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Bachelor Thesis

“Soft Hand Exoskeleton Actuated with SMA Fibres”

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ABSTRACT

The current project is based on developing a wearable and comfortable soft hand exoskeleton actuated with Shape Memory Alloy (SMA) fibres. The main purpose of this device is both, to be involved in rehabilitation exercises and assistive therapies for patients suffering from hands' damage. This innovative idea presents an affordable and convenient alternative in the exoskeletons' field, combining a light and non-expensive actuation along with biocompatible materials specifically tailored to patient's hand anatomy. To generate the perfectly fitting glove, plastic moulds were 3D-printed after sketching them with Creo Parametric software. Then, silicone was poured into the casts and it cured maintaining the desired shape. Taking advantage of Joule's effect, the current which flows though the SMA wires is capable of increasing temperature, causing a microstructure change and thus inducing contraction. This motion can be accurately controlled by a MATLAB-Simulink interface, achieving both flexion and extension so as to perform pincer grip. Furthermore, a force sensor embedded on silicone finger's tip is used as a force feedback to evaluate the pressure applied by the subject when holding distinct objects.

Keywords: silicone, hand, Shape Memory Alloys, robotic orthosis, sensors

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To my family, who never stopped believing in me. They have always been my strongest encouragement. Being far from them has shown me how important they are in my life. I will never thank you enough.

To my friends. To the ones who have shown me that distance will never be a problem. Also, to those who have taught me how to become essential in four years. Thank you. It would have been impossible to reach my goals without you.

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“I have not failed. I have just found 10,000 ways that won’t work”, Thomas A. Edison

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1. INTRODUCTION

1.1. Motivation

The current fast ageing of population is causing an increase in health problems and the need for improving people's quality of life. Thanks to the medical advances that have been developed lately, the life expectancy approaches 100 years and more than 30% of Spanish population is predicted to be above 65 years by 2050 [1].

Along with this noticeable society ageing, an increase in diseases such as arthritis, arthrosis, osteoporosis or high blood pressure has been found [2]. Arthritis and arthrosis directly affect joints, hindering movement due to swelling and cartilage reduction, respectively. Osteoporosis is related to a reduction in bone density and rise in fragility. High blood pressure is a dangerous condition that increases the risk of suffering cardiovascular events, which could lead to blood block in certain body areas causing paralysis.

Therefore, focusing on upper extremities, the loss of hand muscle function is a widely spread problem affecting a significant amount of population. People suffering from muscle disease, neuromuscular junction disease or nervous system disease present important difficulties in finger movement and hand force [3].

In order to contribute to muscle recovery or to facilitate performance of daily tasks. There are two main methods: rehabilitation and assist devices. Rehabilitation is based on exercising the affected zone through specific repetitive movements – under expert supervision. On the other hand, assist devices involve the use of external apparatus which provide force and guide the muscles when required.

In this case, the device aimed to be designed is a soft hand exoskeleton able to function as an assist device as well as in rehabilitation active processes. With a simple mechanism, and taking advantage of SMA (Shape Memory Alloy) actuation, the glove is expected to substitute or reinforce finger movements and grasping ability.

This exoskeleton is an example of successful combination of robotics with human care. Nowadays there is a significant increase in the creation of automatic devices intended to help during rehabilitation procedures, opening a new wide field of study and improvement.

1.2. Objective

This project is focused on developing a soft hand exoskeleton actuated with SMA fibres. The elaboration of a soft open glove, made of silicon, is intended to constitute a comfortable and easy mechanism for finger movement and provide force support.

Fingers will be guided using non-actuated tendons, which will lead the displacement, based on the normal movement performed by a healthy hand. These non-actuated tendons will be connected through a potentiometer to SMA fibres, the ones able to contract to the desired position.

Shape Memory Alloy (SMA) fibres are a light and effective way of actuating the device, providing sufficient force and displacement in response to certain applied voltage.

Incorporating force sensors on the finger tips, it will be possible to record patients' force while pressing. These values will be used as a feedback for controlling the whole apparatus.

Provided the information of force sensors and potentiometers, it will be enable us finger control, their location and force required for performing the desired move.

The electronic control of SMA fibres will be implemented in MATLAB-Simulink, using the feedback output from the incorporated sensors to decide the appropriate values in each case.

This exoskeleton will be mainly useful for executing pincer grip and help users grasp objects effortlessly, either during daily tasks or rehabilitation procedures in case of loss of muscle function.

1.3. Regulatory framework

The current increase of robotics in our daily life routine has created the need of regulating to which extent they could be involved in human activities. Therefore, specific norms were stablished to ensure human safety.

Although the purpose of this project was to recreate a hand exoskeleton prototype, the final aim of this apparatus would be its use as a medical device in rehabilitation exercises.

Depending on the degree of risk associated to instruments' usage, they are classified in four classes: I, II, III and IV, including in this last one the most critical apparatus. In order for medical devices to be accepted and commercialized, they need to satisfy highly specific requirements, which vary depending on the country and its legislation. The most noticeable differences are found between Europe and United States.

In the case of the European Union, particular and explicit rules are set depending on the robotics' field that is being evaluated. The ones concerning the regulatory framework applicable to this device are medical robots and rehabilitation [4]. It is assumed that rehabilitation robotics are intended to perform repetitive and accurate tasks, acting as support for doctors. It is stated the necessity to access robot control and its maintenance at any time.

Onwards from 1990, any device commercialized in the European market has to satisfy specific conditions to obtain a Conformité Européenne (CE) mark. This certification is provided by a Competent Authority [5] – a governmental body. When the product is a low risk one, a simple CE mark is sufficient for introducing the device to the market. Instead, if its complexity is higher, it will also require a Notified Body approval in order to have its performance and reliability tested, i.e. the benefit must be proven to clearly outweigh the possible presented hazards.

Particularly, medical devices need: to satisfy 'essential requirements', to have been fabricated through an appropriate route – which varies depending on the device class -, to be marked as CE and to be made subject to surveillance [6].

On the other hand, United States base their regulations on the criteria specified by Food and Drug Administration (FDA) [7]. In this case, only three device's classes are considered.

- <u>Class I devices</u> just need to satisfy fabrication standards and quality control, due to its high similarity to previous approved products or its low risk.
- <u>Class II devices</u> require a 510k review, trying to determine whether the de apparatus is 'substantially different' to previous ones.
- <u>Class III devices</u> are the highest risky ones. Therefore, they require a PMA (Pre-Market Approval) so as to test its security and effectiveness during a disease treatment.

Comparing to other similar devices that have already been regulated, the proposed soft hand exoskeleton would probably be considered a Class II device. As presented by FDA in “Powered lower extremity exoskeletons” [8], there are several features to take into account. Among the numerous characteristics presented, the biocompatibility of the parts which were to be in contact with the body, the electrical safety or the presented instructions (for cleaning, maintenance, programming the device and fitting the patient) were basic requirements that all powered exoskeletons needed to fulfil. Likewise, a physician training program or a control verification and non-clinical performance test were also aspects to consider.

To sum up, the main ideas representing the regulatory framework important for the current project - both in Europe and US - aim to satisfy patients’ security and a considerable improvement with respect to previous alternatives. A medical orthosis, such as the soft hand exoskeleton, needs to be categorized as a specific device class, meet explicit requirements related to its risk and be subjected to continuous controls, so as to ensure device correct performance and patient safety.

1.4. Structure of the document

This bachelor thesis is organized in seven chapters in which different aspects studied throughout the project are explained.

The introduction - chapter one - exposes the motivation and objectives of this project, as well as the regulatory framework required to follow to develop the project. It is focused on the aim that was attempted to be achieved and what lead to deciding the proposed solution, satisfying the necessary regulations.

The second chapter deeply analyses the state of the art. It studies the anatomy and physiology of the hand, explains the different pathologies affecting to mobility and the treatments carried out to solve them – specifically, exoskeletons for rehabilitation. At the end of the chapter, current similar solutions are described so as to compare with the suggested design as well as the different possibilities of actuation mechanism, analysing in detail SMA.

Materials, device’s design and its development process are studied on the third chapter. The layout of this exoskeleton is stated, and material selection discussed. Several properties of silicon are commented as well as the use of SMA fibres for generating movement. Diverse models are compared, along with the different techniques required for carrying out the final device.

Once the hand exoskeleton has been developed, some trials are required in order to test mechanical capabilities, comfort and usefulness of the apparatus. All these results are included in the fourth chapter, being contrasted with expected and theoretical values. Both SMA contraction accuracy and force sensor actuation are measured.

The fifth chapter evaluates the results obtained. It analyses the behaviour of both sensors and the different data that has been obtained. It tries to understand and explain the differences between different reference signals, their time duration and SMA contraction profile as well as finger tip’s sensor performance.

An economic study including the required budget to develop the presented project and a review of the socio-economic impact it is predicted to cause, is included in chapter 6; i.e. it consists of a deep cost analysis of the whole process taking into consideration both materials and human labour.

The last chapter provides a final overview of the resulting exoskeleton and its characteristics. Lastly, it includes possible improvements that could be thought about for future projects. Technical information, data sheets and additional material can be found at the end of the documents, in the appendix.

2. STATE OF THE ART

To understand the current situation of hand exoskeletons focused on passive rehabilitation, there are several aspects required to be considered. First of all, the main functions of upper extremities will be explained, specifically hands, as well as its relevance throughout the development of daily life activities.

Hands' functionalities and movements are directly related and conditioned by its anatomy. Therefore, the location of bones, muscles and joints will also be described so as to fully comprehend the range of possible mobility of fingers.

Regarding pathologies, there are distinct conditions that hinder hand motion and reduce exerted force. The most common ones will be fully explained, including causes and consequences of them, together with possible treatments.

One of the main treatments that are carried out when hand's motion is affected is rehabilitation, sets of repetitive exercises controlled by a physician or therapist that are starting to be complemented with robots - the field we are aiming to enter.

To conclude, different current hand commercial exoskeletons are presented in order to compare them and explain the advantages this proposed design will offer in the rehabilitation task. Furthermore, several actuation mechanisms are evaluated, focusing on SMA and its working principles.

2.1. Hands' functions and its importance

Hands are found at the distal part of upper extremities and play an essential role in the normal development of daily life activities (DLA). Their tasks range from essentially sensory to those with a strong motor component, and we can differentiate four functional categories: tactile sensing, active haptic sensing, prehension, and non-prehensile skilled movements [9].

Tactile sensing is referred to as the ability of measuring external stimuli, such as mechanical changes in the environment (temperature, pain) and its tactile spatial resolving capacity. Active haptic sensing combines cutaneous inputs from skin with inputs generated due to muscle, tendon or joint activity. Prehension is related to kinematics of object manipulation, including fingertip force adaptation depending on the grasped object or sensorial feedback. Non-prehensile skilled movements involve any finger or hand motion which does not imply object grasping, as gestures.

Taking into consideration these cited functions, hands are essential for human beings both in sensory and motor activities. In this project, the motor part will be mainly exploited, trying to reproduce the pincer grasp (Figure 2.1) [10].

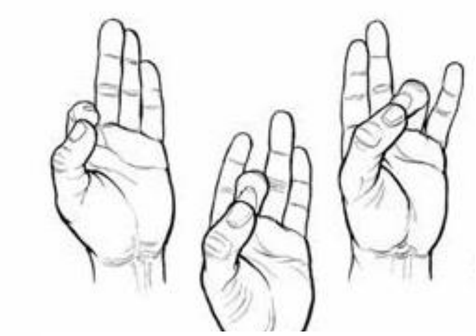
Figure 2.1.- Pincer grasp [10]

Arising during early childhood development, this movement is fundamental on a daily basis. It involves fingers' flexion and force ejection – enabling people to grasp objects, write or open doors, amongst many other tasks.

When a person suffers from a hand disease or any kind of lesion, hand mobility can be hindered- even in some cases reaching paralysis. Depending on the condition, either ability for finger motion or strength may be reduced. Accordingly, an external device capable of compensating these weaknesses may be required to continue developing activities in a normal manner.

2.2. Anatomy, Physiology and Biomechanics of the hand

So as to design an actuated hand exoskeleton and treat several diseases it is essential, firstly, to study its anatomy and physiology.

Hands consist of wrist, palm and fingers- whose movements, illustrated in Figure 2.2, are controlled by both extrinsic (in forearm) and intrinsic (within the hand) muscles [11].

To differentiate between movements, anatomical terms are used [10]:

- <u>Flexion</u>: referred to bending motion that decreases the angle.
- <u>Extension</u>: straightening movement of fingers or hand that increases the angle.
- <u>Abduction</u>: motion that separates structures away from middle finger.
- <u>Adduction</u>: movement of fingers towards the middle one.

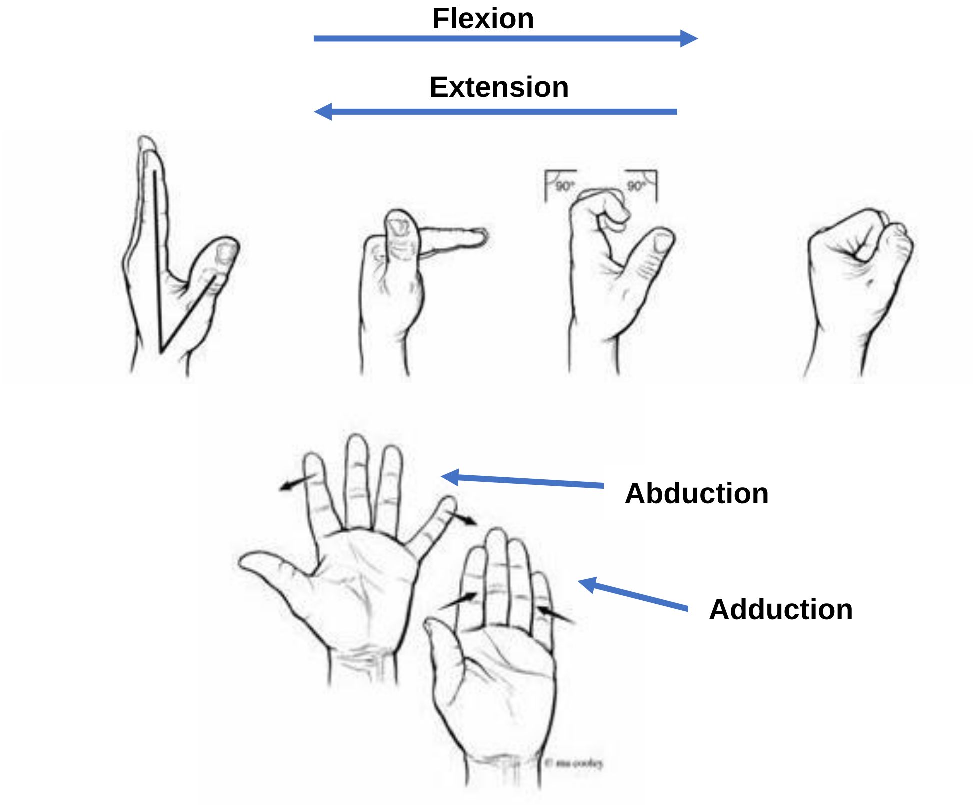

Figure 2.2.- Hand movements [10]

In order to carry out any voluntary movement, nervous impulses in the form of electrical signals travel from the brain (Central Nervous System) through nerves until they get to specific muscles. The connection between nerve and muscle takes place in the neuronal synapse [12]; when the electrical signal reaches the neuromuscular junction (final part of the neuron), it triggers the release of neurotransmitters, initiating the chemical signalling.

The binding of these neurotransmitters to specific receptors in muscle stimulates its contraction. When muscular tissue contracts, they eject force that in turn is transmitted to bones through tendons. Tendons are composed of soft tissue and physically connect muscle to bone, having a critical role in movement performance. Therefore, the tendon’s placement on hands dictates the artificial tendon’s position on exoskeleton (see Figure 2.3) [13], required to recreate motion as natural as possible.

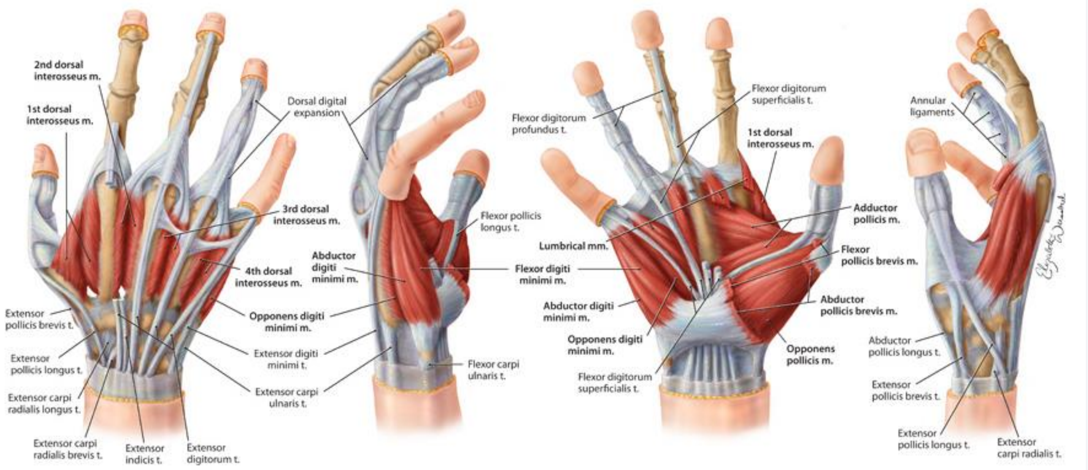

Figure 2.3.- Muscles and tendons present in the hand [13]

Instead of considering the whole hand motion, for the aim of this project, it will be enough to focus on fingers mobility. To describe it carefully, the different joints need to be taken into account [14]:

Only one present in thumb (interphalangeal)

- ***Distal Interphalangeal joint*** (DIP) – located at the tip of the finger, just before the nail starts, joining the distal and middle phalanges.

- ***Proximal interphalangeal joint*** (PIP) – situated between first two bones of fingers (proximal and middle phalanges).

- ***Metacarpophalangeal joint*** (MCP) – it connects metacarpal (hand bone) and proximal phalange.

- ***Metacarpocarpal*** or ***Carpometacarpal joint*** (CMC) – provides flexibility to the hand. Each finger CMC joint has its own freedom of motion, being the thumb the most mobile one. It lets the hand adapt to object grasping changing its shape.

Only present in thumb

- ***Trapeziometacarpal*** or ***Scaphotrapeziotrapezoid joint*** (STT) – found at the base of the thumb in the wrist and composed of three wrist bones.

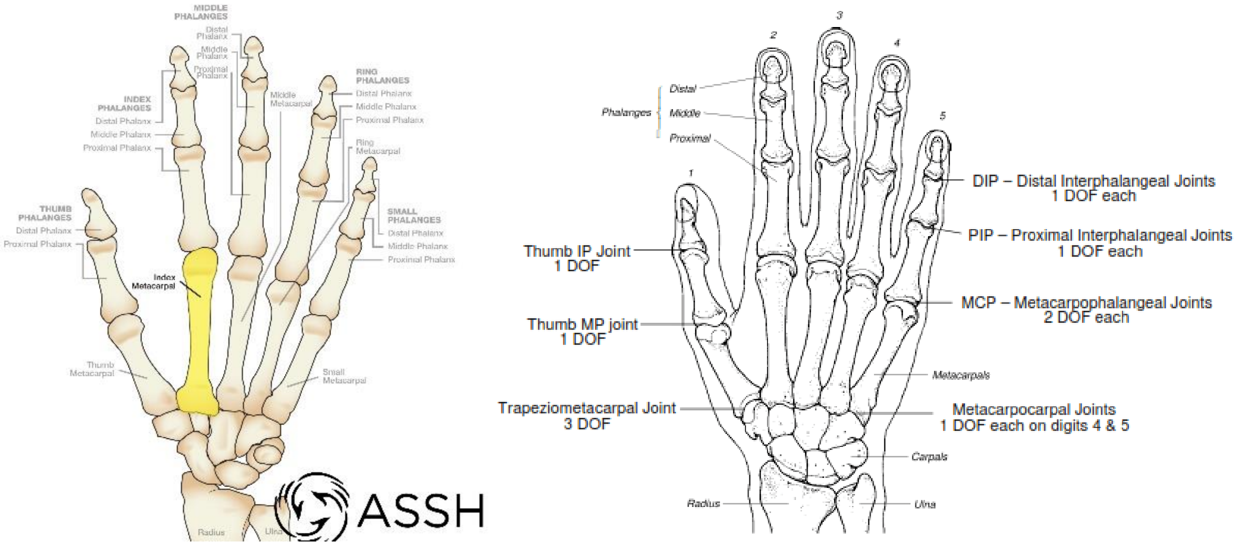

Figure 2.4.- Finger bones and hand joints [15] [16]

This specific anatomic configuration of bones, shown in Figure 2.4 [15], provides a wide range of mobility, in particular 27 degrees of freedom (DOF) for the whole hand [16]. It is the result of combining the different degrees of freedom given by finger joints, wrist mobility and other hand movements. Six DOF can be distinguished given by wrist rotation and translation, 4 degrees of freedom for each finger – 3 for extension and flexion and 1 for abduction and adduction- and 5 degrees of freedom in the case of the thumb – because it presents STT joint.

In order to develop this project, flexion and extension of thumb, middle and index fingers were chosen, given that they represent the movements corresponding to pincer grasp performance [17].

2.3. Hands' pathologies: causes and treatments

As it has already been mentioned, there are different conditions that hinder hand's movement and its strength. It can be clearly differentiated between diseases that directly affect joints and bones and those who cause damage or paralysis indirectly due to cardiovascular failure.

Regarding the ones first ones, which affect joints, bones or ligaments, are characterized by joint stiffness and pain, it exists a distinction between arthritis and arthrosis [18]. Arthritis is the general term used to define conditions involving joint inflammation, among which the most frequent one is arthrosis. Arthrosis – also named osteoarthritis- is caused by cartilage deterioration and results in pain and swelling due to bone-to-bone contact.

Another condition that has been commented is high blood pressure (hypertension). Blood pressure is described as the force exerted by blood against the walls of the arteries when it is pumped from the heart. If most of the time the levels are between 140/90 mm Hg or above, the patient suffers from hypertension [19].

The main problem with hypertension is the lack of symptoms. It is a ‘silent’ disease that does not cause pain or physical evidences during its development and it is therefore difficult to diagnose. This significant pressure increase may appear due to atherosclerosis – partial artery blockage with plaque-, smoking, overweight or kidney failure (Figure 2.5). Consequences usually range from artery or heart damage to aneurysm or stroke.

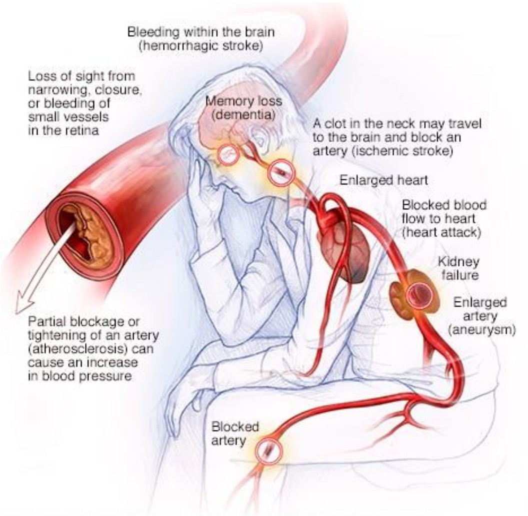

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Figure 2.5.- Hypertension’s effects [22]

Stroke occurs when a part of the brain is deprived of oxygen and nutrients with subsequent cell death [20]. The brain is part of the central nervous system and controls all the voluntary movement signals received by muscles.

For muscle contraction, electrical impulses that start in the brain and are transmitted through nerves need to reach muscle fibres. After stroke, brain damage impedes neurons from generating regular electric impulses, which leads to loss of muscle function [21]. Depending on the stroke’s severity, the damage could be reversible through rehabilitation exercises or irreversible, in which a device would be required to perform the lost function.

After a stroke, in order to attempt regular muscle movement recovery, there are several treatments to follow which include physical activities, technology-assisted physical activities and cognitive exercises [22]. The main goal is to regain strength and coordination of the specific part of the body affected by the paralysis.

These repetitive exercises constitute the rehabilitation therapy, that can be divided in active or passive. In active rehabilitation the patient carries out the task stipulated by the therapist whereas in passive rehabilitation the therapist itself or an external device generates the movement.

Robotic technology -a clear example of passive rehabilitation-, which is included in technology-assisted physical activities, involves repetitive tasks performing using robotic devices with the aim of increasing muscle strength and function.

2.4. Wearable robotics

As defined by J.L. Pons, “a wearable robot (WRs) is a technology that extends, complements, substitutes or enhances human function and capability or empowers or replaces the human limb where it is worn” [23]. It is a person-oriented robot that is worn by the patient to supplement or replace the function of a limb; i.e. they can act complementary to human limbs when the patient suffers from a condition that hinders movement or be placed after limb amputation to completely supplant its function.

There are three main types of WRs [23]:

- Empowering robotic exoskeletons – originally called extenders- are a robot type that extends human strength beyond its natural ability. An important feature of these wearable rotos is that their structural mapping with human anatomy.

- Orthotic robots. A mechanical structure that maps on to the anatomy of the limb and aims to recover its lost function is called orthosis. Actuated exoskeletons are the robotic equivalents aiming the restorage of the handicapped function.

- Prosthetic robots. When the patient is amputated a limb, there are electromechanical wearable robotic limbs able to replace the lost function. A prosthesis is an electromechanical device, that combined with robotic technology can reproduce desired movements.

So as to accomplish robotic rehabilitation, exoskeletons are one of the most used devices. An exoskeleton is a wide term associated with any wearable robotic apparatus that is placed on a specific body part and acts in ‘tandem’ with it. The key aspect is that it is not intended to replace any body part, as a mechanical prosthesis would do, but instead to reinforce, augment or restore human performance [24].

It must be composed of different parts [25]:

- Support: the mechanical reinforcement of the exoskeleton should be built with light materials but enough strength to withstand the body weight and exoskeleton's elements in a safe and way.

- Battery: light and with high durability, in order to function independently the longest time possible and to achieve the lowest weight.

- Sensors: record and send information about how the patient is willing to move. They are used to monitor factors such as position or force generated.

- Controller: receives the information sent by sensors, analyses it and provides the adequate signals to the actuators.

- Actuators: are in charge of moving the exoskeleton. With the signals provided by the controller, they use battery power to move the device and the patient's limb.

Using an analogy to human body, the supportive framework, controller and actuators could be identified with bones, brain and muscles respectively. This way, we are combining with a human limb an analogous structure capable of reproducing similar functions and help in rehabilitation processes.

In the case of the presented hand exoskeleton developed through this thesis, it will have two main functionalities. The first one is to operate as an assistive device for rehabilitation processes, since it is a comfortable wearable exoskeleton able to lead the movement specified by the physician or physical therapist. The second function is acting as an orthosis, enhancing patients' force when grasping objects.

2.5. Current hand exoskeletons

Although exoskeletons' field has increased noticeable during the last years, they are not a new concept. Current designs direct them towards a more functional and comfortable device, useful in the rehabilitation process to complement therapist exercises and for patients' activities of daily living (ADL) performance.

The final aim of this project is to build a soft hand exoskeleton, and thus the understanding of commercial products is required. Nowadays, there are plenty of options on the market depending on the specific actuation used and purpose to be satisfied; the most relevant ones will be further explained so as to comprehend the actual market needs and patients' requirements.

- **Gloreha hand rehabilitation glove** [26]**.** This device consists of an open glove and it is actuated by a motor system placed on the base, shown in Figure 2.6. Each finger's motion is controlled independently either passively or actively; i.e. it can act as a response of a patient's voluntary movement or without need of stimuli (programmed by the therapist). The glove is also connected to an interface which helps the patient to visualize its performance and entertain him during the exercises. The actuation of this device combines pneumatic actuation – the tubes can be observed on the left image-, for driving joints and electrical actuation for conducting the tendons.

Figure 2.6.- Gloreha exoskeleton [26]

- **Rapael smart glove** [27] is a light elastomeric exoskeleton monitored taking advantage of bending sensors (Figure 2.7). These variable resistors are placed on top of the fingers and control their position precisely at any time. This device is connected to an app that introduces the patient exercises throughout rehabilitation games. [28]

Figure 2.7.- Rapael smart glove [27]

- **Hand of hope** [28]**,** [29] is basically a powered glove exoskeleton. Focused on stroke patients or people with conditions that require regaining hand mobility, EMG (Electromyography) sensors record muscular signals and connect them to the actuators; this way, the exoskeleton obeys the patient's desire enhancing neuroplasticity – capacity of neurons to adapt and form new pathways in order to recover neuromuscular function. It also includes an interface with games to keep patients engaged during the rehabilitation process. The working principle of this device is shown on Figure 2.8.

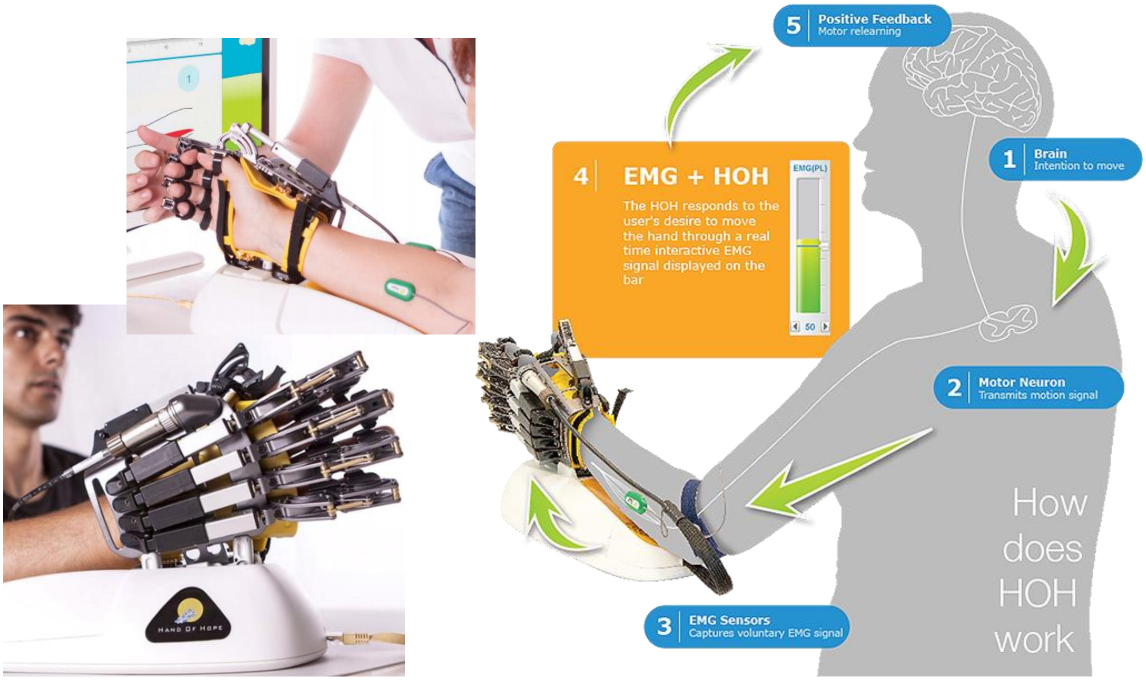

Figure 2.8.- Hand of hope and it's working principle [29]

- **Amadeo** [30] is another option used for finger and hand rehabilitation purposes. It is a very versatile device that easily adapts for different hand sizes and exercises, as it can be seen on Figure 2.10. It can be configured in 3 different modes of operation: active, passive or interactive therapy, which are fully controlled by the therapist at any time. It consists of an arm support connected to a fixed platform with plastics to be attached to fingers independently, which allows the patient to perform a wide variety of exercises. Additionally, it is highly recommended for children because of the interactive interface and its comfort.

Figure 2.10.- Amadeo [30]

- **Exo-glove poly** [31]**.** This novel soft exoskeleton design was developed at Seoul National University aiming to be used as an assistive technology for disabled people. It consists of a silicon glove - presented on Figure 2.9- able to move two fingers and maintain the thumb in a fixed position, to favour objects' grasping. Controlled by external motors, this approach resulted in a convenient design which was proved to help patients to perform daily living activities in a simpler way. It is also adaptable to several hand sizes and waterproof – suitable for being used every day.

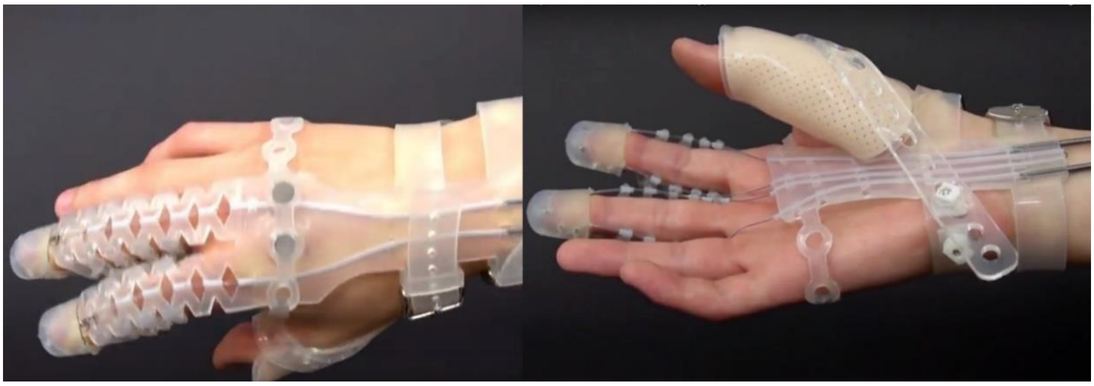

Figure 2.9.- Exo-glove poly [31]

After evaluating the hand exoskeletons which are curently commercialized or in the final step of development, there are several key characteristics to consider.

The first attribute is patient comfort; rehabilitation is a process that usually involves long hours performing exercises and these therapies may last months. Therefore, creating a device that does not harm the patient during these process is crucial.

Other features to consider are adaptability and hygiene. Hence, the apparatus must be versatile, in order to be used by patients with different hand sizes and shapes. In terms of sanitary measures, a device intended to be placed at a rehabilitation room - used by several patients a day – or used on a daily bases as an assistive device, needs to be washable.

The last consideration is the option of various operation modes; having an exoskelleton able to function both as an active and passive rehabilitation device augments its range of uses. Furthermore, connecting the device to patient's natural signals through EMG signals analisys is the innovative functionality that is being included.

As well as the previously mentioned considerations, the actuation mechanism is another important design characteristic. Most of the presented devices are electrically actuated, having independent motors to control the motion.

In this thesis, the development of the soft hand exoskeleton will be mainly guided by the design of exo-glove poly presented in [31]. The device will only cover the same three fingers as the commercial one, but the thumb will also be actuated. In order to fulfill sanitary and comfort requirements, it will be basically made of silicon, a soft material with high biocompatibility and easy to clean. In this case, the actuation of the exoskeleton will be guided by SMA fibers, not by motors.

2.6. Actuation mechanisms

2.6.1. Actuation in current commercial devices

The actuator is the part of the device in charge of converting energy into physical motion [32]. Depending on the motion they are able to generate, they can be divided in linear and rotational.

Exoskeletons, as stated before, aim to imitate finger motion, which is driven by tendons. In order to contract muscles, tendons are contracted in a linear manner, and therefore linear actuators are used to mimic their motion.

Among linear actuators, we can distinguish three main types: electrical, hydraulic and pneumatic. To characterize and understand the usefulness of each one, there are three main mechanical specifications needed to be taken into account; the maximum and minimum distance the actuator is able to move, its force and its speed.

TABLE 2.1- TYPES OF ACTUATORS: ADVANTAGES AND DISADVANTAGES [33]

	ADVANTAGES	DISADVANTAGES
ELECTRIC	- Precise and reliable - Silent - Easy control and installation	- Limited power
PNEUMATIC	- Low cost - Fast - Simple	- Special installations - Noisy
HYDRAULIC	- Fast - High charge capacity - Stability against the presence of static charges	- Expensive - Special installations

Considering the provided specifications, electric actuators are commonly used for applications in which the robot performs repetitive and accurate movements; hydraulic actuators are integrated in big robots which require faster movements and higher loads; pneumatic actuators are used in applications that only present two possible states (such as open and close) [33].

In relation to linear actuators, apart from DC linear actuators (electrical motors), pneumatic and hydraulic ones, we can also identify solenoids and muscle wires [32]. Solenoids are based on the use of magnetic fields and composed of a coil wound surrounding a mobile one; they provide high speeds.

A muscle wire [34], on the other hand, is an actuator type which contracts when electrical current goes through it and recovers the original size when the current is gone – after a cooling process. These fibres are composed of shape memory alloys, such as Nitinol, given the combination of nickel and titanium crystal structures they present shape memory effect, being able to contract by 5% when current is applied.

2.6.2. Shape memory alloys (SMAs) working principles

Although the majority of current exoskeletons are guided using motor actuation, the exoskeleton present on this project will be actuated through SMA fibres. This material presents a competitive substitute for motors, being lighter and simpler to use.

There are several materials’ combinations that present these characteristics, but the most common one is Nitinol (nickel and titanium alloy) due to its low cost and excellent biocompatibility. It presents a silent actuation along with high strength, being able to do 100 times more work per cycle than human muscle.

SMA stands for Shape Memory Alloys [35], a type of shape memory materials (SMMs) which are able to memorize the initial shape, and return to it, after specific stimuli. This stimulus is a ‘memorisation process’ that involves a phase transition between two crystalline structures (austenite and martensite) and may be temperature or magnetic field dependent.

The effect occurring in these materials is called Shape Memory Effect. It is based on the existence of two stable crystal structures at different temperatures. At a lower temperature, martensite is the stable configuration; as temperature increases, the material starts to be transformed in austenite.

Austenite consists of an ordered structure in which atoms are perfectly aligned. In contrast, in martensite atoms are weakly bound, conforming a more delicate arrangement easily deformable, presented on Figure 2.11. However, if the material in martensite phase is heated, it will rapidly recover its austenite form [36].

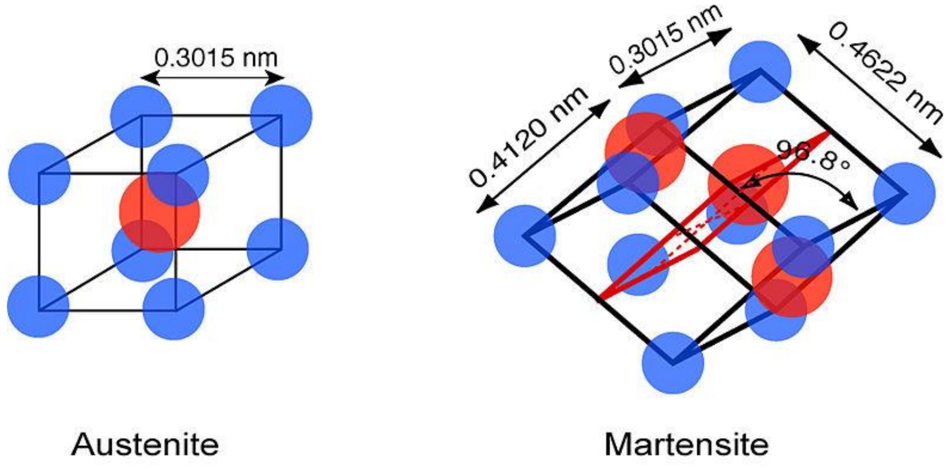

Figure 2.11.- Nitinol austenite and martensite [37]

The shape memory effect is represented with a hysteresis loop, illustrated in Figure 2.12. Hysteresis is defined as the materials’ tendency towards maintaining a certain property in the absence of the stimulus that has generated it. This implies that the direct and inverse processes follow different paths.

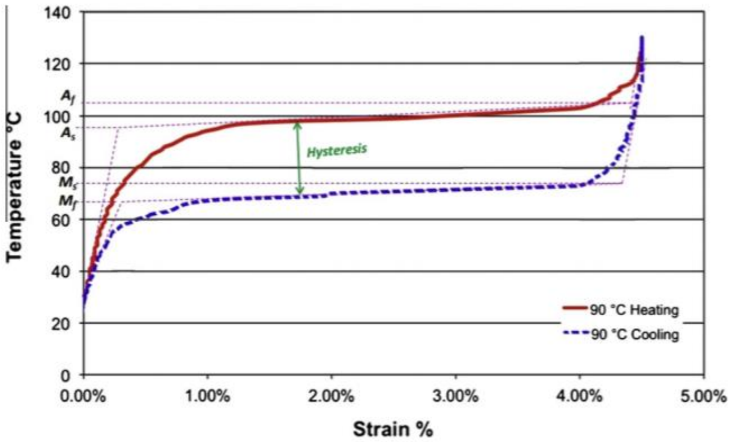

Figure 2.12.- Nitinol SMA phase transformation hysteresis loop [35]

In the specific case of SMAs, there can be distinguished several important temperatures that indicate the transition from one microstructure arrangement to the other [35]. When this material is heated, martensite starts to be transformed into austenite at austenite-start-temperature (As), until the temperature reaches austenite-finish-temperature (Af) and recovering at the same time the original form. For the reverse process – cooling-, the material starts to convert into martensite at martensite-start-temperature (Ms) and its transformation is completed once reached martensite-final-temperature (Mf).

As it was stated before, the austenite structure is more compact and difficult to deform, whereas martensite has a lower Young’s modulus, being softer and malleable. The different phases and crystal structures are illustrated on Figure 2.13.

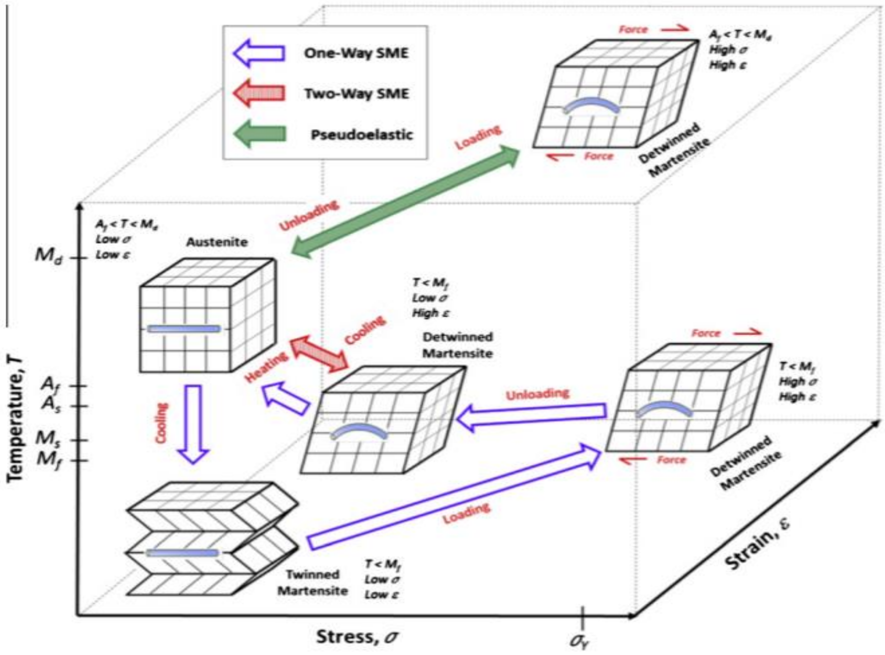

Figure 2.13.- SMA phases and crystal structures [35]

Besides Shape Memory Effect, Nitinol possesses another important feature: super elasticity [38]. This property explains phase transition not only as a temperature effect but as a stress-induced response – when the material is above transformation temperature-, presenting a spring-like behaviour.

In order to use SMA fibres as the actuation mechanism in the robotic field, we will take advantage of both features, because with an external applied stress martensite is able to stretch elastically between 4-8% [35] of the total length. As long as the deformation is elastic, the material is able to recover its initial shape, and therefore return to the original length when heated.

As it has been already explained, applying an external current to muscle wires – such as Nitinol fibres – results in an instantaneous contraction, which will be used to contract hand muscles and help fingers in flexion and extension movements. This contraction is due to the microstructure change explained previously, from martensite to austenite, and can be controlled in terms of temperature range by changing the concentrations of each alloy component.

In practice, temperature increase is controlled by the current going through the wires. Nitinol, being a conductor material, presents joule effect, i.e. heat production resulting from current flowing through it. As stated in Joule's first law, 'the power of heating generated by an electrical conductor is proportional to the product of its resistance and the square of the current' [39]. Therefore, knowing the wire resistance, it is possible to determine the required external current for obtaining the temperature increment that favours SMA contraction.

Taking into consideration all the important features of Nitinol, there can be described several advantages and disadvantages when used as the actuator mechanism.

The main advantages presented are [40]:

- High force-weight ratio, comparable characteristics to electrical motors or hydraulic actuators but with a lower weight.
- Mechanical simplicity and easy miniaturization. They are actuated by connecting them directly to a current supply, without the need of extra reductors or amplifiers, which provides them with a facile maintenance.

- High biocompatibility and reduced noise, therefore perfect for being used in medical applications in which contact with the body is required. These actuators do not generate noise as they are not based on friction mechanisms nor produce dust particles, thus facilitating cleaning mechanisms.

- Low cost and good corrosion resistance, being convenient for building affordable medical devices that are not suffering electrochemical deterioration by the environment.

Evaluating the main counterpoints of these wires, there can be highlighted [40]:

- Low speed, due to material hysteresis. As the material is able to maintain its properties once the stimulus has been removed, heating and cooling are slow processes which delay actuation.

- Reduced energetic efficiency because most energy is dissipated as heat emitted to the environment.

- Imprecise control, that although it has been improved lately, hysteresis and non-linear material properties hinder fibres' control.

- Fatigue and degradation. Its long-term viability highly depends on the tension wires need to withstand and maximum temperature they are subjected to. If we exceed in heating or applied force, the operational life may be reduced.

3. DEVELOPMENT OF THE DEVICE

To carry out the design and development of the proposed soft hand exoskeleton, there were several steps to follow in order to achieve the final goal, including both system's hardware and software.

Regarding the hardware, it can be divided in two parts: a soft open glove and the electronic system which controls the actuators. On the other hand, the software includes two MATLAB-Simulink algorithms, one in order to program the microcontroller and the second the PWM control signal. The electronic system as well as the control algorithms were already studied in a previous master thesis developed by Gabriela Verdezoto [41], so the existent components and programs were adapted to fit the exact purposes of the current project.

The first step in the developing process was to decide the materials and specific design that the final exoskeleton would have. Then, after determining the accurate measurements, it was required to draw a 3D sketch and print it, to obtain the mould.

After having the cast, silicon had to be poured on it – mould-making process-, embedding both the wires in charge of leading the movement and the pressure sensors to obtain force feedback. Once the silicon – which was selected with appropriate mechanical properties – cured, the prototype was connected to the actuators, so as to test its performance.

As it was explained, actuators were already designed from previous projects; they consisted on electronic circuits connected to linear potentiometers, which were joined at the same time to SMA fibres and non-actuated tendons.

3.1. Materials' selection and properties

Taking into consideration that each part of the design required different properties to satisfy different functions, several materials needed to be evaluated and chosen. Three main components were required for building the soft glove: silicone, SMA wires and Teflon tubes. Besides this, several devices and electronic components were required for the actuation mechanism and final assembly.

3.1.1. Silicone

Silicone is a polymer made of silicon and oxygen atoms. The most important properties of this material are given by the functional groups attached to silicon [42].

For building the entire glove, covering the palm and back of the hand, as well as the upper part of three fingers and finger tips, cured liquid silicone was used.

As it was a material that needed to be in contact with the body during long hours, high biocompatibility was required. Therefore, in order to avoid any type of adverse skin reaction, the silicone used hand already been commercialized to be applied as a face mask, and thus fulfil the biocompatibility conditions.

A silicone sort which presented softness was also desirable. As this device was intended to be placed on a patient's hand for performing rehabilitation exercises, being soft and comfortable would make the device more convenient.

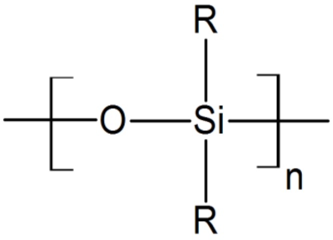

Figure 3.1.- Silicone polymer structure

To create a compact apparatus, the artificial tensors would be introduced inside the hand glove, and therefore elasticity and flexibility of silicone needed also to be studied.

Elasticity is defined as materials' capacity to recover the initial shape after removing the forces that were deforming it [43]. Flexibility, though, is the ability of a material for being stretched without breaking [44].

For this application, a combination of both properties was essential. As tensors would be embedded in silicon, the material needed to be both elastic and flexible but only to a certain extent; i.e. it required elasticity to return to the original state but without opposing a great resistance, and the possibility of deforming without breaking was important to adapt to hand features, but it was not desirable to be highly deformed if it was not returning to the starting form. In other words, the material needed to be more elastic than flexible, as this would allow tensors movement without fracture.

Among several commercial options which satisfy the mentioned properties, two different liquid silicones were decided to be used: Dragon skin 30 [45] and Mold Star 15 Slow [46]. These two silicone types were a liquid substance but with different curation times and colours. Exact specifications are included in the appendix.

The liquid silicone was commercialized in two separate components, that had to be mixed in equal amounts. After that, the material needed to cure, without being contaminated by any other substance and if available be introduced it in a vacuum chamber. In our case, there was not that possibility so the solution to avoid bubbles was to carefully apply a homogeneous layer of the component and smooth the surface.

3.1.2. SMA fibres - Nitinol

For the elaboration of this exoskeleton, two different types of SMA fibres -size, diameter, temperature, …- were used as artificial tendons. The SMA cables introduced inside the silicone glove were not actuated, whereas the external ones were connected to the power supply, so as to induce its contraction.

The non-actuated ones were introduced inside Teflon tubes and inserted into the silicone glove in the same place actual fingers' tendons are situated naturally. They are used to lead the movement of the complete finger. The diameter of these fibres is 0.1mm and the material is resistant to withstand pulling force without breaking.

Figure 3.2.- SMA fibres - used for non-actuation purposes

As well as the cited ones, there were other SMA wires were used for actuation purposes, taking advantage of the several properties already explained. They were also isolated wrapped in Teflon tubes and then introduced inside a Bowden cable.

In order to generate hand flexion and extension, Nitinol needed to contract a certain length. Therefore, knowing that the fibres were able to contract up to a 4% of their initial length, the specific longitude was obtained with Equation (3.1)

$$L_0 = \frac{\Delta L}{0.04}\ [cm]\ ,\ \ being \tag{3.1}$$

ΔL *the cable deformation length* $[cm]$ *and* L_0 *the initial length of the cable* $[cm]$

Each finger had a different movement range, so the length of each SMA wire was different in each case. Specifically, the thumb needed 3.2cm, the index 4cm and the middle finger 3cm.

The SMA cables used in the previous project developed by G. Verdezoto [41] were of 120cm. Using this data and rearranging Eq. 3.1:

$$L_0 = \frac{\Delta L}{0.04}\ [cm] \rightarrow\ \ \Delta L = L_0 * 0.04\ \ [cm]\ ,\ \ being\ L_0 = 120cm$$

$$\Delta L = 120 * 0.04 = 4.8\ cm$$

As this deformation was sufficient for the movement range required in order to fully expand and contract the three fingers, the same SMA cables were used. A Nitinol wire with a 0.51mm diameter was used, for the actuating mechanism, as it satisfied the force requirements as stated by the manufacturer.

3.1.3. Teflon tubes

Teflon tubes were used for two different purposes. When embedded in the silicone, the main aim was to avoid friction between artificial tensors and the glove itself. This way, SMA non-actuated wires had the path already generated by the tubes.

The other application was to isolate the SMA actuated fibres inside the Bowden Cable. Since the current generated a huge amount of heat in order for Shape Memory Alloys to contract, using Teflon it was possible to isolate that thermal energy so as not to burn the patient.

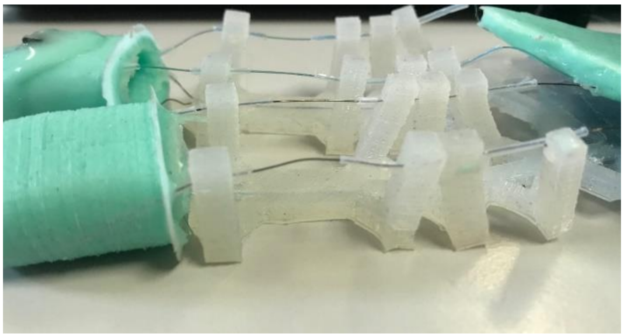

Figure 3.3.- Non-actuated SMA wires embedded in silicon through Teflon tubes

3.1.4. Bowden cable

SMA cables isolated with Teflon tubes were also introduced inside Bowden cables. Although these cables increase friction between the different surfaces reducing the performance, they are used to provide flexibility and lead the movement, as well as increase patients' safety.

Figure 3.4.- Bowden cables with SMA and Teflon tubes inside

3.1.5. Microcontroller - STM32F407

The microcontroller used was STM32F407 Discovery. It is a low cost programable device which consists of an integrated system. Microcontrollers are able to run the orders previously stored in its memory.

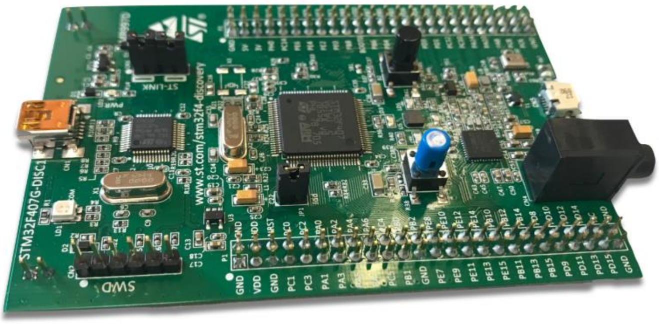

Figure 3.5.- STM32F407-DISCOVERY

MATLAB-Simulink was used to generate the code to be saved on the microcontroller, enabling to manage the sensor measurements as a feedback inputs and determine the required SMA fibres' current supply.

3.1.6. Force Sensitive Resistor small - SEN-09673 Sparkfun

Figure 3.6.- FSR small - SEN-09673 [47]

So as to measure the patient force when performing pincer grip and its ability to hold objects, it was decided to introduce a force sensor in the finger's tip.

As seen on Fig 3.6, it consists of a circular sensing area and 2 pins extended from the bottom part of it.

The Force Sensitive Resistor (SEN-09673) [47] is a variable resistor, able to respond when an external pressure is applied. Being able to record forces in the range 0.1N-10N, it is light, flexible and easy to handle; although it may not be completely accurate, it is cost effective and robust.

Its specifications show a pressure-resistance inverse dependence. When no force is applied to the sensor, the resistance is higher than 1MΩ [48]; this value decays -in an almost linear manner- to 0.25KΩ when maximum pressure is applied.

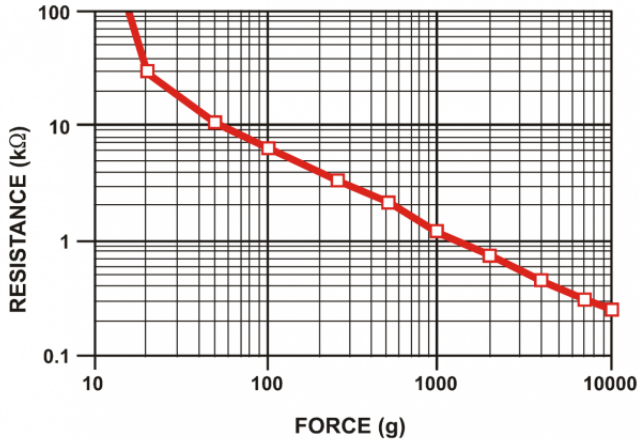

Figure 3.7.- FSR response to an applied force [48]

3.1.7. Position sensor – PTA series: Low Profile Slide Potentiometer

As a feedback control of SMA fibres' contraction, linear potentiometers were used. These slide potentiometers worked as variable resistors, changing the value depending on the different fingers' position.

This way, using six variable resistors it was possible to monitor both flexion and extension of the three fingers actuated with the exoskeleton. Important technical characteristics of PTA6043-2010CIB103 are presented in the table below.

TABLE 3.1.- TECHNICAL CHARACTERISTICS OF PTA6043-2010CIB103 [49]

CHARACTERISTICS	VALUE
Resistance	10KΩ
Nominal Power	100mW
Resistance Tolerance	20%
Sliding Life	15,000 cycles
Resistance Tapers	Linear, Audio

Figure 3.8.- Low Profile Slide Potentiometer [49]

3.1.8. Power generator

In order to activate SMA fibres, the system takes advantage of joule's effect. This concept, that was previously explained, consists of a temperature increase due to current flowing through the wire.

However, the voltage supply required so as to activate SMA fibres changes depending on the Nitinol wire characteristics. Therefore, the specifications presented in the Table 3.2 were required to achieve the adequate current through the fibres.

TABLE 3.2.- FLEXINOL ACTUATOR WIRE TECHNICAL AND DESIGN DATA [50]

DIAMETER SIZE [MM]	*RESISTANCE [OHMS/METER]*	*APPROXIMATE** CURRENT FOR 1 SECOND CONTRACTION (MA)*	*COOLING TIME 158° F, 70°C "LT" WIRE*** (SECONDS)*	*COOLING TIME 194° F, 90°C "HT" WIRE*** (SECONDS)*
0.025	1425	45	0.18	0.15
0.038	890	55	0.24	0.20
0.050	500	85	0.4	0.3
0.076	232	150	0.8	0.7
0.10	126	200	1.1	0.9
0.13	75	320	1.6	1.4
0.15	55	410	2.0	1.7
0.20	29	660	3.2	2.7
0.25	18.5	1050	5.4	4.5
0.31	12.2	1500	8.1	6.8
0.38	8.3	2250	10.5	8.8
0.51	4.3	4000	16.8	14.0

The SMA fibre type used in this case was the highlighted ones – 0.51 mm diameter and high temperature. The temperature influences the rate at which cooling is achieved. Using the high temperature ones, the difference with room temperature is more significant and therefore the recovery of its initial temperature is faster than using the low temperature ones. This fact reduces the time required to wait in between cycles for SMA wires to be activated again.

Knowing that the cable length was 120 cm, as calculated before, and the total resistance for each wire is:

$$R_{wire} = length * \frac{resistance}{length} = 1.20\ m * 4.3 \frac{\Omega}{m} = 5.16\ \Omega \tag{3.2}$$

Assuming that the three fingers needed to be actuated at the same time, they are in parallel orientation. Given that the current required in each wire for contraction is 4A, as shown in the Table 3.2, the total intensity could be calculated as follows:

$$I_t = I_1 + I_2 + I_3 = 3 * I = 3 * 4A = 12\ A \tag{3.3}$$

To calculate the total resistance of the three wires: (3.4)

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{3}{R_{wire}} \rightarrow R_t = \frac{R_{wire}}{3} = \frac{5.16}{3}\Omega = 1.72\Omega$$

Applying Ohms' Law:

$$V = I_t * R_t = 12\ A * 1.72\ \Omega = 20.64V \tag{3.5}$$

If instead of actuating the three fingers simultaneously it was only one finger actuated at a time, the voltage required would be the same. This is due to the fact that resistance would be three times bigger but the current three times lower, resulting in the same voltage requirement.

3.2. Model generation

3.2.1. Exoskeleton design: 3D prototype

Taking into consideration the wide range of possibilities currently available for hand exoskeletons, it was decided to create a small device attached to the hand on its superior part, similar to the 'Exo-glove poly' presented previously [31].

As one of the most important features when creating the design was patient comfort, generating an open glove made of a soft material completely satisfied this requirement.

Moreover, for patients who present hand rigidity, the option of using an open glove is much more convenient than a closed one, as it would not involve them an effort to introduce the hand on it.

Therefore, the first paper sketch, illustrated on Figure 3.9, was drawn trying to satisfy the previous requirements.

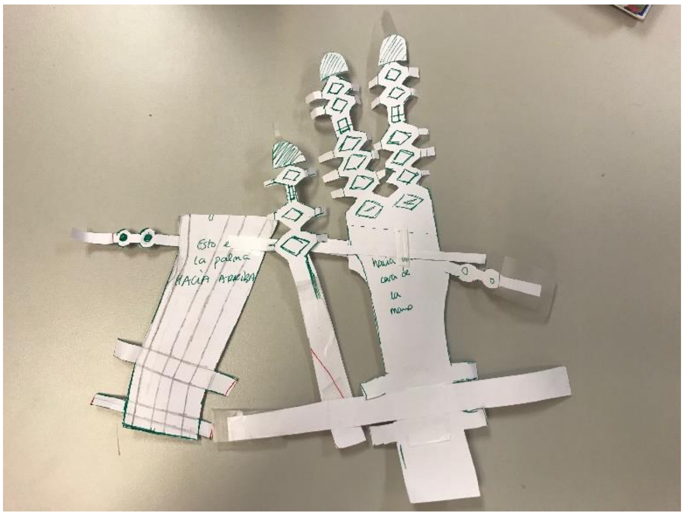

Figure 3.9- Paper sketch of the glove

Once the paper sketch was designed, its adaptability was tested. This glove was designed for the right hand and only covered the upper part of three fingers, with a small supportive part on the palm and back of the hand. This prototype had a strap around the wrist in order to fix the position of the exoskeleton during exercises.

As shown in the Figure 3.10, the design fitted correctly the hand and adapted to the shape of fingers in a convenient manner. However, the small strips that surrounded fingers had to be bigger, so as to fingers not to slip easily.

Figure 3.10.- Paper prototype on the hand

The next step was to digitalize the previous paper sketch using a 3D designing software, called Creo Parametric. This program allows users to generate from scratch the 3D designs and visualize the created structures.

The first approach followed was to generate the different 3D parts of the device and, once they were printed, use modelling clay to generate the inverse shape and use it as a mould for pouring silicone (see Figure 3.11).

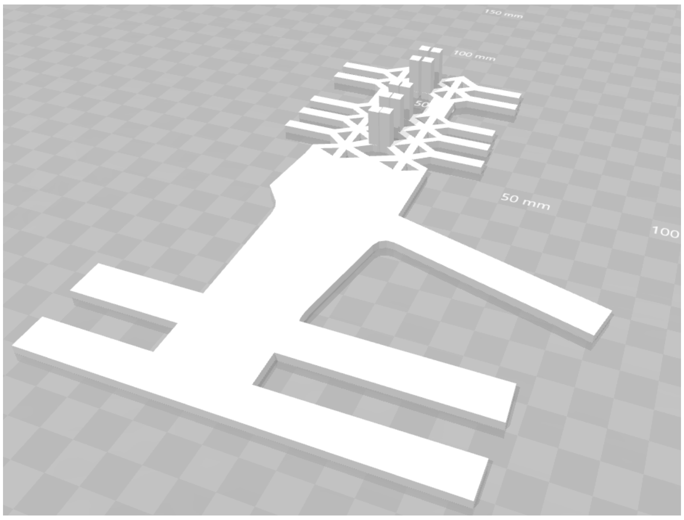

Figure 3.11.- 3D upper part of the design

Nevertheless, this procedure presented two main problems. The first one was that the modelling clay stuck to the plastic printed piece, and therefore the smaller features were not accurately reproduced. The other issue faced was that, when the silicone cured over modelling clay, the shape was not fully preserved. This was due to the high deformability of the cast, which did not provide enough strength to maintain the shape.

To overcome this handicap, a new idea was followed. As the modelling clay was not a good idea for generating the mould, it was decided to repeat the 3D digital models and print the negative ones; i.e. to print a plastic cast in and pour silicon on it, as shown in Figure 3.12.

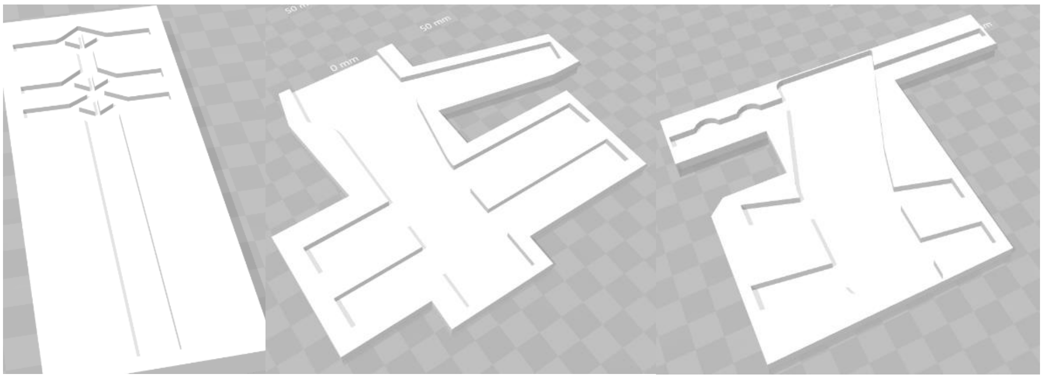

Figure 3.12.- Negative 3D designs of hand exoskeleton

The difficulty with the final printed mould was that the material, as it had been 3D printed, was not completely solid and uniform. It presented small holes, and although silicone is a dense material, it leaked before curing, generating non-homogeneous parts on the glove.

To avoid this phenomenon, a thin layer of water-based paint was added to the mould surface. Thus, leakage was prevented without damaging the cast or the silicon.

3.2.2. Silicone's mould making process

Once all the presented issues were solved and the moulds were ready to withstand silicon while curing, different similar designs were compared to use the one that best fitted hand shape (Figure 3.13).

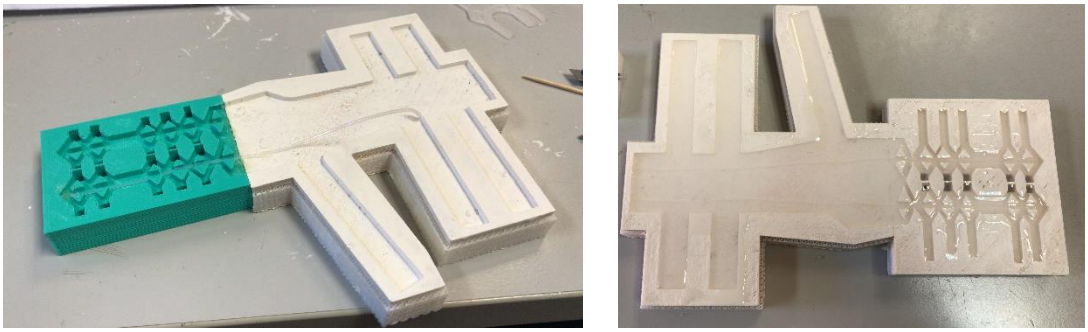

Figure 3.13.- Two different possible designs; the first model was the selected one

Among the two different studied structures, the one which presented all strips downwards was the selected one. Although both of them were able to adapt to the hand and finger shape in a correct manner, the one on the right figure (Figure 3.13) did not attached so easily to the finger. Instead, it required force to maintain the exoskeleton in a fixed static position.

Subsequently, when the best cast's design was selected, silicon was added to cure inside. As silicone was presented in two separate components, a previous mix was required, generated with equal amounts of each components.

When the mixture was homogenized, it was poured into the different plastic items. In order to create a perfect cured silicon without bubbles, a vacuum chamber was recommended. However, as it was not available, spreading the viscous material in a thin uniform layer was enough to eliminate most of the possible bubbles. After that, the material needed to be curing for 24 hours before removing it from the cast.

Along with the addition of silicon, the Teflon tubes were introduced at the same time in a straight manner following the disposition of tendons in the hand. It was advisable to use this Teflon tubes so as to reduce the friction between the artificial tensors and the silicone. This way, the tensors were conducted through specific paths without directly interfering with silicone and avoiding the possibility of tearing the glove during exoskeleton flexion or extension.

3.2.3. Finger tips: design and force sensor embedding

The structures which conformed the planar part of the device were simply replicated and generated with plastic 3D printed designs. However, to connect actuation mechanism and drive the movement through the fingers, silicone finger's tips needed also to be designed.

Before reaching the definite design, different options were evaluated and tested. Apart from the fitting and comfort when placed surrounding the finger, the shape required also an appropriate part in order for the force sensor to be introduced.

The first design consisted of a planar silicon cross-like structure. It was designed in a 2D fashion and expected to bend in order to link upper and lower glove parts. However, this option did not fit well with the finger's tip, and motion was not led correctly.

Figure 3.14.- First finger's tip design

As a 2D-flat design (Figure 3.14) was not an appropriate idea, 3D cilinder-like plastic moulds were built. The problem with this technique was sensor embedding. As the sensor needed to be placed on the lower part of the finger tip, if the model was generated in a cilinder structure, it needed to be fixed vertically.

The following designs were small hollow cilinders in which silicon was introduced, as well as the force sensor, and modelling clay or a cone-like plastic piece was placed on to of it to mimick finger position.

The final design was similar to these ones, but with a rounded tip, in order to better fit the finger's anatomy. Moreover, a finger model was 3D-printed in order to better simulate the finger position inside the tip.

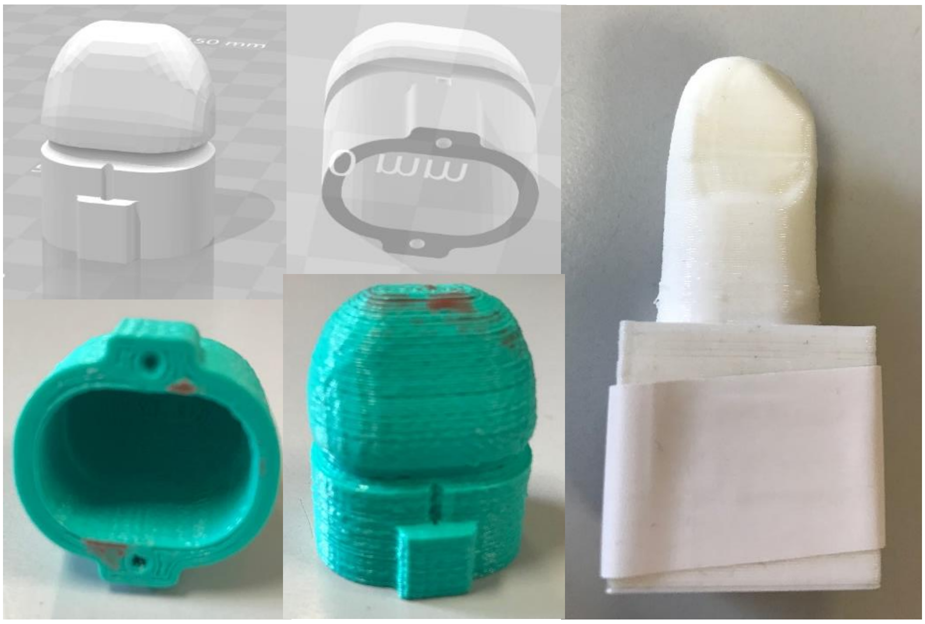

Figure 3.15.- Final 3D designs, moulds and finger model

The sensor was easily embedded into silicone before the material cured and also Teflon tubes were introduced to avoid friction of SMA non-actuated cables with silicone. The idea of introducing the sensor just on the finger tip was trying to control wether the patient was pressing and performing pincer grasp.

Figure 3.16.- Final index finger's tip

3.2.4. Assembly of independent exoskeleton parts

As the parts of the device needed to be cured separately, in different moulds, a final step was required to finally assemble all the separate structures into a unique glove.

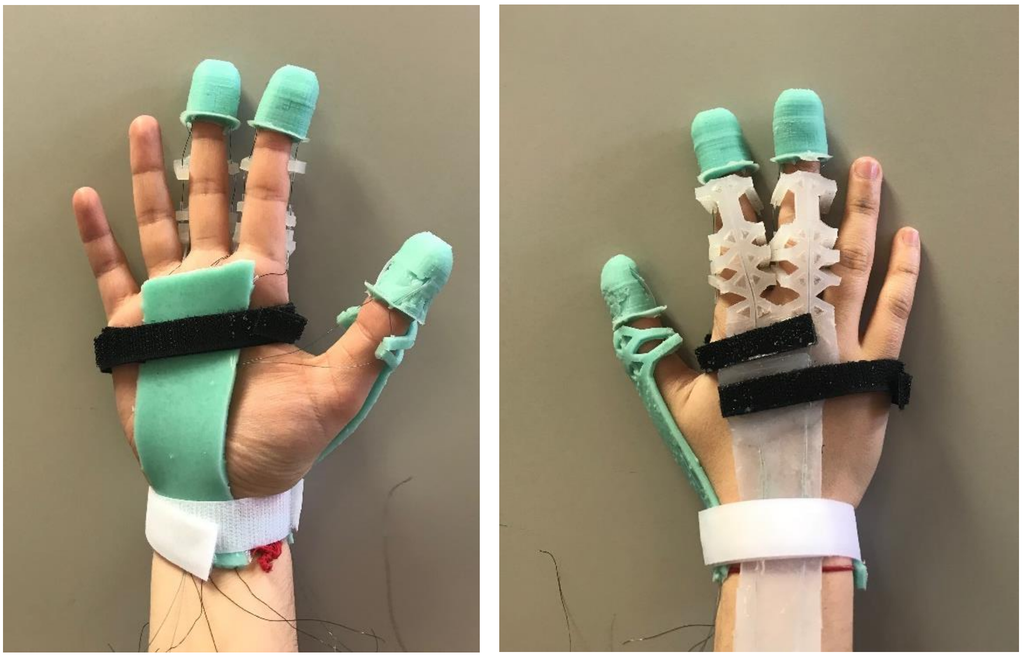

Figure 3.17.- Final exoskeleton design

When all the silicone parts were independently cured, two mechanisms were used to link them. For the areas that needed to be firmly attached, silicone was used as adhesive; uncured silicone was used, placing the already generated parts in a planar surface and in close contact with both silicone and among them. After letting another twenty-four hours, the recently added silicon had attached to the previous structure obtaining a uniform hand glove.

On the other hand, for the parts that were expected to be adaptable to different hand sizes or shapes, Velcro straps were employed. Specifically, one strap was attached to the wrist and the other one surrounding knuckles. This way, an adaptable open glove was obtained, adjustable to possible hand's features of the patient (Figure 3.17).

Furthermore, to connect the non-actuated SMA fibres to the mechanical structure containing the linear potentiometers and in turn to actuated SMA, these wires were attached to small round wire connector crimps; they provided a hook with sufficient force to withstand the tension caused by actuators' contraction.

3.3. Electronic system

The SMA fibres needed to be actuated using a power source, as it was previously explained. In order to drive the current through the wires and produce the desired contraction, the amount of current had to be accurately controlled. However, as the parameters required fitted with the ones used in the master thesis presented by G. Verdezoto [41] and continued by P. Enríquez [51], the same electronic system was used.

It was based on introducing a reference signal to the microcontroller and, using a PID that was adjusted by trial and error, increase the current that was going through the wires in order to achieve the stated position value.

The PID determined the PWM, i.e. the cycle's time on-off in order to modulate the current and therefore the fibres' response. This type of controller required three parameters: proportional, integral and derivative. By changing these values, the time needed for achieving the final value variated, as well as its accuracy or oscillation around the exact final value.

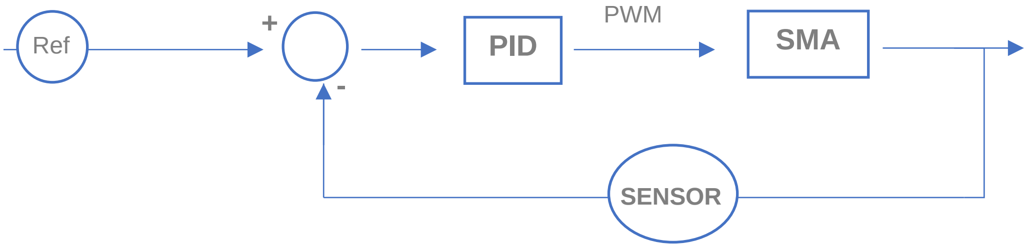

Figure 3.18.- Schematic of the electronic system

To fulfil this purpose, there were three fundamental components. Firstly, a sensor was required, in this case a position one, which was able to record the current position of the system. Secondly, a controller - in this case the microcontroller STM32F407 Discovery- capable of receiving and sending signals in connection to the computer. Lastly, an actuator mechanism, which received the microcontroller’s signals and got activated, such as SMA fibres.

3.4. Power board

The generated PWM which led the actuation of the SMA wires was sent to the power board, which acted as an intermediate in order to actuate independently each fibre; i.e. the power board was the circuit required to receive the PWM generated by the microcontroller and generated the power to control separately the different SMA cables.

This component was already built and used in many other electronic systems to guide SMA; it was created by Robotics Lab in order to manage Shape Memory Alloys’ technology.

3.5. Mechanical structure

A mechanical structure was required so as to tighten the wires and connect the artificial tensors in the glove with SMA fibres. Provided that the required contraction performance fitted with the values studied in the master thesis presented by G. Verdezoto [41] and bachelor thesis developed by P. Calzada [51], this project took advantage of an already existent structure, shown in

Figure 3.19.

It consisted of a small metallic box in which there had been placed six linear potentiometers. Each one was attached to a small metallic cart situated above a rail. Besides connecting linear potentiometers with carts, these small pieces also connected SMA fibres and steel cables – in charge of hooking the actuators to the artificial tendons in the glove.

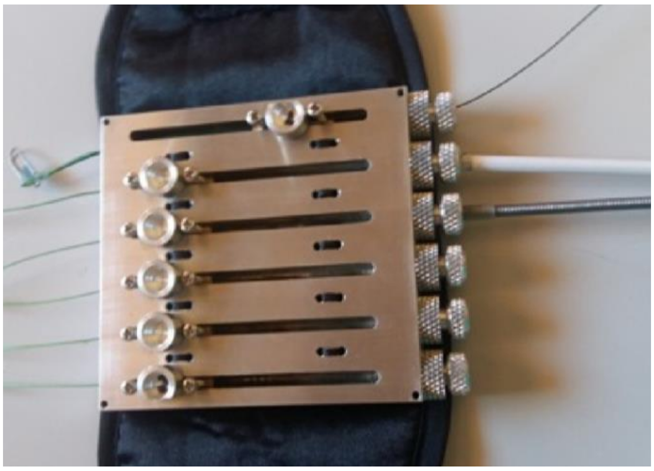

Figure 3.19.- Sensors and actuators connection [41]

3.6. Control system - Software

The programs in charge of leading wires' contraction were saved on the microcontroller. They were developed using MATLAB and Simulink. To activate the SMA cables and read or save the values to the computer, two different MATLAB codes were required. This software had already been generated by Robotics Lab for different research projects, starting from the PhD of A. Flores [52] which facilitated the rapid code generation for controlling the system.

- ‘Target’: this ‘target’ Simulink model was in charge of the microcontroller, maintaining a constant bidirectional communication with ‘host’ model. It received the reference values the user aimed to reach, and using a PID controller, it generated the signals to activate the SMA fibres.

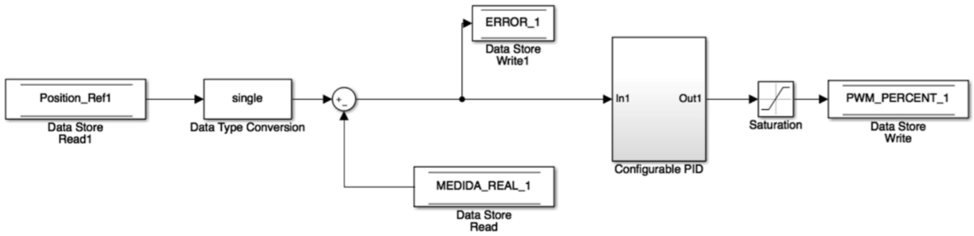

Figure 3.20.- Target Code for control loop of SMA 1

Each actuated wire was supplied with the necessary power defined by the control loop presented on **Error! Reference source not found.** This s ame diagram was repeated 6 times in order to control separately the fibres in charge of hand’s flexion and extension – three for each movement. The main outputs of this program were both the current sensor position and the PWM value, which was sent to the power board and hereafter activated Nitinol artificial tendons.

- ‘Host’: this model executed on the PC gave us the opportunity of modifying the reference signal (GAIN), and taking use of the plots, it was possible to visualize the real-time variations of previously cited variables, sent by the target program. The information concerning PWM, sensor position and error could also be recorded through this code.

The code was used with small modifications in order to perform finger grasp; i.e. a common GAIN value was applied to perform three-finger flexion and a different common GAIN value was set for their simultaneous extension, as seen in Figure 3.21.

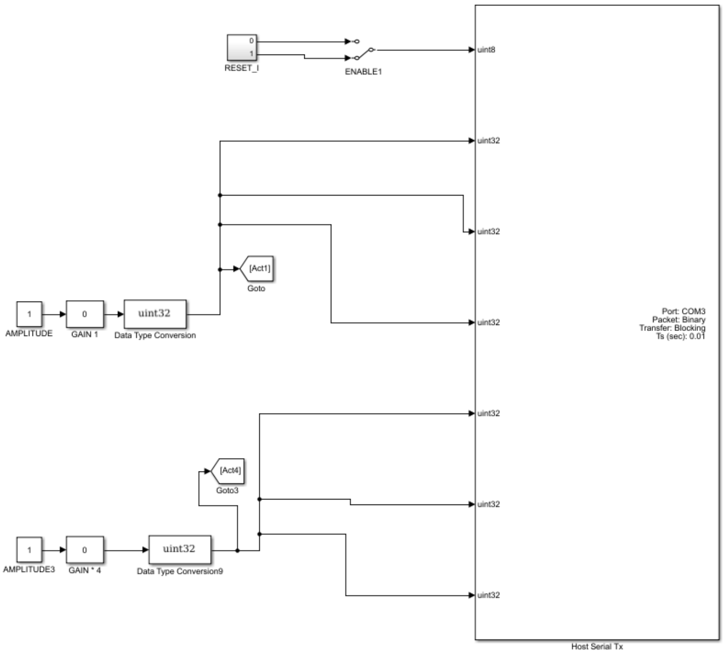

Figure 3.21.- Target modifications to perform pincer grasp

Once the ‘target’ program was saved on the microcontroller and the ‘host’ one was run on the computer, several data plots were stored in order to further analyse the given results.

4. RESULTS

In the exoskeleton presented there were two different sensors which provided independent information of the patient and device performance. The force sensor, which was placed on the finger's tip, was introduced in order to measure the patient's force. By calibrating it, it was used to read the value provided and study whether the patient was exerting force. Moreover, if the code was slightly modified, it could also be used as feedback for fibres actuation, for example inducing contraction when the patient was not pressing with enough force.

On the other hand, the linear potentiometers situated on the mechanical structure and connected to SMA and artificial tendons were used to measure the accuracy and performance of the actuation mechanism. A reference signal was introduced to the system, and then both the time required for the fibres to reach it and the specific fingers' position at each time moment were recorded. As it was provided the theoretical value expected to be reached and the actual one, this was another effective way of evaluating the accuracy of this method.

In summary, this chapter presents different parameters which influence the exoskeleton's performance and device usefulness: user's force and fingers' movement range.

4.1. Force sensor

4.1.1. Force sensor calibration

Although there was an already known relation between the sensor values and the force exerted, this sensor was embedded in silicon. As it was a soft material, capable of storing energy and deforming when a pressure is applied, a new calibration was required.

To facilitate force measurements and improve force sensitivity, a small plastic piece was introduced together with the sensor inside the silicon finger's tip. This little component directed the force towards the circular part of the sensor, which was in charge of measuring the force.

Using the Sparkfun sensor -previously specified- embedded in silicon, the calibration measurements were performed with a scale. By pressing with the index finger on the scale and recording the sensor measurement at each position in time, it was possible to obtain an approximate relation between the sensor output and the force exerted by the patient, presented on the figure below.

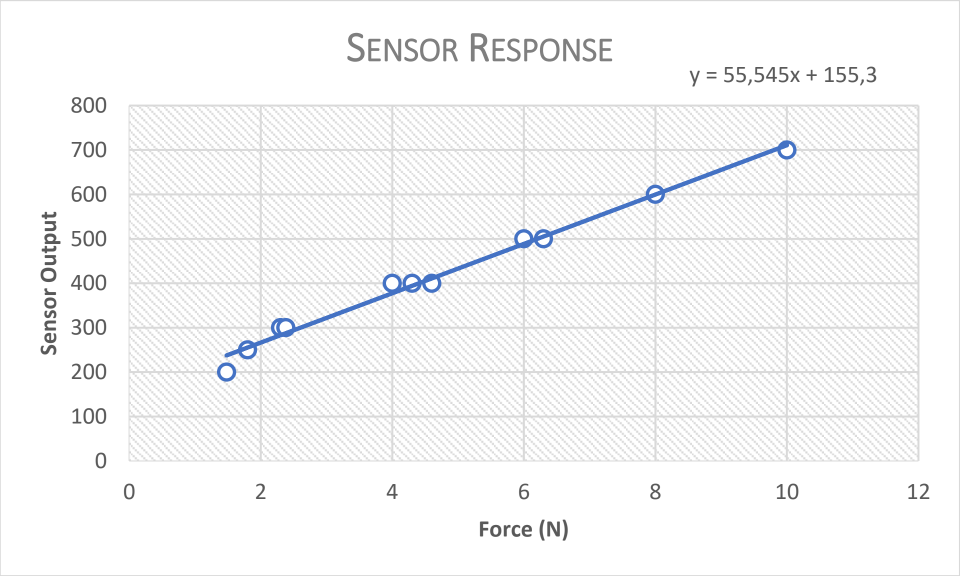

Figure 4.1.- Sensor calibration curve

4.1.2. Force sensor response

The force sensor was further studied by using the conversion obtained through the previous experiment and applying it to a known-weight object. By picking objects of different sizes and mass, the sensor performance and consistency was evaluated.

$Provided\ the\ linear\ fit\ equation\ that\ relates:$

$$SensorOutput \ = \ 55.545 * \ Force \ + 155.3 \tag{4.1}$$

$Rearranging\ terms\ and\ clearing\ Force$

$$Force \ = \frac{(SensorOutput - 155.3)}{55.545} [N] \tag{4.2}$$

The force in the y-axis was obtained with the previous equation (Eq. 4.2), knowing the sensor response and the linearization already developed. Four different trials were performed (Figure 4.2): 200g, 100g, small light box and scissors; provided that having different shapes and sizes could change the sensor response.

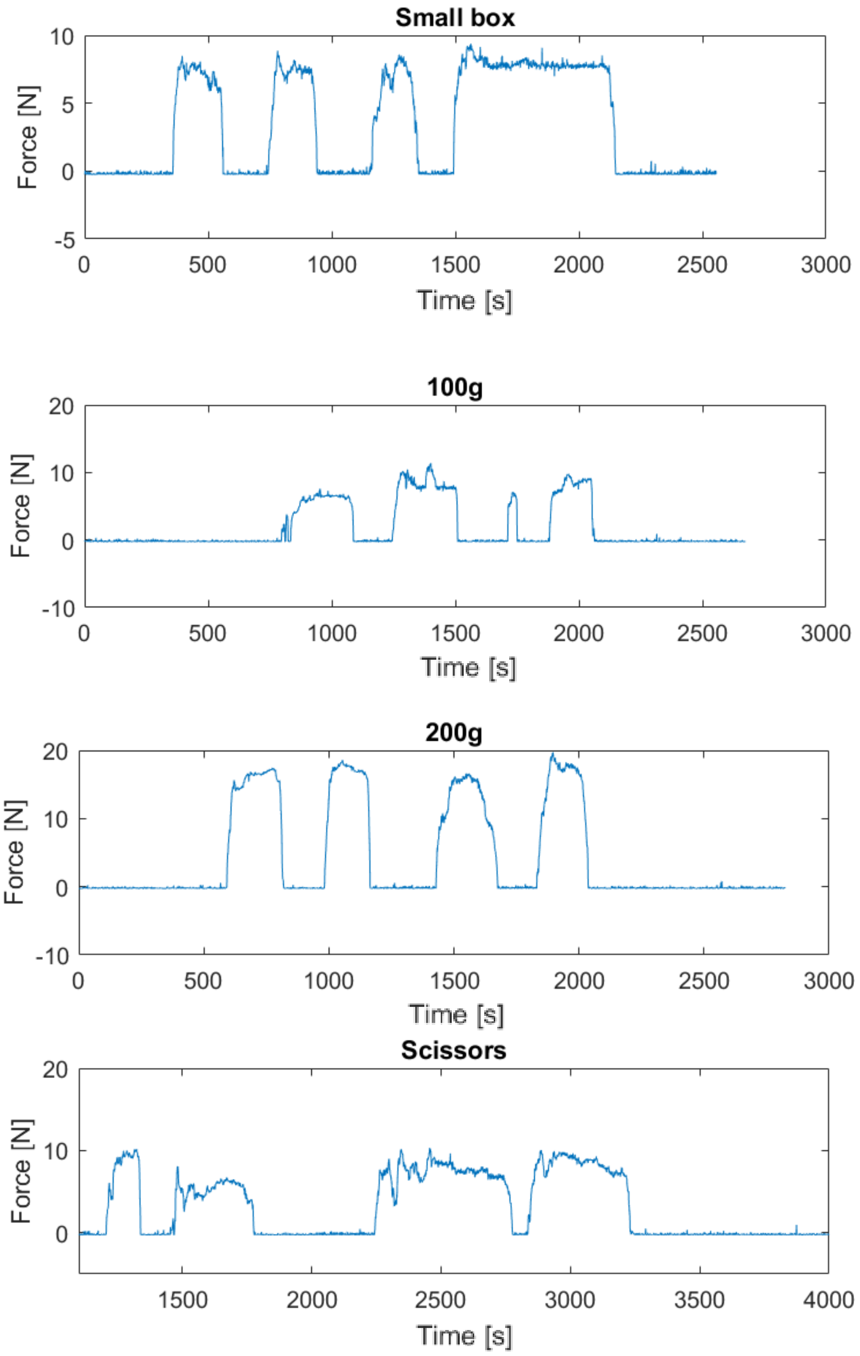

Figure 4.2.- Sensor's response to different objects hold

4.2. SMA actuators

Different trials were carried out to test the SMA performance as concerns accuracy and velocity of movements. First, fingers were tested independently, to ensure the functioning of all cables. Then, three fingers' flexion was tested simultaneously, followed by its extension, proving the efficiency of this device when performing pincer grasp.

4.2.1. Independent finger movement

The first trial that was carried out aimed to prove SMA contraction behaviour when a current was applied. In this case, thumb, middle and index fingers were actuated separatedly to perform their independent flexion.

A reference signal was generated and the SMA response measured, in order to evaluate the accuracy of the movement and the time it took to reach the fixed position, as shown in Figure 4.3.

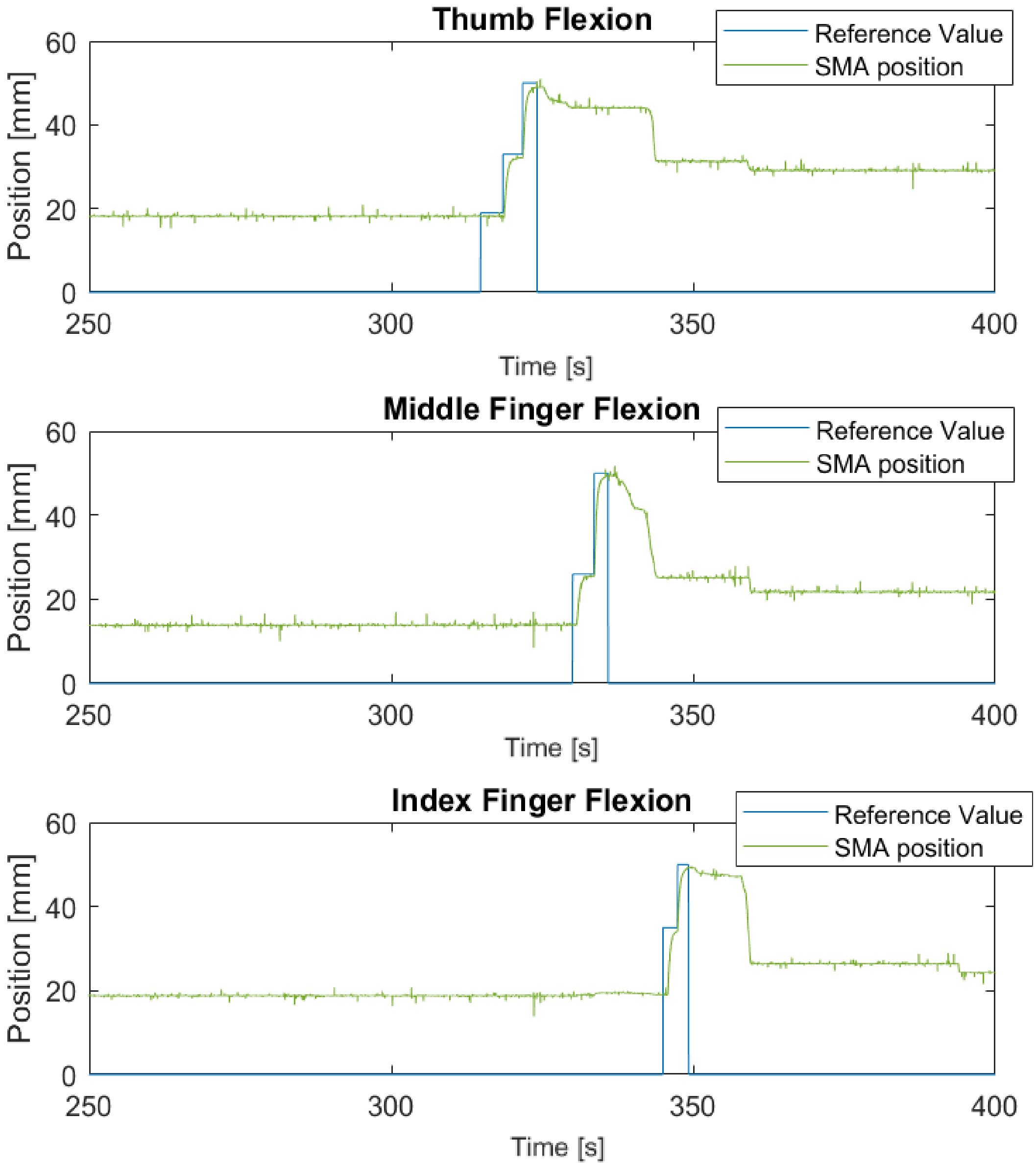

Figure 4.3.- Independent finger flexion

4.2.2. Pincer grasp

Once individual finger flexion was tested, a different set of trials were performed. As the final objective of the present hand exoskeleton was to perform simultaneous three-finger flexion and extension – so as to help in pincer grasp and rehabilitation exercises – this movement was tried out.

Several simultaneous cycles were developed. The goal was to obtain three-finger flexion followed by their corresponding extension, after a small rest to allow SMA cooling and prevent its breakage.

- First trial- only flexion, no extension performed in this case. The following graphs show three flexion cycles of all actuated fingers at the same time. The complete performance took approximately one minute. The first flexion was irregular due to the fact that the Nitinol wires were heated from room temperature; the subsequent two flexion movements were faster and more accurate. The reference value was only followed when ENABLE was 1 – which could not be shown in the graph.

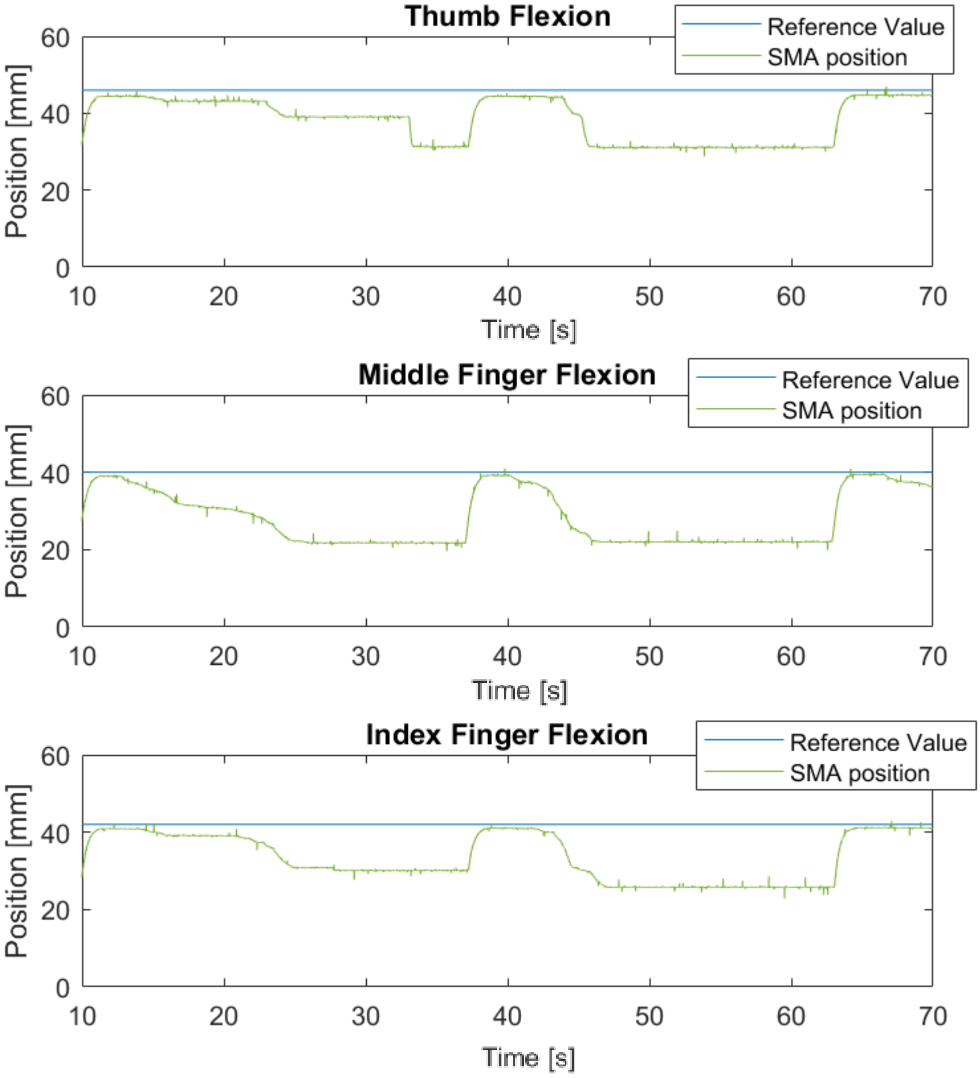

Figure 4.4.- First trial: simultaneous three-finger flexion.

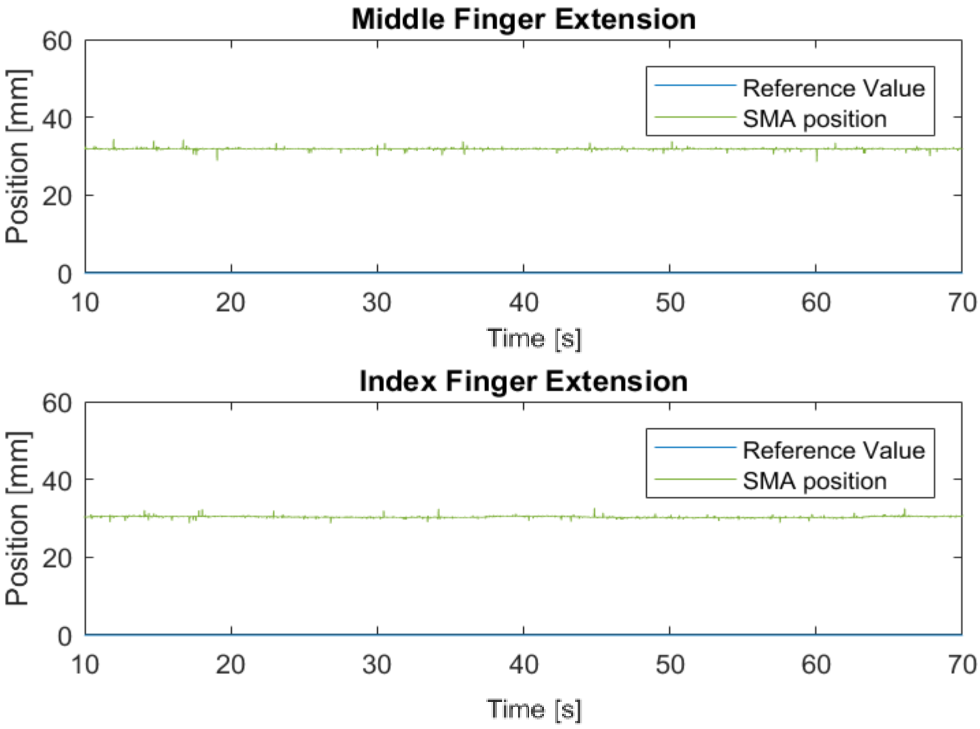

Figure 4.6.- First trial: non-actuated extension

- Second trial- in this case both flexion and extension were carried out in index and middle fingers but only flexion in thumb. A delay slightly lower than 5 seconds is observed in the following graphs, and after that time interval the SMA fibres accurately reached the fixed reference value.

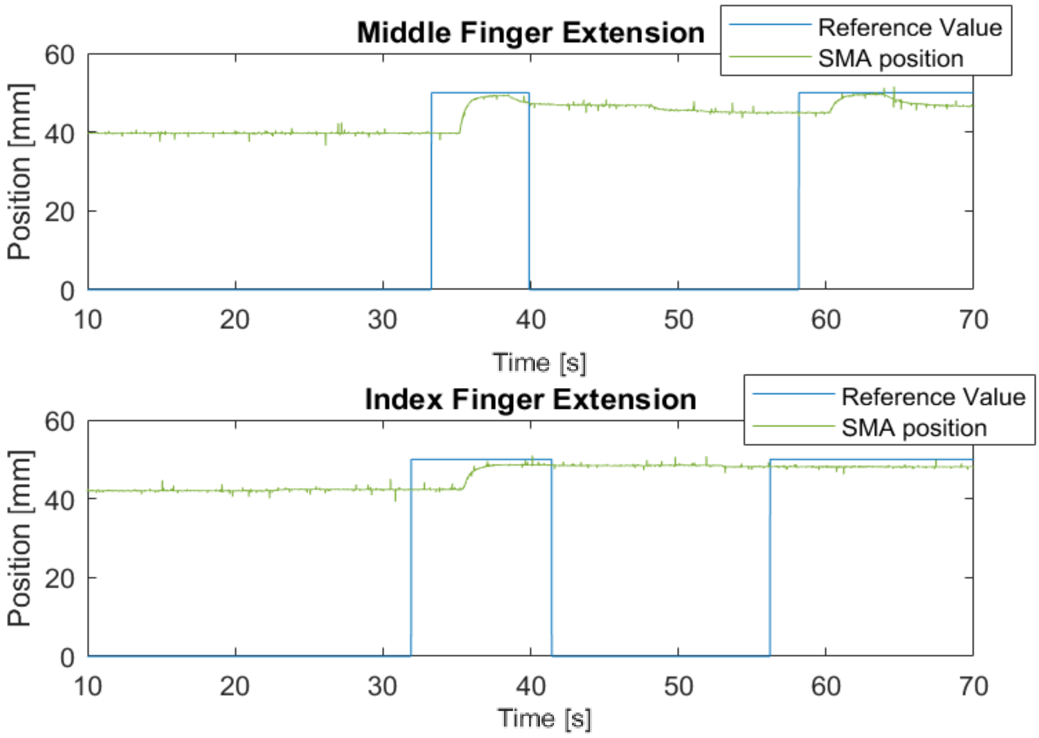

Figure 4.5.- Second trial: middle and index finger extension

In flexion plots, a longer delay is present in the first activation process. This is caused due to the temperature factor cited previously. As SMA was at room temperature before starting the experiment, it took longer for current to activate it and get to the stated positon. Moreover, middle finger flexion presented a strange behaviour that will be more precisely explained on the next chapter.

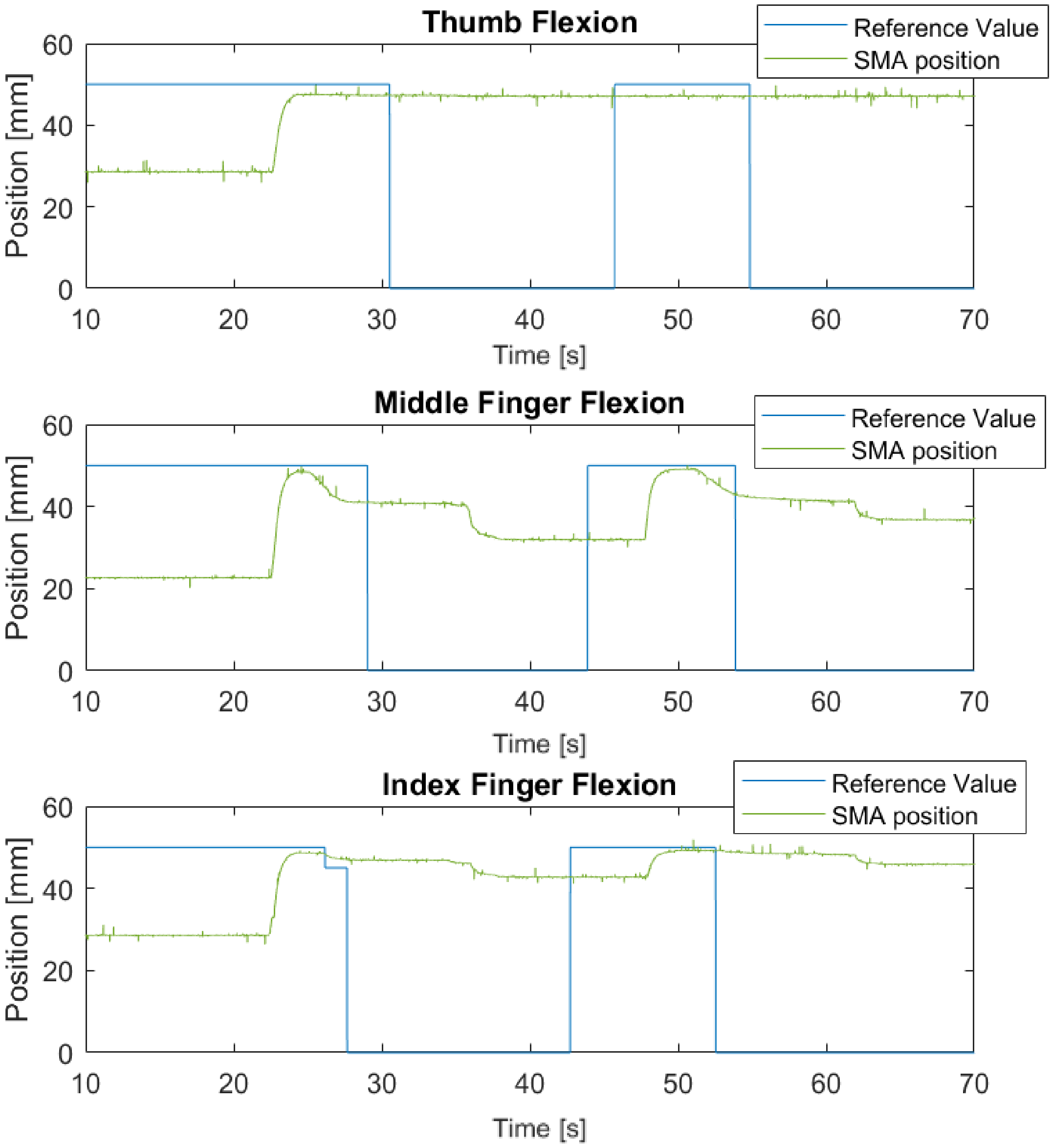

Figure 4.7.- Second trial: simultaneous three-finger flexion

During the first test -represented on Figure 4.4 and Figure 4.6-, the ENABLE, which is not represented on the graph, was alterning between 0-1. This way, the reference value was only taken intro consideration when the ENABLE was 1. During the second trial –Figure 4.5 and Figure 4.7-, the ENABLE was always on. Therefore, the reference value governed the SMA heating or cooling.

- Third trial (Figure 4.8 and Figure 4.9) – three-finger flexion and extension. In this case 6 SMA cables were actuated having a constant ENABLE of value 1. By changing the GAIN in short time periods we acquired the corresponding wires' contraction.
  The activation of Nitinol was achieved through two different square waves of 10 seconds period and 40% dutty cyle: one for flexion and a different one for extension. Both presented an amplitude of 50 (corresponding to 50 mm in sensor position) and were sent with a delay of 5 seconds. This way, a one-second relaxation period was observed between flexion and extension in order to allow SMA cooling and prevent breakage.

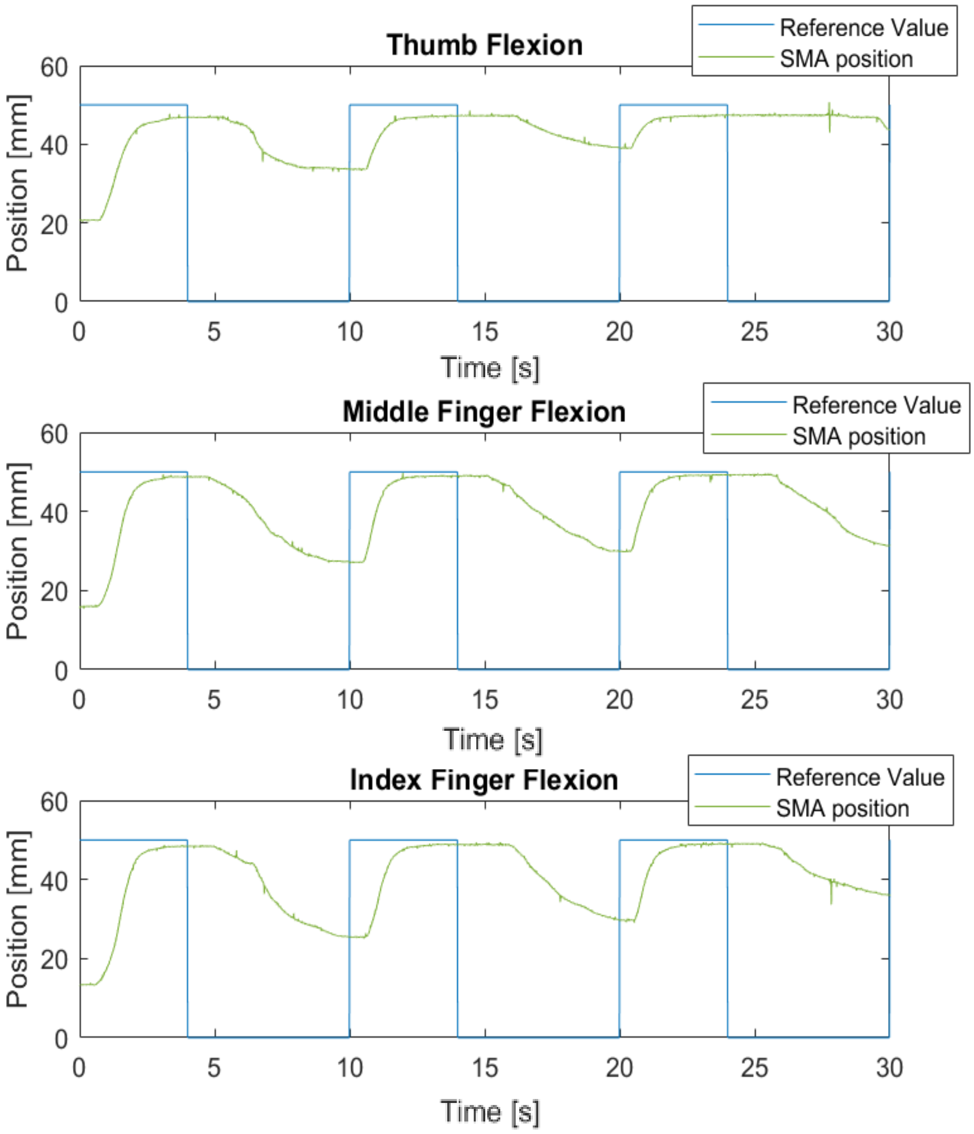

Figure 4.8.- Third trial: simultaneous three-finger flexion

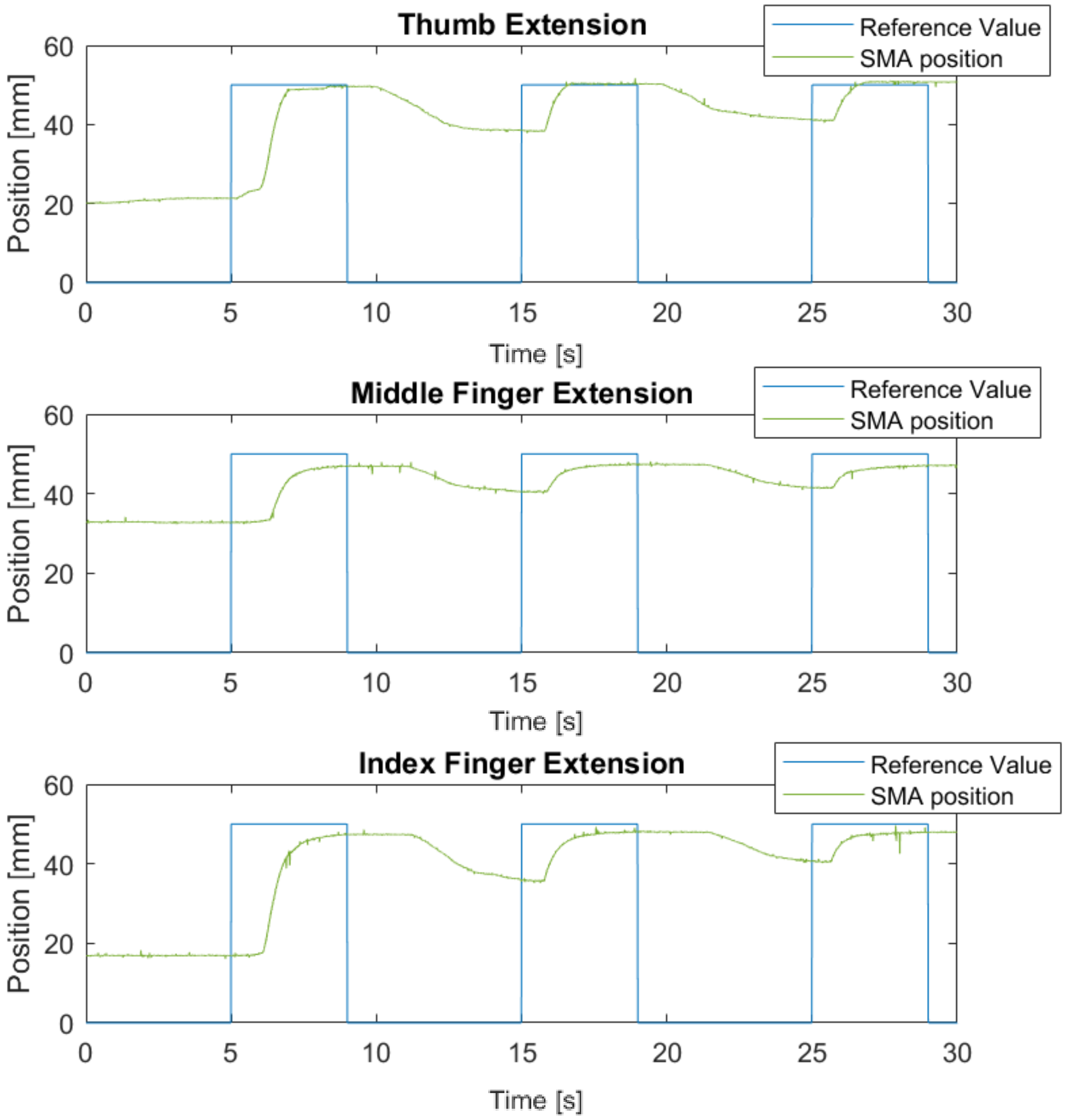

Figure 4.9.- Third trial: simultaneous three-finger extension

In all of the cases the SMA achieved the target value at the final part of the square signal. It was clearly shown in the plots the correspondance between flexion and extension and their matching activating time; i.e. in extension graph, a decrease in position was noticed in accordance to the extension performed in that same time interval (seen in Figure 4.8 and Figure 4.9). This results will be further explained in the following chapter.

In future experiments, it would be required to change the actuation time, trying to identify the changes in SMA performance and wires' heating due to differences in actuation time.

In Figure 4.10, it can be visually understood how this movement was performed. By using a small light bottle, pincer grip was stimulated in several consecutive cycles.

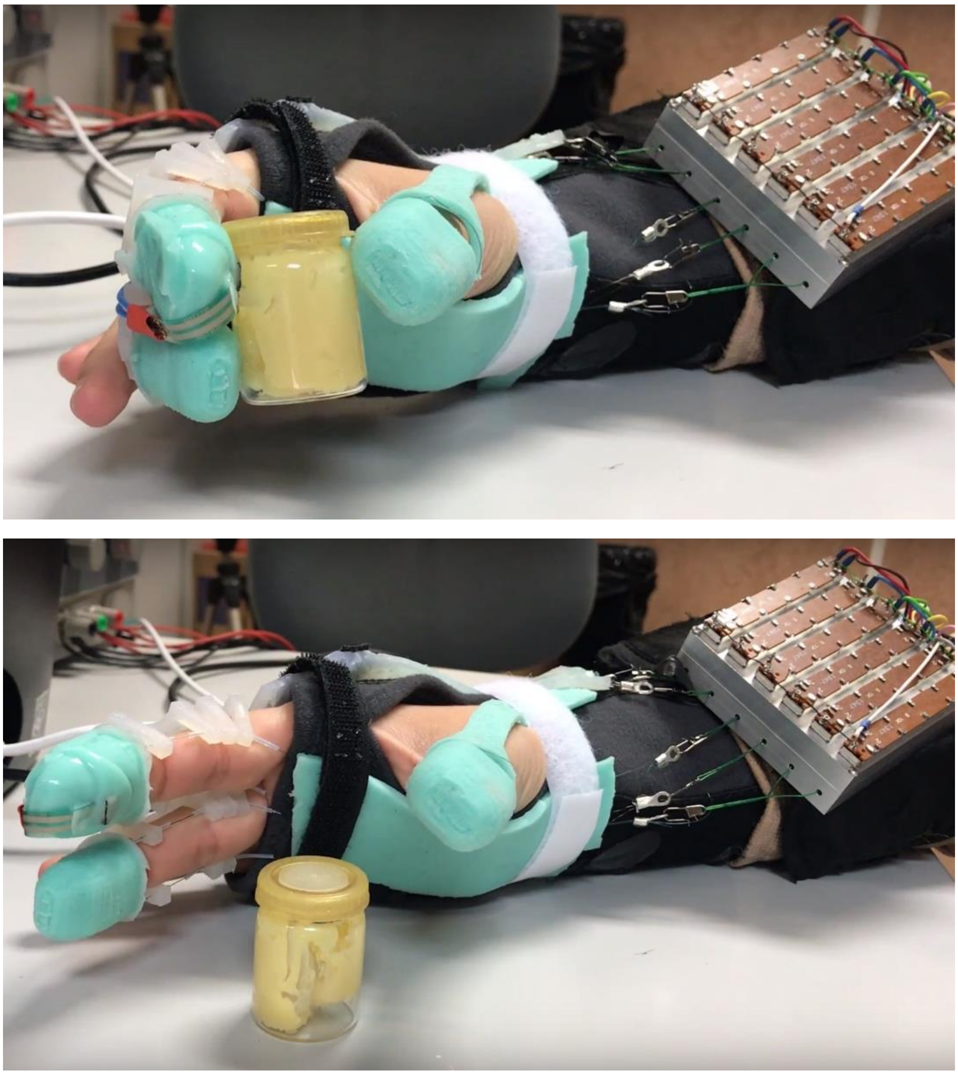

Figure 4.10.- Pincer grasp performance

5. DISCUSSION

The results presented on the previous chapter were obtained through several experiments that tested soft hand exoskeleton performance. In order to evaluate it, it was required to compare the resulting values with the expected theoretical ones.

First, the calibration of force sensor was developed. After calibrating it, several objects with different shapes and sizes were used to measure the sensor response and the calibration that had just been obtained.

After testing the force sensor, the SMA contraction mechanism was also analysed. Knowing the reference signal that was being introduced, different trials were used to evaluate Nitinol's response.

5.1. Force sensor evaluation

As previously mentioned, the first relation to be obtained was a calibration curve for the silicon embedded sensor. In this case, the response started to produce a measurable response with an applied load of 100g. Therefore, it had an approximately sensitivity of 1N. This experiment was performed with a balance, recording simultaneously the weight it shown and the sensor output.

In order to prove the calibration curve obtained, the grasping of several objects was performed. In this case, the sensor output response when holding a 100g-object was around 10N and a 200g-object around 20N as shown in Figure 4.2 . When holding a small box and scissors, the response was similar to a 100g-object, being the last one more irregular. These irregularities presented in the scissors graph may be due to its non-uniform shape; therefore, when grasping from different parts the force required was dissimilar.

It is difficult to calculate the exact force required for holding an object. If only the weight was considered, applying Newton's Law:

$$F_g = m * a \cong m * 10\ [N], \qquad (5.1)$$

$$being:\ m = 100g \rightarrow F_{g1} = 0.1 * 10 = 1N$$

$$m = 200g \rightarrow F_{g2} = 0.1 * 10 = 2N$$

So, if we supposed that the subject was only counteracting the applied load the results would be 10 times higher than the theoretical ones. However, in order for objects not to slip and to maintain them hold, the patient needed to eject a force much higher than the weight, which corresponded to the obtained data.

Another aspect to consider was that the measuring zone in the force sensor is small. Hence, a change in orientation of the same object would also cause a different sensor output value, if it got out the sensing area.

Concluding, it could be argued that although the finger-tip sensor response was linear and scaled, the value was an approximated one since the method used for obtaining it was slightly rudimentary. Moreover, the force each patient applied when grasping objects of the same size and weight was different, being therefore a very subjective measurement.

However, the easiest and most efficient way to use this sensor was to apply a threshold. Recording data from several subjects, it could be estimated the force they were performing and the minimum to consider an active movement. Using this value as a feedback, SMA could be activated when the force sensor noticed that the patient was not pressing with enough force to grasp the object.

In the development of this project, nevertheless, the force sensor value was only used as an informative parameter, to prove its usefulness when embedded in silicone.

5.2. SMA contraction during flexion and extension

Wires' contraction was measured both when actuators were activated simultaneously and when each fibre was activated at a time. In order to produce the Joule's effect that induced fibres contraction, the GAIN – which represented the distance tendons move in [mm] – was set to a value between 0 – 60 [mm]. When this GAIN was fixed, it worked as the reference signal aimed to achieve.

The first test performance was to prove that the supplied voltage was appropriate and that SMA actually contracted when a reference signal was applied. The GAIN was set to 50 in two small time intervals, successively for each finger, and the SMA response was observed on Figure 4.3. It was proved that the position fixed to each finger was achieved with high accuracy and almost immediately, proving that the current going through the fibres was enough to activate them. It could also be observed that the position after removing the stimulus was not the same as its initial value, since the Shape Memory Alloy presented hysteresis.

Once the independent movement of fingers was studied, pincer grasp needed to be evaluated. This motion corresponded to simultaneous flexion of three fingers, as shown in Figure 4.4. During this experiment, no extension was performed; in fact, it could be argued that the cables in charge of performing extension were not tightened because the measured position did not change, as observed in Figure 4.6. If the tendons were clamped, the sensor would also notice a change in extension graph although this process was not actuated.

In the development of this experiment, a constant GAIN value between 40 - 50 was fixed. In order to control SMA contraction, the ENABLE function was alternating between 0-1, as stated on the previous chapter. In this case, the extension was not actuated but active by the patient, thus the recovery of the initial position was achieved due to the subject’s force.

The second pincer grasp trial consisted both on extension and flexion of three fingers but thumb (only flexed). These results were interesting to understand whether the antagonist movement was important. In this case, and in the following experiments, the ENABLE was maintained constant in 1 and only the reference signal was alternating between a high position (around 50) and 0, causing SMA heating and cooling.

It can be seen that as thumb had not been extended and the subject did not move it voluntarily either, the thumb SMA wire only responded to the first pulse flexion signal (Figure 4.7). Once it reached the maximum position, it kept that value, as no antagonism mechanism changed it and the reference signal sent during the second cycle was equal to the first one. A similar behaviour seemed to occur for index finger extension; however, its flexion was being performed correctly and therefore in this case the problem may have been that the wire was not firmly tightened to perform extension to the desired extent – after the first cycle.

Middle finger flexion of this same trial presented a strange behaviour (Figure 4.7). When the GAIN signal was still on 50, the SMA fibres decreased their position. This could be a problem with the controller. If PID values were not the perfectly fitting this experiment, the SMA could exceed the reference position or not be able to maintain it, as occurred in this case. However, as this was the only trial that did not work as expected, the controller is assumed to be adequate for this purpose, although a further study would be recommended.

So as to perform the last experiment, both flexion and extension of three fingers simultaneous was carried out. In this case, no patient active force was applied, so as to test the real contraction generated by the exoskeleton.

In this trial, the goal was to study the behaviour of SMA fibres when a square wave was introduced as an input both for flexion and extension – with a 5 second delay in order to avoid the activation of contrary movements at the same time.

Three consecutive flexion-extension cycles were performed using small pulses (4 seconds width) with a reference signal of value 50. In all cases, the reference value was accurately achieved at the end of the square pulse. It could be observed that the cables still maintained the previous position once the reference signal was set to zero; i.e. during 2-2.5s after the GAIN was set to 0, the SMA was at position 50mm.

This phenomenon could be explained with two reasons. The first one, the fact that SMA cooling was not achieved and therefore, although current was not flowing through the wires, they still maintained their temperature and size. As joule's effect was based on increasing Nitinol's temperature and the fibres were introduced inside Bowden cables so as not to damage the patient, heat dissipation was not achieved. Hence, when several cycles were performed the temperature increased with the number of repetitions, causing wires' recovery to be slow and relaxation position to increase with each cycle.

The second one was the fact that the exoskeleton was the only mechanism that moved the hand. When the three fingers acquired a flexed position, and there was no antagonism actuation, they stayed at the previous one. As it could be seen on the plots, once the contrary motion was active, the fingers move in the opposite direction acquiring their extension.

Another interesting feature that proved the functioning of this system was the correspondence between flexion and extension plots. If a flexion and extension plot of the same finger were superimposed as in Figure 5.1, it could be easily identified the correspondence in position between them. A short time gap was required between the opposite movements so as not to break the SMA fibres – allowing cooling.

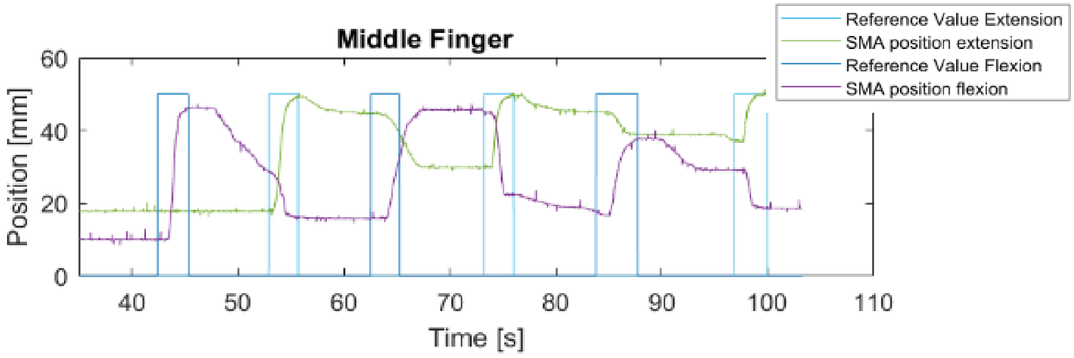

Figure 5.1.- Superimposed flexion and extension of middle finger

In summary, taking into consideration all the data obtained from the several tests performed, there were specific conclusions that could be reached. The first one could be that the SMA behaviour essentially mimicked what expected; the fixed position was reached with high accuracy and immediately after the pulse was generated. This way, SMA fibres acted as an easily controlled actuator mechanism in this exoskeleton.

Another conclusion to bear in mind is the fact that temperature increases with the number of cycles. Therefore, if we were intended to develop the exercise for too long, the SMA contraction would be successively reduced, as the range of movement would decrease due to materials' hysteresis and lack of heat dissipation.

The consistency of these results could be proved with the concordance between flexion and extension when the cables were sufficiently tightened, such as in the last two trials, and visually observed with fingers' movement (Figure 4.10).

6. ECONOMIC EVALUATION

The final estimation of the developing cost of the device should include both the cost of the independent components and the human labour required for carrying out the prototype design and assembly. Moreover, in this chapter it is also evaluated the socio-economic impact of this device on the current society.

6.1. Materials' budget

To evaluate the final cost of the device itself, all independent components should be evaluated individually. Electronic components, actuators, software licenses, exoskeleton's glove materials and sensors need to be taken into account for this price estimation, as shown in TABLE 6.1.

TABLE 6.1.- FABRICATION AND MATERIALS' COST

	COMPONENT	PRICE
ELECTRONIC SYSTEM	- Microcontroller	16.50 €
	- Power board	26.82 €
	- Connectors and cables	20 €
TOTAL ELECTRONIC		63.32 €
ACTUATORS	- Linear potentiometers	9 €
	- Mechanical structure	1,000 €
	- Bowden Cable (1.2€/m * 1.2m/wire * 6wires)	8.64 €
	- Teflon Tubes (1.4€/m * 1.2m /wire *6 wires)	10.08 €
	- SMA (6€/m * 1.2m /wire * 6 wires)	43.20 €
TOTAL ACTUATORS		1,070.92 €
SOFT EXOSKELETON GLOVE	- Silicone Mold Star 15 slow	29.00 €
	- Silicone Dragon Skin 30	31.00 €
	- Teflon Tubes (1.4€/m * (0.40m/w *4w + 0.2m/w*2w))	2.8 €
	- Non-actuated SMA (6€/m * (0.40m/w *4 + 0.2m/w*2w))	12 €
	- Velcro	1.5 €
	- Force sensors – Sparkfun	5.05 €
	- 3D plastic pieces	50 €
TOTAL SILICONE GLOVE		131.35 €
SOFTWARE LICENSES	- MATLAB – Simulink	2,000 €
	- Creo Parametric	1,000 €
TOTAL SOFTWARE		3,000 €

It must also be considered that both the actuators and electronic system were already created. Therefore, that money has not been invested in the development of this project. Another aspect to be taken into consideration is that with University agreements, both MATLAB and Creo Parametric licenses are of free use.

So, the cost of the current project corresponds mainly to ‘Total Silicone Glove’ cost, although the real value of the entire system would imply adding up software, electronic and actuators expenses.

6.2. Human’s labour budget

The elaboration of this soft hand exoskeleton has been a laborious process which has required human work in order to achieve it. Therefore, for obtaining a cost estimate of this product it is also required to evaluate the personal needed on the entire process, presented on TABLE 6.2.

TABLE 6.2.- HUMAN’S LABOUR COST

	Time	Price per Hour	Total
Biomedical Engineering Student	360 h	8 €	2,880 €
Engineering Supervisor	30 h	15 €	450 €
Total			3,330 €

**Assuming that the approximate workload corresponds to 12 ETCs but the student requires expert supervision; the price per hour is also an estimation based on a monthly salary of 2,400 € for an engineering and 1,280 € for an undergraduate student at internships -full time in both cases.*

6.3. Socio-economic impact

The presented exoskeleton was built to be used in rehabilitation exercises or to function as an assistive device. Nowadays, as it was already mentioned, with the progressive population’s ageing, mobility problems in upper extremities are becoming more frequent. Therefore, creating a comfortable, low-cost and accessible device able to improve hand function would imply a significant patients’ benefit.

A soft hand exoskeleton such as the one developed during this project represents an individualized solution for patients with hand mobility problems. Constructed with a mould making silicone, it is an easy procedure to adapt the shape and size to the specific patient hand. Furthermore, silicone is an easily washable and biocompatible material, hence making it useful in daily life activities.

Regarding the cost, it is a low-cost product if compared with commercial alternatives. Without taking into consideration the software licenses, this proposed solution is around 1,300 €. Evaluating the current devices on the market that were already presented on the State of the Art, their price is significantly higher. Hand of hope [29] offers the whole rehabilitation apparatus for both hands, which includes the EMG sensors, the glove and the interactive games, at a final price of 20,000 €. Rapael polymeric robotic device [27] is more expensive, as its selling price, either for a clinic or personal use, is around 15,000 € - including only one hand exoskeleton. Exo-glove poly is intended to be more affordable, but it does not explicitly state the final price of the device, as it has not been introduced to the market yet. Finally, Amadeo [30] system, an instrument expected to be used in clinics, has a final estimate price of 86,000 €. Taking into consideration this figures, a complete soft hand exoskeleton with a final price lower than 1,500 € presents a very competitive solution.

Furthermore, this device is a good alternative in rehabilitation therapies; having several exoskeletons would reduce the number of therapists, who would only be required to supervise. This way, sanitary system would obtain an economical benefit, since buying these devices would reduce the number of physiotherapists, and therefore the wages' expenditure.

Apart from the monetary profit if introduced in rehabilitation therapies, the main advantage would be the social improvement when functioning as an assistance device for patients with paralysis. Recovering hand function could allow patients to become self-sufficient again whilst performing routine activities.

So, it could be stated that if this new device was introduced to the market, it would produce a favourable outcome from both a social and economic point of view. It would present an affordable alternative for exercising and recovering hand function.

7. CONCLUSION

In this last chapter, the final product is discussed. The objectives that have been satisfied with the resulting device are argued as well as the aspects that were not completely covered by it and therefore require further study.

7.1. Project outcome

The resulting exoskeleton developed throughout this bachelor thesis satisfies the proposed objectives. The final device is very light, not noisy and low cost. All electronic components and SMA fibres are isolated, being safe for patient use.

The final product lightless can be proved with a final weight lower than 500g. The exoskeleton glove only weights 97g and the mechanical structure carrying the linear potentiometers - which needs to be positioned around the arm- 330g. The electronic components, Bowden cables and other parts of the device are not accounting for the final weight because they are not required to be held by the patient.

Moreover, it is an adaptable hand exoskeleton. If the patient’s hand does not fit correctly with the developed glove, slight adjustments could be performed on the mould dimensions without modifying the working principles. Since it is an open glove, it makes it easier for the patients to put it on, even for those suffering from hand rigidity or paralysis.

SMA actuation provides a fast and not noisy actuation mechanism. Therefore, being very convenient for usage in daily life activities, in comparison with electrical motors or hydraulic actuators.

Finally, this soft hand exoskeleton proposes a comfortable device, affordable both for individual use and for being included in rehabilitation centres. An actuated device capable of implementing hand flexion and extension which costs less than 1,400€ presents a competitive alternative to similar current commercial products, as it was discussed in previous section.

Together with this presented project, there are a set of light, low-cost, SMA-actuated exoskeletons that are being built in the Robotics lab, which were developed with similar objectives and in order to take advantage of the favourable characteristics presented by Shape Memory Alloy actuators [53] [51].

Specifically, this soft hand exoskeleton was also used with a different software program and in combination with EMG signals recorded from a special bracelet. Using the software developed by C. Ibáñez for another bachelor thesis [53], it was possible to record and analyse what the subject was doing – either catching or releasing an object – and use this signal to stimulate SMA contraction of the actuated glove, enhancing the usefulness and versatility of this device.

I hence conclude that this product successfully satisfies the requirements proposed and that the outcome is in general satisfactory. Although there may be several aspects that could be improved, the motion performance, patient safety and well-being are insured goods.

7.2. Future work

Taking into consideration the final device weaknesses, there are still several aspects that could be improved.

Firstly, the mechanical support. This structure is heavy, if compared with the exoskeleton glove, and totally rigid. It is rectangular and not flexible, having all the sensors placed in parallel orientation, equidistant from both sides.

In order to perform both flexion and extension with the same mechanical structure, sensors should be oriented in a different manner. If it was a rounded structure, instead of the current rectangular one, it would fit better on the patients' arm. Furthermore, if the linear potentiometers were placed three and three, with a small gap between these two groups, it would be easier for having a completely linear motion both in flexion and extension.

Reducing the size of this structure would also be beneficial, as the weight would decrease, and patient comfort would be enhanced.

Another aspect that could be improved is the force sensors placed on the finger's tip. There are two concerns regarding them: the size and its use. If we introduced a slightly bigger sensor in the exact same place, the force measurement would be much more accurate than the one obtained with the current sensors.

The other aspect to be changed may be their utility. For the current exoskeleton, this force sensor output is not used as any feedback variable. However, assuming that this device is intended to help patients to perform pincer grasp, it could be used as the reference signal to stimulate flexion. If the patient is trying to grip an object and the force sensor provides a low value, this could initiate SMAs' contraction in order to help him to catch it. On the other hand, if he is ejecting enough force, it could be seen as a stop signal to stop flexion or even initiate extension.

Regarding the electronic system, the controller should be deeply analysed. It works as expected in most of the trials but presents a strange behaviour in one of the movements performed. Therefore, a further study of PID values or an evaluation of different controller alternatives may be another key future step so as to improve the final device performance.

Considering all these enhancements, it would be possible to achieve a completely reliable and compact device intended to be used in both rehabilitation exercises and in assistive therapies, going a step further in the proposed objectives.

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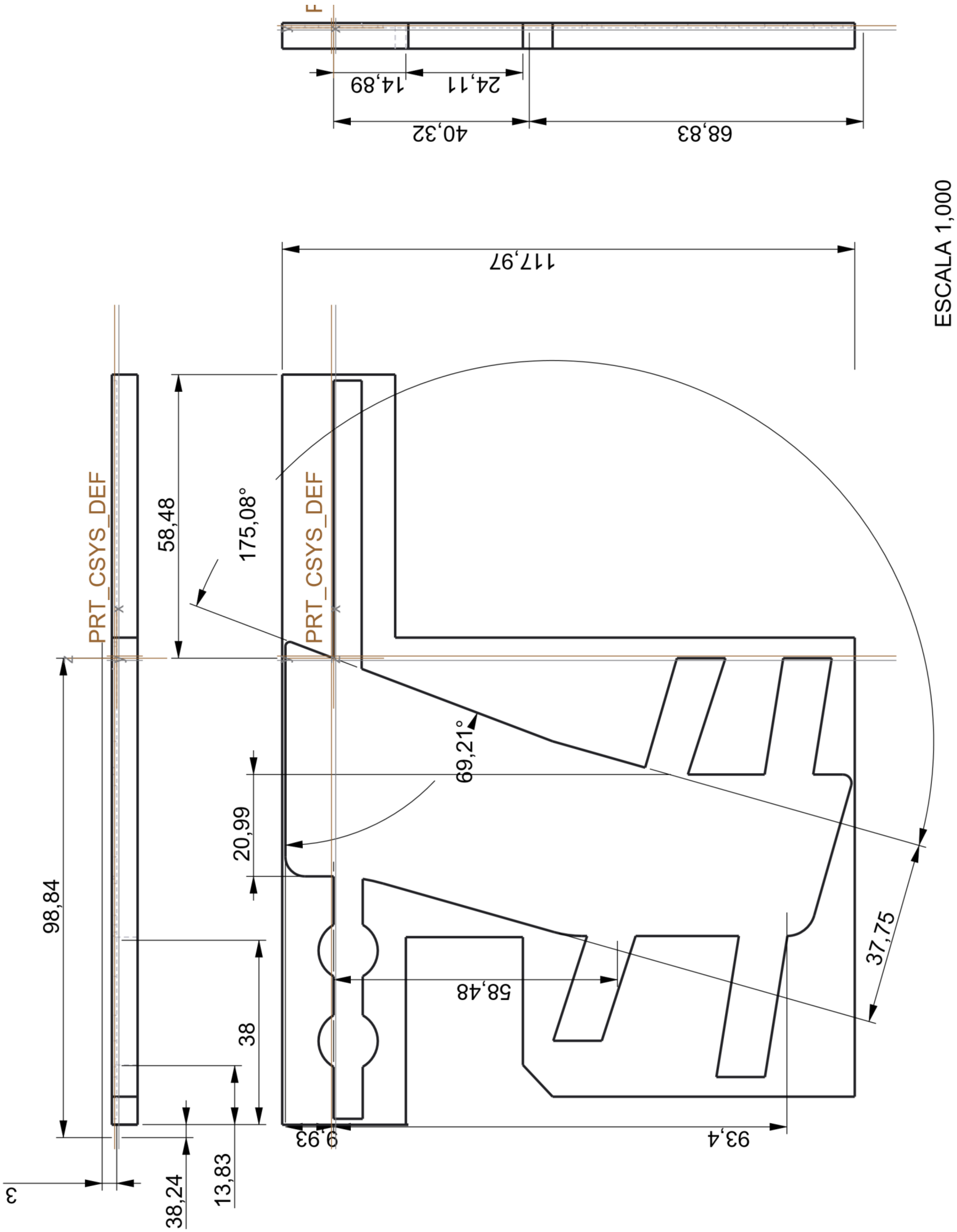
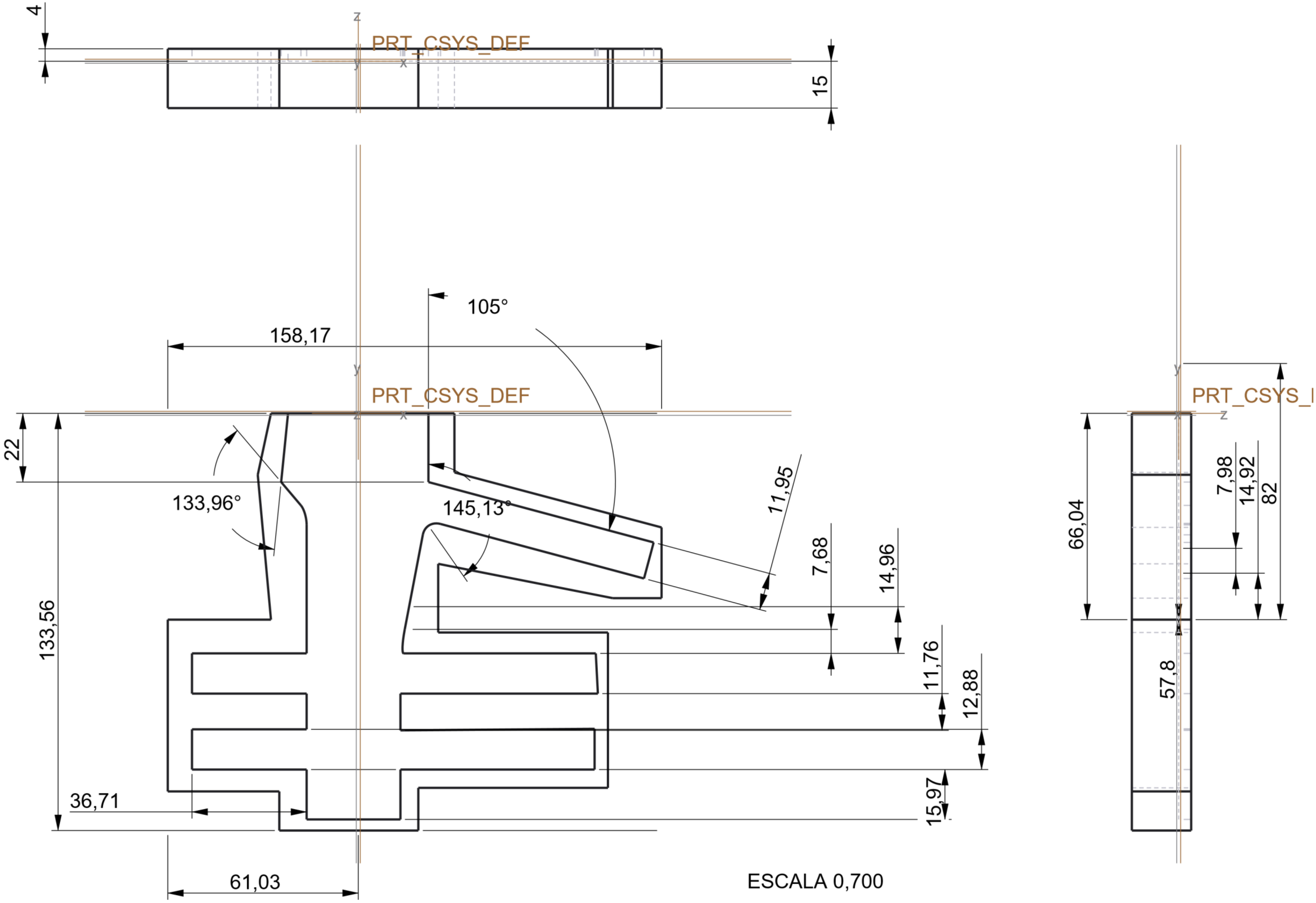
APPENDIX A - DESIGN PLANS OF PLASTIC MOULDS

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PRT_CSYS_DEF
105°
158,17
PRT_CSYS_DEF
22
133,96°
145,13°
11,95
7,68
14,96
11,76
12,88
15,97
133,56
36,71
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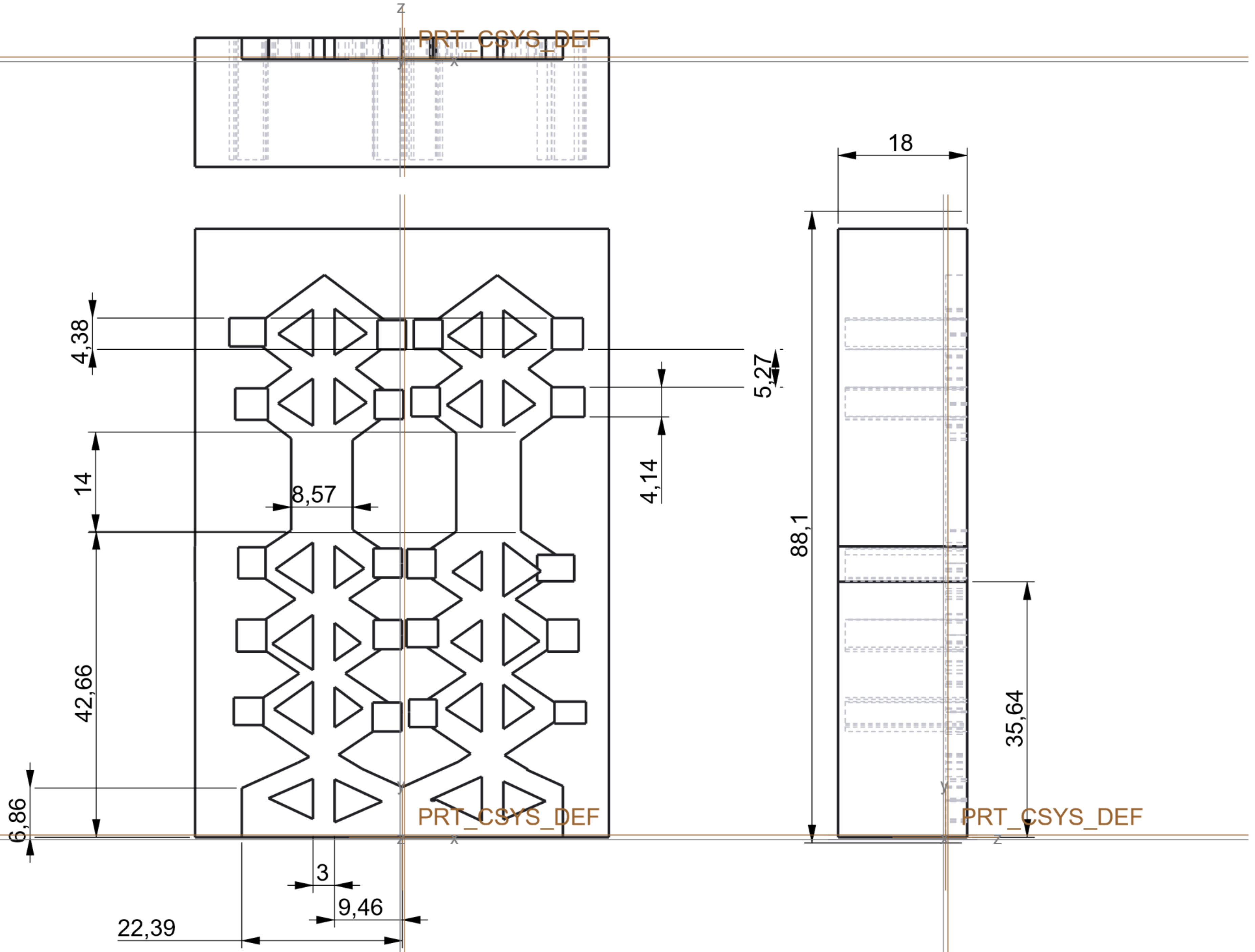
PRT_CSYS_
66,04
7,98
14,92
82
57,8
ESCALA 0,700

ESCALA 1,400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z
y
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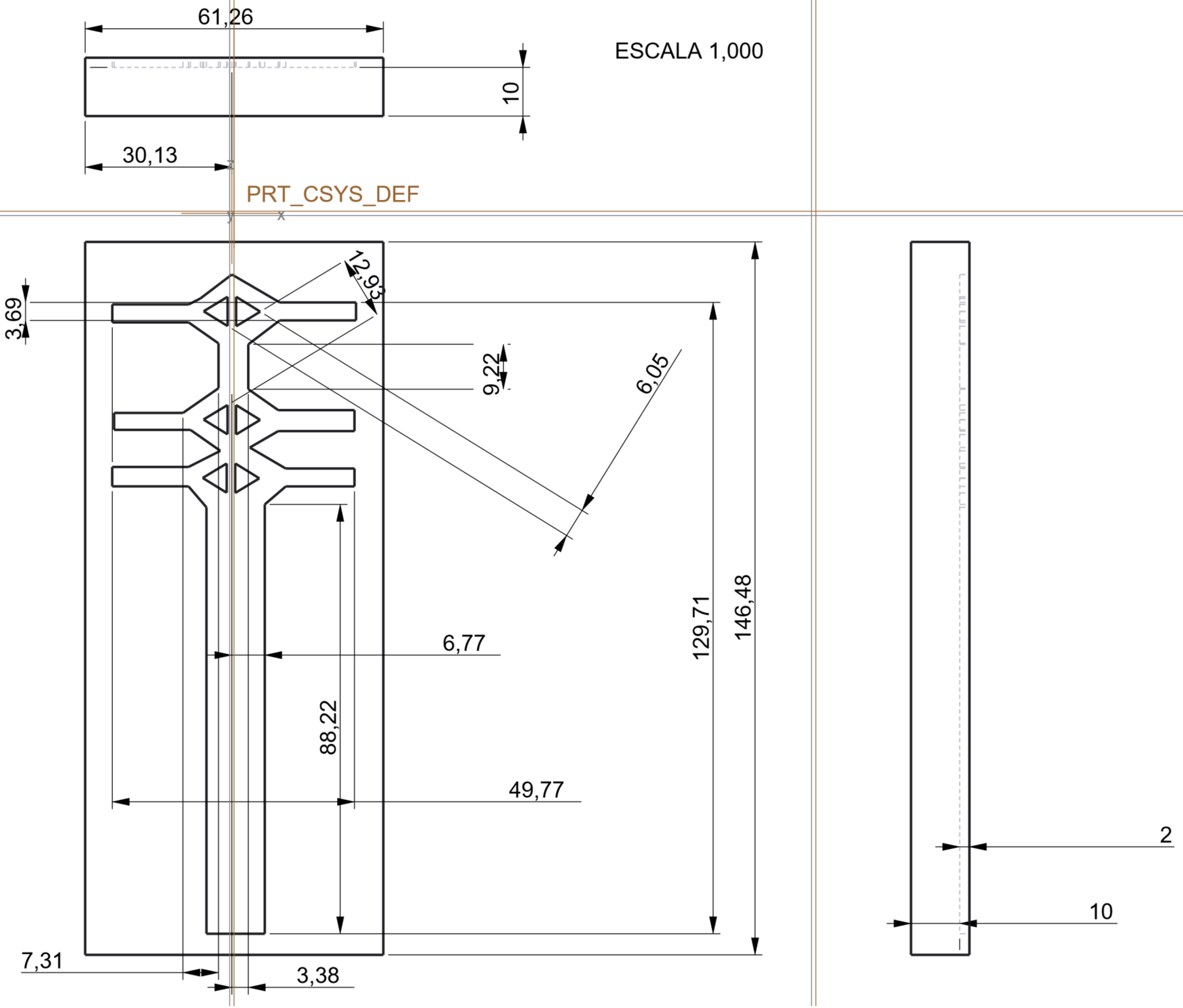
42,66
6,86
PRT_CSYS_DEF
x
3
9,46
22,39

ESCALA 1,000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y
x
z
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3,69
9,22
6,05
6,77
88,22
49,77
129,71
146,48
7,31
3,38
2
10

APPENDIX B – LOW PROFILE SLIDE POTENTIOMETER

Features

- Carbon element
- Metal housing
- 15-60 mm travel
- Single and dual gang
- Center detent option
- Dust cover option
- RoHS compliant*

BOURNS® PRO AUDIO

PTA Series - Low Profile Slide Potentiometer

Electrical Characteristics

Taper	Linear, audio
Standard Resistance Range	1 K ohms to 1 M ohms
Standard Resistance Tolerance	±20 %
Residual Resistance	500 ohms or 1 % max.
Insulation Resistance	Min. 100 megohms at 250 V DC

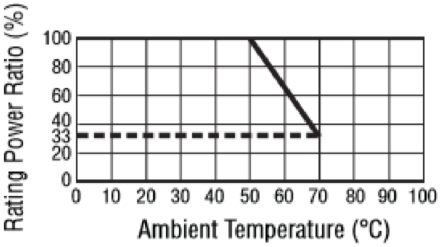
Environmental Characteristics

Operating Temperature	-10 °C to +50 °C
Power Rating, Linear	
15 mm	0.05 W (0.025 W Dual Gang)
20 mm	0.1 W (0.05 W)
30 mm	0.2 W (0.1 W)
45 mm	0.25 W (0.125 W)
60 mm	0.25 W (0.125 W)
Power Rating, Audio	
15 mm	0.025 W (0.015 W Dual Gang)
20 mm	0.05 W (0.025 W)
30 mm	0.1 W (0.05 W)
45 mm	0.125 W (0.06 W)
60 mm	0.125 W (0.06 W)
Maximum Operating Voltage, Linear	
15 mm	100 V DC
20-60 mm	200 V DC
Maximum Operating Voltage, Audio	
15 mm	50 V DC
20-60 mm	150 V DC
Withstand Voltage, Audio	1 Min. at 300 V AC
Sliding Noise	100 mV maximum
Tracking Error	3 dB at -40 to 0 dB

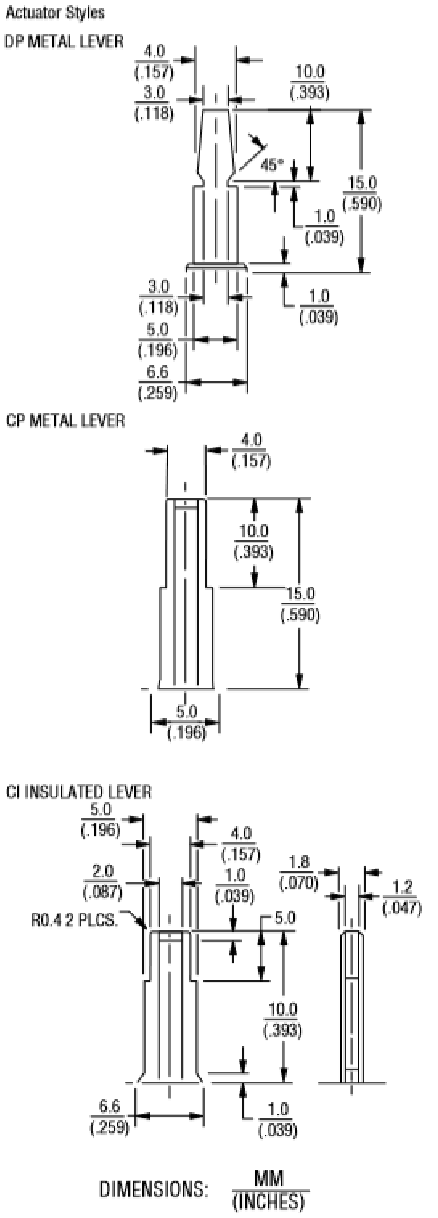
Mechanical Characteristics

Operating Force	30 to 250 g-cm
Stop Strength	5 kg-cm min.
Sliding Life	15,000 cycles
Soldering Condition	300 °C max. within 3 seconds
Travel	15, 20, 30, 45, 60 mm

Derating Curve



Lever Style & Product Dimensions



How To Order

PTA 15 4 3 - 2 0 10 DP B 203

Model

Stroke Length
- 15 = 15 mm
- 20 = 20 mm
- 30 = 30 mm
- 45 = 45 mm
- 60 = 60 mm

Dust Cover Option
- 4 = No Dust Cover
- 5 = Rubber Dust Cover**

No. of Gangs
- 3 = Single Gang
- 4 = Dual Gang

Pin Style
- 2 = PC Pins Down Facing

Center Detent Option
- 0 = No Detent
- 2 = Center Detent

Standard Lever Length (See Table)
- 10 = 10 mm (CI Lever)
- 15 = 15 mm (DP, CP and CI)

Lever Style
- DP = Metal Lever (Refer to Drawing)
- CP = Metal Lever (Refer to Drawing)
- CI = Insulated Lever (Refer to Drawing)

Resistance Taper
- A = Audio Taper
- B = Linear Taper

Resistance Code (See Table)

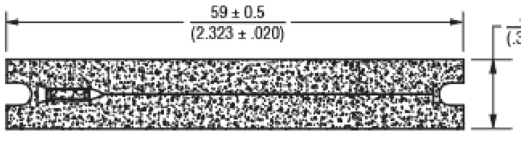
Other styles available.

** Part numbers with dust covers must be mounted with screws to a panel to prevent issues with the dust cover during usage.

Standard Resistance Table

Resistance (Ohms)	Resistance Code
1,000	102
2,000	202
5,000	502
10,000	103
20,000	203
50,000	503
100,000	104
200,000	204
500,000	504
1,000,000	105

Optional Dust Cover



NOTE: DUST COVER HAS ADHESIVE BACK.

T = $\frac{0.3 \pm 0.1}{(.0118 \pm .004)}$

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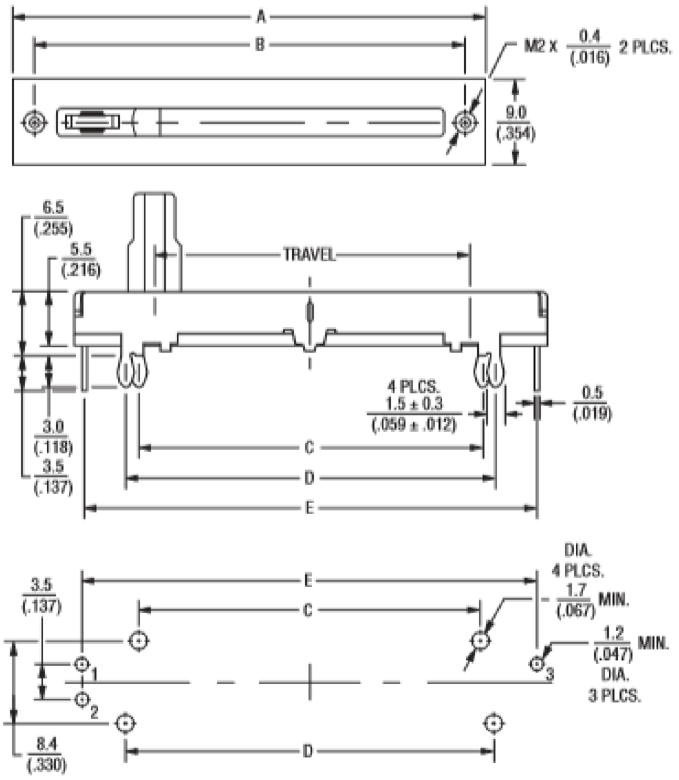
*RoHS Directive 2002/95/EC Jan. 27, 2003 including annex and RoHS Recast 2011/65/EU June 8, 2011.
Specifications are subject to change without notice.

PTA Series - Low Profile Slide Potentiometer

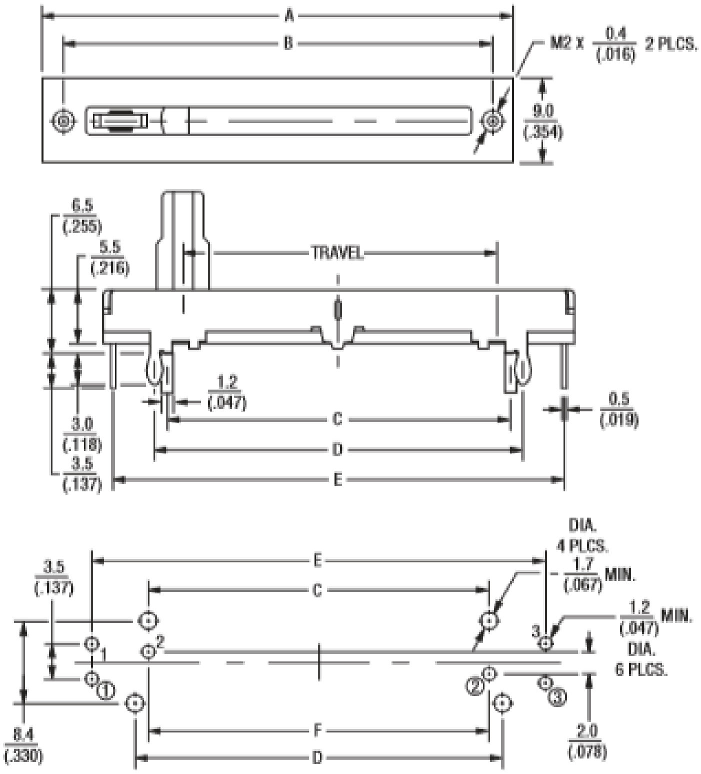
BOURNS®

Product Dimensions

PTAxx43



PTAxx44



DIMENSIONS: MM (INCHES)

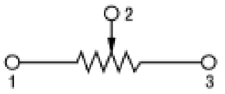
Single Gang Dimensions

Model	A	B	C	D	E	Travel
PTA1543	30 (1.18)	26 (1.02)	17.8 (.700)	20.2 (.795)	28.5 (1.12)	15 (.59)
PTA2043	35 (1.37)	31 (1.22)	22.8 (.897)	25.2 (.992)	33 (1.29)	20 (.787)
PTA3043	45 (1.77)	41 (1.61)	32.8 (1.29)	35.2 (1.38)	43.5 (1.71)	30 (1.18)
PTA4543	60 (2.36)	56 (2.20)	47.8 (1.88)	50.2 (1.97)	58.5 (2.30)	45 (1.77)
PTA6043	75 (2.95)	71 (2.79)	62.8 (2.47)	65.2 (2.56)	73.5 (2.89)	60 (2.36)

Dual Gang Dimensions

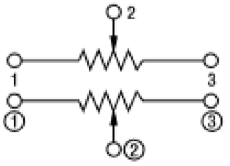
Model	A	B	C	D	E	F	Travel
PTA1544	30 (1.18)	26 (1.02)	17.8 (.700)	20.2 (.795)	28.5 (1.12)	18 (.708)	15 (.59)
PTA2044	35 (1.37)	31 (1.22)	22.8 (.897)	25.2 (.992)	33 (1.29)	23 (.905)	20 (.787)
PTA3044	45 (1.77)	41 (1.61)	32.8 (1.29)	35.2 (1.38)	43.5 (1.71)	33 (1.29)	30 (1.18)
PTA4544	60 (2.36)	56 (2.20)	47.8 (1.88)	50.2 (1.97)	58.5 (2.30)	48 (1.88)	45 (1.77)
PTA6044	75 (2.95)	71 (2.79)	62.8 (2.47)	65.2 (2.56)	73.5 (2.89)	63 (2.48)	60 (2.36)

SINGLE GANG



SCHEMATIC

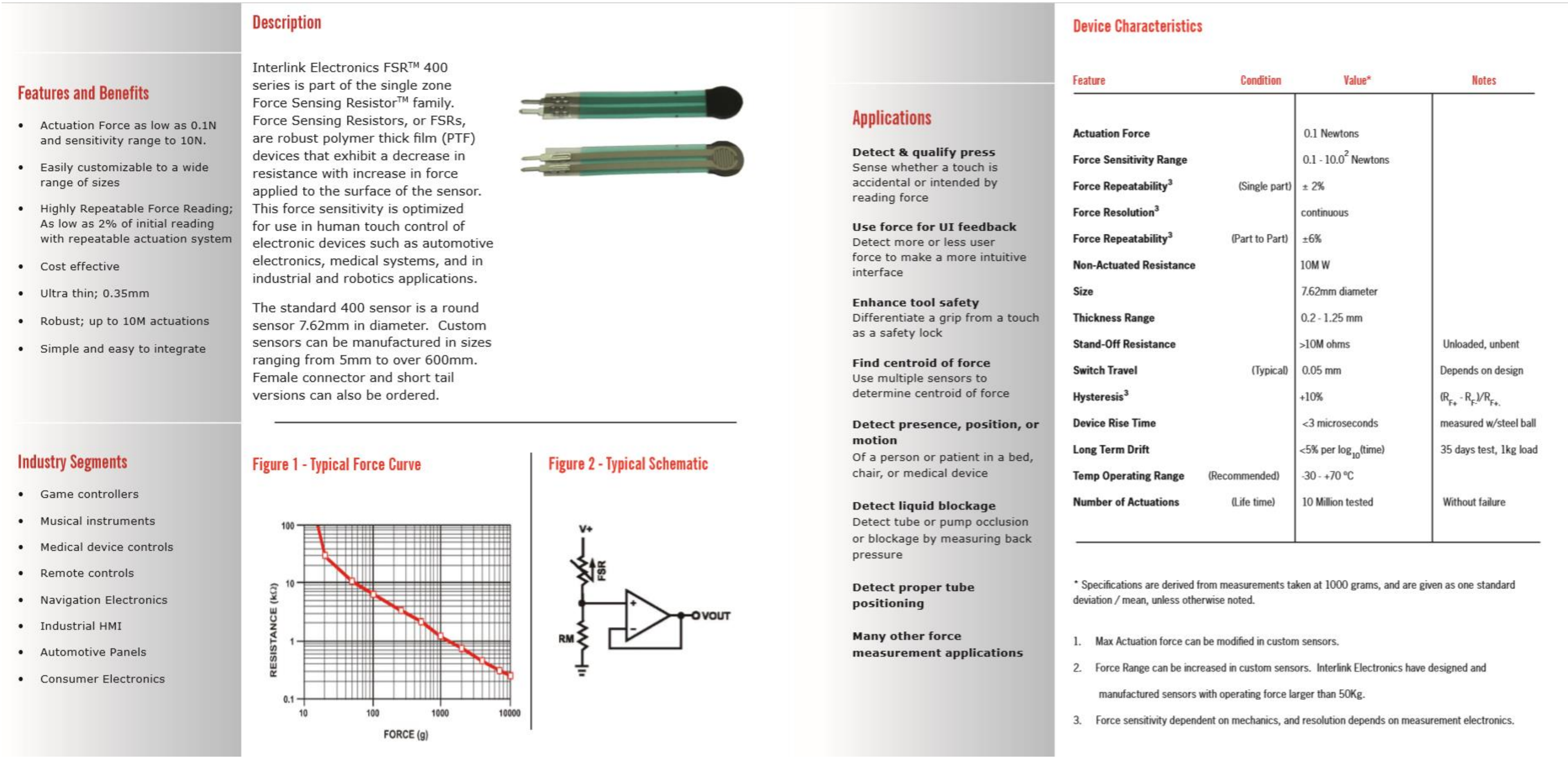
DUAL GANG



SCHEMATIC

REV. 12/14

APPENDIX C – SPARKFUN SENSOR CHARACTERISTICS



Features and Benefits

- Actuation Force as low as 0.1N and sensitivity range to 10N.
- Easily customizable to a wide range of sizes
- Highly Repeatable Force Reading; As low as 2% of initial reading with repeatable actuation system
- Cost effective
- Ultra thin; 0.35mm
- Robust; up to 10M actuations
- Simple and easy to integrate

Industry Segments

- Game controllers
- Musical instruments
- Medical device controls
- Remote controls
- Navigation Electronics
- Industrial HMI
- Automotive Panels
- Consumer Electronics

Description

Interlink Electronics FSR™ 400 series is part of the single zone Force Sensing Resistor™ family. Force Sensing Resistors, or FSRs, are robust polymer thick film (PTF) devices that exhibit a decrease in resistance with increase in force applied to the surface of the sensor. This force sensitivity is optimized for use in human touch control of electronic devices such as automotive electronics, medical systems, and in industrial and robotics applications.

The standard 400 sensor is a round sensor 7.62mm in diameter. Custom sensors can be manufactured in sizes ranging from 5mm to over 600mm. Female connector and short tail versions can also be ordered.

Figure 1 - Typical Force Curve

Figure 2 - Typical Schematic

Applications

Detect & qualify press
Sense whether a touch is accidental or intended by reading force

Use force for UI feedback
Detect more or less user force to make a more intuitive interface

Enhance tool safety
Differentiate a grip from a touch as a safety lock

Find centroid of force
Use multiple sensors to determine centroid of force

Detect presence, position, or motion
Of a person or patient in a bed, chair, or medical device

Detect liquid blockage
Detect tube or pump occlusion or blockage by measuring back pressure

Detect proper tube positioning

Many other force measurement applications

Device Characteristics

Feature	Condition	Value*	Notes
Actuation Force		0.1 Newtons	
Force Sensitivity Range		0.1 - 10.0^2 Newtons	
Force Repeatability^3	(Single part)	± 2%	
Force Resolution^3		continuous	
Force Repeatability^3	(Part to Part)	±6%	
Non-Actuated Resistance		10M W	
Size		7.62mm diameter	
Thickness Range		0.2 - 1.25 mm	
Stand-Off Resistance		>10M ohms	Unloaded, unbent
Switch Travel	(Typical)	0.05 mm	Depends on design
Hysteresis^3		+10%	$(R_{F+} - R_{F-})/R_{F+}$.
Device Rise Time		<3 microseconds	measured w/steel ball
Long Term Drift		<5% per $\log_{10}$(time)	35 days test, 1kg load
Temp Operating Range	(Recommended)	-30 - +70 °C	
Number of Actuations	(Life time)	10 Million tested	Without failure

* Specifications are derived from measurements taken at 1000 grams, and are given as one standard deviation / mean, unless otherwise noted.

1. Max Actuation force can be modified in custom sensors.
2. Force Range can be increased in custom sensors. Interlink Electronics have designed and manufactured sensors with operating force larger than 50Kg.
3. Force sensitivity dependent on mechanics, and resolution depends on measurement electronics.

Application Information

FSRs are two-wire devices with a resistance that depends on applied force.

For specific application needs please contact Interlink Electronics support team. An integration guide is also available.

For a simple force-to-voltage conversion, the FSR device is tied to a measuring resistor in a voltage divider configuration (see Figure 3). The output is described by the equation:

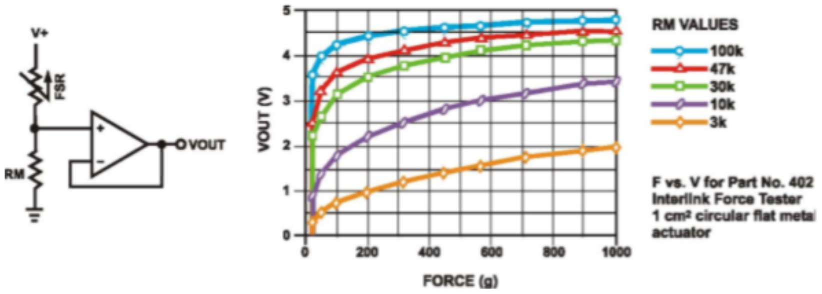
$$V_{OUT} = \frac{R_M V+}{(R_M + R_{FSR})}$$

In the shown configuration, the output voltage increases with increasing force. If R_{FSR} and R_M are swapped, the output swing will decrease with increasing force.

The measuring resistor, R_M, is chosen to maximize the desired force sensitivity range and to limit current. Depending on the impedance requirements of the measuring circuit, the voltage divider could be followed by an op-amp.

A family of force vs. V_{OUT} curves is shown on the graph below for a standard FSR in a voltage divider configuration with various R_M resistors. A (V+) of +5V was used for these examples.

Figure 3



Part No. 400

- Active Area: 5.08mm
- Nominal thickness: 0.35 mm

Mechanical Data