction of report	Supervisor																					
Submission of report to examiner																						
Examiners report review	Examiner																					

Appendix 2. MUMSA

This appendix summarizes the functioning of the evolutionary algorithm MUMSA developed by the University of Málaga. All concerning data is included in the articles: A. Bataller, J.A. Cabrera, M. Clavijo, J.J. Castillo “Evolutionary synthesis of mechanisms applied to the design of an exoskeleton for finger rehabilitation” and A. Bataller, J.A. Cabrera, J.J. Castillo, F. Nadal “Síntesis evolutiva de mecanismos aplicada al diseño de un exoesqueleto para la rehabilitación de los dedos de la mano”

The design of the exoskeleton of the present project is personalized for a specific patient; this implies that a personalized measurement, of each user, must be taken to create the device so that the exoskeleton fits perfectly to the dimensions of the fingers and the hand. So, the use of anthropometric tables is excluded, these are measures that are established according to age, sex, race...

The design variables that are needed for the synthesis process for the creation of a fully functional finger are the following Figure 39.

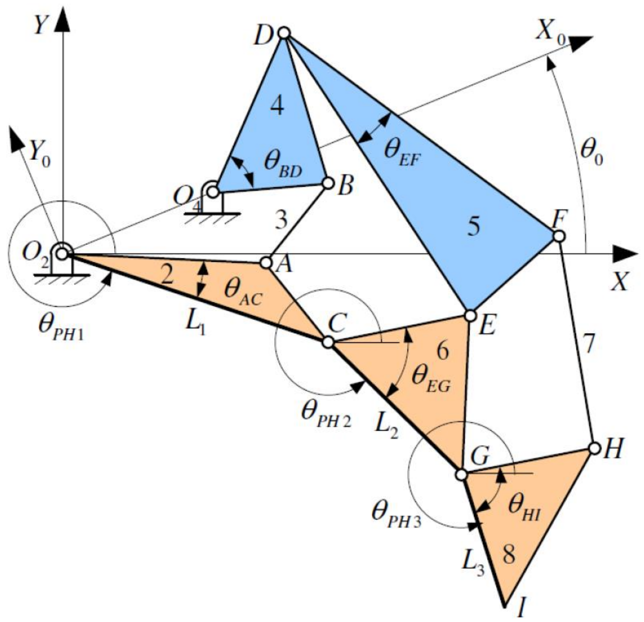

Figure 39. Proposed mechanism with the design variables

Where:

Table 15. Input data and design variables.

Variable	**Description**
θ_0	Angular position of link 1
r1	Length of link 1 (O_2O_4)
r2	Length of link 2 (O_2A)
r3	Length of link 3 (AB)
r4	Length of link 4 (O_4B)
θ_{AC}	Angle $\widehat{AO_2C}$
r_D	Length of O4D
θ_{BD}	Angle $\widehat{BO_4D}$
r5	Length of link 5 (DE)
r6	Length of link 6 (CE)
r_{DF}	Length of DF
θ_{EF}	Angle $\widehat{EDF}$
θ_{EG}	Angle $\widehat{ECG}$
r7	Length of link 7 (FH)
r8	Length of link 8 (GH)
θ_{HI}	Angle $\widehat{HGI}$
Input variables	**Description**
θPH1	Angular position of proximal phalanx
θPH2	Angular position of middle phalanx
θPH3	Angular position of distal phalanx
L1	Length of proximal phalanx
L2	Length of middle phalanx
L3	Length of distal phalanx

To obtain the synthesis variables that define the geometry of the mechanism is going to be formulated as a problem of optimization of the form:

$$\min_{\chi}\{M \cdot f(\chi)\} \tag{1}$$

Where X is a vector whose components are the design variables of Table 9.

f (X) is the objective function that defines the problem and M is a factor linked to the restrictions imposed on the problem; it will be detailed later.

$$\chi = \begin{bmatrix} \theta_0, r_1, r_2, r_3, r_4, \theta_{AC}, r_D, \theta_{BD}, r_5, \dots \\ \dots, r_6, r_{DF}, \theta_{EF}, \theta_{EG}, r_7, r_8, \theta_{HI} \end{bmatrix} \tag{2}$$

The objective function will quantify how different a mechanism moves, whose geometry is contained in the values of vector X, with respect to the actual movement of the patient's finger. The first is defined by the values of the angular positions of links 2, 6 and 8 of the mechanism: θPH1g, θPH2g and θPH3g. The second, by the angles measured on the patient's finger in the photos: θPH1, θPH2 and θPH3.

This function will impose that the sides 0_2C, $\overline{CG}$ and $\overline{GI}$ of the mechanism are parallel to the proximal, middle and distal phalanges respectively.

Since the first phalanx is directly linked to the motor link of the mechanism, we can analyse its behaviour in the same angular positions that have been extracted from the photos, so that θPH1g = θPH1, and the error committed will be zero.

To determine the values of θPH2g and θPH3g, it is necessary to solve the problem regarding the position of the mechanism. The angle of the motor link θ2 is directly related to the angle measured for the proximal phalanx (θPH1), so that:

$$\theta_2 = \theta_{PH1} - \theta_{AC} \tag{3}$$

Where θ_{AC} is the angle $\widehat{A02C}$ of link 2.

The position of point C with respect to the absolute coordinate system OXY, whose origin is located at the centre of the joint of the proximal phalanx O_2 is defined by:

$$\begin{bmatrix} C_X \\ C_Y \end{bmatrix} = \begin{bmatrix} r_2 \cos(\theta_2 + \theta_{AC}) \\ r_2 \sin(\theta_2 + \theta_{AC}) \end{bmatrix} \tag{4}$$

Next, we propose the closing equation of the four-bar mechanism $\{r1, r2, r3, r4\}$ with respect to a relative coordinate system OX0Y0, originating in O2 and with the positive part of the X axis in the direction of the O_2O_4 segment.

$$\left.\begin{array}{c} r_2 \cos\theta'_2 + r_3 \cos\theta'_3 = r_1 + r_4 \cos\theta'_4 \\ r_2 \sin\theta'_2 + r_3 \sin\theta'_3 = r_4 \sin\theta'_4 \end{array}\right\} \tag{5}$$

The lengths of the links are known, with the unknowns θ'_3 and θ'_4. The angle θ'_2 can be easily calculated as:

$$\theta'_2 = \theta_2 - \theta_0 \tag{6}$$

Once the equation 5 is solved and the angles of bars 3 and 4 are calculated, we can calculate the positions of points B and D with respect to the relative coordinate system OX0Y0.

$$\begin{gathered} \begin{bmatrix} B_{X_o} \\ B_{Y_o} \end{bmatrix} = \begin{bmatrix} r_1 \\ 0 \end{bmatrix} + \begin{bmatrix} r_4 \cos\theta'_4 \\ r_4 \sin\theta'_4 \end{bmatrix} \\ \begin{bmatrix} D_{X_o} \\ D_{Y_o} \end{bmatrix} = \begin{bmatrix} r_D \cos(\theta'_4 + \theta_{OD}) \\ r_D \sin(\theta'_4 + \theta_{OD}) \end{bmatrix} \end{gathered} \tag{7}$$

These positions can be calculated with respect to the OXY absolute coordinate system with the equation (8):

$$\begin{gathered} \mathcal{R} = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{bmatrix} \\ \begin{bmatrix} B_X \\ B_Y \end{bmatrix} = \mathcal{R} \begin{bmatrix} B_{X_0} \\ B_{Y_0} \end{bmatrix} + \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \\ \begin{bmatrix} D_X \\ D_Y \end{bmatrix} = \mathcal{R} \begin{bmatrix} D_{X_0} \\ D_{Y_0} \end{bmatrix} + \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \end{gathered} \tag{8}$$

From the positions of points C and D, we can analyse the datum RR $\{r_5, r_6\}$. We start by calculating the length of the CD segment, and its angles with the horizontal (θ_{CD}) and with the bar 6 (β).

$$\begin{gathered} \overline{CD} = \sqrt{(C_X - D_X)^2 + (C_Y - D_Y)^2} \\ \theta_{CD} = atan\left(\frac{C_Y - D_Y}{C_X - D_X}\right) \\ \beta = acos\left(\frac{\overline{CD}^2 + r_5^2 - r_6^2}{2 \cdot \overline{CD} \cdot r_5}\right) \end{gathered} \tag{9}$$

With the values obtained with equations 8 and 9, we calculate the Cartesian coordinates of point E with respect to the absolute coordinate system OXY, and the angular positions of links 5 and 6.

$$\begin{bmatrix} E_X \\ E_Y \end{bmatrix} = \begin{bmatrix} D_X \\ D_Y \end{bmatrix} + \begin{bmatrix} r_5 cos(\theta_{CD} - \beta) \\ r_5 sin(\theta_{CD} - \beta) \end{bmatrix}$$
$$\theta_6 = atan\left(\frac{E_Y - C_Y}{E_X - C_X}\right) \quad (10)$$
$$\theta_5 = atan\left(\frac{E_Y - D_Y}{E_X - D_X}\right)$$

Next, we can obtain the positions of points F and G with respect to the OXY absolute coordinate system, such as:

$$\begin{bmatrix} F_X \\ F_Y \end{bmatrix} = \begin{bmatrix} D_X \\ D_Y \end{bmatrix} + \begin{bmatrix} \overline{DF} cos(\theta_5 + \theta_{EF}) \\ \overline{DF} sin(\theta_5 + \theta_{EF}) \end{bmatrix}$$
$$\begin{bmatrix} G_X \\ G_Y \end{bmatrix} = \begin{bmatrix} C_X \\ C_Y \end{bmatrix} + \begin{bmatrix} L_2 cos(\theta_6 + \theta_{EG}) \\ L_2 sin(\theta_6 + \theta_{EG}) \end{bmatrix} \quad (11)$$

Known the positions of points F and G, we analyse the last datum RR $\{r_7, r_8\}$. To do this, we calculate the distance between the points F and G, the angle of the segment GF with the horizontal and the angle δ formed by the bar 8 with said segment.

$$\overline{GF} = \sqrt{(G_X - F_X)^2 + (G_Y - F_Y)^2}$$
$$\theta_{GF} = atan\left(\frac{G_Y - F_Y}{C_X - D_X}\right) \quad (12)$$
$$\delta = acos\left(\frac{\overline{GF}^2 + r_7^2 - r_8^2}{2 \cdot \overline{GF} \cdot r_7}\right)$$

Finally, the angular position of link 8 is obtained with the Cartesian coordinates of point H with respect to the absolute coordinate system OXY.

$$\begin{bmatrix} H_X \\ H_Y \end{bmatrix} = \begin{bmatrix} F_X \\ F_Y \end{bmatrix} + \begin{bmatrix} r_7 \cos(\theta_{GF} - \beta) \\ r_7 \sin(\theta_{GF} - \beta) \end{bmatrix} \quad (13)$$
$$\theta_8 = atan\left(\frac{H_Y - F_Y}{H_X - F_X}\right)$$

The angles of the middle and distal phalanges of the mechanism during movement will be given by the angles of the CG and GI sides:

$$\theta_{PH2g} = \theta_6 - \theta_{EG}$$
$$\theta_{PH3g} = \theta_8 - \theta_{HI} \quad (14)$$

The proposed objective function (15) computes the quadratic error between the angles measured for the middle and distal phalanges in the photos, θPH2 and θPH3, and the angles corresponding to the same phalanges in the mechanism, θPH2g and θPH3g.

$$f(\chi) = \sum_{i=1}^{N} \left[\left(\theta_{PH2}^{i} - \theta_{PH2g}^{i} \right)^{2} + \left(\theta_{PH3}^{i} - \theta_{PH3g}^{i} \right)^{2} \right] \quad (15)$$

Where N is the number of positions to be compared, and X is the vector defined in (2).

Finally, it is necessary to limit the value taken by synthesizing variables, for this reason, a range of possible data for the initial values is established. The optimization has been solved with the previously mentioned MUMSA algorithm, which will generate a mechanism up to a desired number of iterations or until the error of the mechanism obtained from the formula (15) is less than previously assigned.

Appendix 3. Servo

This appendix is dedicated to the servo used to operate the exoskeleton. The data below shows the datasheet of the servo.

The "Micro 9G SG90 TowerPro" servo will be used. This servo was selected due to its small size, light weight and high output power. The servo can rotate approximately 180 degrees (90 in each direction) and works just like the standard kinds but in a smaller size. You can use any servo code, hardware or library to control these servos. Good for beginners who want to build any projects without building a motor controller with feedback & gearbox, especially since it will fit in small places. It comes with 3 bolsters (arms) and connection cables.

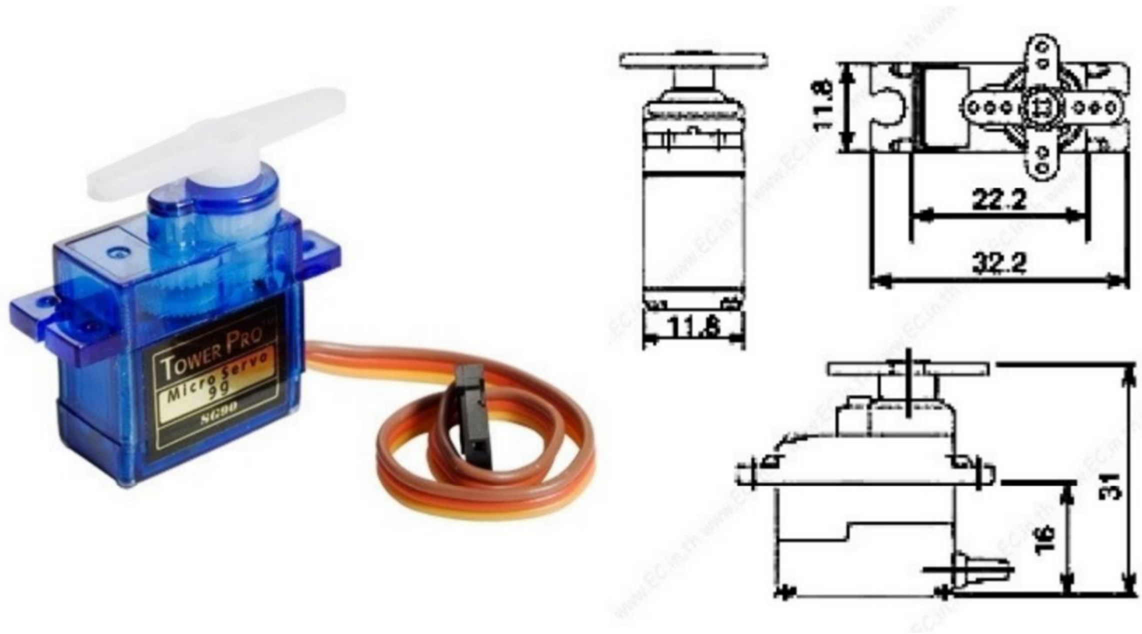

Figure 40. Micro Servo 9g SG90.

All engine specifications are:

- Weight: 9 g
- Dimensions: 22.2 x 11.8 x 31 mm approx.
- Stall torque: 1.8 kgf.cm
- Operating speed: 0.1 s/60 degree
- Operating voltage: 4.8 V
- Dead band width: 10 µs
- Temperature range: 0 ºC – 55 ºC

Position "0" (1.5 ms pulse) is middle, "90" (~2 ms pulse) is all the way to the right, “-90" (~1 ms pulse) is all the way to the left.

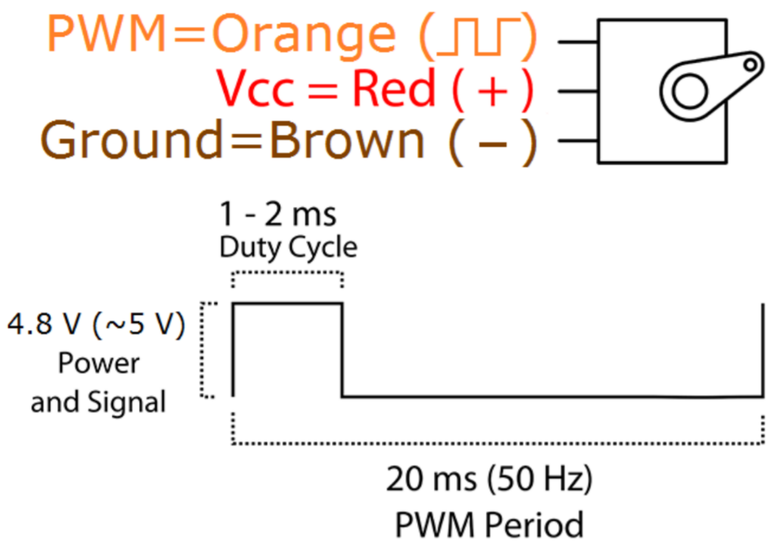

Figure 41. Servo information.

The servo is operated using Arduino. The connection to the board is as follows:

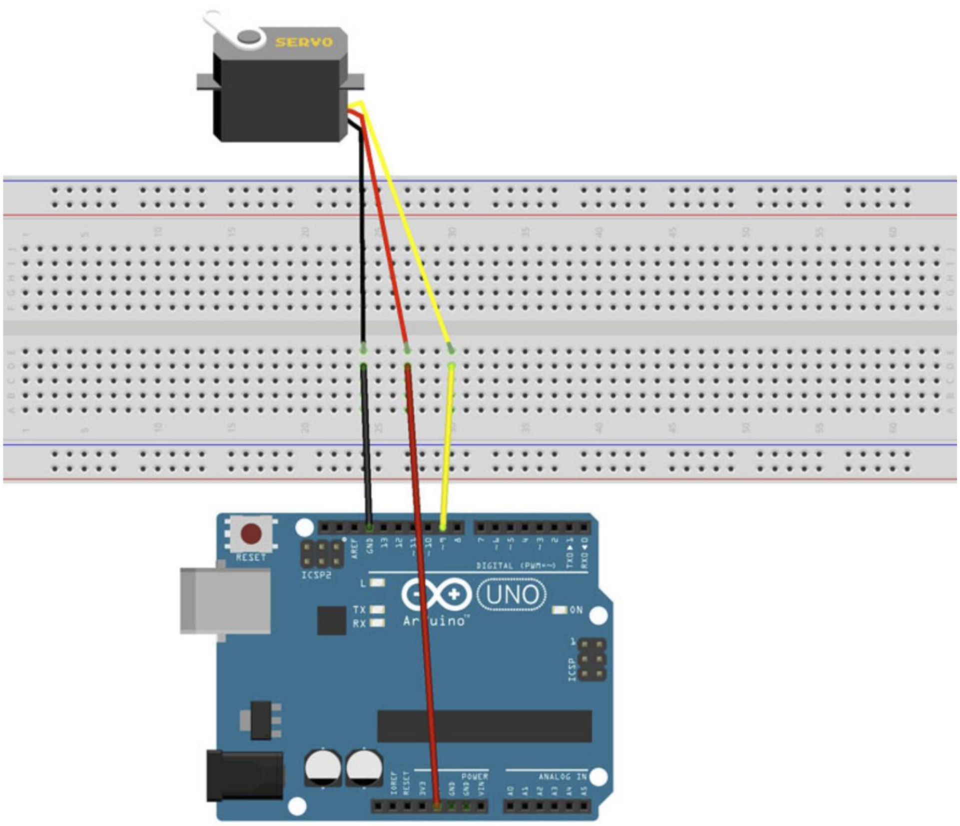

Figure 42. Board connection.

The servo has 3 cables. One will go to ground, another to the battery of 5 Volts and the third to a PWM pin.

For the code in Arduino, it is necessary to use an external library to operate the servo. The specific library is called servo and it is easy to find in Arduino Software 1.8.5.

The following code allows the user to control the servo sweep from 0 to 180 degrees. First from 0 to 180 and then the opposite direction. The code, (del Valle, 2018), will be the same on each finger except that the limit degree will change:

```
#include <Servo.h> // It includes the library to control the servo

// We declare the variable to control the servo
Servo servoMotor;

void setup() {

 // We start the serial monitor to show the result
 Serial.begin(9600);

 // We start the servo so that it starts working with pin 9
 servoMotor.attach(9);

 // Initialize angle 0 servomotor, in each finger this data is different (Index: 20º – Middle: 30º –
Ring: 30º – Pinkie: 20º) In this example is used the zero.
 servoMotor.write(0);
}

void loop() {

 // We are going to have two loops, one to move in a positive direction and the other in a
negative direction, it is possible to modify the limit angle, in this example will be 180
 // Positive
 for (int i = 0; i <= 180; i++)
 {
  // We move to the corresponding angle
  servoMotor.write(i);

  // We can pause 25ms
  delay(25);
 }

 // Negative
 for (int i = 179; i > 0; i--)
 {
  // We move to the corresponding angle
  servoMotor.write(i);

  // Pause again 25ms
  delay(25);
 }
}
```