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Bachelor in Biomedical Engineering
2017-2018

Bachelor Thesis

"Soft hand exoskeleton with SMA actuation of each finger separately"

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SUMMARY

This Project, grounded on a previously undertaken Master's Final Project (TFM) by Gabriela Verdezoto, develops a soft hand exoskeleton actuated by SMA (Shape Memory Alloy) for the rehabilitation of patients with low hand mobility. The use of 6 SMA cables as actuators allows the movement of each finger independently to perform complex exercises as well as opening and closing the whole hand at once.

The device consists on steely cables sewed to a glove in a way that allows a correct flexion and extension of the fingers when being pulled. The cables are connected to the SMA through a cage with position sensors. The electronics consist on a STM32F407VG Discovery kit microcontroller and a power stage that regulates the current delivered to the SMA. A MATLAB Simulink program controls it all.

The main objectives of the device are: to be light, cheap and simple to use.

The performance of the planned movements is achieved, and an optimization in the electronic system and software is performed to take a step forward in the design of a future rehabilitation device for clinical use.

Keywords

Exo-glove, rehabilitation robotics, shape memory alloys.

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I would like to thank my family (Mum, Dad and Silvia) for always cheering me when I got something to actually work although they didn't know exactly where my excitement came from. Also, for watching my one-minute long videos waiting for some "Iron Man"-like movement and pretending they were not disappointed at the capabilities of the glove.

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Iñigo, I simply cannot write here how much of a support you are to me in every aspect of my life. I love you.

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1. INTRODUCTION

Currently, the Systems Engineering and Automation department at Universidad Carlos III de Madrid has a number of students and researchers from various backgrounds developing projects on exoskeletons for all the joints of the human body. These are inside the scope of the RoboHealth Project [1]-[2], whose main objective is the development of upper-body exoskeletons (shoulder-arm-hand) for the rehabilitation of patients in hospital environments. The focus is on low-cost systems; and the development of new actuators for making robots lighter, safer and more robust. For this purpose, the use of SMA (Shape Memory Alloys) is a major key as a lighter and cheaper option than motors. Also, SMA has the advantage of being silent and smooth, imitating very accurately the natural movement of the muscles. The hand is one of the more complex organs due to the 27 degrees of freedom it possesses; therefore, its exoskeleton is the most difficult one to control and design. For this reason, a specific project parallel to Robohealth was launched, the EDAM Project [3]. The main objective of the EDAM project is to develop a hand exoskeleton where all fingers could be individually moved. The actuating system will be based on SMA wires. A complete sensor system will be implemented on the device to give the therapists a quantitative measurement of the rehabilitation exercise performance that could be used in the diagnosis and evaluation of the patient's evolution.

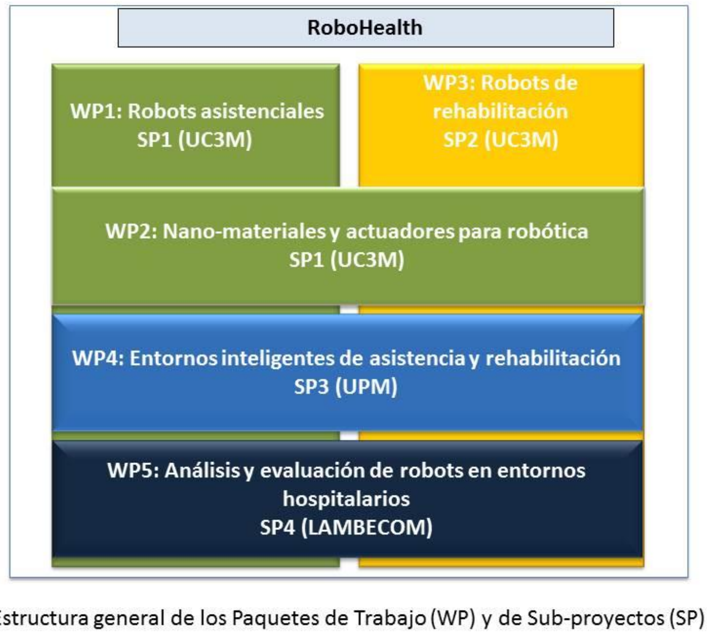


Figure 1-1. General structure of RoboHealth [1]

1.1 Motivation

According to the WHO (World Health Organization), 15% of the population of the world has some kind of disability; this means more than a thousand million people. This number is growing due to the increasingly old population and the augment in occurrences of chronic diseases [4].

Disabled people are at a very high risk of marginalization. They have statistically poorer education achievements and higher rates of poverty. This is especially true for those suffering from low hand mobility. The hand is an organ that develops the intellect by being a tool for creative progression and non-verbal communication. It has to be able to perform both very delicate and strong movements to be functional [5]-[6].

Hands are fragile because of their anatomical complexity. Aging affects them very directly through the deterioration of its muscles, bones and joints or through diseases associated with age like rheumatoid arthritis, Parkinson's, etc [6]-[7]. It has been proven that for elderly people, more than 50% of the decrease in neurologic functions in the upper extremities is found in the hand force steadiness, speed of movements in hand and arm and vibration sense [8].

There is an importance for these population to have the opportunity to improve their quality of life by doing rehabilitation. Agencies like the NIDILRR (National Institute on Disability, Independent Living, and Rehabilitation Research) in the US or the SERMEF (Sociedad Española de Rehabilitación y MEdicina Física) in Spain, work to make people with any kind of disability independent, so that they can perform the activities they want, and to have society provide them the opportunities and needs they require [9][10]. Nevertheless, in Spain, president of the SERMEF, Roser Garreta, claims, Physical Medicine is not a very known specialization for students of medicine. A better Government strategy to educate them and a unification of the means that the State expends on this field would have a clear impact on society, economics and health [11].

The improvement of health systems thanks to technology has been decisive towards a revolution in the diagnosis and treatments in a cost-effective way. The introduction of technology on rehabilitation is the aim of this project. To help both the professional and the patient by automatizing a process with an organ as complex as the hand would be a major step towards the improvement of the rehabilitation process.

1.2 Objectives

This Project is the continuation of a Master's Final Project (TFM for its Spanish acronym) by Gabriela Verdezoto (which can be seen in Figure 1-2) in 2016 [12] which developed a soft hand exoskeleton for rehabilitation that achieved a comfortable movement of all the fingers at the same time either for a movement of flexion or extension (As we will see later, the wat the device is designed, it allows the flexion if located on the anterior part of the wrist and the extension if the device is located on its posterior part). Based upon what she got to develop, the proposal of objectives is the following:

- Optimize the design of the glove in such a way that the thumb can perform a correct opposition to the rest of the fingers in its flexion position so that more complex movements can be performed apart from the previously designed by Gabriela. Extension design will be optimized for the fingers to do a more natural exercise when performing that movement.

- Upgrade the electronic system. The adaptation needed to make each SMA independent electrically from the others so that an individual control of each one can be made and, therefore, each finger can move on their own. The minimization of the electronics to a cage for the compacting and easier movement of the device with a power stage designed by the Department for SMA powering purposes [13].

- Upgrade the MATLAB Simulink program to a more complex one in which we can perform an independent control of each of the SMA cables.

- To work hand-in-hand with two other projects being developed in the department based on hand exoskeletons. To support and complement each other for the better development of tools that help patients with hand disabilities. These two projects, by Laura López and Cristina Ibáñez, are based on the development of another exoskeleton for the hand made of silicon[14] and an artificial intelligence program that activates an exoskeleton respectively [15]. Both are aimed towards aiding people with reduced hand strength in the process of gripping objects.

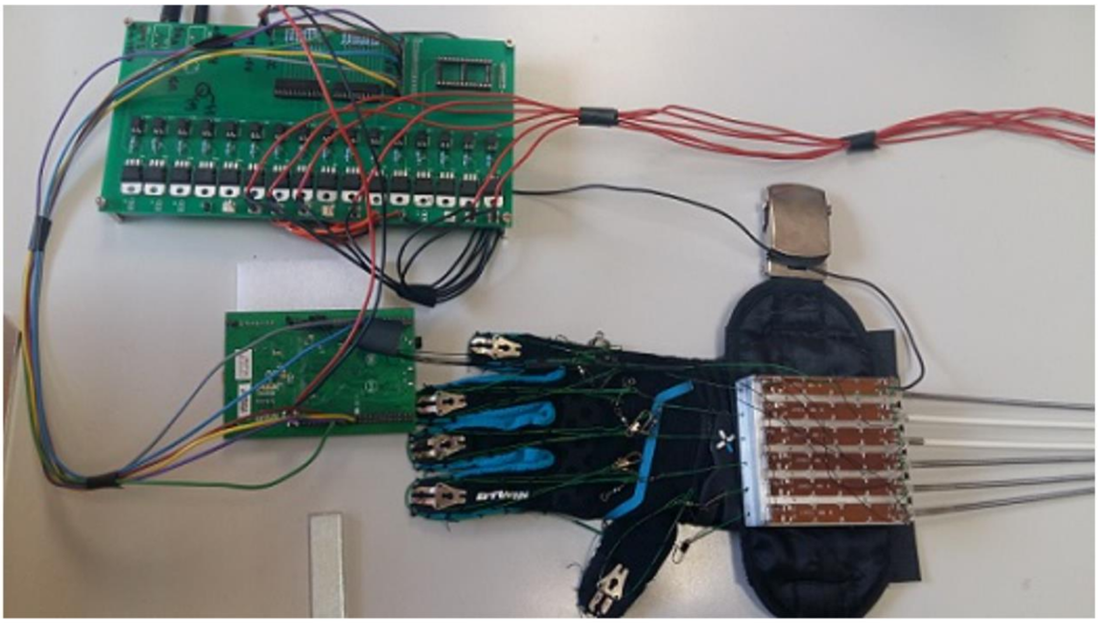


Figure 1-2. Previous Exoskeleton- TFM by Gabriela Verdezoto [12]

As previously mentioned, our aim is to make the device light weight and cheap. This would make it accessible for a daily use in hospitals.

1.3 State of the art

1.3.1 What is an exoskeleton?

An exoskeleton is a wearable machine powered by any actuation method that allows the movement of limbs with increased strength and endurance [16]. It is a very complex field, among others like prosthesis, inside Rehabilitation Robotics. The first ones were invented in the 1960s to improve the abilities of humans mostly for military applications [17].

1.3.2 What is SMA?

A Shape Memory Alloy (SMA) is a metallic alloy that can regain, when heated above its transformation temperature, its original “memorized” shape after being deformed in a cold state, due to a transition between its two different phases (austenite and martensite, which can be in two different crystal structures: twinned and detwinned) [18].

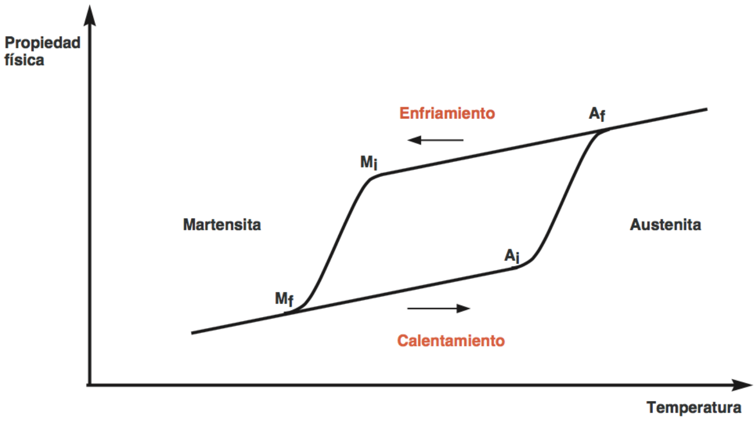


Figure 1-3 Hysteresis cycle of SMA [19]

Austenite is the most stable structure at high temperatures, and martensite at lower ones. When SMA is heated, it gradually transforms from martensite to austenite. “As” and “Af” mark the temperatures at which austenite begins to appear and at which the complete structure is made out of austenite only, respectively. Beyond “As” the material contracts to recover its original form (this property is called super elasticity [20]). This transformation can happen even under high pressures, resulting in high actuation energy densities. When cooling, the process reverses, also with a “Ms” and “Mf” to show the temperatures at which martensite appears and forms the complete structure of the material respectively. This is called the Shape Memory Effect. For this structure there is also a third temperature, “Md”, which represents the highest temperature at which martensite can no longer be stress induced [19]-[21].

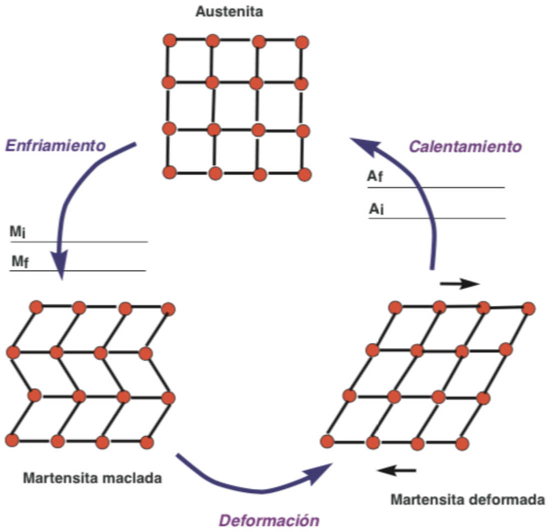


Figure 1-4 Shape Memory Effect [19]

Above this mentioned temperature, a stress on the material will mean a plastic deformation like any other metal. These temperatures and the hysteresis loop behaviour are influenced by the composition of the SMA material and can be measured with various techniques. Austenite and Martensite have different thermal conductivity, resistivity, thermal expansion coefficient and Young Modulus. When varying the temperature, the percentage of each component varies, making the properties of the whole material change in a hysteresis cycle. Austenite has a higher Young's modulus while martensite is softer and more malleable [21].

- Advantages and Disadvantages of SMA compared to other actuation methods [18]-[22]-[23].

	Advantages	**Disadvantages**
Pneumatic	• Simple • Accurate • Low purchase cost (50-150$) • Fast	• Loud • Can leak • Low efficiency
Electric	• Fast • Best position accuracy • High efficiency	• Not suited for all environments • Motor overheats
Hydraulic	• Easy to control • Slow	• Loud • Can leak • High cost

SMA	• Silent • Spark free • Low weight and volume • Smooth response (mimics muscle) • Cheap • Long actuation life	• Difficult to control • Low displacement (linear deformation o 2-5% only) • Low operation frequency (they have to cool down) • Low efficiency

Table 1-1 Actuation methods comparison

History, Applications and Future:

SMA has been used since the 1980s for diverse robotic systems, especially as artificial muscles. Medical applications include: endodontics, stents, anchors for attaching tendon to bone, implants…
The superplastic behaviour of the material fits the stews-strain behaviour of human bone and tendons. SMA stents bend according to the form of the vessel, rather than forcing it to stay straight like steel stents do [21]-[24].

1.3.3 What has been done already?

Through the years, the world of the exoskeletons has evolved very actively and, nowadays, many papers of projects on any type of exoskeleton can be found. To shorten the quest, only the relevant ones for the hand project were analysed.

Researchers from the Worchester Polytechnique Institute designed a soft robotic exo-hand connected to a backpack with servomotors as it can be observed in Figure 1-5. It aided stroke survivors who had loss motor function to close and open their hand. It was controlled by Electromyography or by a program in which you could select the desired movement to be performed. The glove was made of Spandex and the cables out of Kevlar [25].

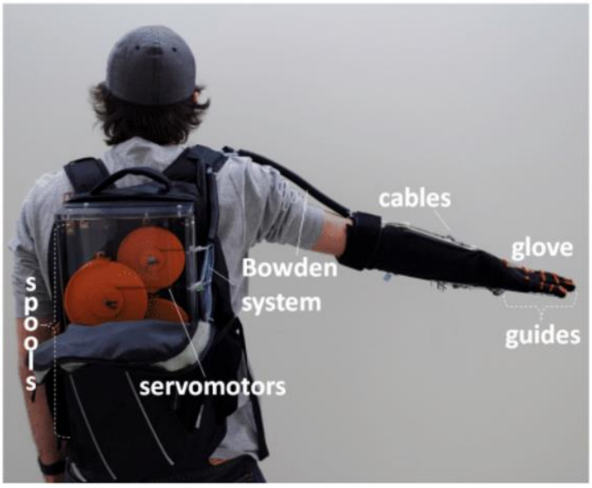


Figure 1-5 Soft robotic exoglove [25]

At Harvard University, scientists developed another glove aimed for anyone with hand pathologies. It used a combination of inextensible and elastomeric materials and used EMG for control. The curious thing about it is that they used elastomeric bladders designed to create specific movements by fluidic pressurization [26][27]. The movements they achieved can be checked in Figure 1-6.

Figure 1-6 Movements performed by Harvard's hand exoskeleton [26]

The Roboglove is a NASA Project that is originally intended to help astronauts do their tasks in space more easily but can have any other kind of application. It uses one tendon per finger and has the electronics and microprocessor in the forearm just as this project does. It has piezo resistive force sensors and performs open/close movements driven by motors [28].

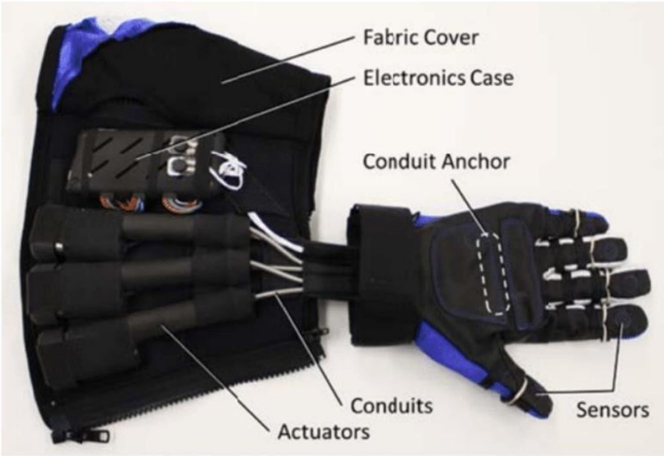


Figure 1-7 Roboglove [28]

Some other designs do not cover the whole hand but only the thumb and the index, and maybe the middle finger too as we can see in Figure 1-8. These, as fabric would not fit, use polymers like silicon, which is also a more sanitary material [29].

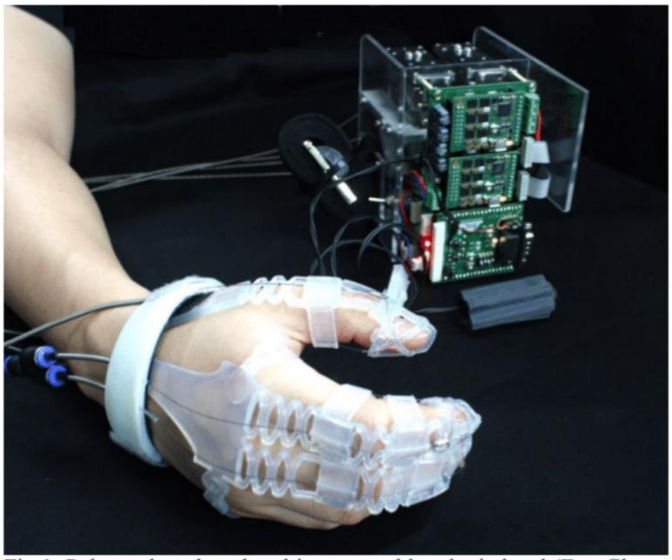


Figure 1-8 Silicon exoskeleton [29]

1.3.4 The hand. Anatomy and Physiology

Before starting the glove design, there is a need to understand the anatomy of the hand so that an accurate mimic of the natural movements it performs can be achieved. To understand some of the terms that will be used for the rest of this document, a definition will be provided. When talking about places in the body, the reference system is a body in anatomical position. This consists on a person standing up, looking front with their hands and legs slightly separated from the body and the palms of their hands and toes of their feet facing and pointing, respectively, forward. Then, to navigate the body, some specific terms are used. For a visual representation of all of these terms, Figure 1-9 can be checked.

* Anterior/Posterior: the most anterior structures in the human body are those that are most forward like the face and the abdomen. Posterior structures are those in the backside of the body, like the spine. Therefore, the spine is posterior to the abdomen.

* Medial/Lateral: this is a way to identify is a structure is close/far from the middle of the body if that is considered to be a vertical axis that cuts the anatomically positioned body in two "symmetrical" parts. Therefore, the arms are lateral to the sternum.

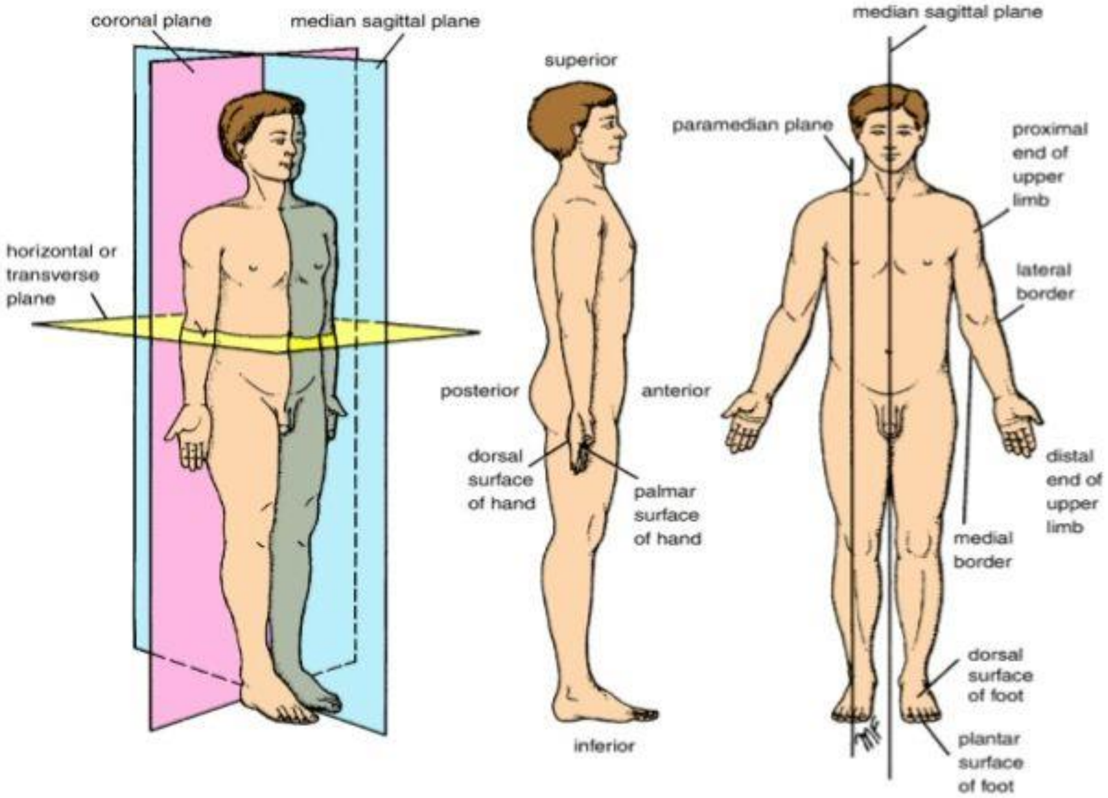


Figure 1-9 Planes, side view and anatomical position of the human body [30]

* Proximal/Distal: these are two terms to determine whether a structure is closer or further away from the trunk or their point of attachment. This means the foot is distal to the knee.

Keeping this in mind we can define flexion as the movement of structures closer to each other on an anteroposterior fashion whilst the extension would be the separation of structures. Both movements are made parallel to the sagittal plane.

The hand's main movements are flexion and extension of each of it joints, and adduction/abduction of the fingers (which will not be tackled here because of the complexity it would generate to actuate such device). The joints we find, that we can see in Figure 1-10, are: metacarpophalangeal (MCP), between the metacarpal and the first phalanx of each finger; the proximal interphalangeal, between phalanx one and two; the distal interphalangeal, between the second and third phalanx of each finger.

For the metacarpophalangeal joint, flexion can go up to 90º. The active extension can reach 30º or 40º, whereas the passive one (with help) can reach 90º as we can see in Figure 1-11 (c). For the abduction/adduction movement every finger except the thumb can reach a 30º lateral displacement from the axis formed in their relaxed state.

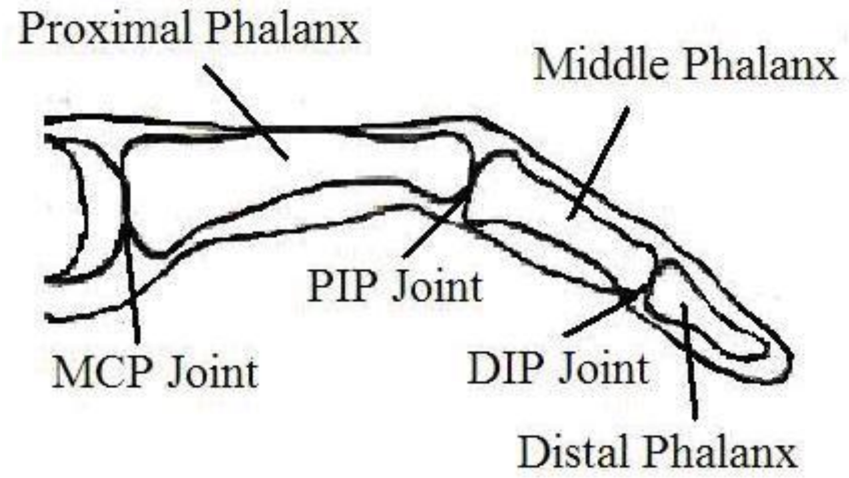


Figure 1-10 Joints of the finger [31]-[32]

For the interphalangeal joint there is only one degree of freedom, allowing flexion and extension. For the proximal one, flexion goes above 90º, at the thumb, to a maximum of 135º at the pinky finger. For the case of the distal interphalangeal joints, the flexion does not reach 90º [33]. A more intuitive way to realize this can be found in Figure 1-11 (b).

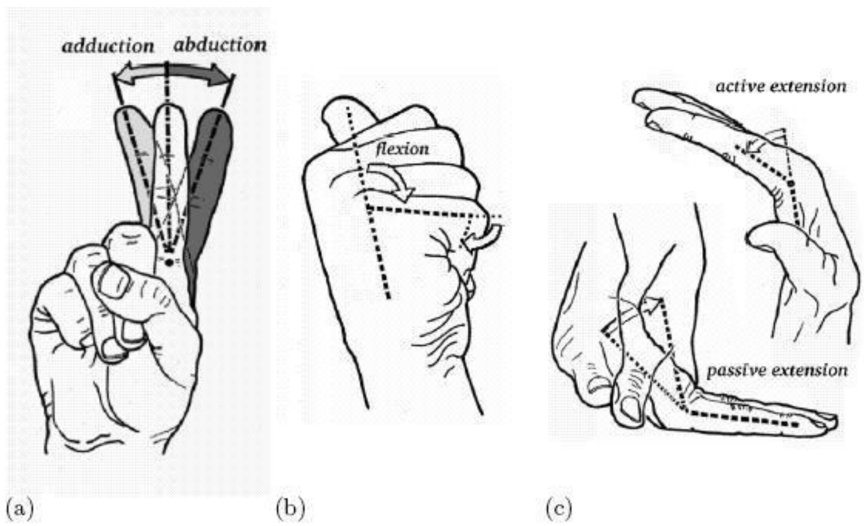


Figure 1-11 (a) Adduction/Abduction movement, (b) Flexion angle increment, (c) Passive and active extension [32]-[34]

The hand is composed by every type of tissue: muscular, nervous, connective (where we find blood vessels, bone, cartilage and tendons) and epithelial.
The ones that result more interesting for this project's purpose are those that allow movement: muscular and connective tissue. Among those muscles, tendons and ligaments that together form the complexity of the hand, the analysis will centre on those that allow the basic movements of flexion and extension of the digital joints.

- Bone

The hand is formed by 27 bones, from which 14 are phalanges. There are three phalanges in each of the fingers, except in the thumb where we can only find two. Typically, phalanges are counted from one to three starting from the most proximal one to the most distal one. There are also 8 carpal bones in the wrist and 5 palmar or metacarpal bones.

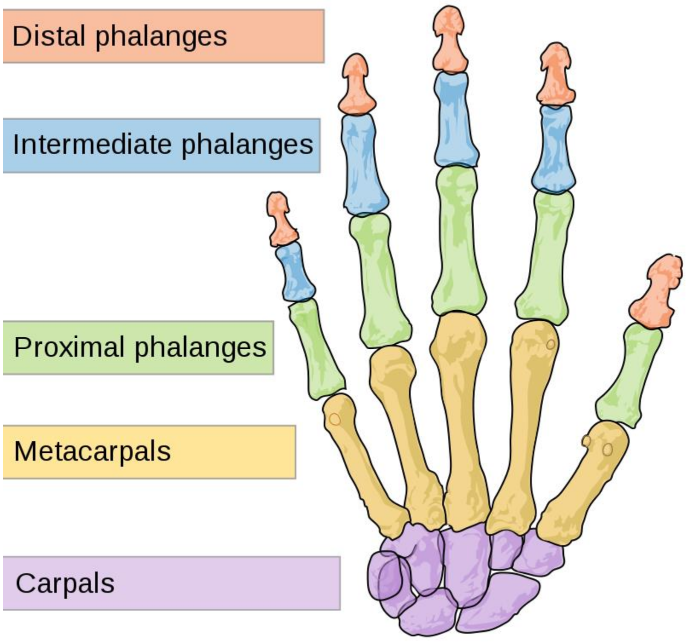


Figure 1-12 Bones of the hand [35]

- Serous sheaths

They are some double layer sheaths: a visceral one, touching the tendon; and a parietal one. A small amount of synovial fluid fills the gap between layers smoothing the movement of one against the other.

- Muscular Tissue and Fibrous Connective Tissue

Two types of muscles are found in the hand. Intrinsic ones are those that have their origin and insertion inside the hand and all of them are found in Figure 1-13. These are:

- Thenar Eminence: muscle mass in the base of the radius and form the base of the thumb.

Muscle	Function
Abductor pollicis brevis abducts	Abduction and internal rotation
Flexor pollicis brevis	Flexion of MCP joint
Opponens pollicis	Opposition, internal rotation
Adductor pollicis	Adduction

Table 1-2 Muscles of the Thenar Eminence and their functions

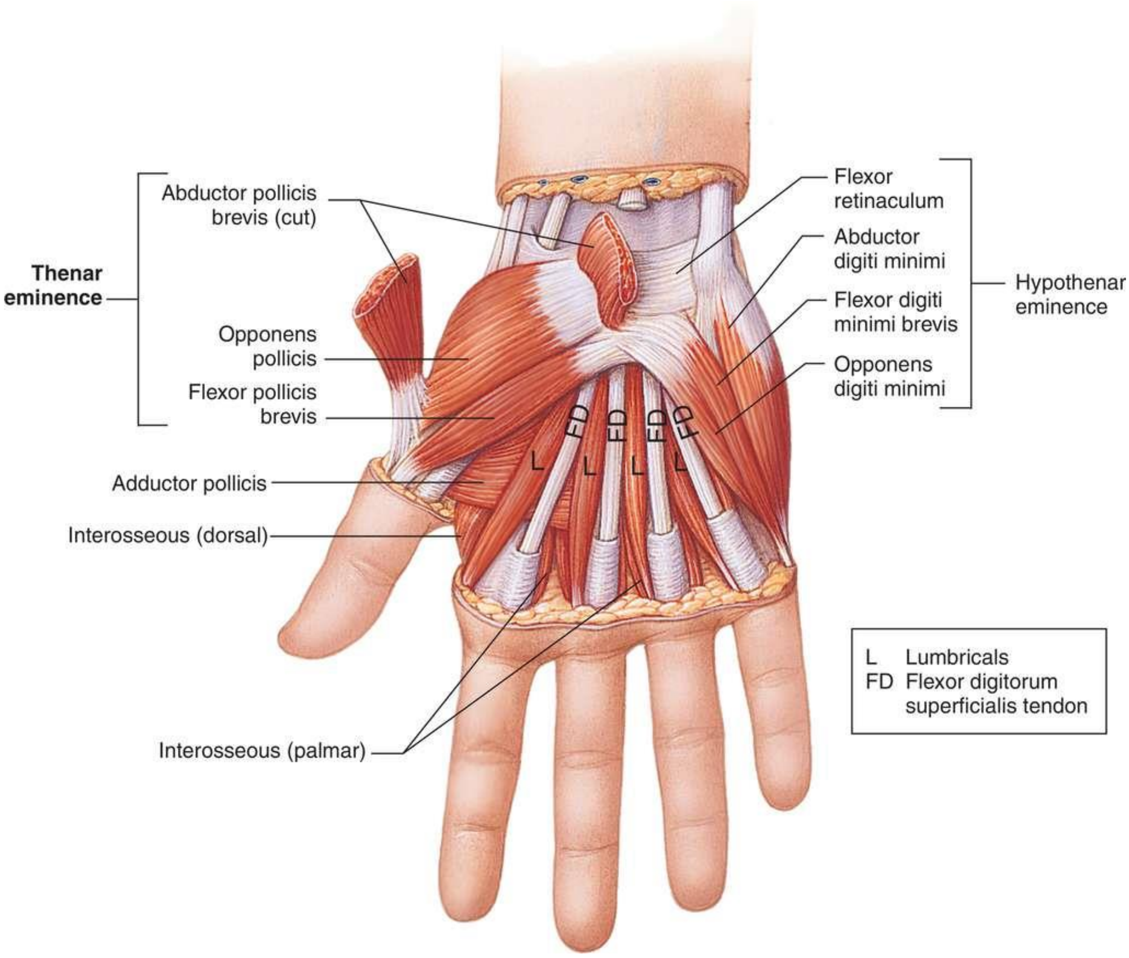


Figure 1-13 Muscles of the hand [36]

- Hypothenar Eminence: smaller muscle group that is found in the base of the pinky.

Muscle	Function
Palmaris brevis	Makes palm concave
Adductor digiti minimi	Abduction of the hand (wrt body)
Flexor digiti minimi brevis	Flexion of MCP joint
Opponens digiti minimi	Moves pinky towards the palm

Table 1-3 Muscles of the Hypothenar Eminence and their function

- Palmar region

Muscle	Function
Superficial layer>4 muscles	
Lumbricals	Flexion of MCP joint. Extension of P2 and P3 over P1
Deep layer, between carpals	
Palmar interossei muscles	Flexion of MCP, Extension of P2 and P3 over P1. Bringing fingers together
Dorsal interossei muscles	Same as previous ones. Separates fingers.

Table 1-4 Muscles of the palmar region and their function

- Palmar and dorsal aponeurosis: are truly a connective tissue fascia that starts at the phalanges and transfers the movement from the extrinsic muscles.

Apart from the above mentioned, the movement of the fingers is affected too by several extrinsic muscles from the arm. They are all represented in Figure 1-14.

Muscle	Function
Flexor digitorum superficialis	Flexes proximal interphalangeal joint, MCP joint and wrist
Flexor pollicis longus	Flexes thumb’s interphalangeal joint
Flexor digitorum profundus	Flexes both interphalangeal joints and MCP joint of each finger. Also flexes wrist
Extensor digitorum	Extends both interphalangeal joints and the MCP joints
Extensor digiti minimi	Extends the MCP joint of the pinky finger and the writs
Extensor pollicis longus	Abduct and extends thumb and wrist.
Extensor pollicis brevis	Extends MCP and wrist
Extensor indicis	Extends interphalangeal, MCP and wrists

Table 1-5 Hand's extrinsic muscles and their function

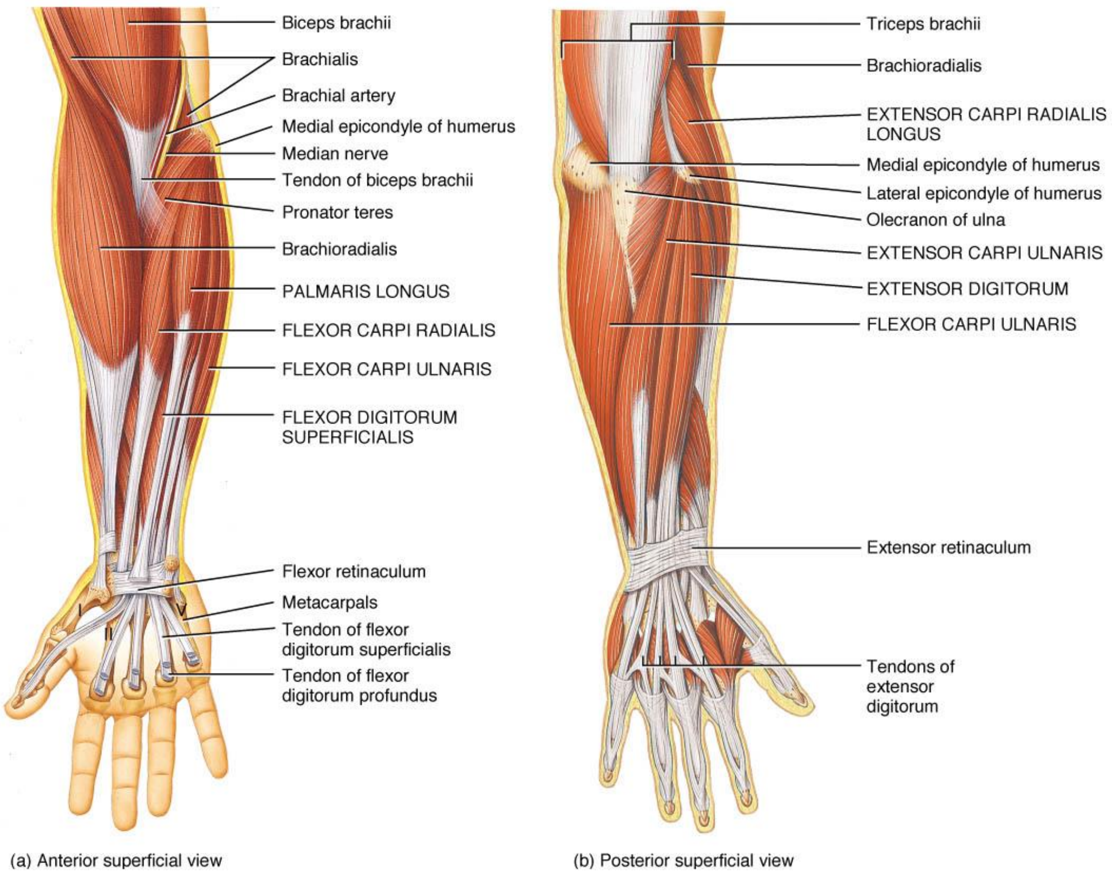


Figure 1-14 Extrinsic muscles of the hand [37]

Now, it will be analyzed the function of the main mentioned muscles in the movements of the fingers that we are interested in: flexion and extension of each phalanx separately and all together.

- Contributing to extension we find:

  - Extensor digitorum: Extends phalanx 1 (P1). Acts on P2 and P3 only if wrist is not flexed. Flexes MCP.

  - Interossei muscles: Flex P1 and extend P2 and P3. Its effects depend on the degree of flexion of the MCP joint, and of the tensional state of the extensor digitorum.
  - Lumbrical muscles: Flex P1 and extend P2 and P3. They are opposite to Interossei muscles. Their function is independent from the position of the MCP joint.

- On the other side, contributing to flexion we highlight:

  - Flexor digitorum: They reach the palmar face of P1, where flexor superficialis divides into two strings in between which we find the flexor profundus.
  - Flexor superficialis flexes P2. Only flexes P3 if P2 is already flexed.
  - Flexor profundus: is inserted in the base of P3 and flexes it, taking P2 with it when doing so.

- In synergy with flexor muscles, we find the previously mentioned extensor digitorum and the extensor carpi radialis.

- Retinacular ligament: fibers that come out of the palmar face of P1 and Project over the lateral strings of the extensor digitorum and over P3. Inversely to these strings they cross the proximal interphalangeal joint in palmar position. From this we can deduce that the extension of this joint tenses the fibers of the retinacular ligament and produces the mechanical extension of the distal interphalangeal joint to half of its usual trajectory.

To be able to slide on the concave face of the hand, tendons need to be held to the skeleton by fibrous sheaths. Three fibrous pulleys are found in each finger: one is above the metacarpal head and the other two in the anterior face of the first and second phalanges. In between these main pulleys, there are more crossed fibers places at every joint.

- Tendon of the flexor superficialis divides in two at the MCP joint to surround the tendon profundus and inserts in the lateral faces of P2.
- Tendon of the flexor profundus muscle: goes through the superficialis and inserts in P3.

We will use this knowledge on the anatomy of the hand to locate appropriately the steel cables that will define the movement of the glove.

1.3.5 Rehabilitation

Before defining the movements that our glove will try to perform, we should see what exercises the professionals have their patients do. The SERMEF offers some examples of typical exercises to treat Arthrosis and Rheumatoid Arthritis that we can see in the figures below. We mention specially those dedicated to hand mobility since those for strengthening are more complex and should be performed for patients with a higher hand capability than those this glove is intended for [38].

Figure 1-15 Thumb opposition [38]

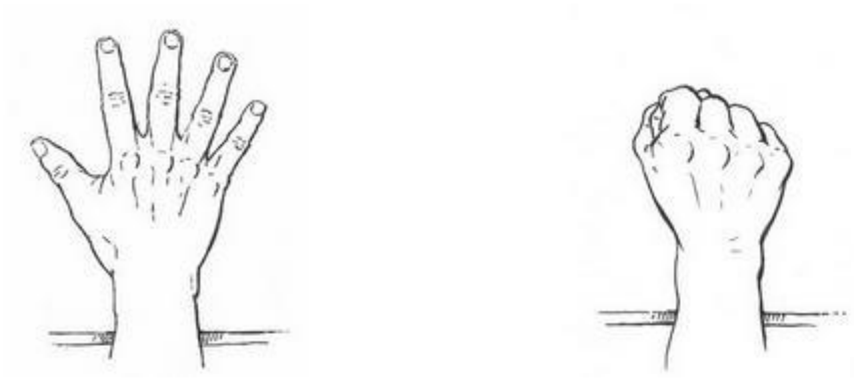


Figure 1-16 Close hand in a fist [38]

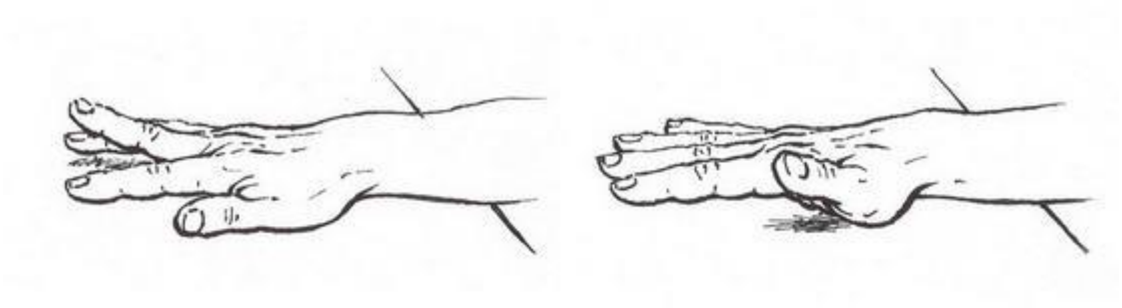


Figure 1-17 Individual extension of each finger [38]

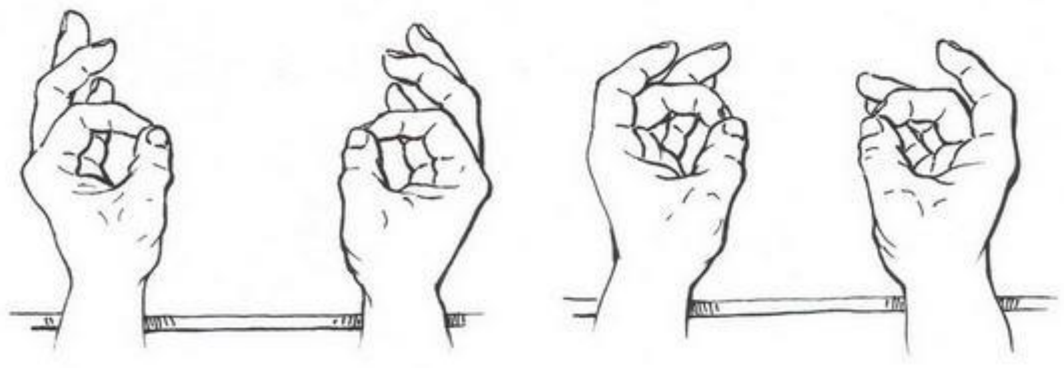


Figure 1-18 Formation of an 'O' with the thumb and every other finger [38]

2. METHODS

To fulfil all the mentioned objectives there is a need to establish a procedure. First, a bibliographic investigation on the background knowledge like the anatomy of the hand, the principles of SMA, the exoskeletons that have already been done, etc. is required. Those have already been explained in the document.
Then, a foresight of the materials needed for the implementation of the desired device should be made. In this case, although an optimization from a previous Project is made, a full list of the materials needed to build the whole device is made. Lastly, a study on the optimal locations of the steel cables on the glove and the adaptation of the hardware and software parts of the control system has to happen.

2.1 Materials

First, as a brief introduction of how the system works, a list of all the materials needed for the construction of this device will be done. This will allow us to go through the implementation process in a faster way.

2.1.1 Glove

A glove of strong fabric but comfortable mobility was bought to withstand the strength of the cables pulling without tearing while allowing natural movements to the fingers.

Figure 2-1 Juba Glove [39]

2.1.2 Wristband. Ligaflex Classic Open

To hold the sensors and immobilize the wrist for a better performance of the pulling motion, a wristband was used.

Figure 2-2 Wristband

2.1.3 Steel cables/Tendons

With pins at their ends for a faster clamping to one another (Clamping made between the ones sewed in the glove to the ones in the sensing cage that we will see later) to be able to change from extension to flexion and vice versa in an agile way. They are aimed for fishing, they can hold 12kg and are 15 cm long (Similar to the ones specified in [40]).

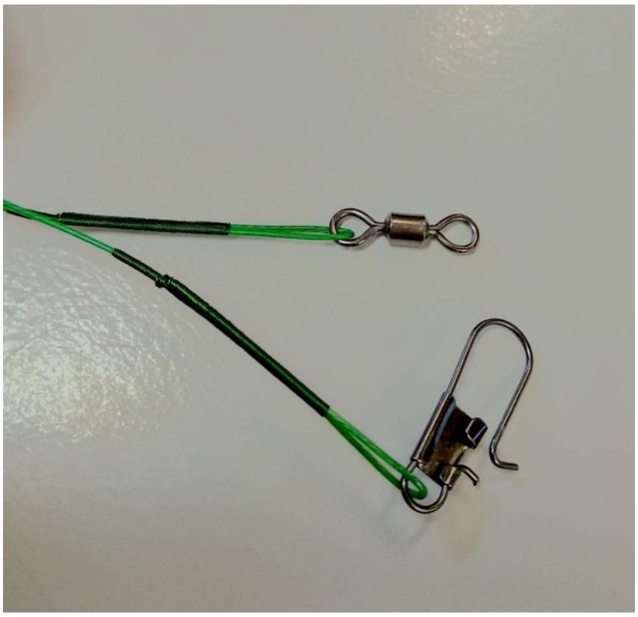


Figure 2-3 Terminals of a steel cable

2.1.4 Silicon thimbles

As a way of strengthening the tips of the glove and allowing for a softer impact of the pulling motion on the finger, silicon thimbles were located inside each finger of the glove. A more comfortable sensation for the fingers is achieved too.

Figure 2-4 Silicon thimbles

2.1.5 Longitudinal potentiometers

Slide Bourns PTA Potentiometer were used as the sensors to provide the position information for each of the fingers. Six of them are added to the circuit.

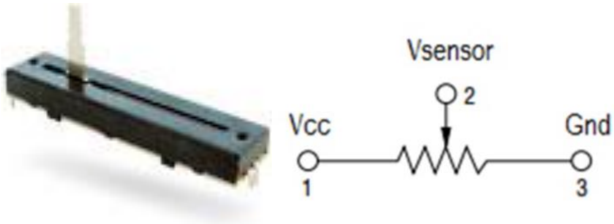


Figure 2-5 Slide Potentiometer [12]-[41]

2.1.6 Structure of the sensors

A cage-like structure that holds the potentiometers on top and both the SMA cables and the steel cables. This cage's purpose is to both, transmit the contraction movement from the heated SMA cables to the steel ones sewed to the glove and to move mechanically the potentiometer's flap for the transduction of this longitudinal change into the electrical circuit. This is done through 6 hollow canals in which a clamping structure joins the SMA and the steel cables for movement transmission. At the same time, in the clamp, there is a cup-like structure that holds the flap of the potentiometer and carries it when moved. This piece was designed for Gabriela's TFM and kept for this project. A Velcro structure to which the cage is glued is used to attach the piece to the wristband.

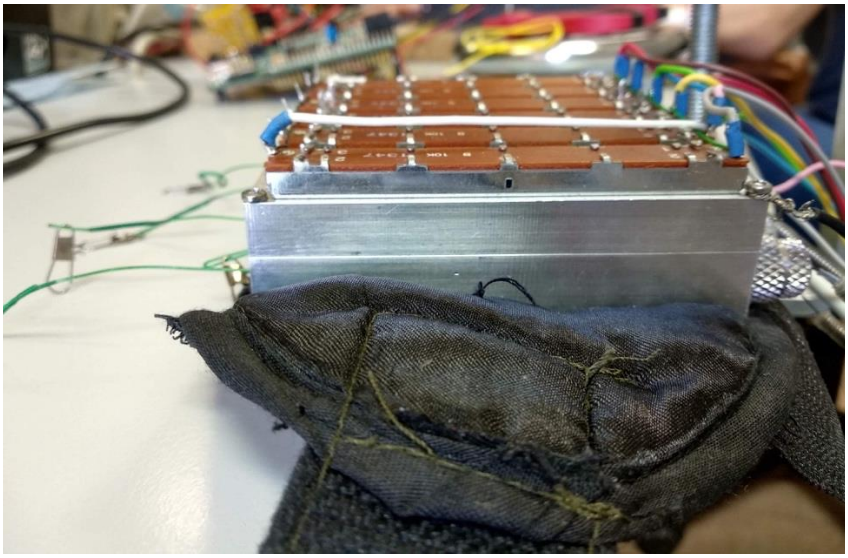


Figure 2-6 Cage side view

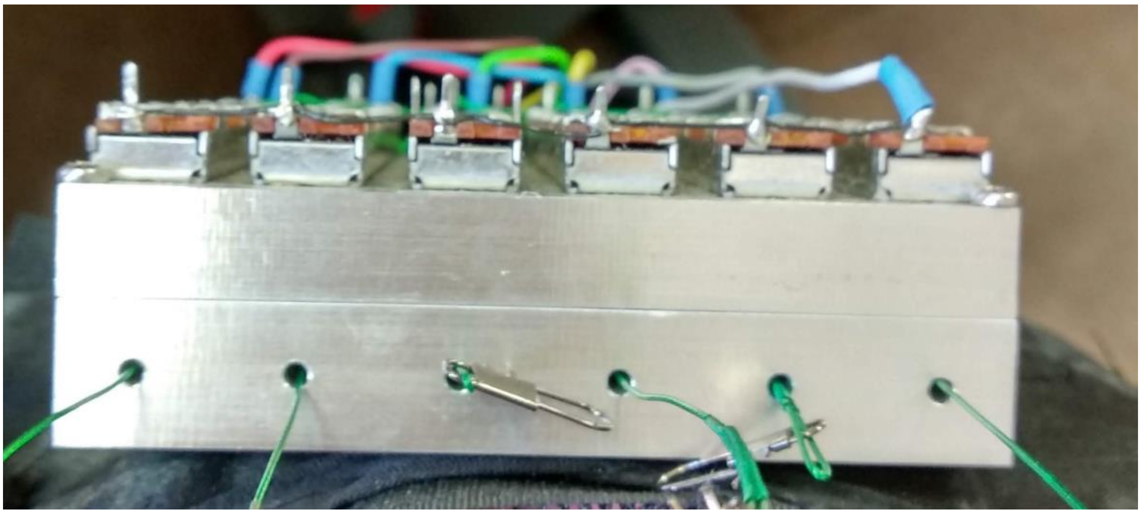


Figure 2-7 Cage front view. Where steel cables come out towards the hand.

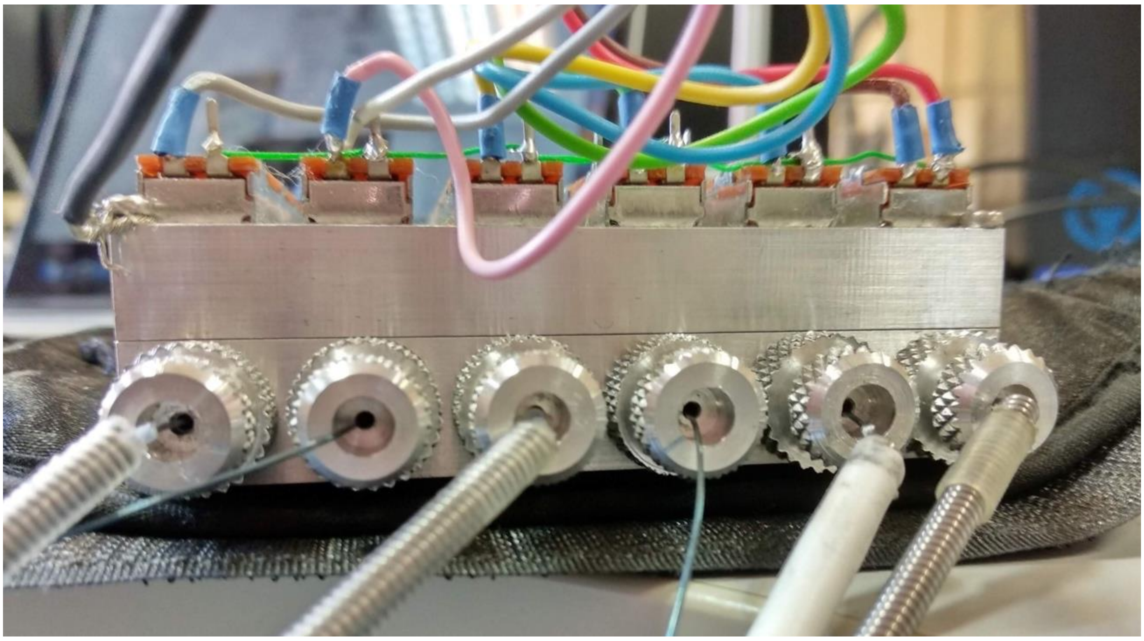


Figure 2-8 Cage back view. Where the SMA cables come out. Cables from the electronic circuit come out of the potentiometers.

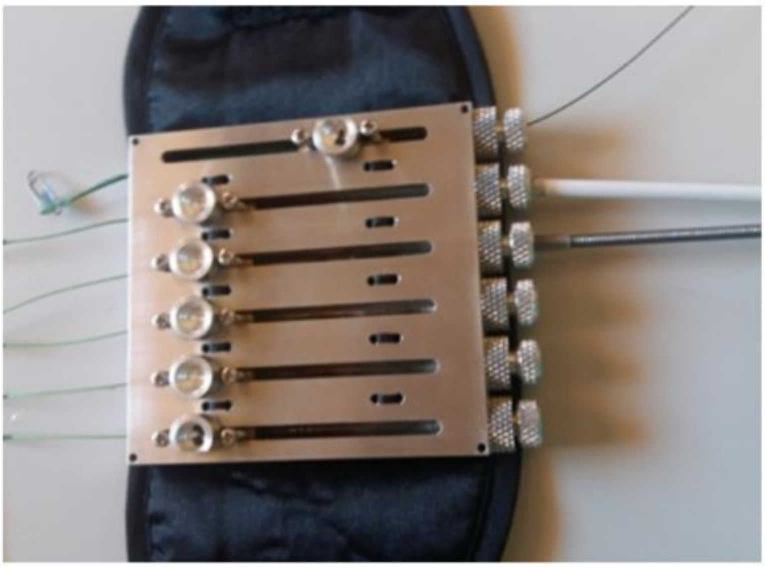


Figure 2-9 Design of the inside of the cage [12]

2.1.7 Actuators: SMA, Bowden, Teflon

Six SMA cables, each of one is inside an isolating Teflon tube and a Bowden cover. The Bowden cable allows for the movement of retraction of the SMA cable to be translated in the pulling motion that we need for our purpose. As designed by Gabriela, the length of all of these components is based on the fact that SMA contracts 2-5% of its length. For an approximate travel distance of 2.5-6cm, 120 cm long SMA cables are used.

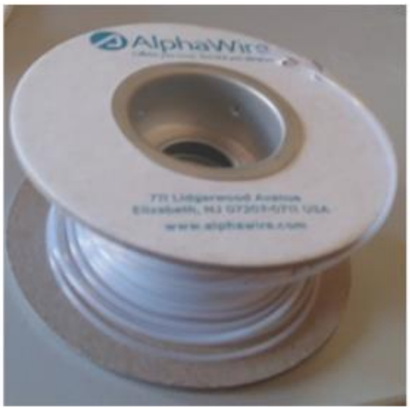


Figure 2-10 SMA cable **Figure 2-11 Teflon**

Figure 2-12 Bowden cover

2.1.8 Electronics: microcontroller, power stage, cables

The microcontroller used is a STM32F407VG Discovery kit. Its functions are the analog to digital conversion of the voltage coming from the sensors through the selected channels and to keep the first MATLAB program to launch the second from the computer. It specifications can be found in the supplier's webpage [42].

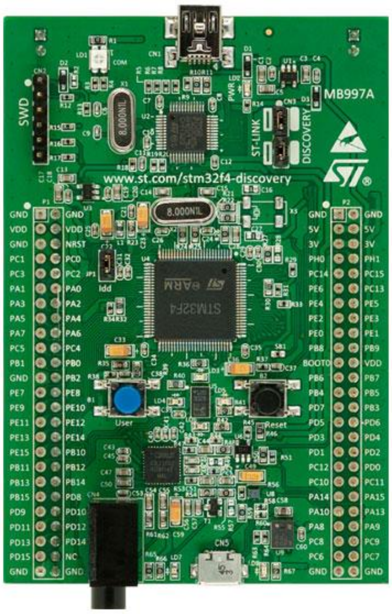


Figure 2-13 STM32F407VG Discovery kit [42]

- The power stage was designed by the Department for the special purpose of powering SMA cables. Its specifications can be found in [13].

2.1.9 Power supply

It should be able to power the 6 SMA cables at the same time with 30V.

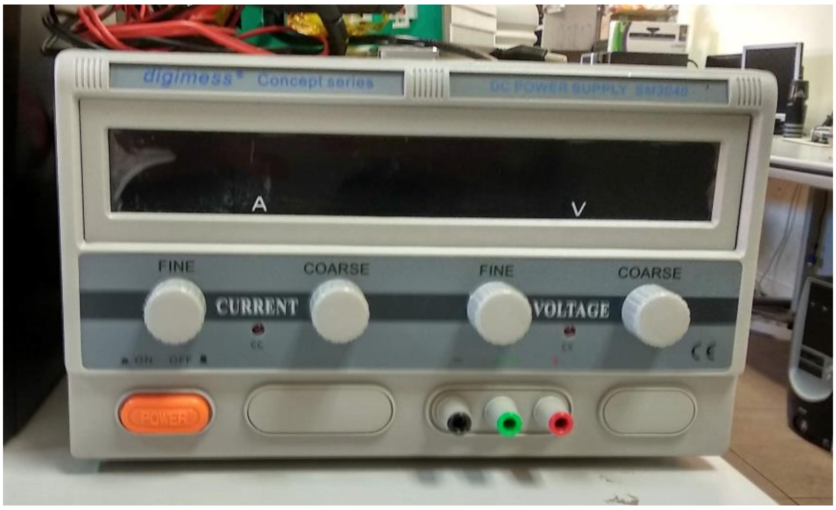


Figure 2-14 Power Supply

2.1.10 Software

Two MATLAB Simulink programs that use the additional libraries “WAIJUN BLOCKSET” by Aimagin and “UC3M ADDONS STM32F4” by Antonio Flores Caballero [43]. The first program (Bilineal Simple, scheme in Figure 2-15) the one we charge into the STM32F407VG Discovery, will be the one that acquires, processes and sends the data. The second one (Bilineal Host, scheme in Figure 2-27)is run in the computer and is in charge of the communication and the interface to see, store and process the signals.

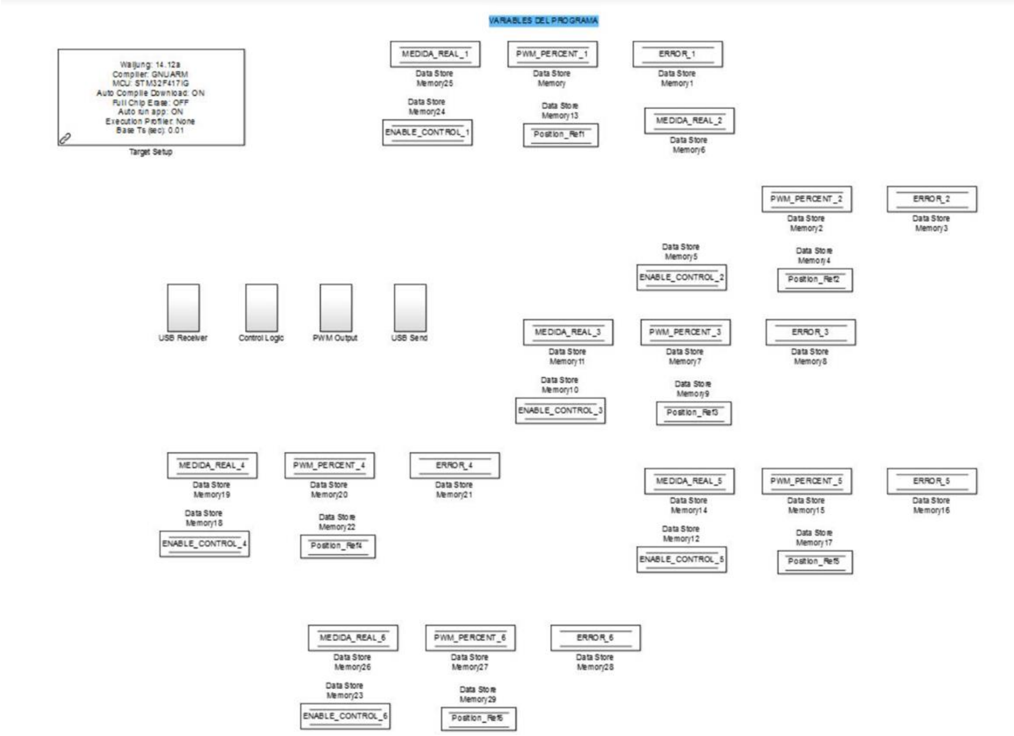


Figure 2-15 Bilineal Simple

2.2 Implementation

As it has been stated in the previous chapters, the objectives of this project included the optimization of an already working system. Nevertheless, most parts were built again from scratch to upgrade their quality and correct some mistakes, therefore, improving the final device’s capabilities.

2.2.1 Glove

The first step done was to design the glove. A multi task glove was bought and, based on the research done for the anatomy of the muscles and tendons in the fingers, several configurations were proposed. The steel cables were sewed onto the glove with a thread that serve, like the serous sheaths in the hand, as pulleys that drive the motion of the fingers inside the exoskeleton. It should be noted that although there are six actuators that could be used, our configuration uses only five, one for each finger. The sixth one could be used, if necessary, to enhance, for example, the movement of the thumb.

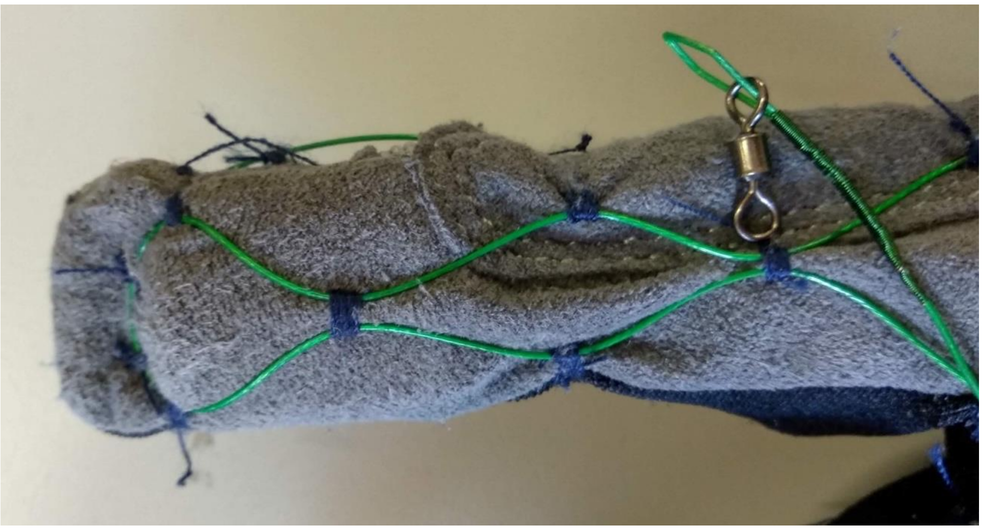


Figure 2-16 First configuration for the flexion of the fingers

First, for the flexion of the index, middle finger, ring finger and pinky, a trial was made with a different configuration to that used by Gabriela. This configuration can be seen in Figure 2-16. The objective was to achieve a higher angle for the flexion of the first and second interphalangeal joints. Nevertheless, the movement that the finger followed when pulling from the steel cables in that configuration was not natural enough, because the fabric of the glove was not stiff enough and it wrinkled in a restraining way for the finger's circulation. For this, the original design by Gabriela, pictured in Figure 2-17, was chosen as the best one and maintained.

Figure 2-17 Final configuration for flexion

Nevertheless, for the thumb's flexion, not enough opposition was achieved with the previous design. A new one was tried taking into account that, as studied in the anatomy of the hand, muscles from both the anterior and the posterior faces of the arm participate in this movement's performance. To be able to lift the base of the thumb, the cable is located around the area we want to belt as seen highlighted by the dashed yellow line in the picture below.

Figure 2-18 Frontal, Back and side view of thumb configuration for flexion. Dashed yellow line marks the steel cable that is involved in flexion.

For the case of the extension, a very unnatural movement was detected for all the fingers except the thumb. The beginning of the movement, from a closed hand position, occurs normally but then, after a certain point of extension is reached, the pressure of the pulling movement centres on the tip of the finger and does not allow the first interphalangeal joint to perform a complete extension as it is represented in Figure 2-19. A new proposed design was made to convert the middle of the second phalanx into a lever point. The cables are crossed there, forcing the first interphalangeal joint to extend completely. This can be observed in Figure 2-20 This was inspired by the fibres that hold tendons to the skeleton.

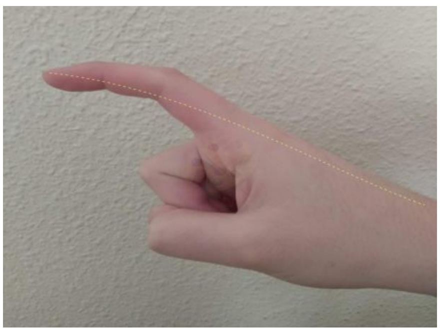


Figure 2-19 Representation of the problem that the previous design for extension had that caused the unnatural movement for the interphalangeal joints.

Figure 2-20 Extension configuration

In the case of the thumb a new approach was taken too because the previous design, with the cables sewed exactly the same way as for the index, tended to pull from the thumb in an unconventional way. This tended to bring the open thumb towards the rest of the fingers (with a slight adduction) when its more natural path tends towards the abduction (separation from the other fingers). For this we tilted the cables towards the MCP joint that, in the thumb, is less marked than in the other fingers and is located lateral to the rest of the finger (thumb). This is seen in the dashed yellow line in Figure 2-21.

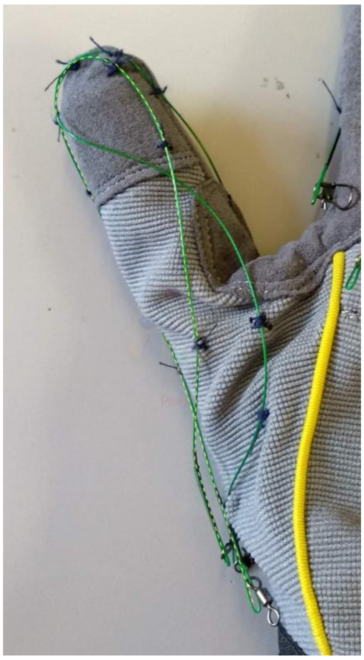


Figure 2-21 Detail of the thumb's extension configuration. Dashed yellow line marks the steel cable meant for extension.

The mentioned silicon thimbles were introduced into each of the gloves sleeves instead of the metal pieces that Gabriela used. These help fingers adapt to the glove and be steered in the correct direction with care.

The actuation stage was left the same in design terms. Maintenance tasks were made by the adjustment of the Teflon isolators This was done to make sure that the SMA cables were not in contact with the Bowden tubes, which are conducting too, for a short circuit not to happen. As the SMA cables were not burnt, there was no need to replace them.

The circuit was rebuilt from scratch because the previous one was in short circuit. The design was planned to receive the sensory information for each potentiometer. Nevertheless, the actual design did not allow that, and the program only read one sensing signal. The SMA cables were all controlled at the same time from that unique signal. Here, they were made completely independent among them and controlled with respect to their potentiometer signal. Therefore, a new microcontroller, power stage and software are used for this new version of the exoskeleton to fulfil this objective.

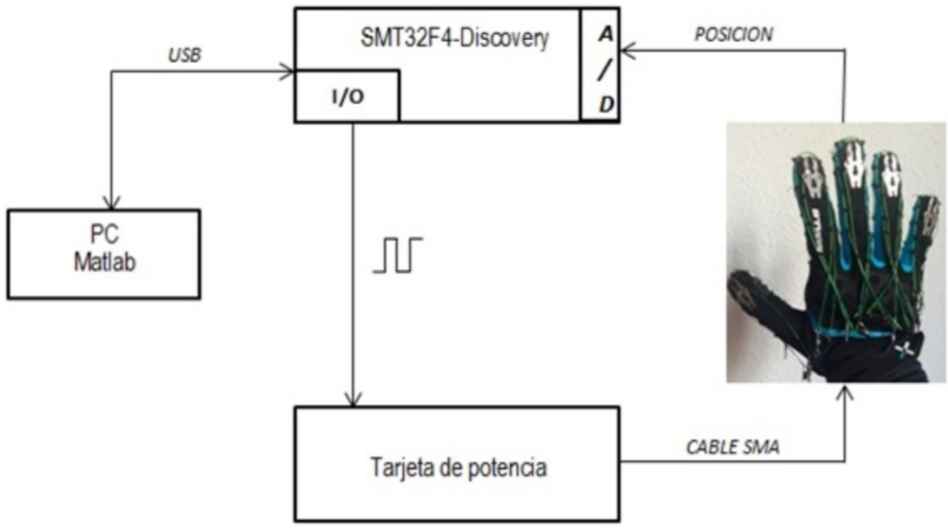


Figure 2-22 Scheme of the electric circuit by Gabriela. [12]

2.2.2 Circuit

The same scheme from Gabriela's TFM (Figure 2-22) can be followed to understand the configuration of the new circuit. The potentiometers are connected to the STM32F4DISCOVERY for the acquisition of the data. They are receiving their ground and 3V supply from that plaque. Each of the sensors is connected through individual cables to the pins described in Table 2-1.

SMA cable	Cable colour	Sensing pin	PWM pin
1	Grey	PA1	PA0
2	Pink	PA2	PB3
3	Yellow	PA3	PB10
4	Green	PA4	PB11
5	Blue	PA5	PE9
6	Brown	PA6	PE11

Table 2-1 STM32F4DISCOVERY

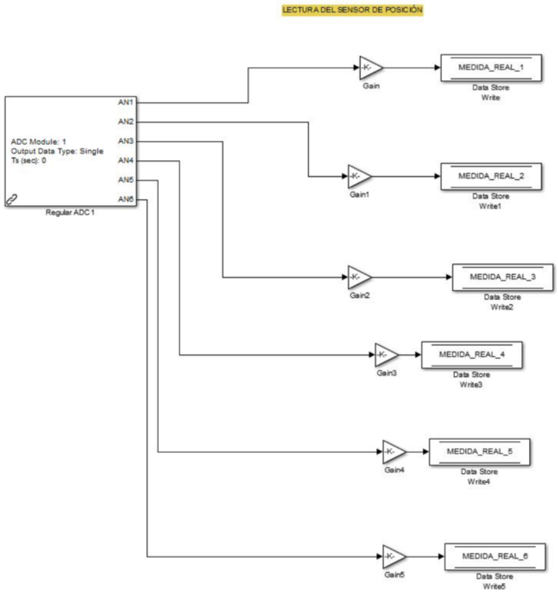
After being processed by the programs, the information of the PWM required to heat the SMA the amount we want, is sent back from the plaque to the Power stages (separated into two plaques: one powers two SMA cables and the other the remaining four ones) through the pins seen in Table 2-1. Those two plaques are powered by the power supply and are connected both to the potentiometers and the SMA cables. The six masses go respectively to the six SMA cables. We connect them at the end, where we leave an uncovered part (without Teflon nor Bowden) for this connection. The positive ends are all clamped together to the mass of the potentiometers to make it a common one. This inversion is caused by the transistor type that the power plaques use.

2.2.3 Program

An adaptation of the one done by Gabriela was implemented for it to be able to perform the sensing, processing and then send the PWM pulses to the six circuit branches that compose the circuit.

- Bilineal Simple

It is the program that is loaded into the microcontroller. All the variables were therefore repeated six times and the “Read sensor” and “USB receiver” are adapted to receive and send six signals to the corresponding ports. The PID control is too done six times, meaning we could have different PID values for each of the SMA cables. The PWM output that is computed from that PID function is sent back to be microcontroller and the power stage to heat the SMA.



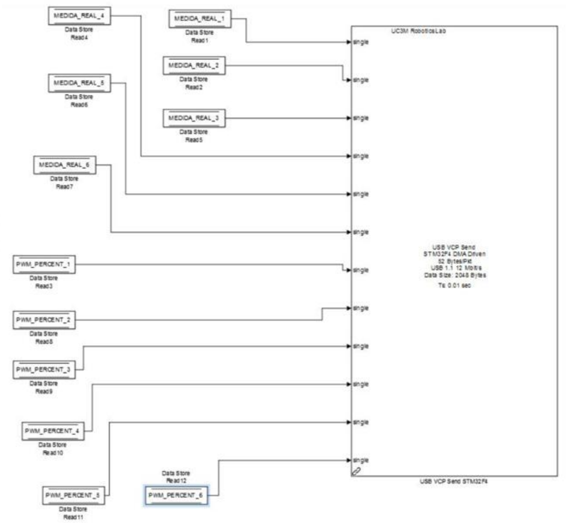
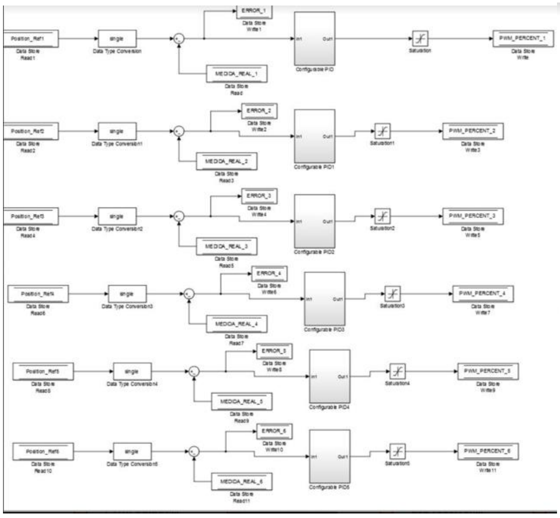


Figure 2-23 Read sensor **Figure 2-24 USB sender**



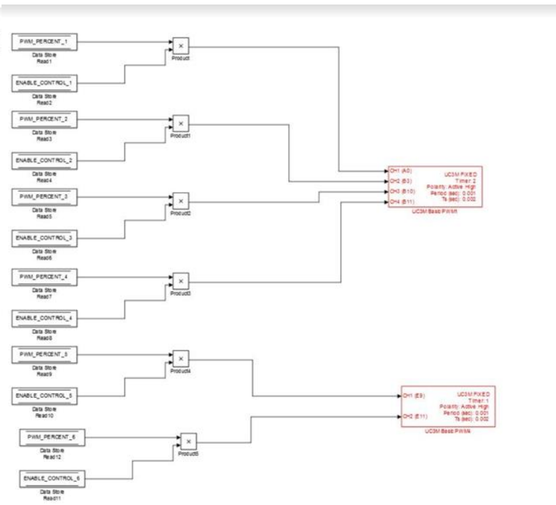


Figure 2-25 PID **Figure 2-26 PWM Output**

- Bilineal Host

Acting as an interface and storage program, is too modified to work with the five extra variables now. Here we can access to plots with the real time variables of both the sensor reading and the gain that the user wants to achieve. This allows us to observe the behaviour of the SMA with respect to time. The actuation of the cables is done by setting manually a “GAIN” between the values of 0 and 50 that translate to the same actual millimetres in displacement.

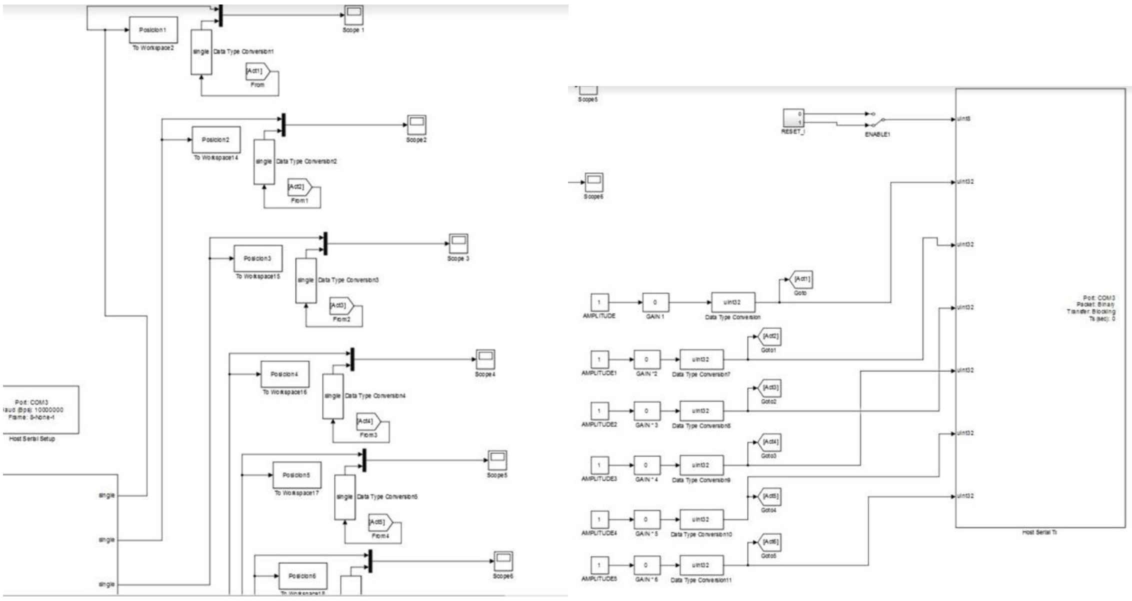


Figure 2-27 Bilineal Host detail

3. RESULTS

The commissioning of the whole device requires several iterations of a trial an error system to solve all the problems that come with a physical complex circuit. Some examples of the most common problems encountered are:

- Incorrect welding which left an open circuit.
- Short circuits caused by uninsulated conducting pieces touching. This caused the SMA cables to consume power but not contract, which can make them burn and break.

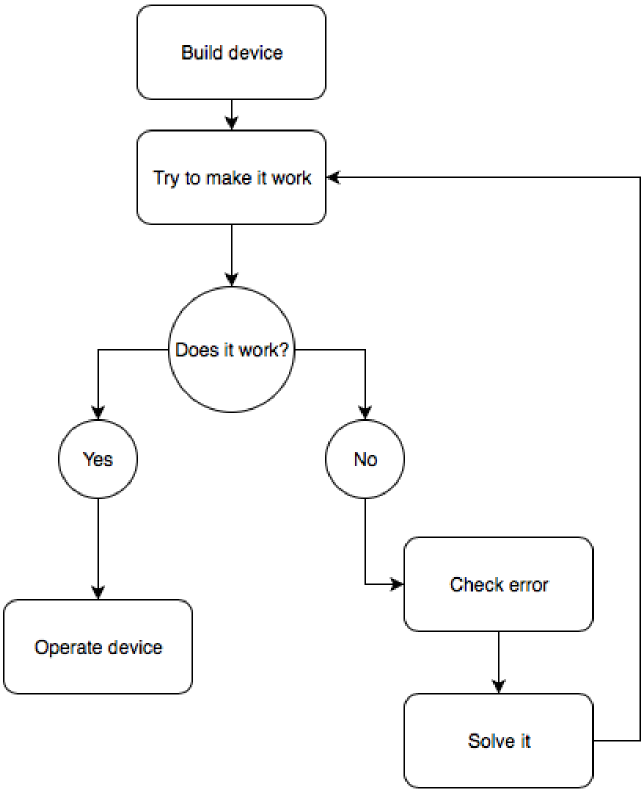


Figure 3-1 Commissioning workflow

3.1 Experiments

Several experiments were carried out to check the correct functioning of the exoskeleton. These are aimed mainly to confirm the design and to observe the behaviour of the SMA for situations similar to the ones it would be subjected to do the rehabilitation exercises. They are done with one healthy subject: female, 22 years old.

First, we checked each finger's movement individually both for flexion and extension to see if the tendon's configurations are correct. For this experiment, each finger was actuated to its highest possible length.

- Index

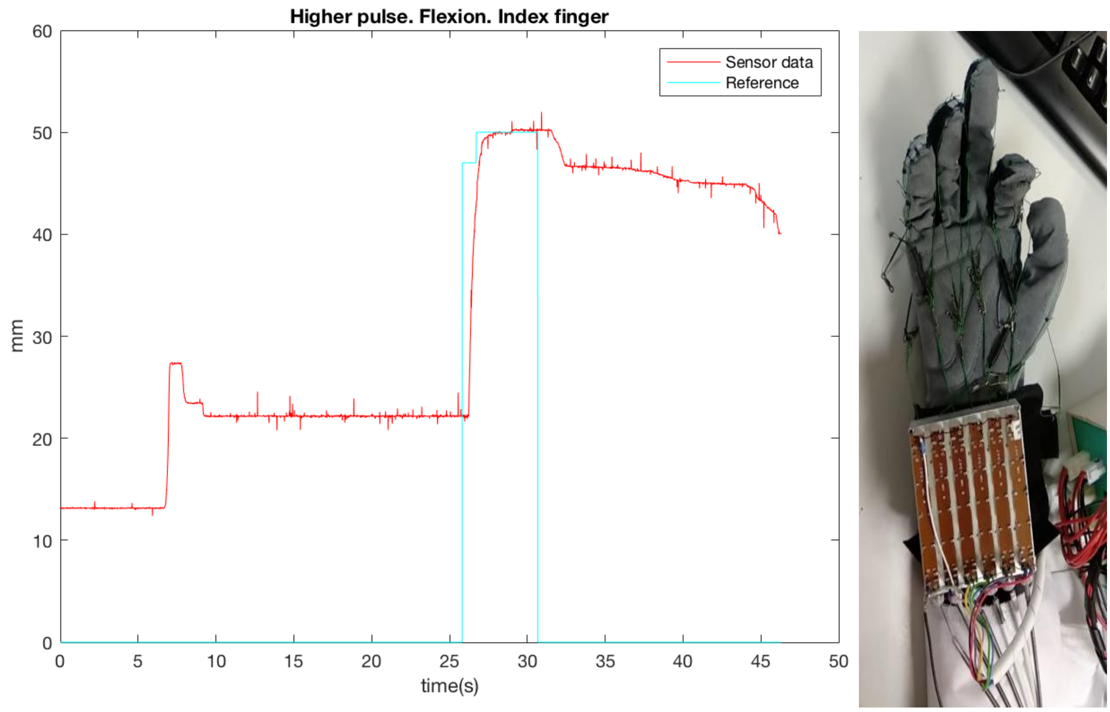


Figure 3-2 Index maximum flexion

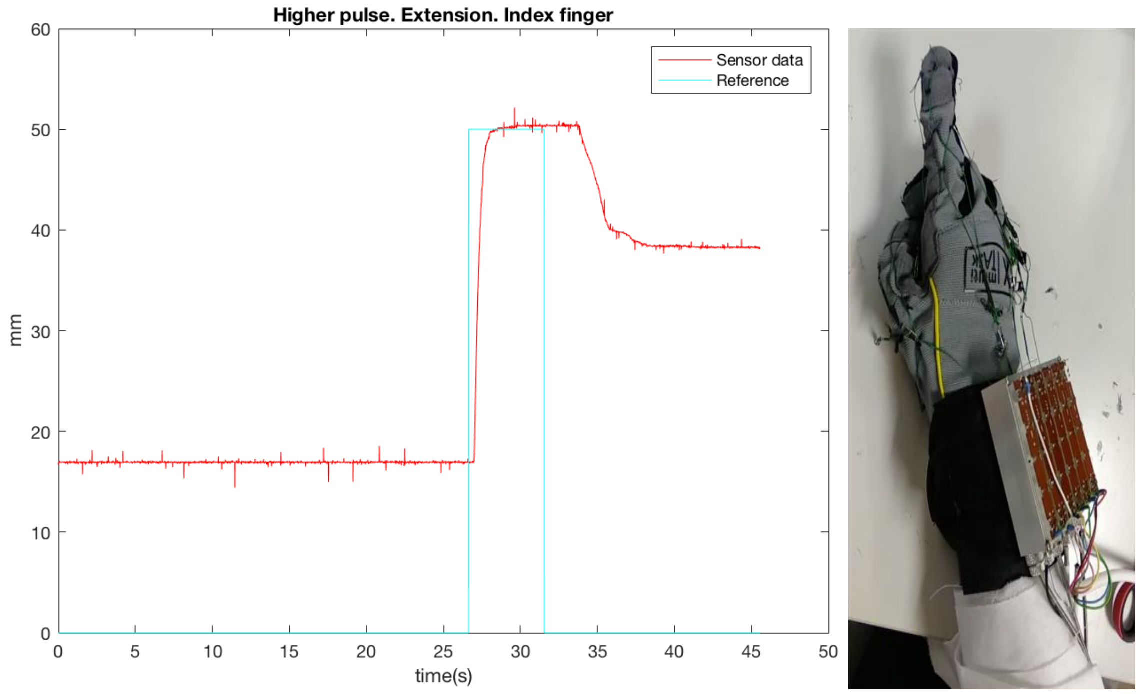


Figure 3-3 Index maximum extension

- Middle finger

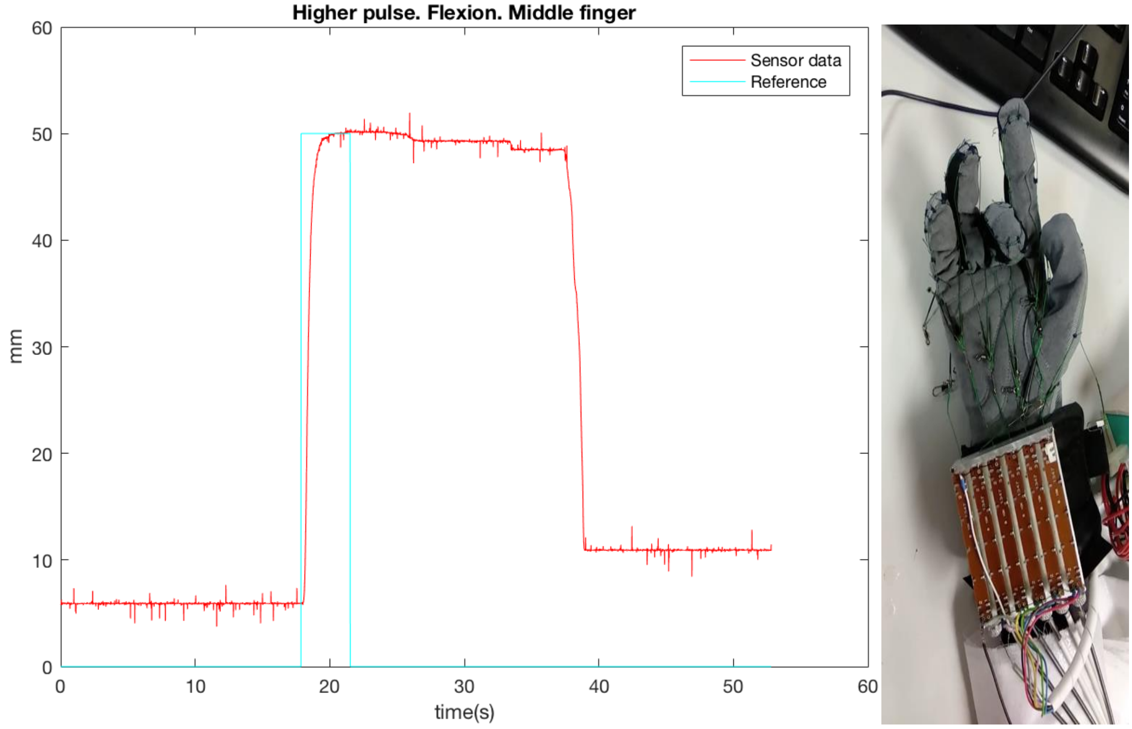


Figure 3-4 Middle finger maximum flexion

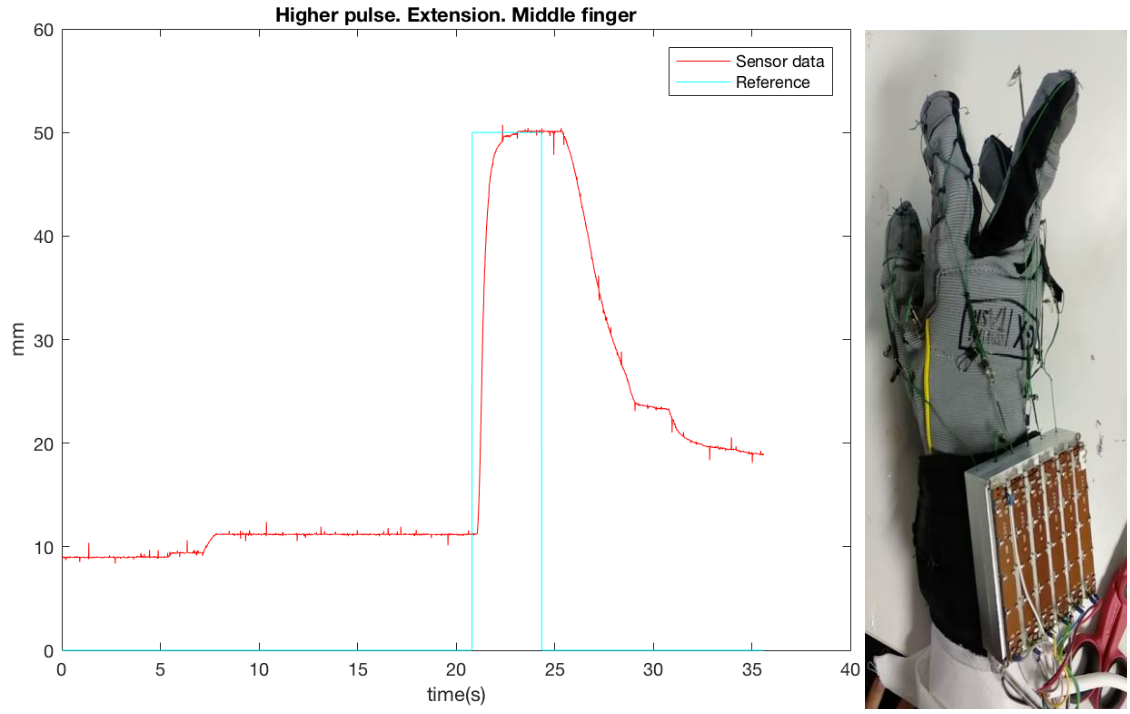


Figure 3-5 Middle finger maximum extension

- Ring finger

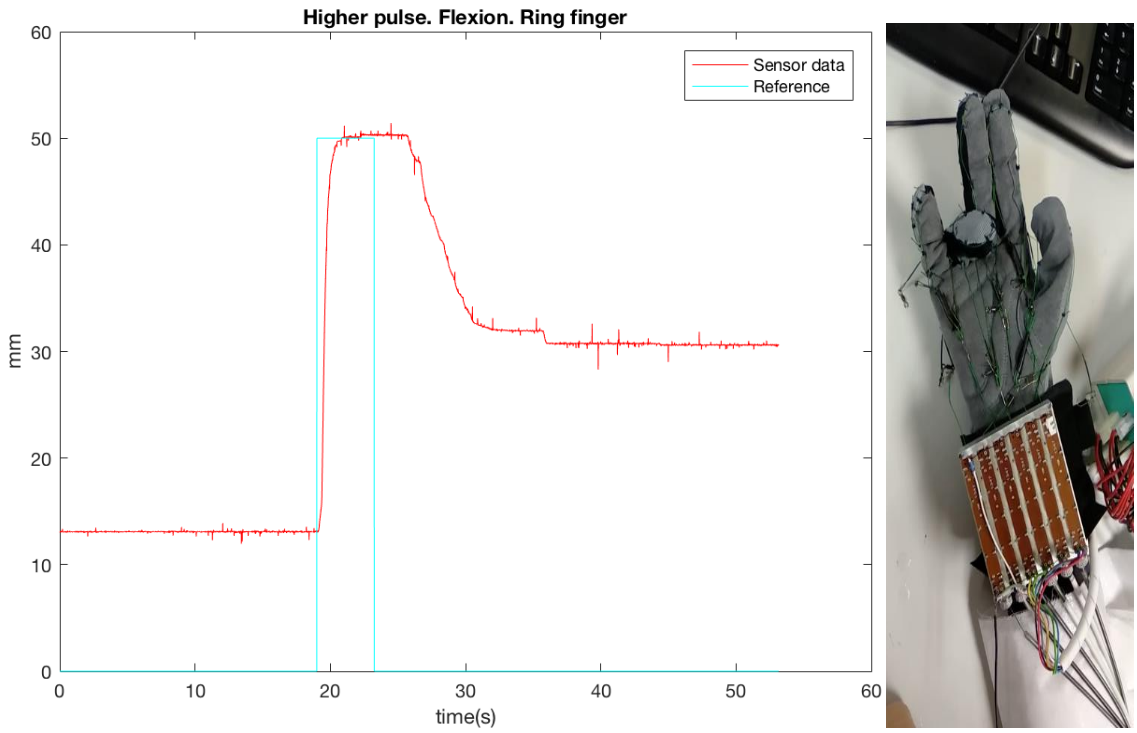


Figure 3-6 Ring finger maximum flexion

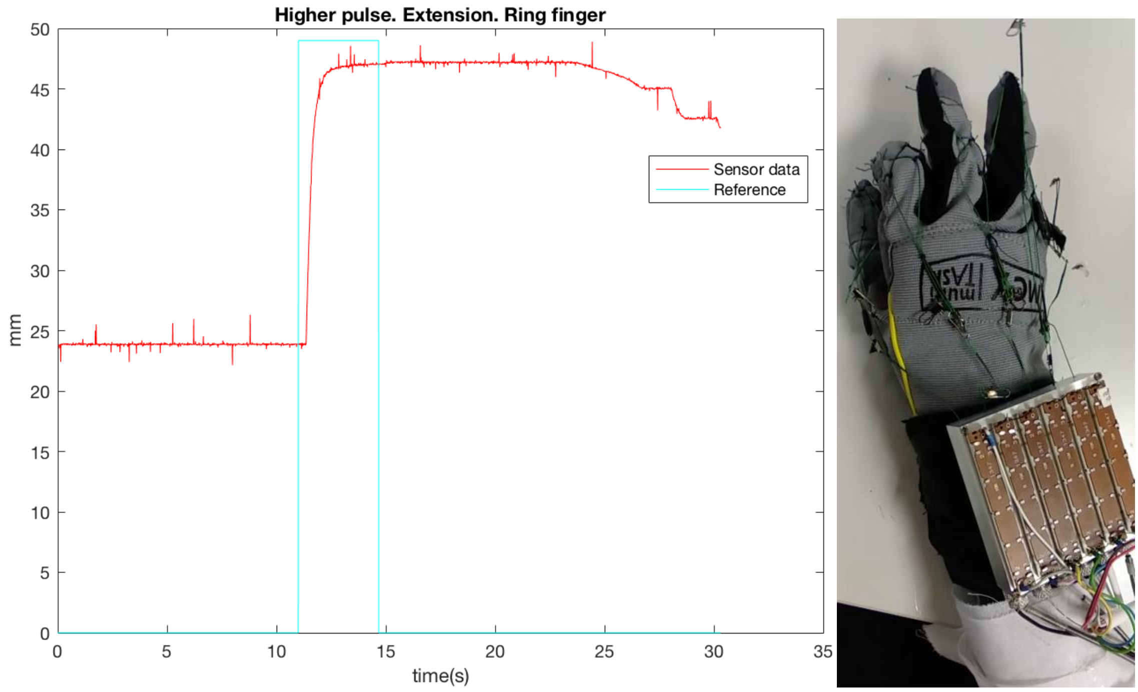


Figure 3-7 Ring finger maximum extension

- Pinky finger

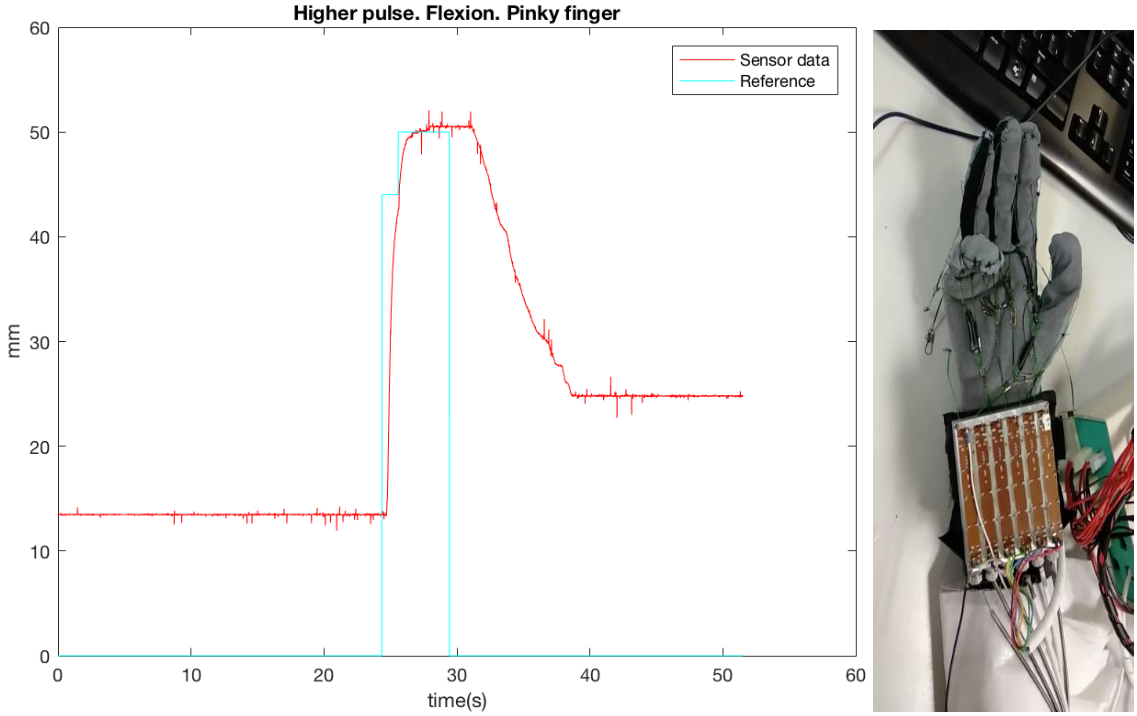


Figure 3-8 Pinky finger maximum flexion

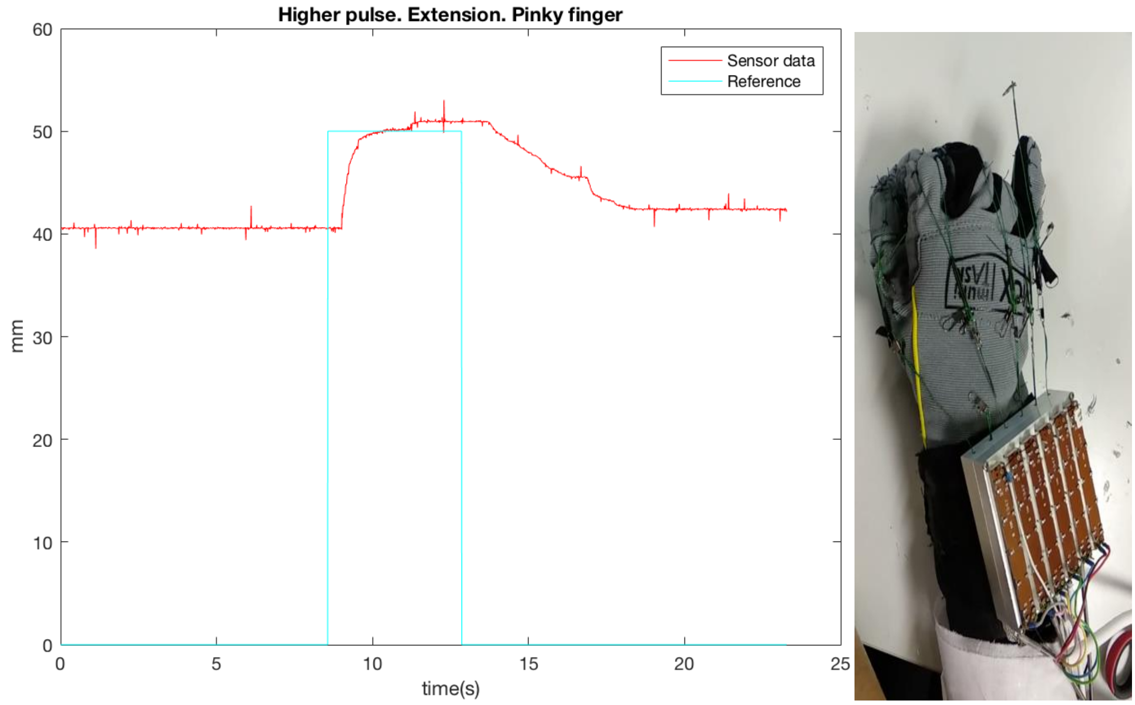


Figure 3-9 Pinky finger maximum extension

- Thumb

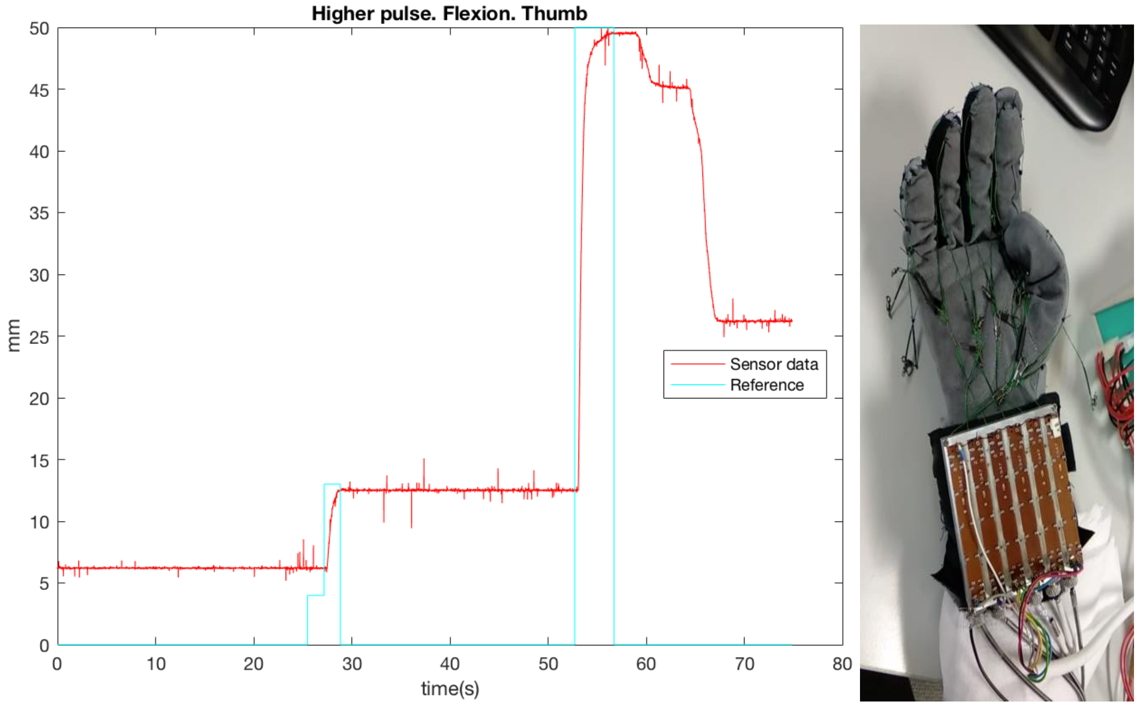


Figure 3-10 Thumb maximum flexion

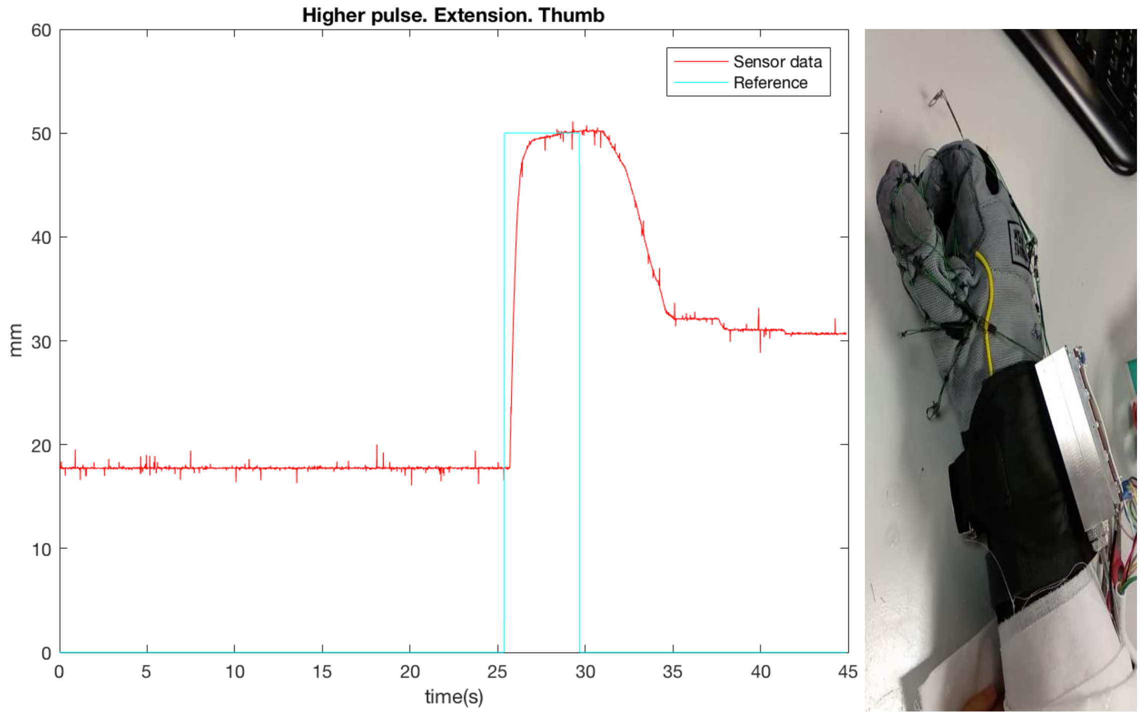


Figure 3-11 Thumb maximum extension

In all the plots above we can see in cyan the Reference always going to 50 which, as we have explained before corresponds to 50mm of linear displacement. This is the maximum because of the limitations that the potentiometers and the SMA wires lengths have. As we can see in red, most of the times the sensor reached the set reference, finding an exception in Figure 3-7. This time the system must have encountered a physical barrier, probably in a bent steel cable that didn't fit through the hole of the sensing cage (see Figure 2-7). As we can see after the pulse is set back to zero, the sensor tends to recover it original position in all the cases. This happens at different rates depending on how fast the SMA wires cool down and how gravity acts and the hand's natural position tends to pull back towards a relaxed state. They mostly recover it in a steady way. We can see several exceptions. Again in Figure 3-7, which stays too long in the same position. This is easily explained because as the control system senses that the reference is not reached, the wire is heated more and more to contract more and achieve it. This overheats the wire and results in a slower recovery. Different cases are Figure 3-4 and Figure 3-10 in which we can see a very fast recovery caused by the pulling motion of the patient towards the relaxed position. This is an artefact caused by our inability to try the device in actually impaired patients for the moment.

Then, a trial to see if a correct grasping motion is achieved by powering the thumb and each of the fingers.

- Index-Thumb

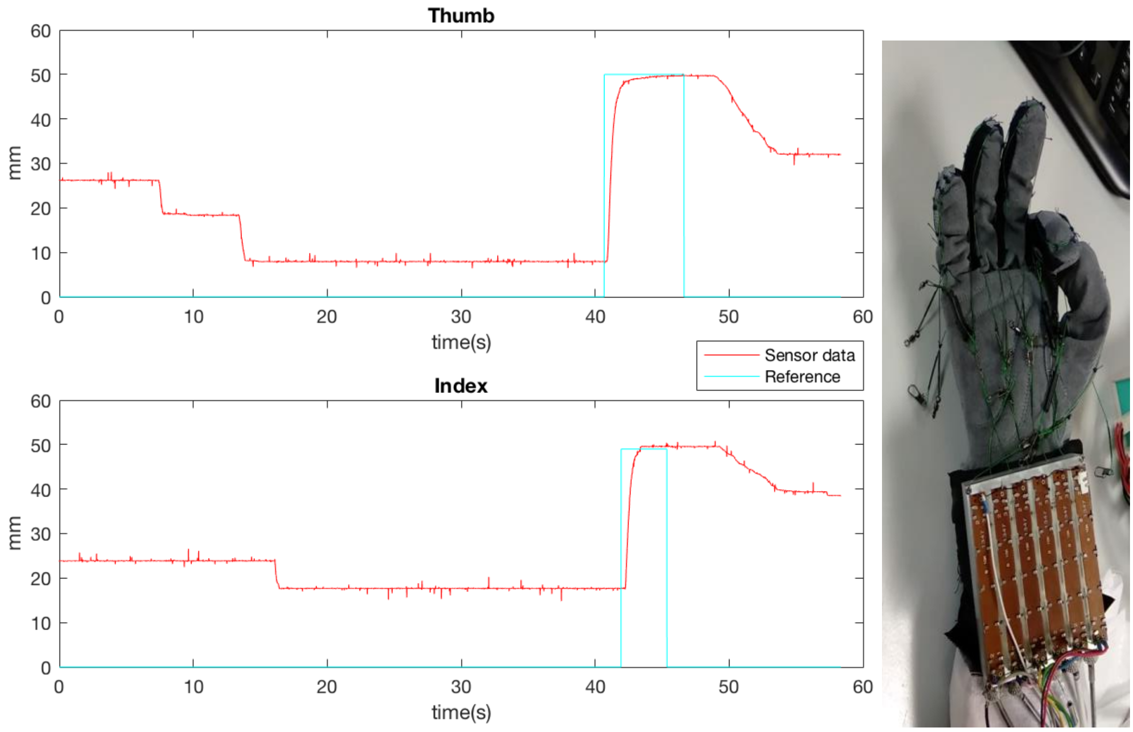


Figure 3-12 Index-Thumb Grip

- Middle finger- Thumb

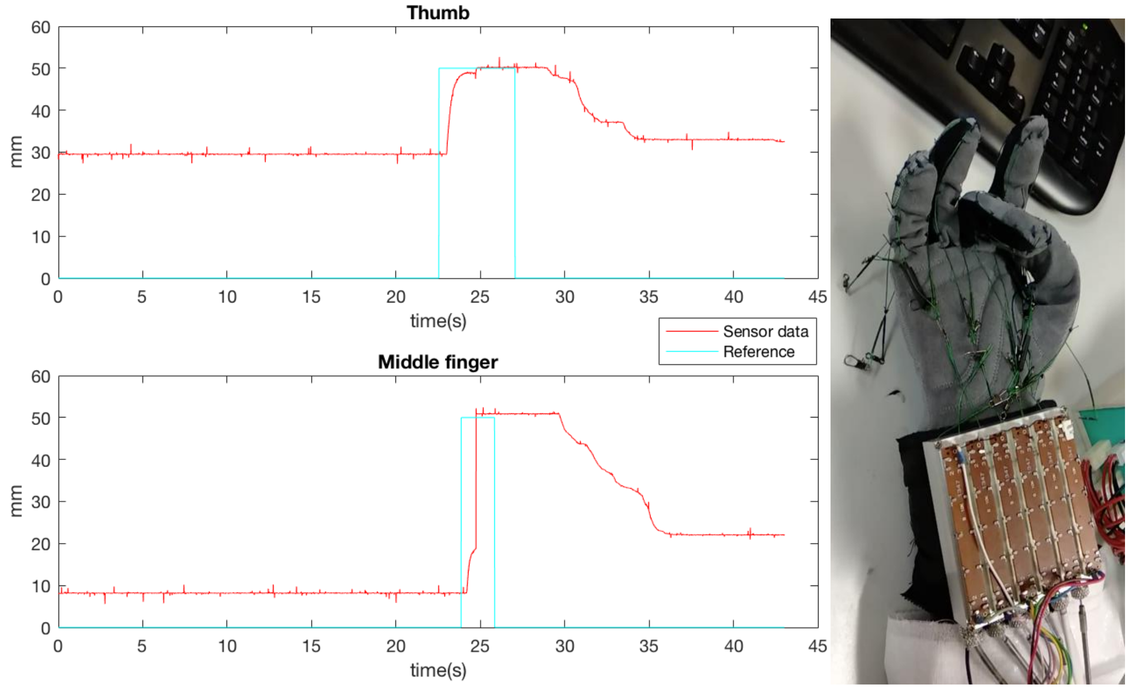


Figure 3-13 Middle finger- Thumb grip

- Ring finger- Thumb

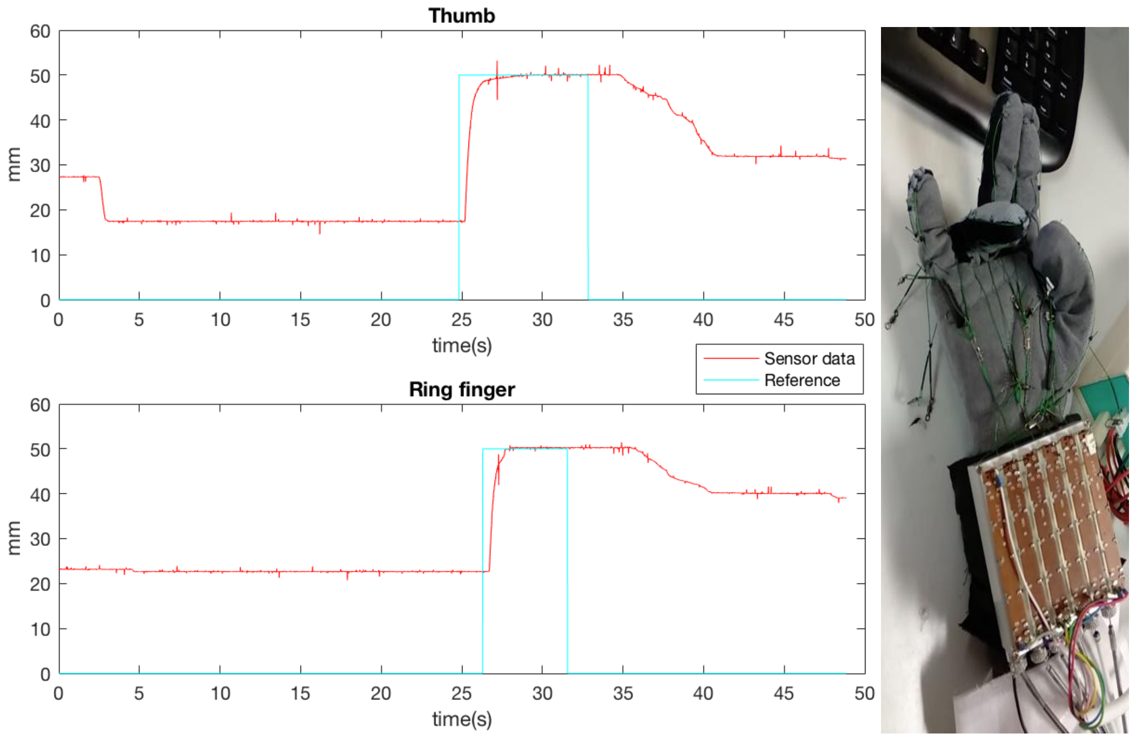


Figure 3-14 Ring finger- Thumb grip

- Pinky finger- Thumb

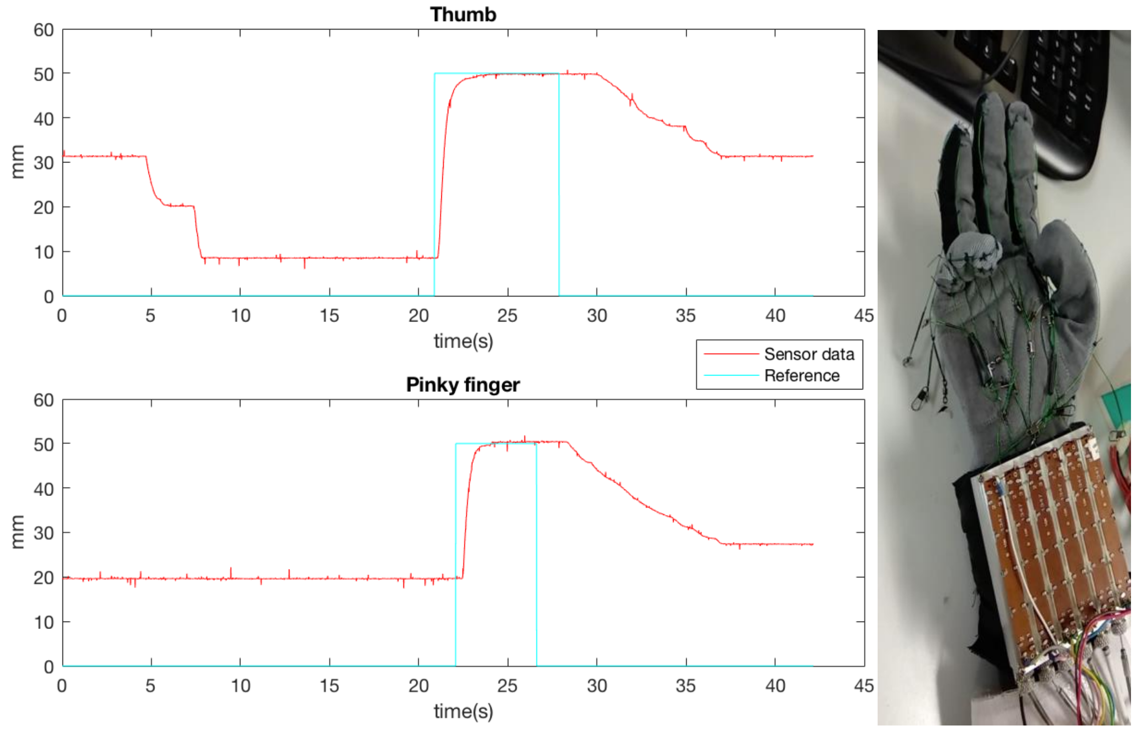


Figure 3-15 Pinky finger- Thumb grip

It should be mentioned that for these gripping experiments, the positioning of the references at its maximum possible value was not automated and that is why we can observe that the cyan pulses do not go up and down at the same time. We observe the sensor reaches its marked position every time and that relaxation occurs more or less normally. The maintenance of the position for a longer time after finishing the pulse than in the previous experiments could be due to the bias of the perfectly healthy patient that keeps the posture by its own muscle strength.

Another trial was done to subject the SMA cables to several pulses of different lengths to see the recovery and the performance after being heated several times. This was tried with one finger, the middle one, in a flexion motion. The experiments were done with pulses lasting 2 and 5 seconds approximately,

- Two second pulses

Figure 3-16 Short pulses

- Five second pulses

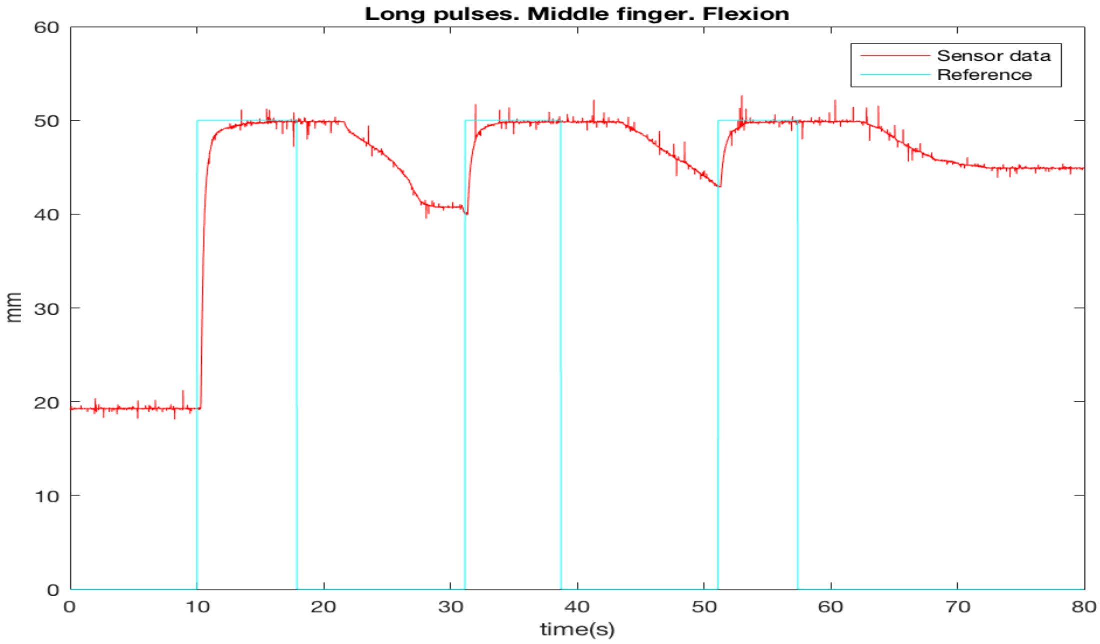


Figure 3-17 Long pulses

It is very clear here that the recovery takes longer the more times we actuate the SMA and the longer we keep the pulse up. This is due to the overheating that makes it harder for them to cool down at ambient temperatures.

Lastly, a trial was done to check the strength and reaction of the SMA to a force against it. The experiment was done on one finger, the middle one, for a flexion movement. The subject, tried to oppose the movement of the tendons when they were actuated to perform the maximum flexion possible. As it can be seen in Figure 3-18, the sensor did not reach the required position because of the opposition of the patient that could happen in an active rehabilitation process to strengthen the muscles. This made the system keep heating the wire to make it contract more and, as it happened in Figure 3-7, the recovery was then slower because of the extra heat that had to dissipate after the effort.

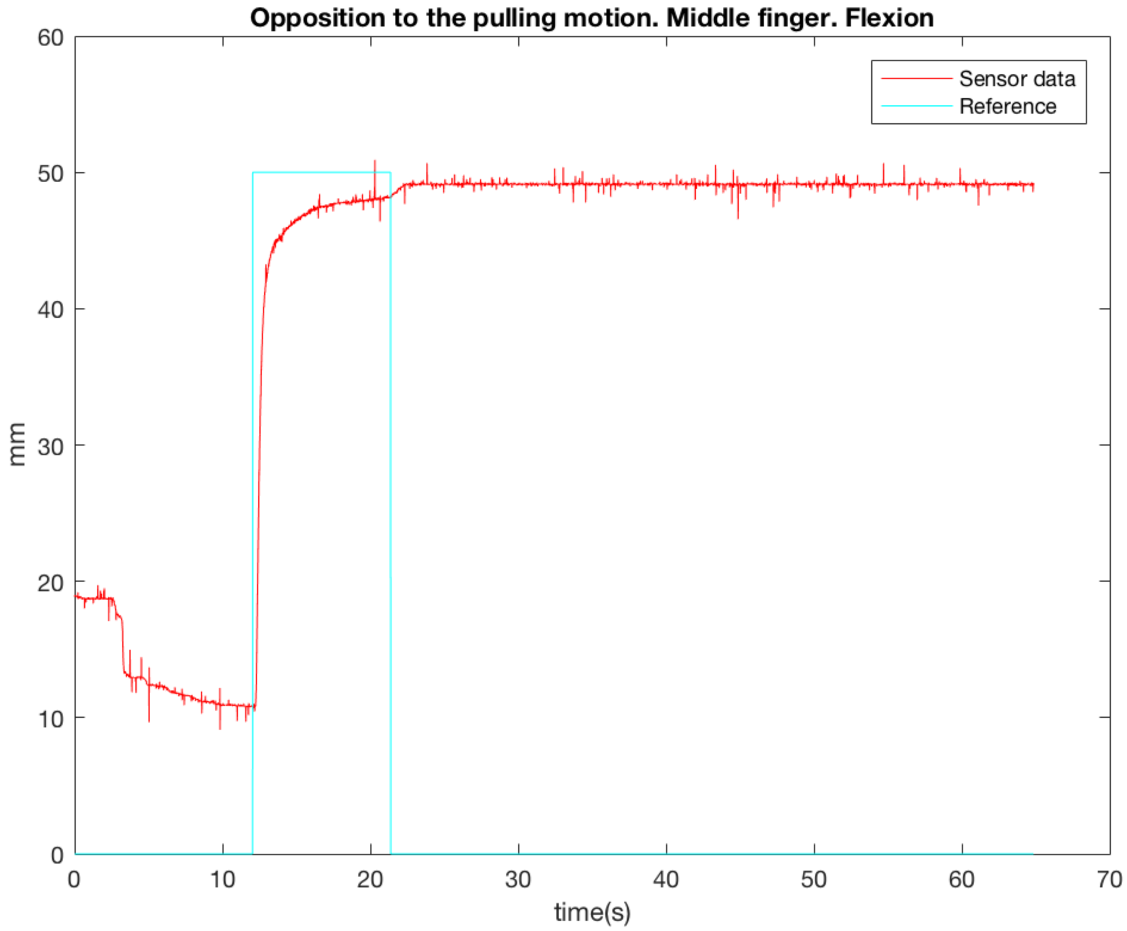


Figure 3-18 Opposition of the patient to flexion pulse in middle finger

As a brief addition, trials of the device have been done for two other Graduation Projects in the department. The whole device was used as an inspection of the efficacy of an artificial intelligence algorithm by Cristina Ibáñez [15]. This uses an electromyographic detector in the arm to detect the aim of the patient to grasp an object or release it. This, ordering a fixed value of movement to the cables, makes them pull for the flexion or extension, depending on the order, of the index and the thumb to aid the patient with decreased muscle strength. We can see in Figure 3-19 one of her experiments to detect the movement of a healthy patient to catch the white cube.

Figure 3-19 Cristina Ibáñez's TFG trials

Then, the electronics were used by Laura López [14], for the actuation of her silicon hand exoskeleton. This project, aiming to cover just three fingers, aids patients to grip objects. We can see her experiments in Figure 3-20.

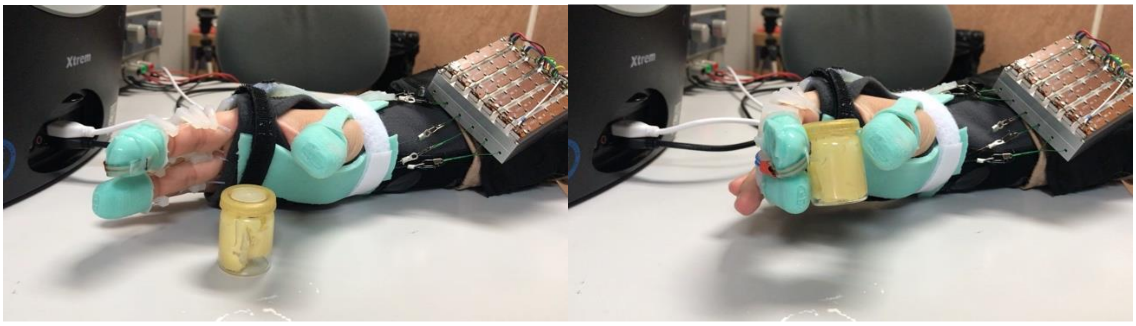


Figure 3-20 Laura López's TFG trials

4. CONCLUSIONS

As a result of this project, a soft hand exoskeleton has been optimized to perform a more variate amount of movements and of a higher naturalness that its previous version.

All the objectives have been performed successfully and, as a result, a step has been taken into the direction of having a functional rehabilitation tool to be used clinically.

The results of the experiments are mostly satisfactory, from which we extract the following conclusions:

- The maximum flexion and extension movements for each finger individually produce a satisfactory configuration and a natural feel for the subject wearing the glove.
- The gripping movement produced by the opposition of the thumb to the rest of the fingers is achieved This allows for the parallel projects, that attempt to aid patients to grip objects with the index-middle finger-thumb grasp, to perform their own experiments.
- From the different lengths pulses we can extract that the position goal is achieved each time, but the recovery is less and less acute as time goes by. This is due to the overheating of the SMA, which is not allowed to refrigerate before the new pulse. This could deteriorate the quality of the rehabilitation process since each time the movement would become less complete.
- The patient opposing the movement made the SMA unable to reach the set position, making it heat more to reach the goal and produce a very slow recovery. This could mean that an active rehabilitation, one in which the patient has some mobility and uses the glove as a muscle strengthening device, could not be performed with this kind of glove.

4.1 Future Works

From the problems that have arisen in the process, we propose the following future works:

- A design of the glove and the tendons to be universally wearable. The closed glove could be difficult to wear for a patient with the hand in a stiff abnormal position. One that could be opened to adapt to the shape of the patient would become a much better option. Another problem is that the size of the glove cannot fit every size of hand. The silicon thimbles solve this to a certain extent by holding the tip of the fingers and steering them whatever their size. Nevertheless, the tendons have to be very tense for the whole movement to be exploited. Tendons that can adapt have their length adapted would solve this problem.

- A lighter sensing box would make the device wearable for longer periods of time. Also, this would make it suitable for the use of two of them to actuate both flexion and extension at the same time. This would make the recovery from the movements faster.
- The design of a more intuitive interface for the rehabilitation professional to select each movement more easily.
- The use of the sixth actuator and sensor for the addition of even more complex movements.

4.1 Regulatory Framework

The European Union does not have yet laws concerning assistance robots since the market has not required them for the moment. In 2017, the European Parliament made a resolution with recommendations to the commission on Civil Law Rules on robotics [44]. These are based on the needs arising from the growing robot market in the last eight years. Rules that set responsibilities and ethical implications but prepared to not interfere with research and innovation should come out of the Parliament for the legislation in the countries.

This resolution mentions the following points about Care and Medical Robots:

- "…recognises that robots could perform automated care tasks and could facilitate the work of care assistants, while augmenting human care and making the rehabilitation process more targeted, thereby enabling medical staff and caregivers to devote more time to diagnosis and better planned treatment options; stresses that despite the potential of robotics to enhance the mobility and integration of people with disabilities and elderly people…"[44]
- "…they have the potential to improve outcomes in rehabilitation, and provide highly effective logistical support within hospitals; notes that medical robots have the potential also to reduce healthcare costs by enabling medical professionals to shift their focus from treatment to prevention and by making more budgetary resources available…"[44]

It is also stated there [44] that no special laws protect the intellectual property rights of robots but the existing laws can be applied to them and that the Union should update its legal framework to include the complex and new risks that threaten human safety, freedom, privacy and dignity. The bases of this ethical framework should be based on those described in Article nº2 of the Treaty on European Union [45] and the Charter of Fundamental Rights.

Having said all of this, we can predict that the regulations surrounding this kind of devices will follow the rules that the European Council sets for those that fall under their strict definition of Medical Device. This is the case since their definition includes those with the purpose of “diagnosis, monitoring, treatment, alleviation of or compensation for an injury or handicap” [46].

4.2 Socio-economic Impact

First of all, it should be taken into account that this project too develops a prototype that is not meant to be put into the market. Therefore, it would not make an impact on society until it is ready for clinical use.

This prepared future device would have its major impact as a social one. It would affect the professionals that work with patients with different hand conditions and also those mentioned patients. As the results have shown, we are one step closer to having a fully functional hand rehabilitation device that could simplify and make much faster the work developed by the professionals that rehabilitate patients. The market of these type of products (meaning rehabilitation exoskeletons) is still very narrow and growing, the first one was accepted by the FDA in 2014 and it helped a paraplegic patient walk and sit. In Spain, on the other side, projects like the Hyper are aimed to help the upper part of the body too and the prototype is not meant for commercialization [47].

If put into the market, a rehabilitation device like this could have a huge economic impact by reducing the costs of the treatments for the Health System. This could be made through the optimization of the time and quality of the treatments offered to patients, which would leave sooner and come back less often.

As a device based on a previously done one, the budget of actually building everything would be very different to that of the expenditure made on this particular project. We will therefore analyse the budget required to build and operate the complete device to have an idea of what would it cost if put in the market.

Component of the device	Price per unit	Units	Price in euros
Microcontroller	17 €	1	17
Power stage	150 €	1	150
SMA cables	6 €/m	1.2 m x 6	43.2

		cables	
Tendons/ Steel cables	1€	1	10
Glove	10€	1	10
Slide Potentiometers	1.5€	6	9
Sensor's cage (if made industrially)	1000€	1	1000
Silicon thimbles	1€	1	5
Power supply	23€	1	23
MATLAB License	69€/60months	3 months	3.45
Wristband	17€	1	17
Tutor's work (x50hours)	15€/h	30h	450
Engineer work (x300hours)	10€/h	300h	3000
TOTAL			4,737.65€

Table 4-4-1 Budget

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