Politecnico Di Torino
Department of Control and Computer Engineering
(DAUIN)

MASTER THESIS

DESIGN AND CONTROL OF A ROBOTIC EXOSKELETON FOR WRIST REHABILITATION

Author: Salim Farran
Supervisors: Prof.Terenziano Raparelli, Prof.Daniela Maffiodo

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Dedication

This thesis work is dedicated to my parents who have been a constant source of support and encouragement during the challenges of life, and whose good examples have taught me to work hard for the things that I aspire to achieve.

Acknowledgements

I would first like to thank my thesis advisor Dorin-Sabin Copaci and Prof. Dolores Blanco of the Robotics Lab at Universidad Carlos III de Madrid(this is where the thesis has been done). Dorin-Sabin Copaci was always available when I had a question about my research or I ran into a trouble spot. He consistently allowed this project to be my own work, but steered me in the right the direction whenever he thought I needed it. And I am gratefully indebted to them for their very valuable comments on this thesis.

I would also like to thank my supervisors Prof. Terenziano Raparelli and Prof. Daniela Maffiodo at Polytechnic of Turin for their availability whenever I needed help and had a question about my research project, and I am also gratefully indebted to them for their very valuable comments on this thesis.

Finally, I must express my very profound gratitude to my parents for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Salim Farran

"Once you stop learning, you start dying" Albert Einstein

Declaration of Authorship

I hereby declare that the work done in this project is my own work. And that I'm the sole author of this master thesis and that I have not used any sources other than those listed in the bibliography and identified as references.

Date: Signature:

Abstract

Exoskeletons are becoming a very powerful tool to help therapists in the rehabilitation of patients who have suffered from neurological conditions. The aim of this work is to design and control a rehabilitation wearable exoskeleton for wrist joint with two degrees of freedom (DOF), for flexion-extension and adduction-abduction (radial and ulnar deviation), actuated using Shape Memory Alloy(SMA) based actuators. These actuators are shown to be appropriate by examining their characteristics. Using these actuators, the proposed device presented a very light weight and noiseless operation, in comparison with similar devices. The preliminary results obtained over real tests with the wrist exoskeleton are presented. This prototype demonstrates that SMA actuator technology is a viable alternative when investigating possible improvement of rehabilitation robotic devices in terms of weight, size and cost.

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Chapter 1

Introduction

1.1 Introduction and Motivation

The upper limb mobility can be affected by many musculoskeletal and neurological accidents limiting one's ability to perform activities of daily living, so its recovery becomes fundamental and a rehabilitation treatment is required to restore the normal function of the joints. Nowadays, robotic exoskeletons are playing an important role in the rehabilitation therapies and have proven to be effective in recovering the mobility of a joint more than manual therapies. They can increase the training intensity during the rehabilitation sessions, can be combined with gaming features and reduce the need for the presence of a therapist which can allow the treatment of several patients by one therapist at the same time and reduces the costs of the therapy sessions.

One of the most joints in the human body exposed to trauma, that is usually caused by falls, is the wrist joint that has an essential role in the human's daily life since it is used in most of the actions done by the human and it gives the ability to grasp and grab objects. Without adequate wrist mobility the flexibility of the fingers and the nerves of the forearm will also be affected. Hence, rehabilitation therapies are required to recover the wrist mobility and restore the correct hand function.

Most of the existing robotic devices used in the rehabilitation therapies to recover the mobility of the human joints are actuated by pneumatic actuators or electric motors. Besides, these commercial devices which are currently marketed can't be transported and installed easily due to their weight and complexity in their installation which obliges the patient to move to the rehabilitation centers which increases the cost on the patient and implicates time. In addition to their complexity, the elevated costs of these devices make them available only in the rehabilitation centers. Undoubtedly, the actuators used in these devices affects their costs and the total weight, and introducing another type of actuators could improve these aspects, and a good alternative solution could be the Shape Memory Alloy actuators.

Shape Memory Alloy (SMA) based actuators are a viable alternative when studying the possibility of improving the robotics exoskeletons that are used as rehabilitation devices, since they can help in constructing a device that presents a low weight, noiseless operation and low costs of fabrication. For this reason, in this work, a robotic exoskeleton for wrist rehabilitation will be developed using the SMA based actuators aiming to design a low-cost and a comfortable device.

1.2 Background

In the Systems Engineering and Automation Department of the Universidad Carlos III de Madrid, many researches had already emerged to develop rehabilitation devices actuated by SMA (Shape Memory Alloy). Within this department, in the RoboticsLab, a project was done by the student David Serrano aimed to design a rehabilitation wearable exoskeleton for wrist joint with two degrees of freedom (DOF) actuated by Shape Memory Alloy based actuators (Figures 1.1 and 1.2).

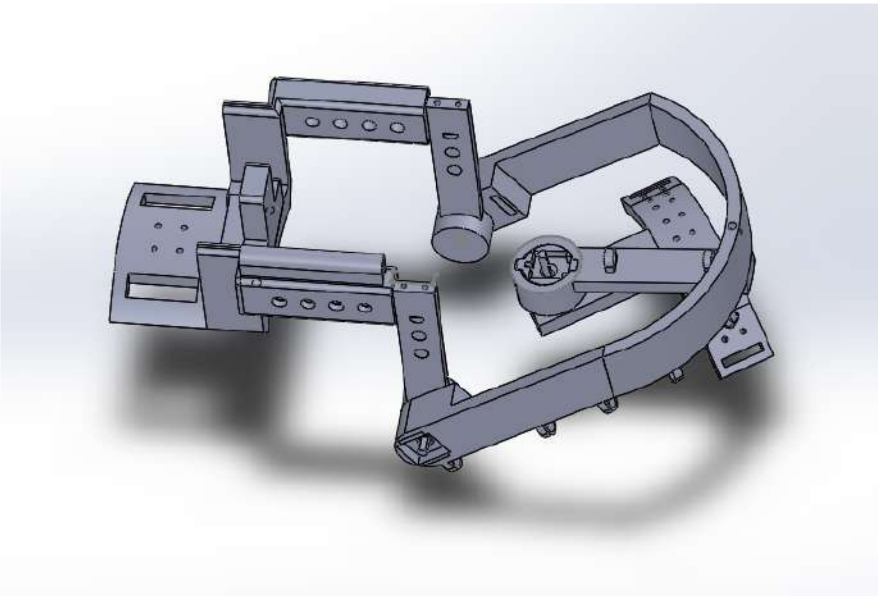


Figure 1.1: CAD model of the prototype proposed by David Serrano [16].

In his master's thesis work, titled "Diseño y Control de Un Dispositivo de Rehabilitación Para La Articulación de La Muñeca", David carried out the design, assembly, control and the necessary tests of a protoype of a wrist rehabilitation device. All the parts of the device were manufactured by 3D printing and from polyamide and aluminum, except 1 piece made completely from aluminum (polyamide to lighten the weight and aluminum to give robustness to the device). While carrying out the analysis of the device, several problems arose that need to be solved. In this project, another prototype will be developed aiming to eliminate to the maximum the problems found in the previous prototype.

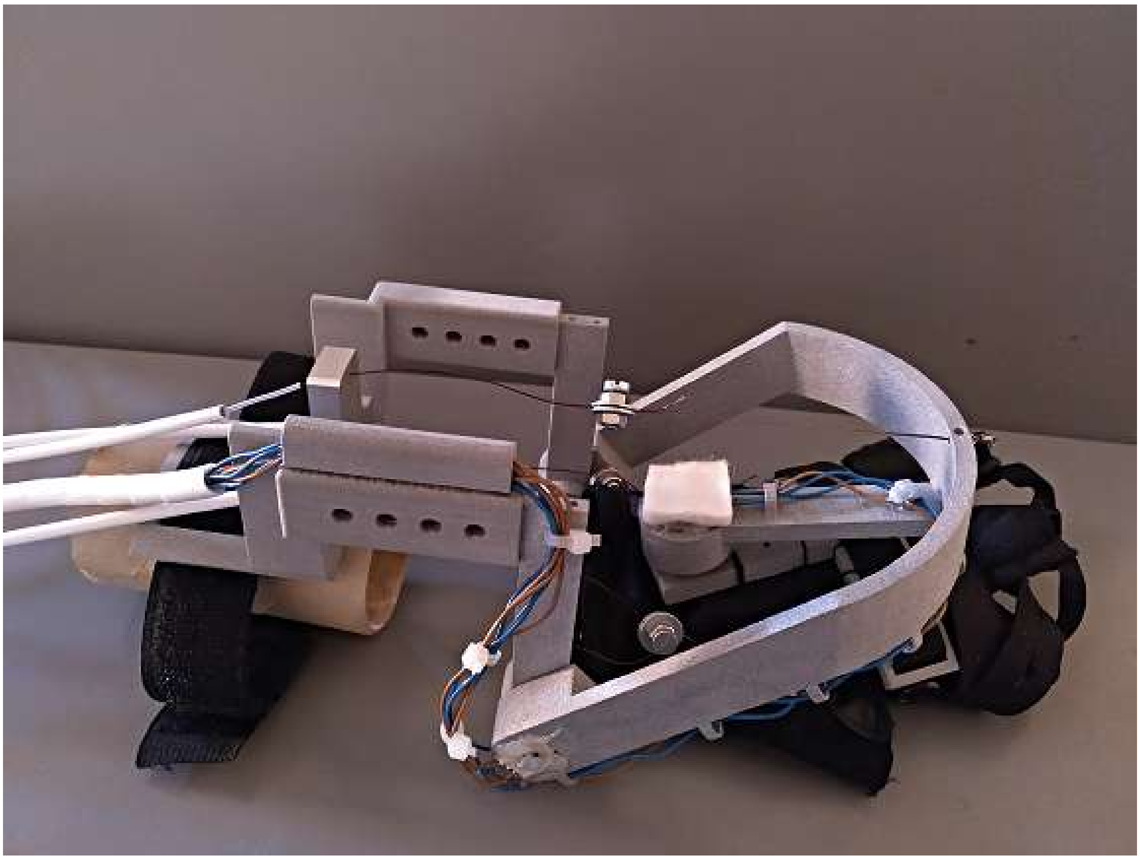


Figure 1.2: Prototype proposed by David Serrano [16].

1.3 Objectives

The main aim of the research presented in this project is to develop a robotic exoskeleton for the wrist rehabilitation exercises taking into consideration some points that should be fulfilled:

- Developing a noiseless device. This objective is very important for the comfort of the patient when using the device.
- Developing a portable device , that can be transported anywhere.
- Reducing the costs as much as possible, so that the price of the device is affordable, and it can be acquired both by hospitals, and directly by patients who need a rehabilitation therapy.
- Developing a secure device that doesn't cause any harm for the patient.
- Developing a light-weight device, also for the comfort of the patient when using it.
- The actuators used must produce the correct movements of the wrist rehabilitation exercises and in the required orientation, without producing any extra movements in the wrist joint which may cause injuries for patients.

The second objective of this project is trying to eliminate the problems found while testing the previous prototype that was done by David. The main problems are:

- The flexion movement depends on the force of gravity that affects the hand, therefore the weight of the hand, and is considerably affected by the process of cooling of the actuator used to do the extension movement. To eliminate this problem, another SMA actuator to produce the flexion movement should be added.

- During ulnar-radial deviation, an extra upwards movement was noticed with each of these movements, which may cause a harm in the wrist of the patient. To eliminate this problem, the SMA actuators used to do these deviations should be repositioned correctly.

- The SMA actuators used were long. The actuator used for extensions was 2.2m long and each actuator of the ulnar-radials deviations was 1.7m long, which could make the device uncomfortable. Using double groove pulleys could help to make the SMA actuators shorter.

- The sensors that were used to obtain the angles of movement are not very precise, and they couldn't be fixed very well in their allocated positions. For this reason, sensors of different type will be used.

Chapter 2

State of the Art

2.1 Exoskeletons

A robotic exoskeleton is an external wearable device that may contain electric motors, pneumatic devices and hydraulic components, or a combination of technologies that allow for limb movement with increased endurance and strength. The robotic exoskeleton usually has a design that permits the device to work in the exact range of motion desired by the user. It may reduce fatigue, prevent injuries, improve productivity and help in the rehabilitation of injured parts of the body. Exoskeletons can be implemented in many fields, such as in the **medical field** to improve the quality of life of persons who have, for example, lost the use of their legs or as a rehabilitation therapies for joints mobilization that aims to restore normal joints range of movement and facilitate normal functioning. Exoskeletons are used also in the **military field** for example to decrease fatigue and increase productivity whilst unloading supplies or enabling a soldier to carry heavy objects while running or climbing stairs. They could be used also in **civilian applications** such as to help firefighters and other rescue workers survive dangerous environments.

The first true exoskeleton in the sense of being a mobile machine integrated with human movements was co-developed by the United States Armed Forces and General Electric in the 1960s. The suit was named Hardiman, and made lifting 110 kilograms (250 lb) feel like lifting 4.5 kilograms (10 lb) and powered by electricity and hydraulics. The suit allowed the wearer to amplify their strength by a factor of 25, so that lifting 25 kilograms was as easy as lifting one kilogram without the suit. However, it was too bulky and heavy to be used in the military field. Nowadays many companies are producing exoskeletons for different purposes such as REX BIONICS, ReWalk Robotics, LOCKHEAD MARTIN...

In what follows we will see different examples of exoskeletons for medical use and other rehabilitation devices.

2.2 Commercial Rehabilitation Devices

2.2.1 ALEx

ALEx (Arm Lightweight Exoskeleton) of the company "Kinetek wearable robotics" shown in Figure 2.1 is a robotic exoskeleton for neuromotor rehabilitation of upper limb functions [1]. The design is derived from the PERCRO laboratory of Scuola Superiore Sant'Anna of Pisa-Italy.

This device is a mechanically compliant exoskeleton for the human upper limb having six degrees of freedom (DOFs). It features four DOFs sensorized and actuated joints (the elbow flexion-extension, and the shoulder flexion-extension, rotation and abduction-adduction), and two DOFs sensorized and passive joints (wrist flexion-extension, and forearm prono-supination). Its special joint kinematics of the shoulder makes the exoskeleton comfortable, easy to put on and adapted to different dimensions of the parts of the human body. Another advantage of this device is the redundant sensing that gives it the ability to detect the patient's intention of movement, even if it is a small intention, and according to the patients' needs it provides the necessary level of assistance. It could be used in both acute and chronic phase of stroke upper limb rehabilitation.

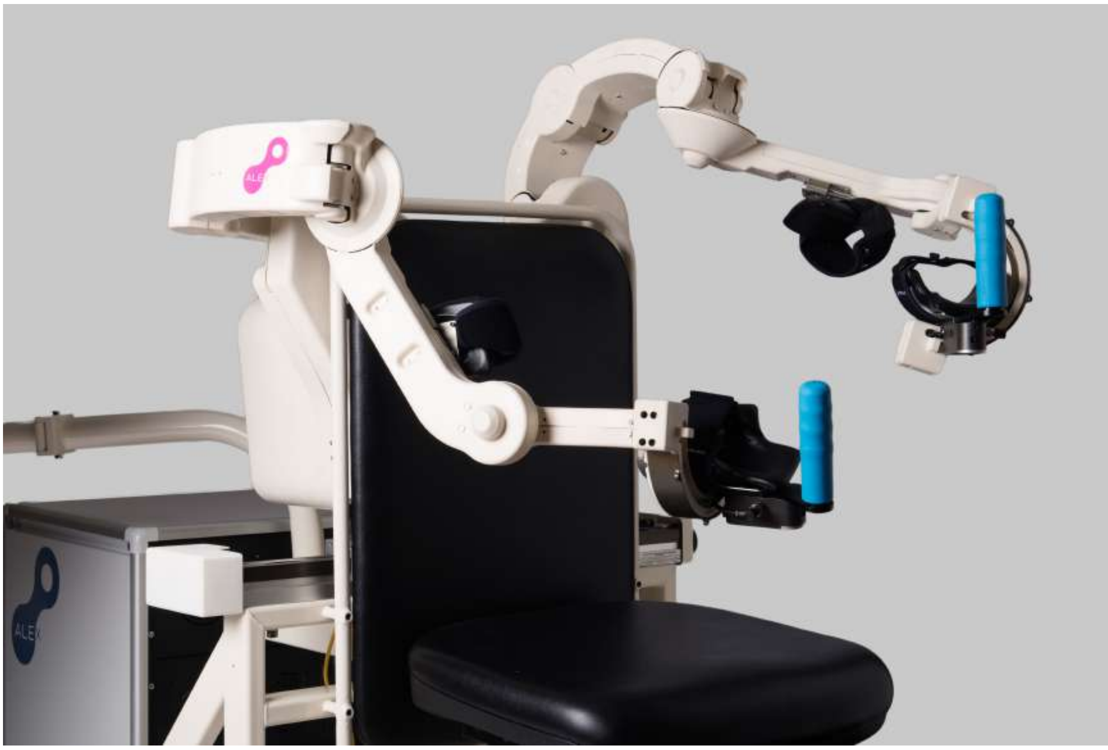


Figure 2.1: ALEx [1].

2.2.2 TRACK-HOLD

Another rehabilitation device is the Track-Hold (Figure 2.2), also fabricated by the company "Kinetek wearable robotics", and is designed for upper limb passive training supported by gravity in spatial movements [1]. It has embedded new position sensing technologies that grants motion tracking of full arm movement.

However, in this device the level of gravity support can be adjusted by the therapist by the removal or addition of physical weights, and this facilitates movement execution in patients with hemiparesis. It also allows the patient to record kinematic data during therapy sessions, tracks the progress and estimate daily improvements in the therapy schedule.

Figure 2.2: TRACK-HOLD [1].

2.2.3 PABLO

The PABLO system (Figure 2.3) is a hand-arm-therapy and assessment unactuated device produced by Tyromotion, and having built-in sensors to track the grip force and range of motion [2]. The PABLO has wireless extensions which are The **PABLO Multiboard** that is used to assist and guide repetitive single- and multi-joint exercises, the **PABLO Multiball** that can be used at an early stage of rehabilitation and supports supination, pronation, extension and flexion of the wrist, and the **PABLO Motionsensor** that can be attached to the body with straps of different sizes and permits asymmetric, symmetric, cooperative and bilateral applications , and can also determine every kind of body movement (arm, head, leg, trunk) with its built-in Inertial Measurement Units (IMU).

Figure 2.3: PABLO [2].

2.2.4 Armeo®Spring

The ArmeoSpring (Figure 2.4) is an unactuated passive arm fixed frame rehabilitation exoskeleton. It is used to apply rehabilitation therapies to patients who have suffered stroke, head injury or a spinal cord injury and are starting to regain active movement of the hand and arm [3]. It has 6 DOF, which allow: shoulder abduction and flexion, horizontal shoulder abduction, shoulder rotation, flexion of the elbow, pronation of the forearm, wrist flexion, hand grip and hand extension.

Figure 2.4: Armeo®Spring [3].

The device has a pressure-sensitive handgrip which can detect the amount of grip force and makes grasp-and-release exercises easier when needed. It also provides arm weight support, which gives the patients the ability to use any remaining motor functions, and depending on therapy goals, it encourages them to achieve higher number of reach and grasp movements. Moreover, the device has a database to store the patients' performance in every therapy session, which permits to analyze the results to figure out the patients' state and therapy progress.

For patients with therapy goals focusing on hand rehabilitation, an instrumented hand orthosis called ManovoSpring (Figure 2.5) could be combined with ArmeoSpring. It offers adjustable hand opening support using a spring mechanism and can be used as a real-time input device for the same software as the ArmeoSpring.

Figure 2.5: ManovoSpring [3].

2.2.5 Armeo®Power

The ArmeoPower (Figure 2.6) is a robotic arm exoskeleton used for hand and arm therapy. It's intended for patients that are still at an early stage of rehabilitation and who have lost completely the function in their arm muscles muscular, spinal or bone-related disorders for example. It also has 6 DOFs, allowing abduction, flexion-extension, and internal-external rotation of the shoulder, flexion-extension of the elbow, pronation-supination of the forearm and flexion-extension of the wrist in the range from 60 to -60 degrees. The device has 6 motorized actuators(one for each degree of freedom) with integrated weight compensation mechanism, and is able to support the weight of the patient's arm and to help the patient during different exercises in a large 3D workspace [3].

The ArmeoPower has two position sensors for each degree of freedom, and uses intelligent algorithms to figure out when the patient can't complete a movement and assists the patient's arm as much as needed to achieve the goal of the exercise successfully. The goal from the assist-as-needed movement guidance is to motivate the patients to participate actively in their training, which helps them in motor relearning. Moreover, the performance data and the active arm movement are stored in the computer so that the patient's progress can be tracked during and after the therapy sessions.

Figure 2.6: Armeo®Power [3].

The ArmeoPower could be also integrated with the ManovoPower (Figure 2.7) which is an actuated hand module that enables the patients to train reaching and grasping with the goal of relearning hand closing and opening, and it assists the patient as much as needed according to the patients level of support needed.

Figure 2.7: ManovoPower [3].

2.3 Laboratory Exoskeletons

2.3.1 Soft Orthosis Wrist

The "Soft Orthosis Wrist" (Figure 2.8) is a soft wearable exoskeleton for wrist rehabilitation, and contains no rigid parts, was developed by "Harvard School of Engineering and Applied Sciences,Cambridge".

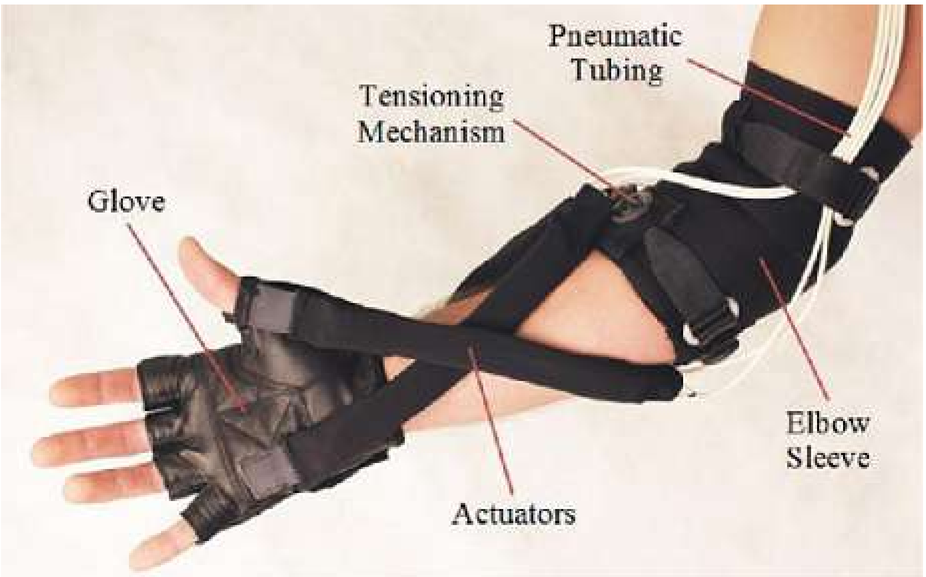


Figure 2.8: Soft Orthosis Wrist [4].

The device consists of a glove and an elbow sleeve to facilitate the anchoring of the actuators in a crossing linear way. Any movement can be fulfilled by activating two actuators. The actuators used are McKib-ben actuators, which is a type of PAMs (pneumatic artificial muscle). The system is endowed with 3 DOF (supports all the 3 degrees of freedom of the wrist) that permits flexion/extension, supination/pronation, and radial/ulnar deviation of the wrist. Moreover, pressure sensors are used to control and monitor the state of the actuators and detect in which position the artificial muscle is found, and to do the control of the device an Arduino Mega 2560 is used. Additionally, the device was tested on a wooden hand (Figure 2.9) [4].

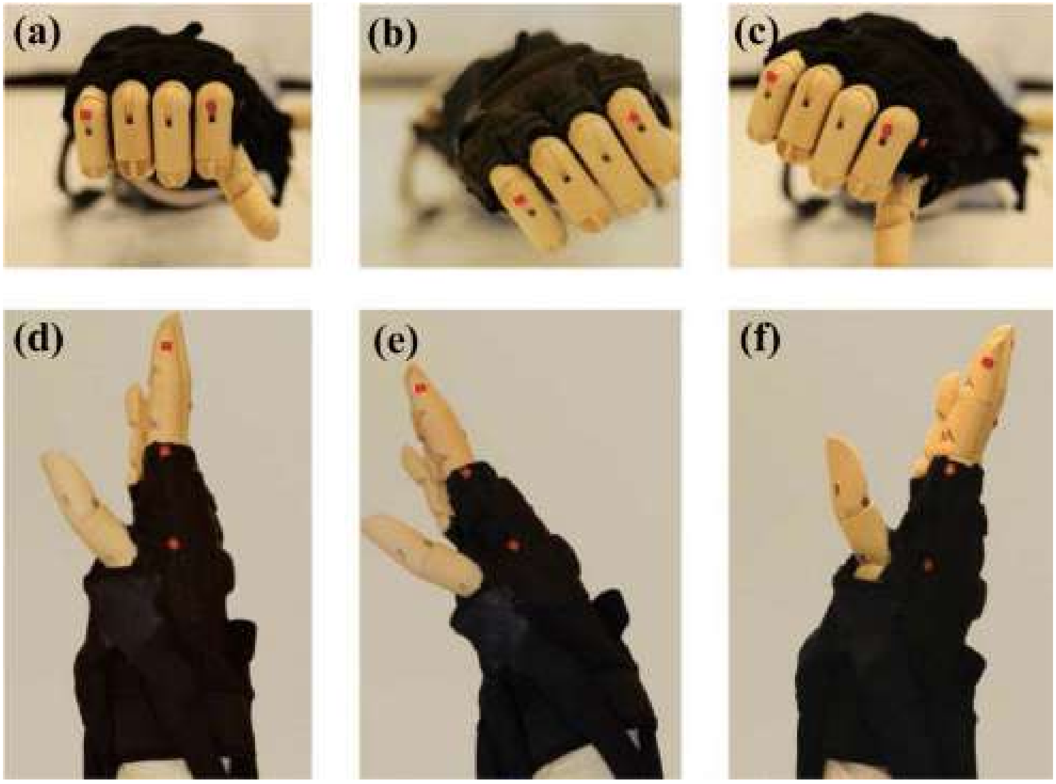


Figure 2.9: (a)Device off, (b)supination, (c)pronation, (d)device off, (e)flexion, and (f)extension [4].

2.3.2 MAHI Exo II

The MAHI Exo II (Figure 2.10) is a robotic exoskeleton developed for forearm, wrist and elbow rehabilitation. The device has 5 degrees of freedom and it is actuated electrically. It has four active DOF, that allow extension-flexion of the elbow, supination-pronation of the forearm, flexion-extension and ulnar-radial deviation of the wrist, and another one passive DOF that permits abduction and adduction of the shoulder that guarantees improved posture and comfort for the user during training). The different movements of the wrist are actuated by three DC motors(Maxon Re-35) that uses cables to extend and retract rigid links and the control of the actuators is done through linear servoamplifiers. Moreover, the device has a 3-revolute-prismatic-spherical (RPS) mechanism as its basic kinematic structure [5]. Finally, the use of this device is limited to medical rehabilitation therapies in hospitals.

Figure 2.10: MAHI Exo II [5].

2.3.3 MAHI OpenWrist

MAHI OpenWrist (Figure 2.11) is another rehabilitation exoskeleton for wrist and forearm and having 3 DOFs (serial RRR mechanism for manipulation) and each degree of freedom is actuated by a brushed DC motor (Maxon RE-series DC motor). The three rotational joints actuate the forearm's supination and pronation, the wrist's flexion and extension, and the wrist's ulnar and radial deviation [6].

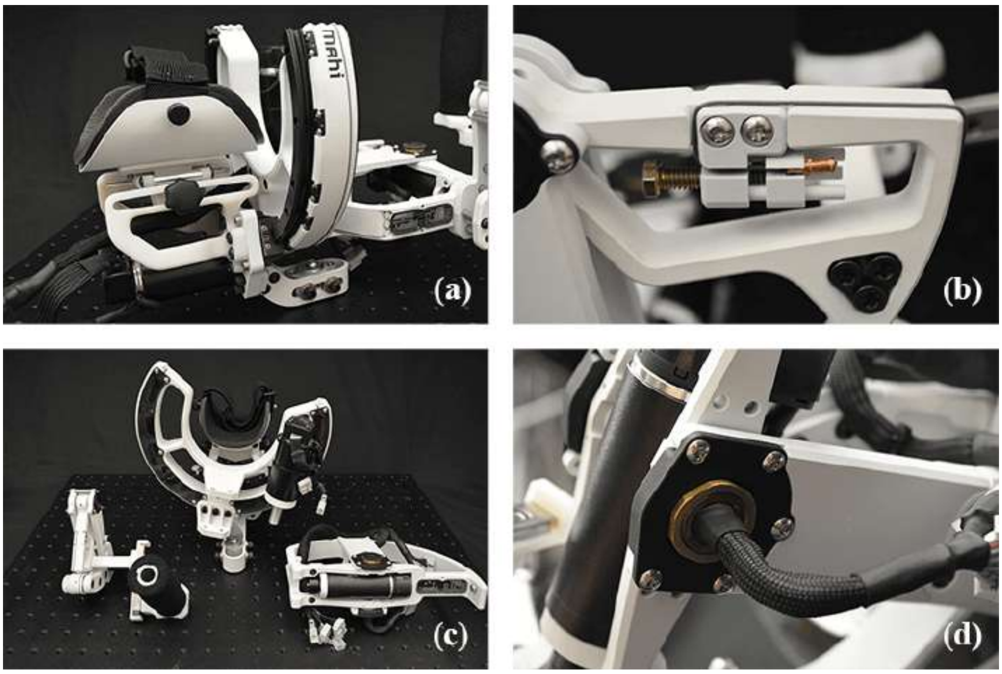


Figure 2.11: OpenWrist Features – (a) central hub with curvilinear rails, (b) integrated quick connect tensioner, (c) modular assembly allows for ambidextrous configurations, (d) electrical wire routing through joint axes[6].

2.4 Shape Memory Alloy (SMA)

As the main objective of this project is to produce a lightweight and noiseless device, the actuators that will be used are Shape Memory Alloy (SMA) based actuators. In this section, a brief summary of SMA and its characteristics will be presented and explained.

SMAs (shape-memory alloys) are metallic alloys that remember their original shape, and when heated they return to their pre-deformed shape as they can be deformed by applying an external force. This material is a lightweight and a good alternative to conventional actuators such as pneumatic, hydraulic, and motor-based systems. These materials have applications in many industries such as in robotics, biomedical, aerospace and automotive industries. The history of SMA development goes back to 1932, when the Swedish physicist Ölander first discovered the solid phase transformation in SMA, who discovered that if the gold-cadmium (Au–Cd) alloys are cool they could be plastically deformed, and when heated they can return to their original shape. The shape memory effect of copper-zinc alloys and copper-tin alloys was also studied by Greninger and Mooradian in 1938. However, the shape memory effect (SME) was extensively described in 1949 by Kurdjumov and Khandros and in 1951 by Chang and Read. All these discoveries draw the attention of many scientists and researchers, but due to the complexity of manufacturing these materials and their high cost in practical applications they could not be realised. In 1959, William Buehler discovered the NiTi alloy (Nitinol alloys) that are cheap and easy and safe to handle. The NiTi alloys have been used in many applications since 1980's and helped in producing lighter and more compact actuators [7].

Practically, Shape memory alloys could exist in two phases with three crystal structures (austenite, detwinned martensite and twinned martensite) and could undergo six possible transformations (Figure 2.12). The SMA is found at the martensite phase at low temperatures while it is found at the austenite phase at high temperatures. When the SMA is heated, it begins to transform from martensite into the austenite phase. The temperature at which the transformation to austenite starts is called **(As)** and the temperature at which this transformation is complete is called **(Af)**. Heating the SMA above the (As) permits it to contract and transform to the austenite structure and recover its original form, even under high applied loads this transformation is possible. When the SMA starts cooling, it starts going back to the martensite phase at the martensite-start temperature **(Ms)** and completes the transformation at the martensite-finish temperature **(Mf)** (see Figure 2.13). Finally, there exists a temperature called Md, which is the highest temperature at which martensite can't be stress induced, and the SMA is permanently deformed above this temperature like any other metallic materials [7].

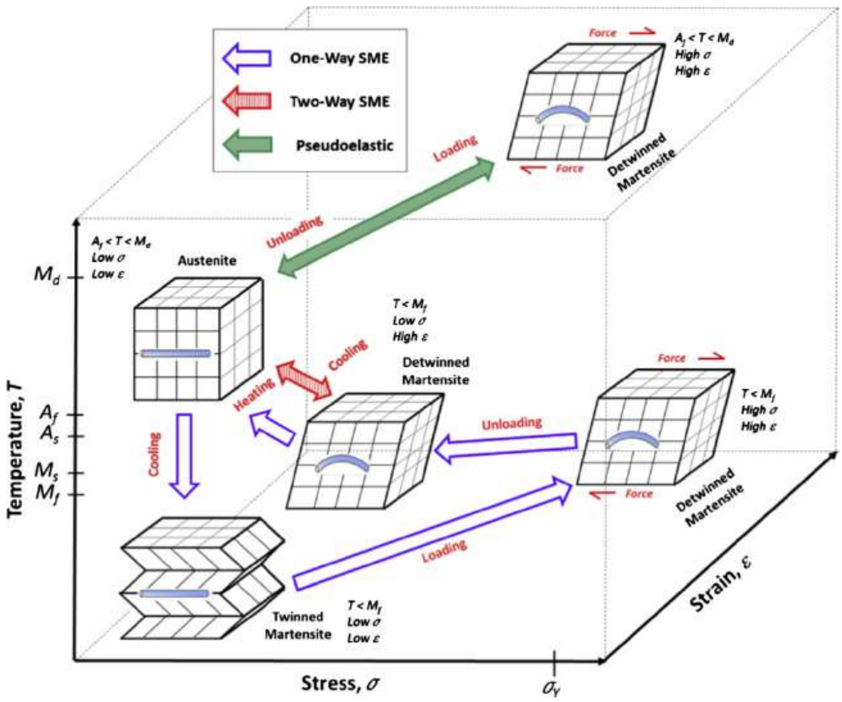


Figure 2.12: SMA phases and crystal structures [7].

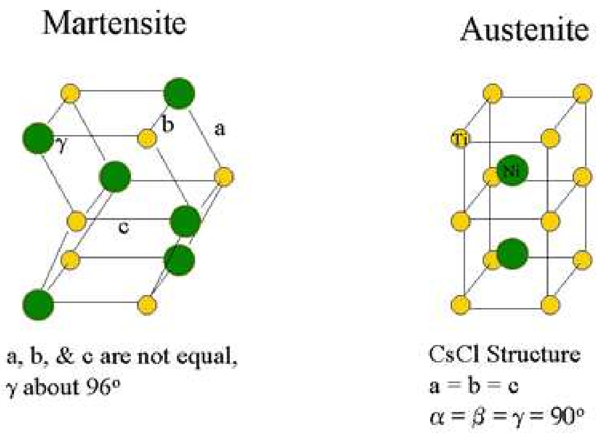


Figure 2.13: Martensite and austenite microstructure of Nitinol.

In Figure 2.13 the martensite and austenite microstructure of Nitinol is shown, while in Figure 2.14 the SMA phase transformation is shown.

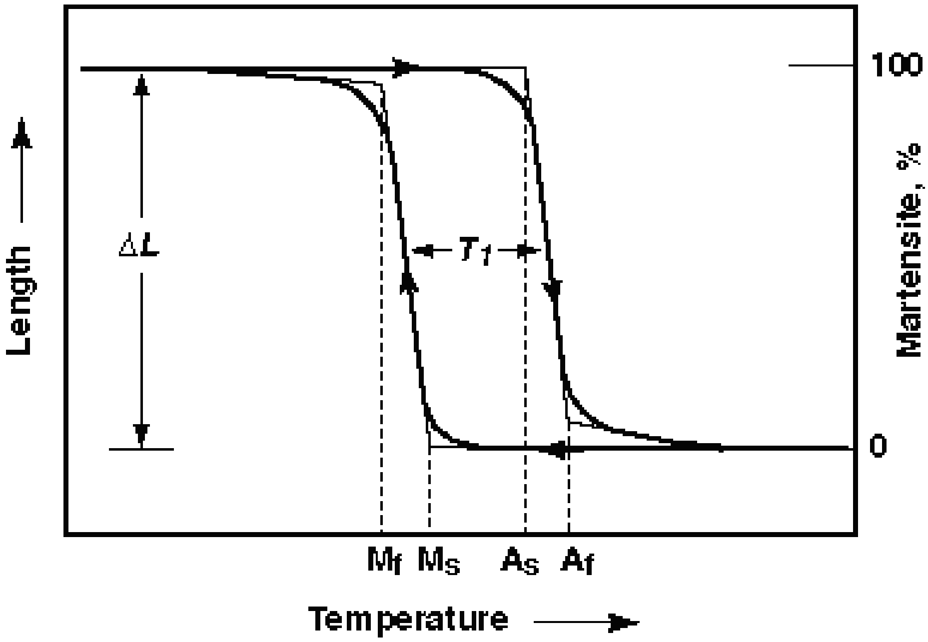


Figure 2.14: SMA phase transformation.

The shape change effects of the SMA, which are known as the shape memory effects (SME) and pseudoelasticity or superelasticity, could be categorized into three shape memory characteristics :

- One-way shape memory effect (OWSME) (Figure 2.15):
  When removing an external force, the SMA maintain a deformed state as it is found in its cold state and it can be stretched or bent. Upon heating, the SMA recovers to its original shape, and it remains in the hot shape after cooling again until deformed again [7].

- Two-way shape memory effect (TWSME) or reversible SME (Figure 2.15):
  The two-way SMA can remember two different shapes, one at high temperatures and the other at low temperatures. This type of SMA needs training which means it can learn to act in a certain way, but it produces about half of the recovery strain provided by the one way SMA making it less used commercially and less reliable than the one way SMA. Among the proposed training methods for this type of SMA, two methods are: Spontaneous and external load-assisted induction [7].

- Pseudoelasticity (PE) or Superelasticity (SE):
  The SMA can recover to its original shape by applying a mechanical loading at temperatures between Af and Md, without any thermal activation [7].

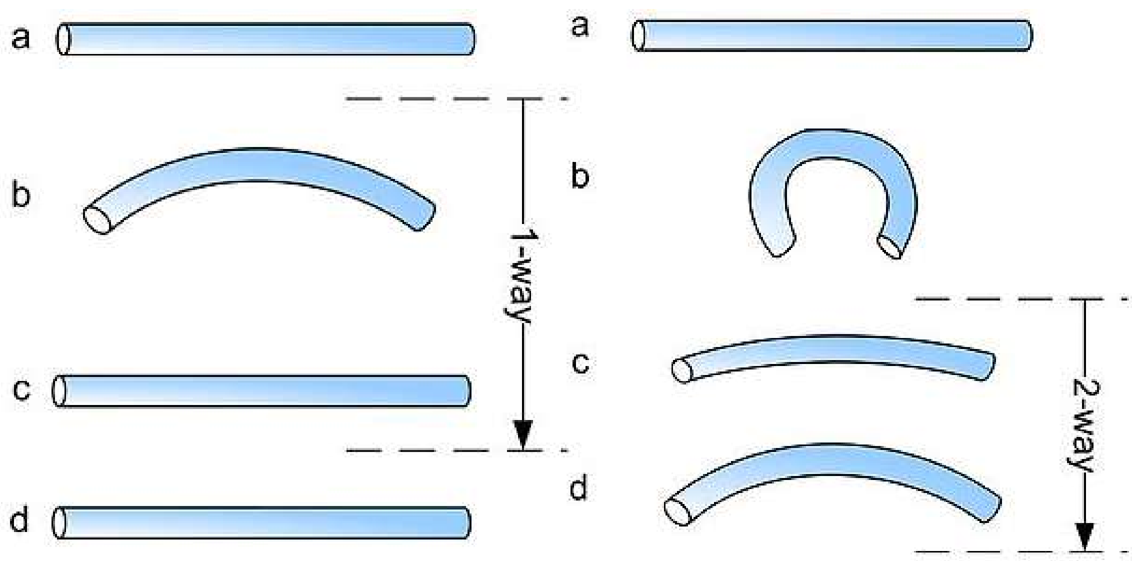


Figure 2.15: 1-way and 2-way shape-memory effects.

Some of the SMAs mechanical and physical properties also vary between martensite and asutensite phases such as electrical resistivity, Young's modulus, thermal expansion coefficient and thermal conductivity. The martensite structure has lower Young's modulus, is more malleable and could be deformed by applying an external force, whereas the austenite structure is hard and has higher Young's modulus [7]. For NiTi alloys, the strain is approximately 8.5% while for copper-based alloys the strain is about 4-5% where the SMA deformation is elastic with recoverable strain, but in most applications the strain level of NiTi alloys is restricted to 4% or less and one of these applications will be in this project, where the SMA used is made from Ni-Ti alloys.

2.5 SMA Based Actuator

The typical characteristic of Shape Memory Alloy wires to ensure mechanical actions if stimulated with electrical current allows the development of simple, more compact and reliable actuators, while the SMA reduces mechanical complexity, noise, size, and weight. When an electrical current passes through the SMA wire, using the Joule effect, the SMA wire will be heated allowing the transformation from martensite phase to austenite phase which causes the contraction of the length of the wire by 4% of its total length.

The mechanical design of the SMA based actuator is simple. The SMA wire is inserted inside a teflon tube which is then inserted into a Bowden cable (Figure 2.16)[19]. One of the ends of the SMA wire should be fixed by a crimp for example to obtain a linear displacement of the SMA wire during contraction, while the other end will be connected to the joint that has to be actuated, . The shape memory alloy used in this project is a Flexinol R wire manufactured by Dynalloy (Technical

Characteristics sheet appendix A).

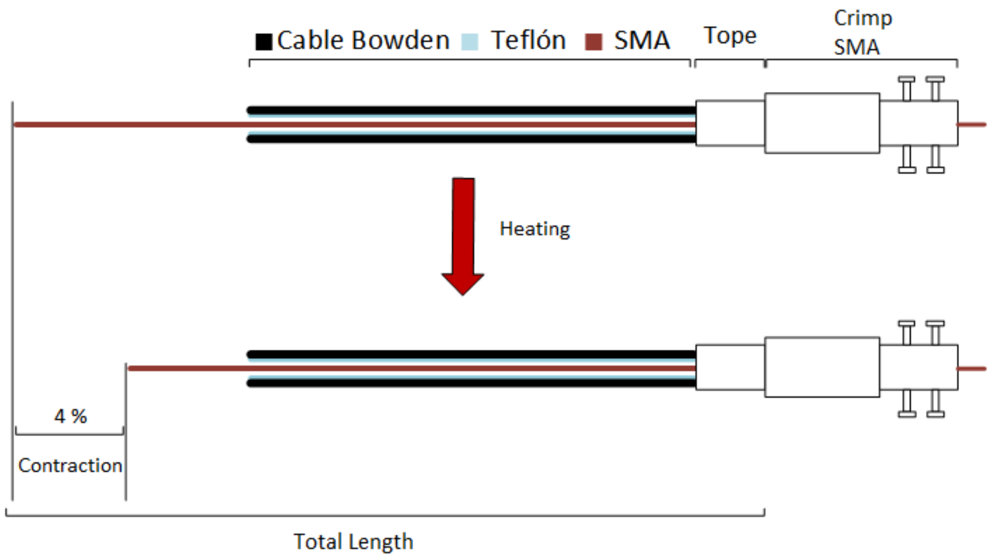


Figure 2.16: SMA actuator design.

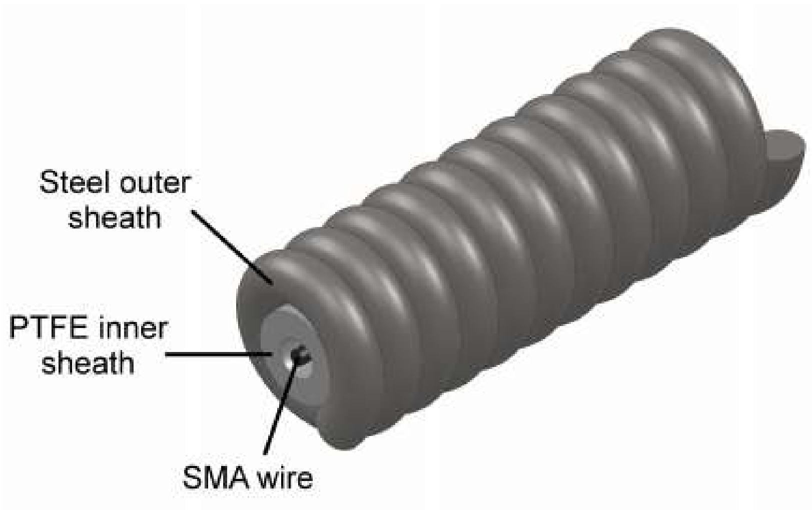


Figure 2.17: CAD model showing the actuator configuration [19].

The use of teflon is justified by its characteristics. It is a highly flexible, chemical resistant, thermal resistant, non-stick and electrically resistant material. It is used to electrically isolate the SMA from the bowden cable. Besides, the teflon is used as a lubricant which reduces friction and allows a smooth contraction of the SMA. Other useful teflon properties are its resistance to water, and thermal stability that permits it to be used between -200 °C and +260 °C without degrading. On the other hand, the bowden cable is used since it is a flexible cable, rigid material and allows the movement only of the SMA wire as it serves as a guide for the SMA wire and allows the actuator to be bent [19]. The bowden cable is formed by a metal spiral covered by a plastic layer, whose role is the thermal isolation. A plastic piece then is used to electrically isolate the metal part of the crimp used to fix the SMA and the end of the metal spiral of the bowden cable.

2.6 High-Density polyethylene (HDPE) Threads

4 strand Dyneema® braid threads with 0.35mm diameter, and made from HDPE (High-Density polyethylene) fibre will be used in this work to pull the palm of the hand in the desired orientation during each movement. It's characteristics made it a good choice to be used in our application instead of using a steel wire. These threads are characterized by their high strength which can support the wight of the palm of the hand easily, their light weight, resistance against water, chemical resistance, durability, and their high breaking resistance [20].

Figure 2.18: Dyneema® HDPE thread [20].

Chapter 3

Design of the Exoskeleton

The main aim of this project is to design and develop a wearable exoskeleton which could be made practical to rehearse wrist rehabilitation exercises. So in this chapter, the mechanical structure and the different components of the exoskeleton will be detailed, starting from a previous prototype fabricated in the Robotics Lab of the Universidad Carlos III de Madrid, and trying to solve all the problems found in the previous prototype. The exoskeleton is adjustable and is intended for the rehabilitation of different people having different sizes of wrists.

3.1 Biomechanics of the Wrist

To proceed with the correct design, the biomechanics of the wrist should be studied. The wrist is the collection of bones and tissue structures that connects the hand to the forearm. It is a complex series of joints that are formed around the carpal bones and the radius and ulna(forearm bones), and it is an ellipsoid type synovial joint, allowing for movement along two axes. This means that flexion, extension, adduction and abduction can all occur at the wrist joint as shown in Figure 3.1.

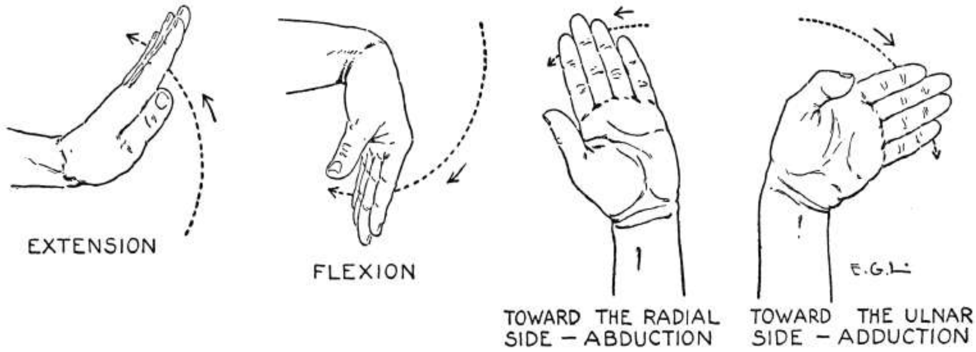


Figure 3.1: Main movements of the wrist.

Another important aspect to consider is the range of motion of each movement of the wrist shown in Table 4.3. In the sagittal plane the wrist joint presents the movements flexion-extension (90 degrees of flexion and 85 degrees of extension) and in frontal plane it presents the ulnar and radial deviation (45 degrees for ulnar deviation and 20 degrees for radial deviation). These range of motions are decreased in activities of daily living (ADL) because in daily activities the joints are never put to the limit of their range of motion. So as Table 4.3 shows, the new ranges of movement in ADL are decreased for flexion to 15 degrees, for extension to 35 degrees, for ulnar deviation to 20 degrees and for radial deviation to 15 degrees [15].

Movement	**Total Range (degrees)**	**ADL Range (degrees)**
Flexion	90	15
Extension	85	35
Radial deviation	20	15
Ulnar deviation	45	20

Table 3.1: Range of motion of the wrist.

Since the aim of the exoskeleton is to return the mobility to the articulation of the wrist of the patient, considering the above ranges of motion is very important for the design of the device. They will also be considered in the control of the device to be able to make the correct tests, and in the correct range of motion, for the rehabilitation of the wrist of the patient.

A first prototype was designed to meet the objectives set for the development of the rehabilitation device such as low weight, low fabrication cost, and noiseless operation. This prototype was then printed using a 3D printer and tested in different movements and ranges but it showed failure during the testing process (it will be explained in the next section). After that, a second prototype was designed piece by piece also to meet the above objectives, then also it was printed using a 3D printer and tested and showed success during the testing process.

The CAD software used in the design process is SOLIDWORKS, that is known for its simplicity. It allows the designer to make changes to designs quickly, solve design problems and decreases inaccuracies. Also with this software it is possible to store the parts in a format compatible with any 3D printer, which allows to manufacture the pieces then with a 3D printer.

3.2 First Prototype

A first prototype for the exoskeleton was proposed and designed as shown in Figure 3.2. This prototype was printed using a 3D printer in the RoboticsLab, and then it was tested. The idea of this prototype was to connect the SMA actuators to the blue pulleys (with diameters of 1cm and 2cm just to keep acceptable dimensions) so that the displacement of the hand during the movements in the abduction and adduction will be doubled and the length of the SMA wires will be decreased, while using normal pulleys for flexion and extension (to keep the piece in the middle where the small pulleys are integrated with small dimensions.

After doing some tests on the prototype printed with the 3D printer and in repetitive movements of flexion-extension and in the ulnar and radial deviation, it gave positive results for the flexion, ulnar and radial deviation, while it failed the test of the extension movement. The problem with the extension movement was that the piece in the middle where the small pulleys for the extension and flexion are integrated, hits the wrist when the hand goes in extension. There was no possibility to fix the problem after trying to change the dimensions of the piece with the small pulleys to fit the extension movement and trying to avoid the contact with the wrist, so the first prototype failed.

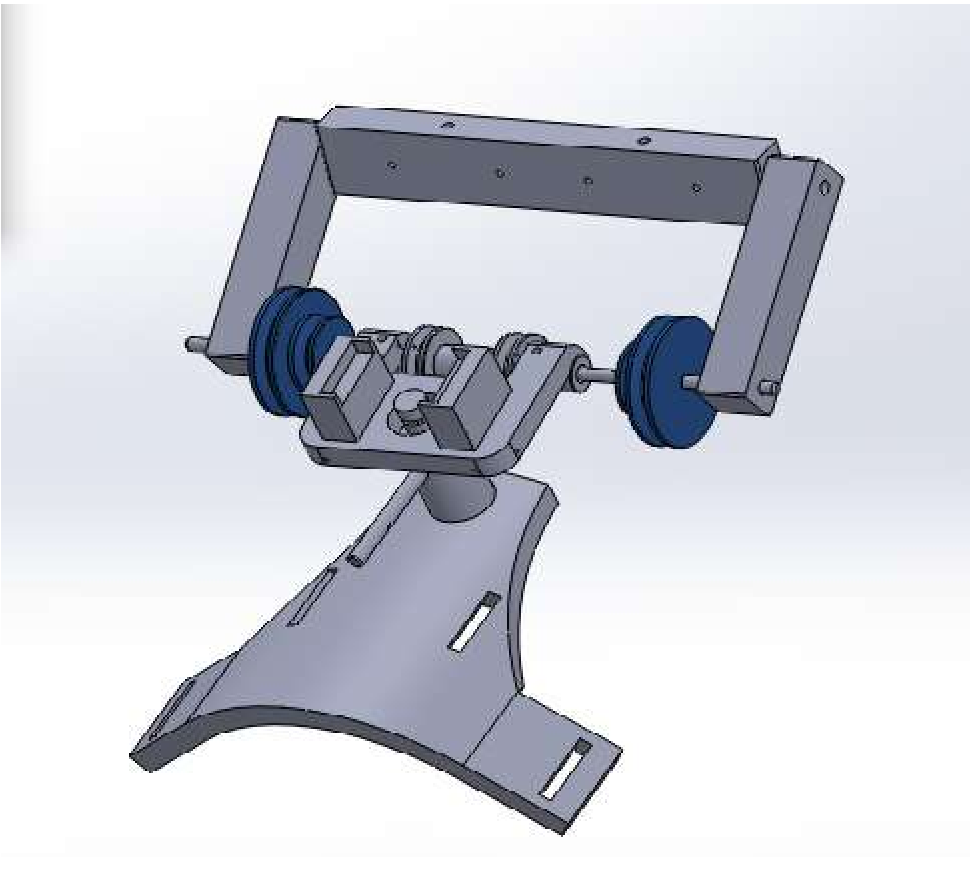


Figure 3.2: First prototype.

3.3 Second prototype

After the failure of the first prototype, another design for the second and final prototype was proposed, that is shown in Figure 3.3. This prototype was printed also using a 3D printer and tested in different movements (Figure 3.4), and showed positive results in all the movements, and it will be considered as the final design in this project. The development of the parts will be detailed in the next subsections.

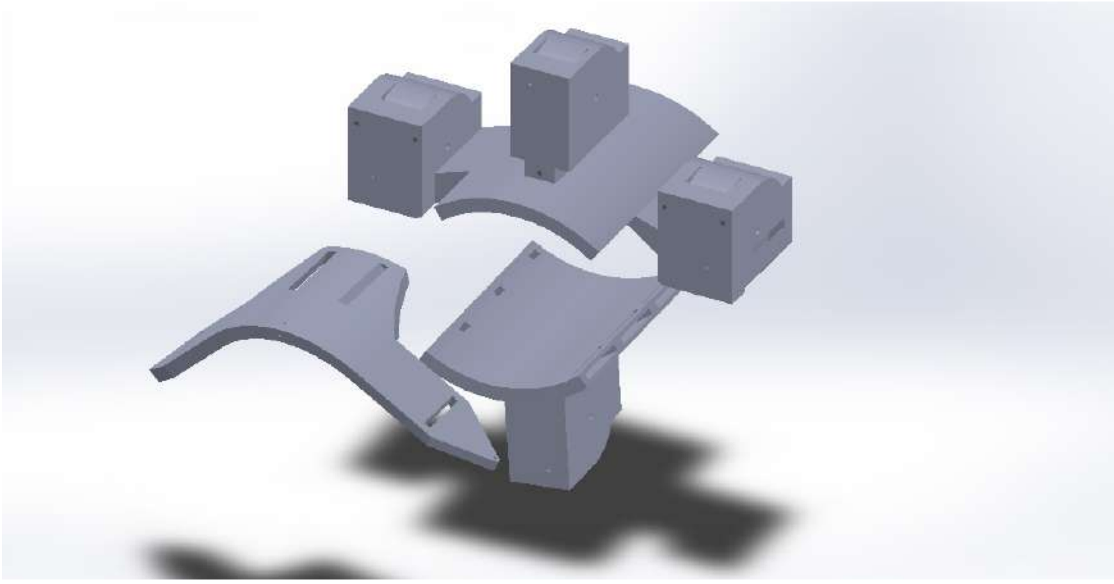


Figure 3.3: Wrist Exoskeleton.

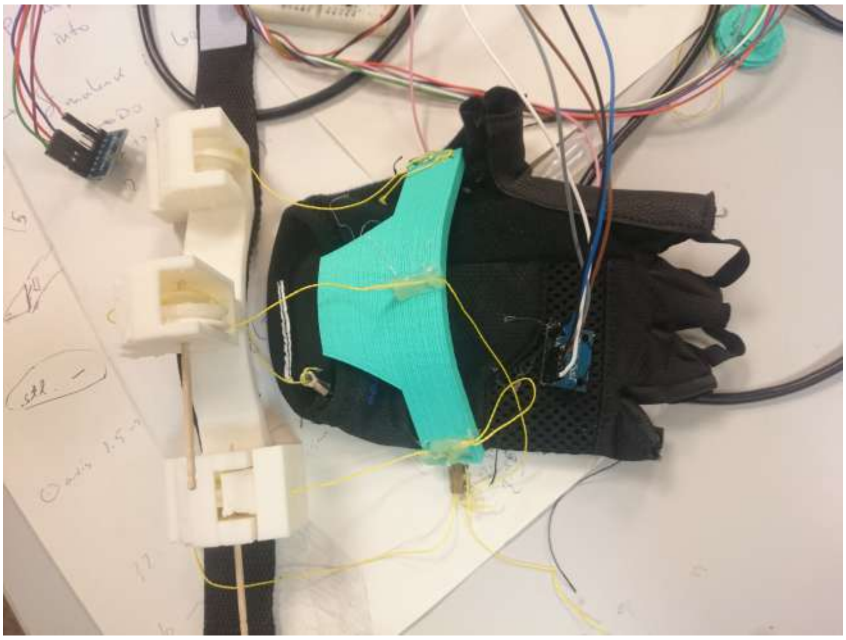


Figure 3.4: Printed Prototype For Testing.

3.3.1 Piece for the Extension-Adduction-Abduction

The first piece shown in Figure 3.5 will be used to fix the pulleys to which the SMA actuators and the HDPE thread will be connected. The HDPE threads will be fixed to the hand also to be able to do the extension, ulnar and radial deviation of the wrist through this piece. The curved part in the middle of the piece was designed to fit the shape of the forearm. In the rear part there is are holes made to insert the SMA from outside.

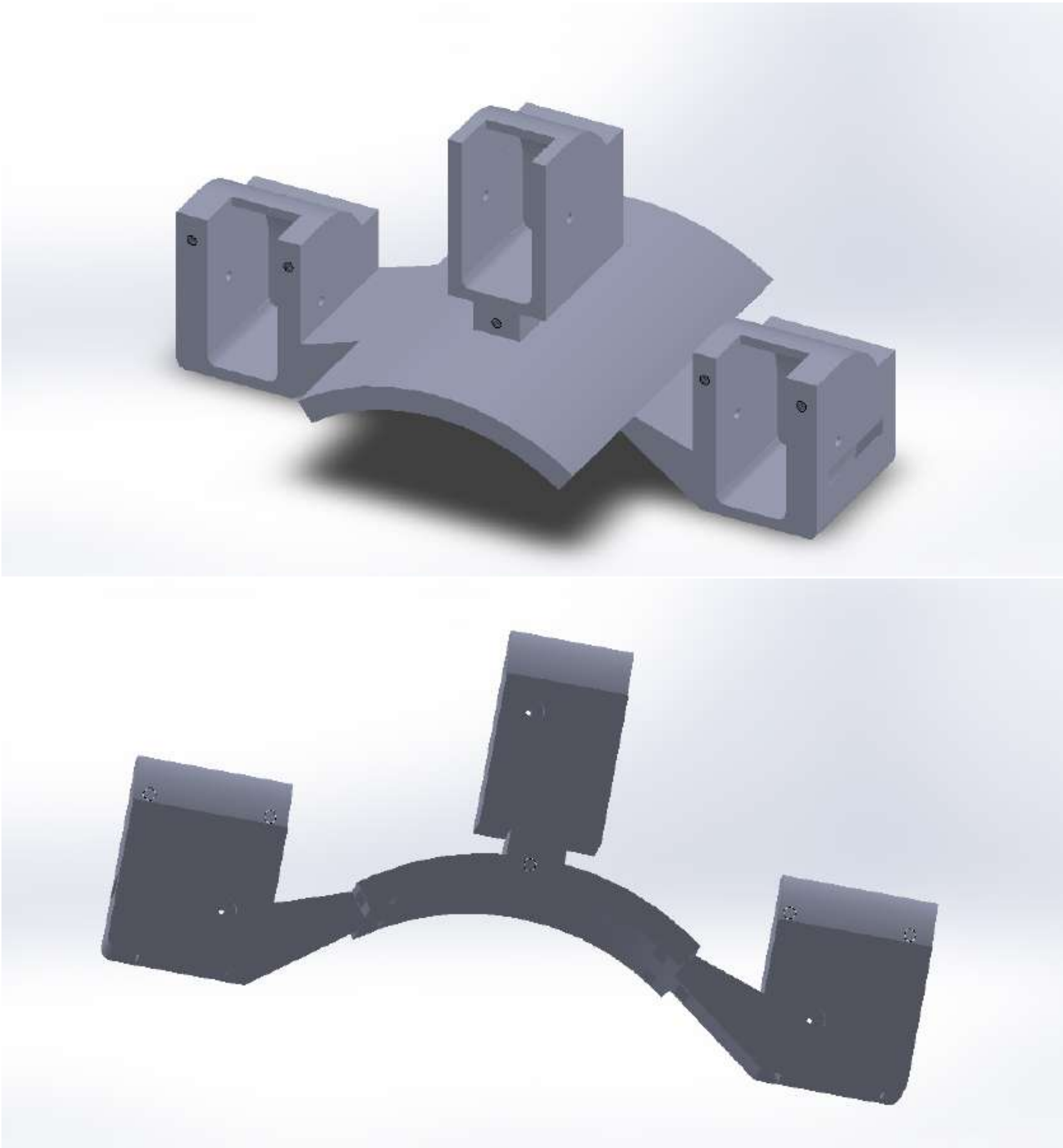


Figure 3.5: Piece for the Extension-Adduction-Abduction.

The piece was fabricated in an external company[21], and the fabrication process is based on sintering. This piece was made from a mixture of polyamide powder and aluminum powder. It was made to fit different hand sizes, and it will be fixed above the forearm using a glove and elastic belts that can be inserted in the piece through holes made for this purpose in the curved part in the middle, and it is adjustable.

3.3.2 Piece for the Flexion Movement

The second piece shown in Figure 3.6 will be used to fix the pulley used to do the flexion movement of the wrist through the SMA actuators and the HDPE threads that will be connected to this pulley. The HDPE thread will be fixed under the hand, and SMA actuators will be inserted from the rear part where a hole have been made for this purpose. The piece was also made to fit the shape of the forearm, it will be fixed under the forearm using elastic belts that will be inserted in the slots made for this purpose in the curved part of the piece, and it will be adjustable.

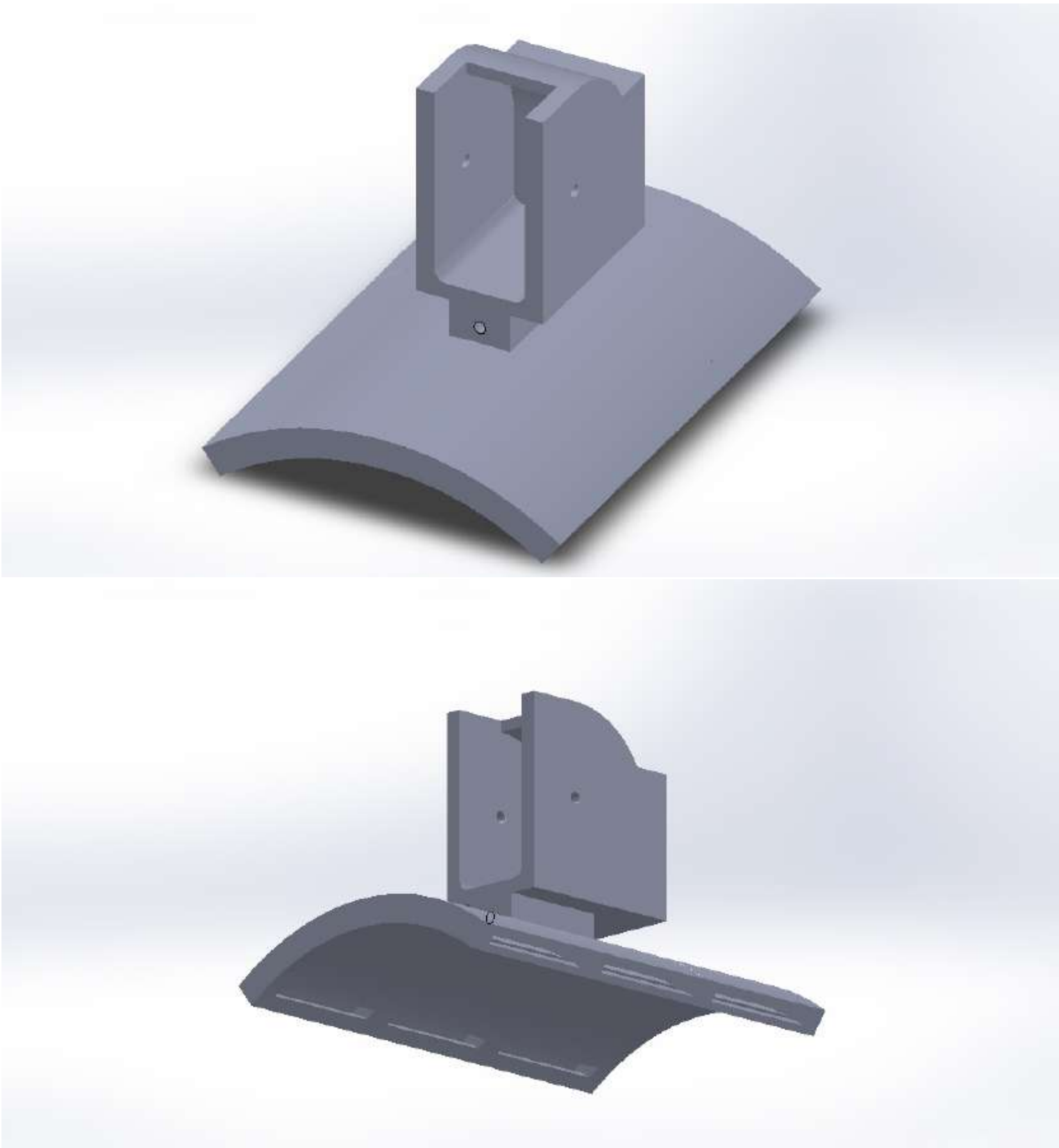


Figure 3.6: Piece for the Flexion Movement.

Also in this case the piece was fabricated from a mixture of polyamide powder and aluminum powder, and the fabrication process is based on sintering.

3.3.3 The Hand

The piece shown in Figure 3.7 will be used to fix the HDPE threads coming out from the pulleys used to do the different movements of the wrist. The HDPE threads will be fixed through holes made on the extremities for the ulnar and radial deviation, and in a hole in the middle for the flexion. The piece is also made to fit the form of the hand, and it will be fixed on the palm of the hand using elastic belts that will be inserted in the slots made for this purpose in the curved part of the piece, and it will be adjustable.

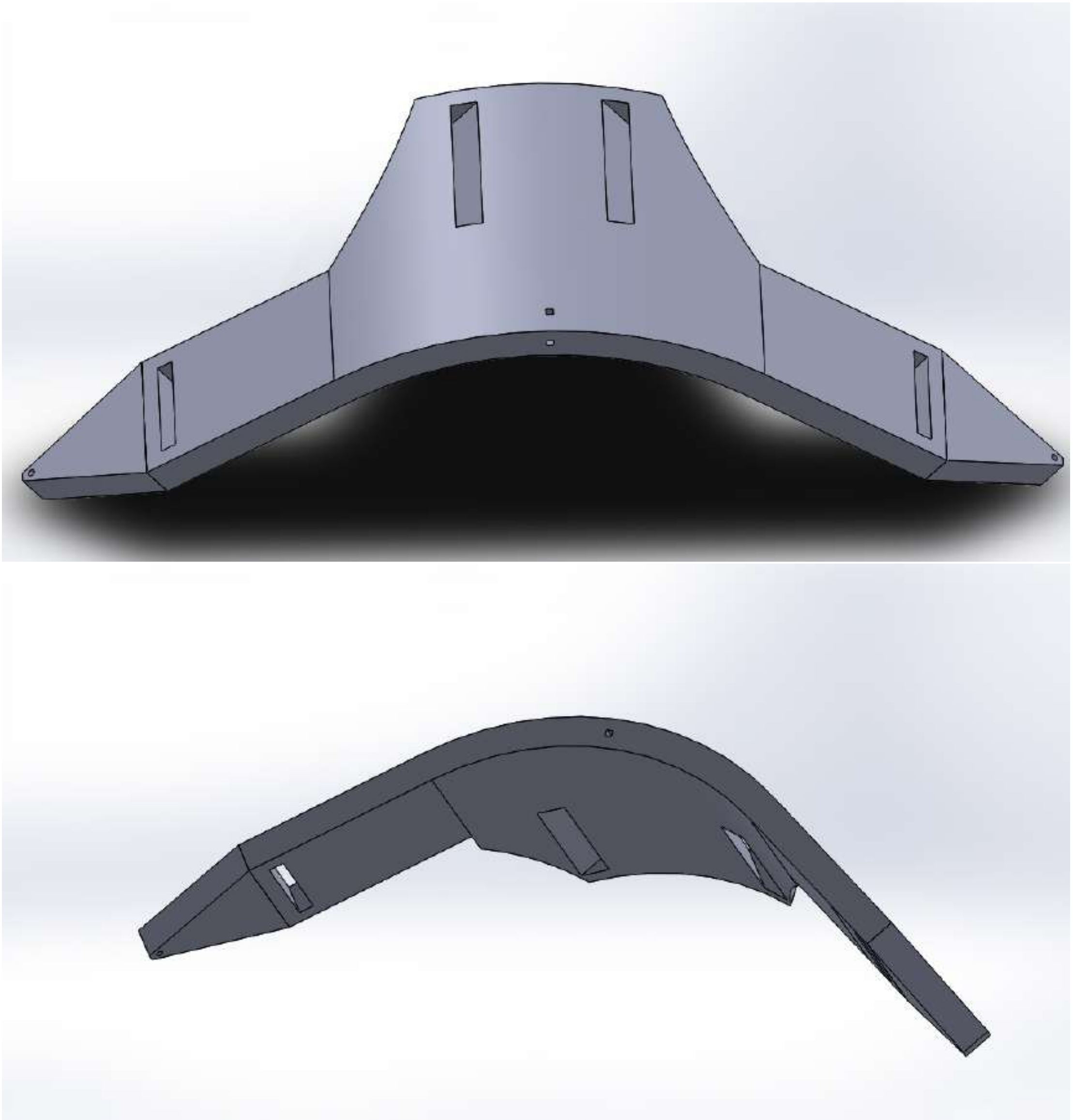


Figure 3.7: The Hand.

This piece is made from polyamide only, without mixing it with aluminum, and the reason behind this is that there is no contact with the SMA wires that will be heated during actuation, so the aluminum is not needed in this case.

3.3.4 Pulley

The double-groove pulley shown in Figure 3.8 is used to fix in one side the SMA actuator and the HDPE threads on the other side. The pulley was designed to double the displacement of the HDPE thread with respect to the displacement of the SMA actuators during actuation, which helps in reducing the length of the SMA actuators and consequently the weight of the device (the displacement of the SMA during actuation is equal to 4% of the SMA total length). This is done actually by designing a double-groove pulley, where the diameter of the pulley in the first groove where the SMA actuator is wrapped is 1cm, while the diameter of the pulley in the second groove where the HDPE thread is wrapped is 2cm,and the choice of these diameters was limited to design constraints. In each groove a 1mm diameter hole is made to insert the wire inside, and on each extremity a screw will be inserted in this hole to fix the wire to prevent it from going out from the pulley. Another hole in the center of the pulley is made to insert the aluminum axis that will be used to fix the pulleys with the other parts.

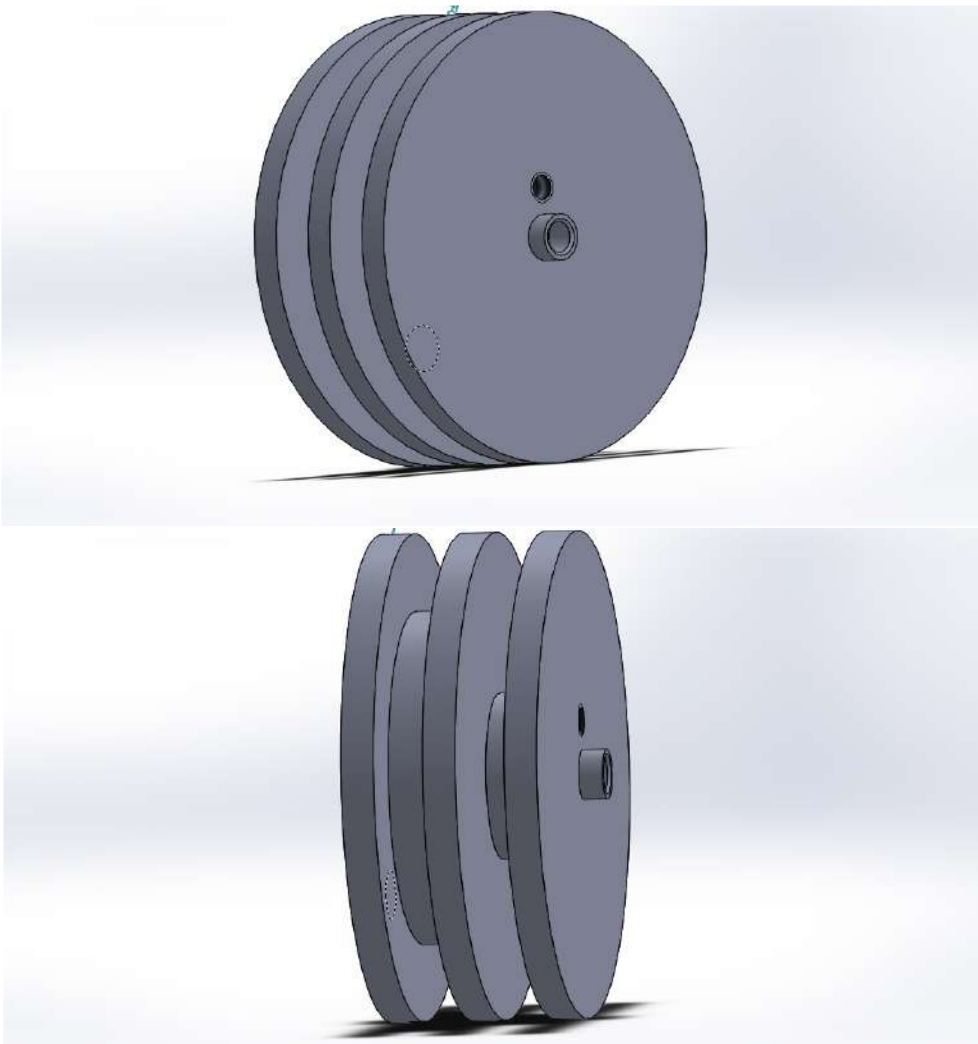


Figure 3.8: Pulley.

Differently from the other pieces, the pulleys were fabricated in the mechanical laboratory of the Universidad Carlos III de Madrid, and they are made from pure aluminum.
In Figure 3.9 it is shown where the pulleys will be fixed in the other pieces. The pulleys are fixed using aluminum axes, where these axes will be fixed on each extremity with the other piece using a collar to prevent it from sliding.

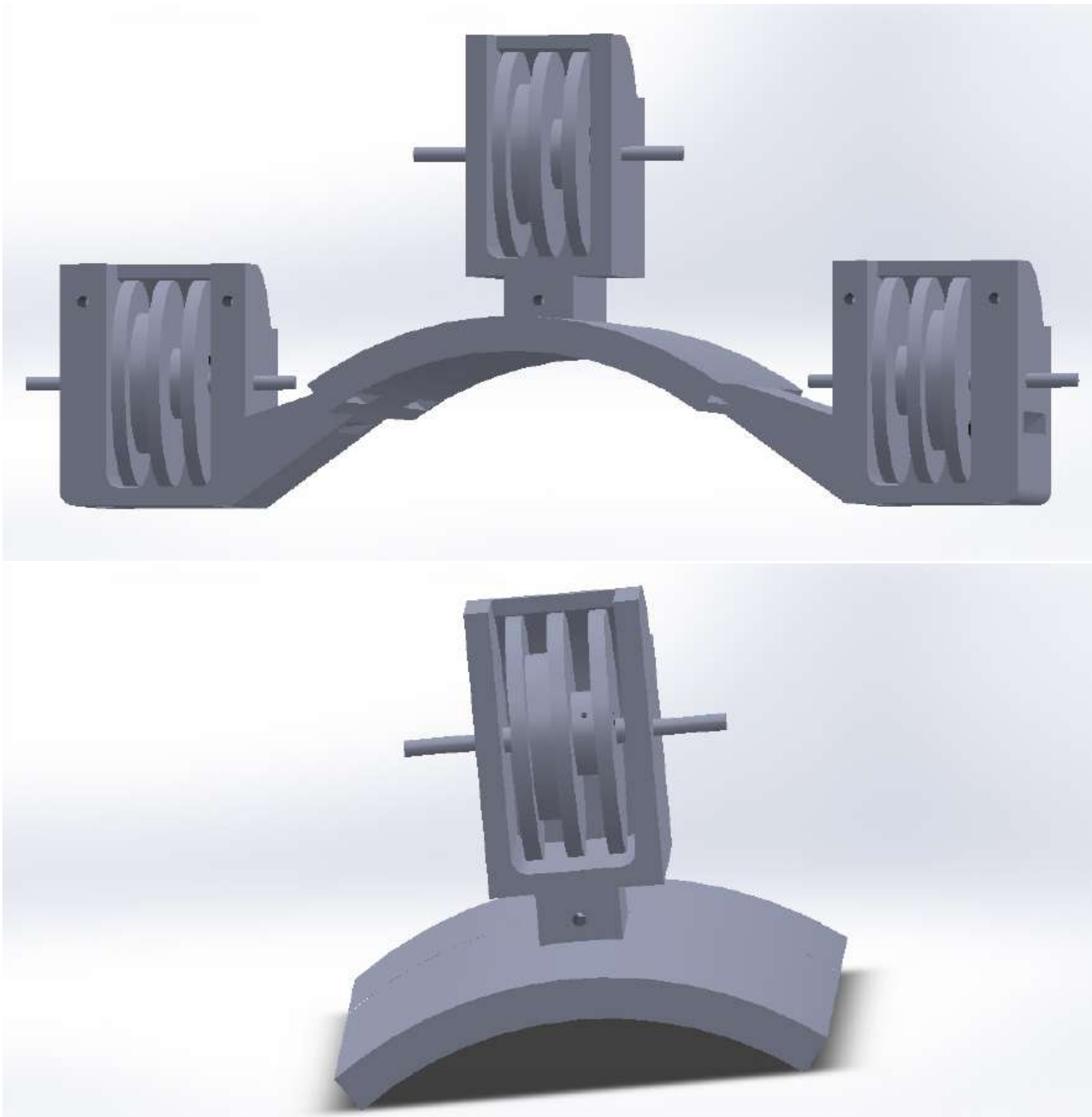


Figure 3.9: Pulley fixing with other pieces.

3.3.5 Taps

To prevent the SMA actuators and the HDPE threads from going out from the pulley during actuation, different taps will be used (Figure 3.10) so that the space between the pulley and the taps and the walls of the other pieces is less than the diameter of the wires and threads. A small hole in each tap is made to insert the HDPE thread through the taps. These taps will be fixed using M2 screws.
The taps are also made from a mixture of polyamide powder and aluminum powder.

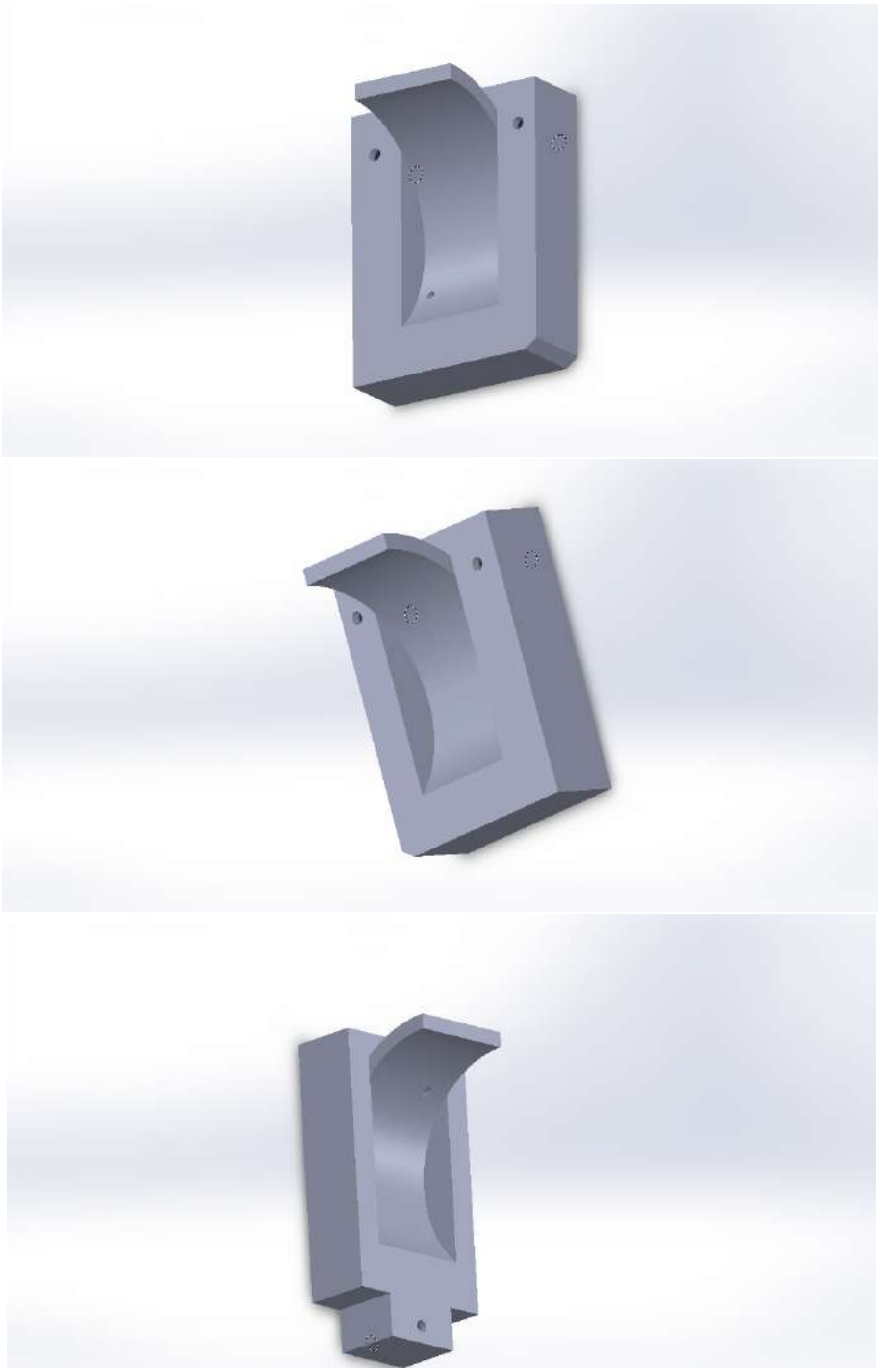


Figure 3.10: Taps.

3.3.6 Final Assembly

The final assembly of all the pieces with the pulleys, taps and the axes is shown in Figure 3.11.

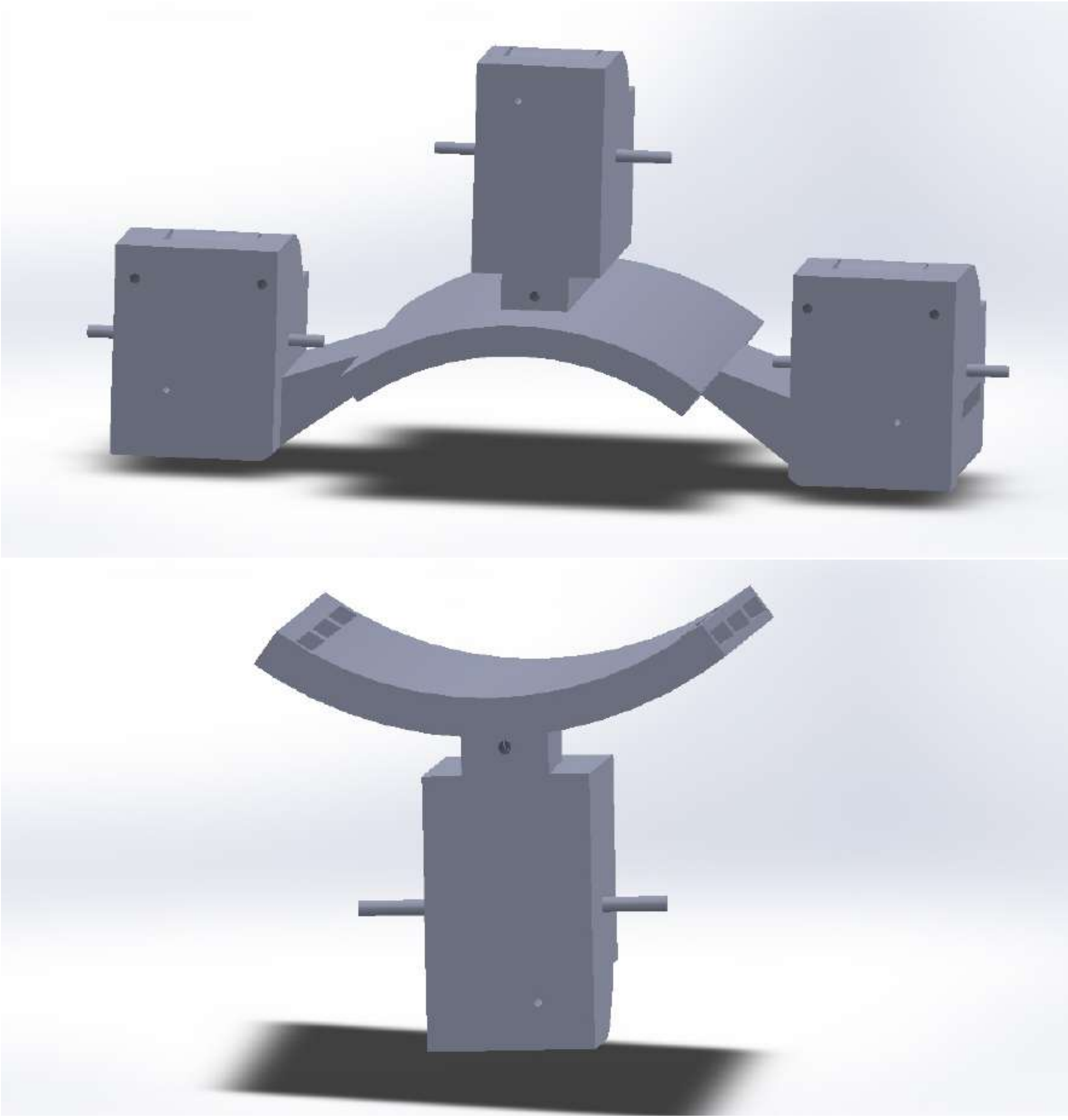


Figure 3.11: Final assembly.

To perform the functional analysis of the exoskeleton, it has been mounted on the right hand as shown in Figure 3.12, therefore the rehabilitation of the right wrist will be performed. However, the device is symmetrical which provides an advantage, since it can be used for both the right and the left wrists, and the only change that has to be done, when the rehabilitation of the other wrist is needed, is changing the glove used for the fixation of the exoskeleton without any difficulties.

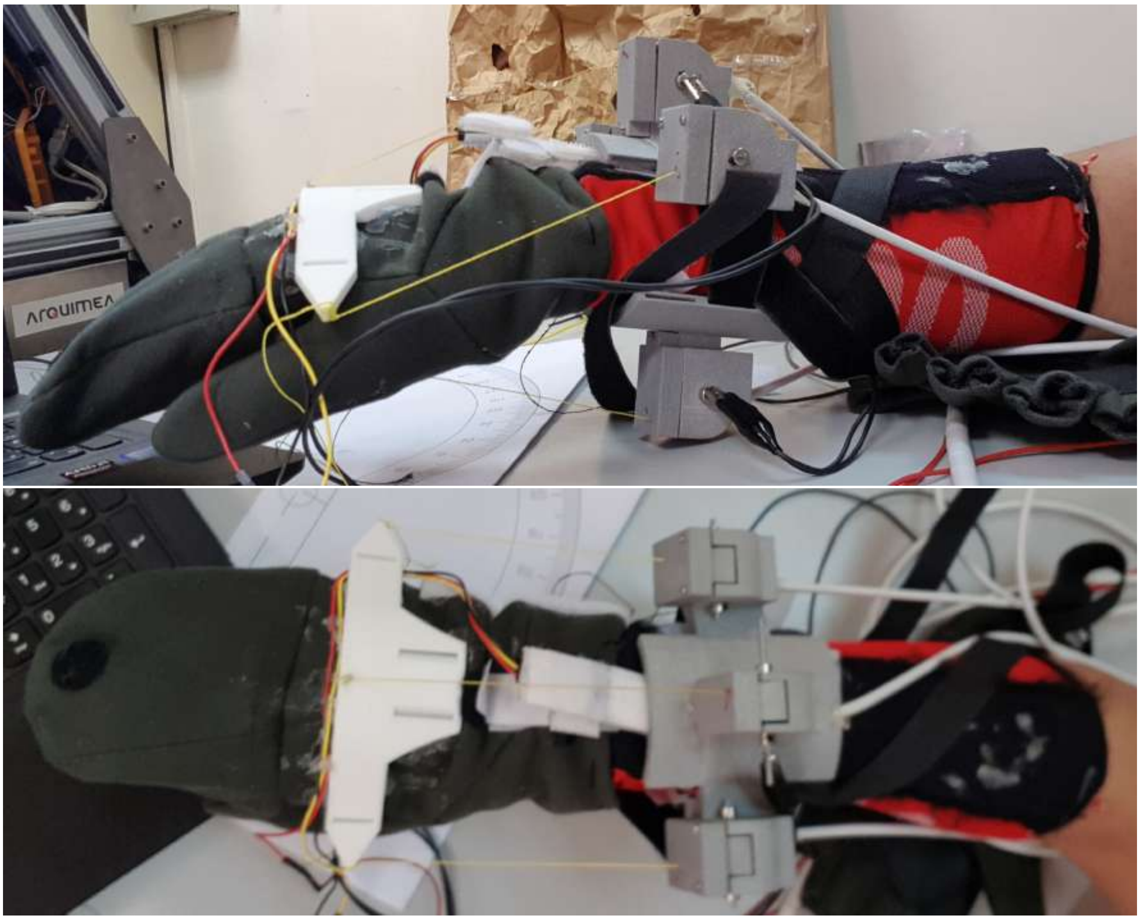
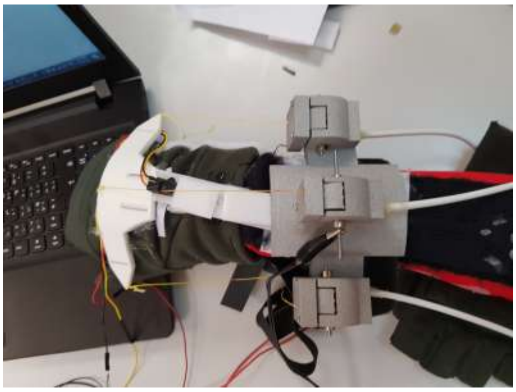


Figure 3.12: Final assembly.

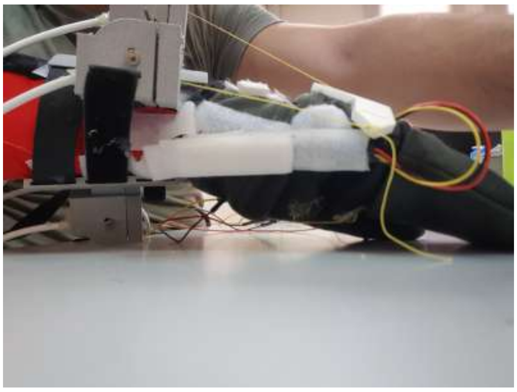
3.4 Position Sensor

In order to measure the angular position of the palm of the hand during the different movements of the wrist (flexion-extension and abduction-adduction) two bi-directional bend sensors (Figure 3.13) will be integrated on the glove. The sensors were fixed on two small plastic pieces to prevent any undesirable bending of the sensor and then one sensor was fixed on the top of the wrist and the other on the right side of the wrist to permit the bending of the sensors (Figures 3.14a & 3.14b). This bend sensor has two layers (upper and lower layer) where each layer simply works as a resistor, and when it is bent it changes its resistance (increases or decreases depending on the bending direction), and obviously the voltage across its terminals. So considering this sensor as two resistors, it could be used in a voltage divider circuit to produce a variable voltage which could be measured by a microcontroller's ADC (analog-to-digital converter). At this point, the voltage at each bending angle of the sensor read by the ADC could be converted to angular position through the software used, which will be used as a feedback to close the control loop. Finally, the bend sensor has 3 pins, where the first one will be connected to the reference voltage (3V), the third one will be connected to the ground and the middle pin that will be connected to the correct pin in the microcontroller is the measurement signal.(Bi-directional bend sensor specification sheet appendix B)

Figure 3.13: Bi-directional bend sensor.



(a) Flexion-extension sensor.



(b) Abduction-adduction sensor.

Figure 3.14: Position of the sensors.

3.5 Length of the SMA Actuators

As a first step, it is necessary to know the number of the SMA actuators needed to do each movement of the wrist. In [8] several biomechanical simulations have been carried out using the software "Biomechanics of Bodies" (BoB) which is a biomechanical modeling package that runs within the MATLAB and Simulink environment, and permits to calculate joint contact forces, torques and the muscle load distribution, and among these simulations one was done for the wrist. This simulation was carried out to move the wrist of a person with a 75 kg weight and 1.75 m height, in the ranges of movement with 80 degrees for extension and 90 degrees for flexion and at frequency of 0.25 Hz which is considered as the maximum frequency in which the rehabilitation process can be carried out, even if it not achieved during the rehabilitation. The results of the simulation showed that the moment couple needed to do the flexion-extension of the wrist is 0.3 Nm (Figure 3.15), where it has been assumed that the individual lost completely the mobility in the wrist and all the force must be exerted by the exoskeleton, and also in the case of the ulnar-radial deviation it doesn't exceed 0.3 Nm.

The SMA wire used is a 0.51mm diameter Flexinol wire from Dynalloy, where this wire can exert a pulling force of about 35.6 N (3.62 Kg). The results of the biomechanical simulation showed that one SMA wire is enough to do each movement needed of the wrist movements, which means that 4 SMA based actuators in total must be used in the wrist exoskeleton that has 2 degrees of freedom (1 actuator to do the extension movement, 1 for the flexion, 1 for the ulnar deviation and 1 for the radial deviation).

In the next step, it is required to calculate the total length of each SMA wire keeping in mind that this wire contracts by 4% of its total length when heated (Figure 3.16). Besides, it is necessary to know the displacement of SMA wires needed to do each movement of the wrist correctly and to reach the desired angular position. This displacement is measured experimentally by fixing the exoskeleton on

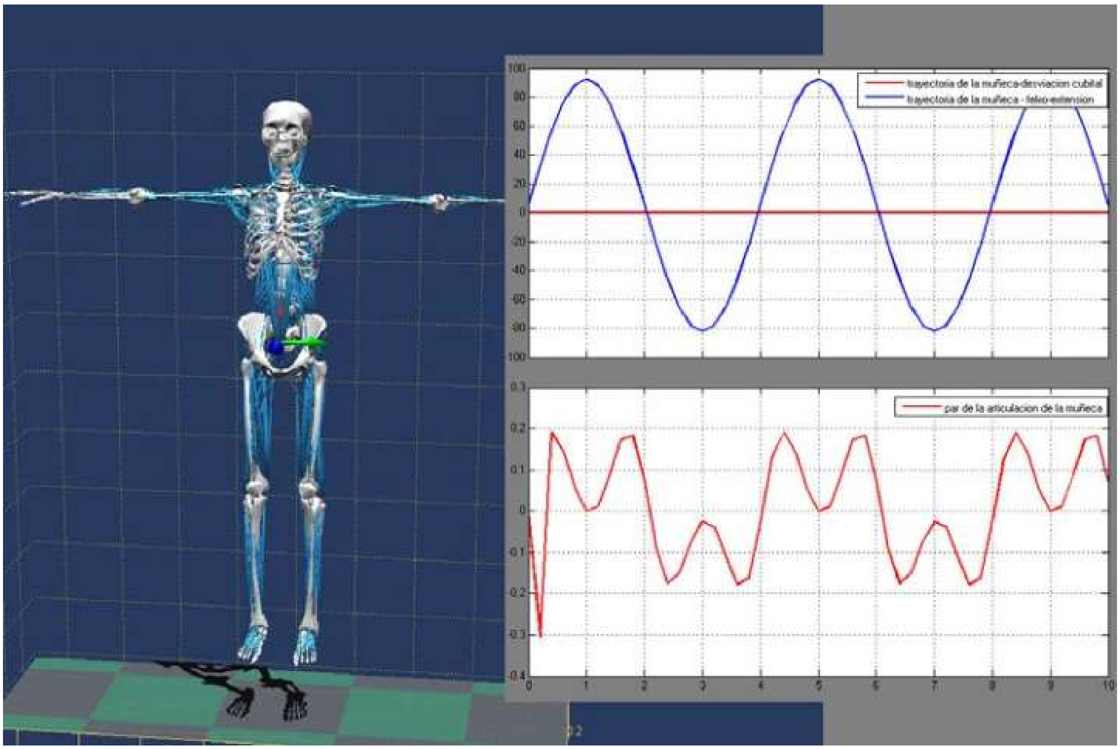


Figure 3.15: Wrist simulation for the calculation of the moment couple [8].

the wrist of an individual, using only polyethylene to measure the displacement and by fixing one thread in each groove of the double groove pulley used and without fixing any SMA wires at this stage. At this point, the thread is pulled from behind until the maximum angle of each movement is reached, and the displacement of the thread that pulls the palm of the hand is measured by a ruler. The displacement of the SMA actuator will be half of the displacement of the thread measured, since the SMA wire is connected to the small diameter pulley of the double groove pulley which has been used for this reason.

For the extension-flexion movements, the experimentally obtained displacement of the threads is approximately the same for both of the movements and is equal to about 8cm for each thread used to do each of these two movements, this is justified by the reason that the hand can reach approximately the same angles in both movements. So the displacement of the actuator needed to do each movement will be 4cm, and the total length of the actuator is calculated as follows:

$$l = \frac{displacement}{strain} = \frac{\frac{8}{2}}{\frac{4}{100}} = 1m \tag{3.1}$$

On the other hand, in the case of ulnar-radial deviations, the hand reaches to a much greater angle in the ulnar deviation than in the radial deviation, so the displacement of the two actuators used in this case won't be the same, and with the

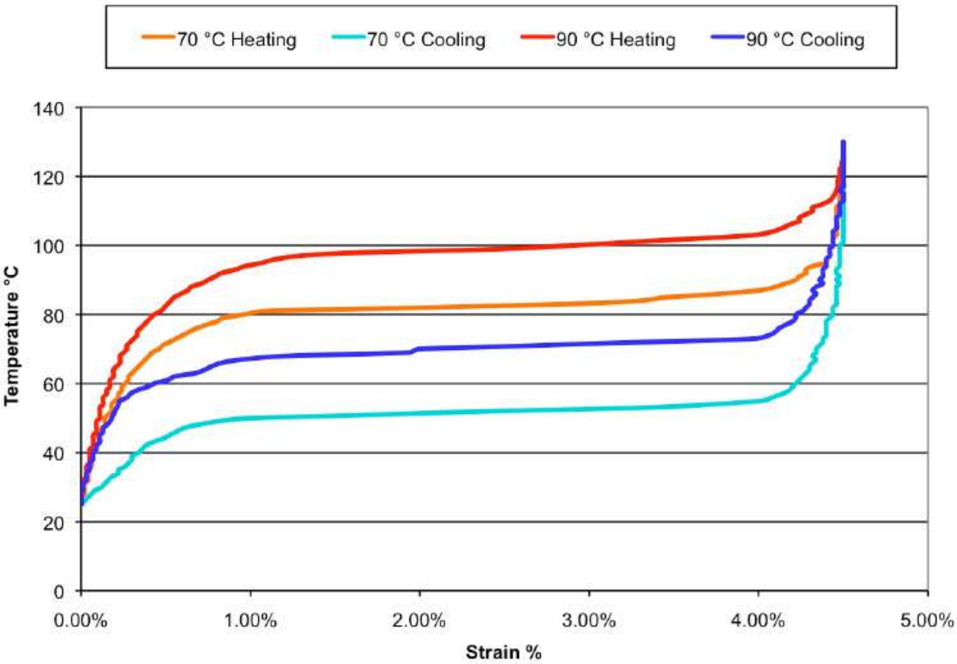


Figure 3.16: SMA strain percentage with the temperature [Appendix A].

objective of making a comfortable device that could be used with both right and left hands, we assume that both actuators should be equal in length. Keeping in mind that it is necessary to maintain the correct functioning of the actuators, the length of the actuators will be determined by measuring experimentally the displacement of the thread that pulls the hand in the ulnar deviation direction that can reach greater displacement, and which is approximately 6cm which means that the displacement of each SMA wire needed to do each of these two deviations is about 3cm. The total length of each actuator is calculated in the same way in which the length of the actuators for the flexion-extension was calculated:

$$l = \frac{displacement}{strain} = \frac{\frac{6}{2}}{\frac{4}{100}} = 0.75m \tag{3.2}$$

Finally, in order to avoid stressing the SMA wires during actuation and to prevent them from working in the maximum strain conditions, and consequently to prevent them from being broken, we increase the length of each of the actuators needed for the flexion-extension movements from 1m to 1.10m each, and we increase from 0.75m to 0.9m the length of the actuators needed for the ulnar-radial deviations.

3.6 Control Hardware and Software

In this section, the hardware and software used to do the control of the exoskeleton will be described and explained. To do the control of the robotic exoskeleton, a microcontroller STM32F4 Discovery will be used, in addition to a board that provides the power electronics for the actuators. On the other hand, the software used for the control is MATLAB/SIMULINK.

3.6.1 STM32F407VG Microcontroller

In this work, the control will be based on the STM32F407VG microcontroller, which belongs to the STM32 microcontrollers family. The STM32F407VG microcontroller (Figure 3.17), produced by STMicroelectronics, is based on the ARM® Cortex^{TM} M4 32-bit CPU [9]. It is known for its light weight and its small dimensions (10cm x 7cm) which make it comfortable for being used in a portable device. Besides, this microcontroller guarantees a better trade-off between high performance and power efficiency compared with other devices found in the market.

Figure 3.17: STM32F407VG microcontroller [9].

This high-performance microcontroller is a low-cost device and uses the easy-to-use STM32F4 Discovery kit for starting and evaluating a development. Additionally, it guarantees greater memory capacity and faster operations. All this advantages of this microcontroller make it a very good choice for the control of the exoskeleton.

3.6.2 Control Software

To implement the control algorithms for the SMA actuators used in the exoskeleton, the software Matlab/Simulink will be used, and through a toolbox called RCP (Rapid Control Prototyping). The RCP system is developed in [10], and specifically it was developed at the RoboticsLab at the Carlos III University of Madrid. This system allows to complete many tests and iterations in less time compared with other methods. It is also characterized by its high level of abstraction which makes it simple and eliminates the complexity of many input/output digital and analog interfaces, and supports the programming of the STM32F407VG microcontroller [11]. Besides, using the language Matlab/Simulink helps to make the programming easier as it provides a graphical programming language and uses simple functional blocks. In addition to the above mentioned software, installing two additional blocksets is required to be able to use the RCP system with Matlab/Simulink, one provided by Aimagin Ltd., and the other is completely in the RoboticsLab at the Carlos III University of Madrid. Finally, the code generation and the loading to the microcontroller is automatically done by the use of one the softwares (IAR Ewarm,Keil Uvision and GNU-ARM)(Figure 3.18).

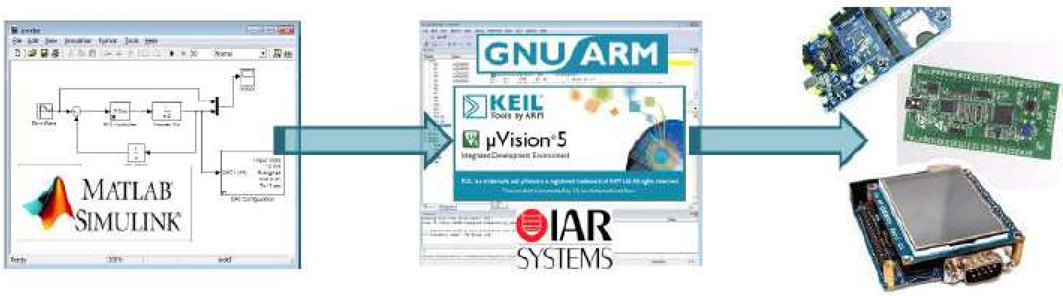


Figure 3.18: STM32F407VG programming stages [11].

To do the control of the SMA actuators, two different programs have been developed in Simulink (Target and Host).

Target

This program is the main program that contains the main control loop and that has to be loaded into the microcontroller. It also contains the algorithm that receives the signal of the sensor and converts it into angular position which will be used as feedback in the control loop. It is responsible to communicate with host in real time in a bi-directional way to represent the signals as the angular position measured by the sensor and the control signal, and it receives the reference signal from the Host. The control of the system is done by activating a PWM (Pulse Width Modulation) signal from the microcontroller, which means that the frequency to control the system could be modified depending on the application. The SMA wires present a nonlinear behaviour due to the effect of hysteresis, which makes it difficult to implement control algorithms and obtain a very accurate model [8]. However, in this project the large effects of hysteresis will be neglected. For this reason, the control is done by implementing a PID controller as shown in Figure 3.19, where the MEDIDA_REAL_1 block is the angular position given by the sensor as a feedback, and the ERROR_1 block is the error calculated by the difference between the reference signal and the real position. However, a saturation block was added to avoid the wind-up phenomenon where the controller reaches the actuator limits which provoke the actuator to become saturated and the system to operate in the open loop. Finally, through the target it is possible also to change the PID controller parameters.

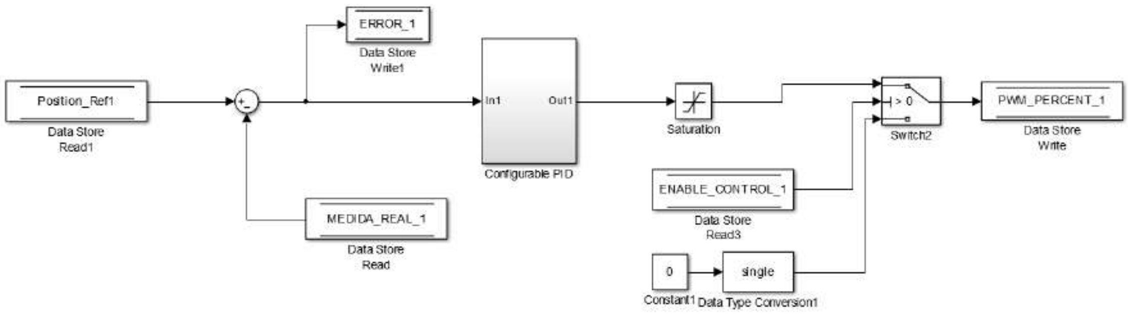


Figure 3.19: SMA control loop.

To be able to activate 2 actuators together, that is to say that to be able to do the 2 movements of each degree of freedom together (flexion-extension and ulnar-radial deviation), 2 PID controllers were implemented together (Figure 3.20), where this time a Matlab function was added to avoid the activation of the 2 actuators at the same time and leaves a delay of 1 second when passing from the activation of the first actuator to the activation of the second one.

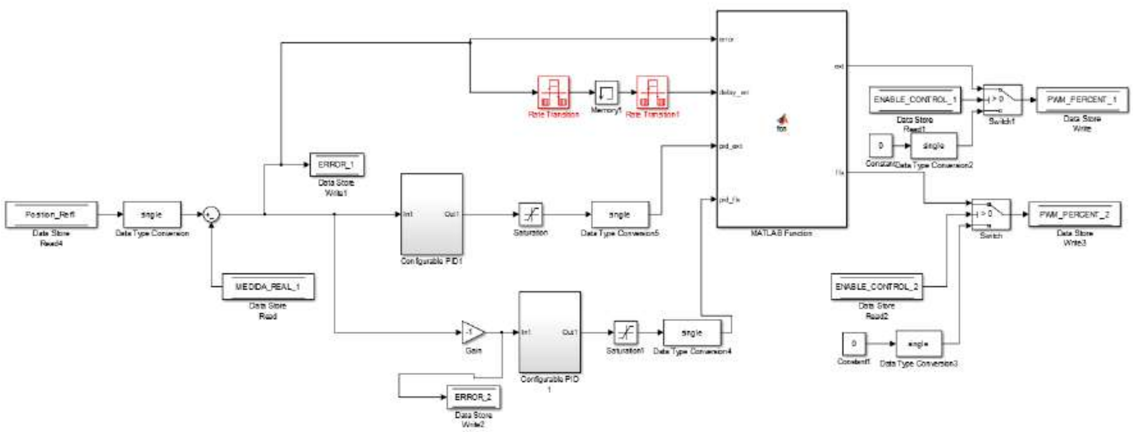


Figure 3.20: Control system for 2 actuators.

Host

The second program to develop in Simulink is the Host (Figure 3.21). This program works as the user interface to control the exoskeleton, and communicates with the microcontroller through a serial port in the computer. It also communicates with the Target as mentioned before in a bi-directional way to receive the necessary data for the control, as the real position, the control signal and the position error in real time. Through this program the user can choose to activate through switches one of the four actuators needed to do the different movements of the wrist separately while deactivating the others, or choose to activate the two actuators of the 2 movements of each degree of freedom together, which means that flexion-extension movements can be done at the same time, and the same applies for the adduction-abduction. Through this program it is also possible to change the reference signal needed for the type of the rehabilitation desired, such as sinusoidal signal or a step signal, and change the frequency also. Besides, the Host also saves all the data after rehabilitation (control signal,position error and the reference signal with the real position) to the workspace in Matlab as a Matlab file where it can be saved and rechecked later when needed.

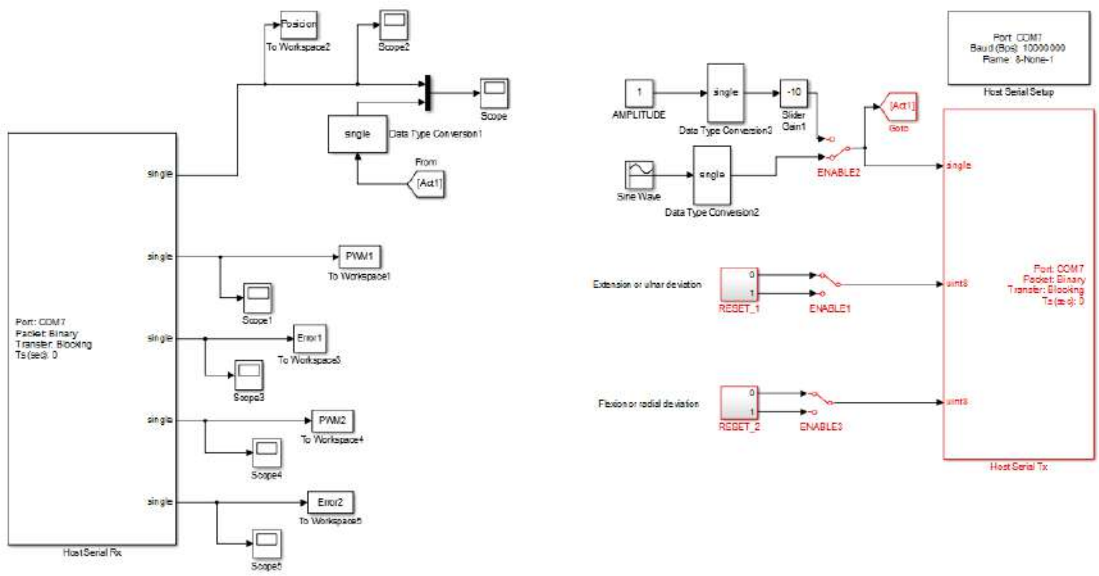


Figure 3.21: Host block scheme to control the exoskeleton.

The activation of the 2 actuators of each degree of freedom needs the activation of the appropriate sensor from the Target and then loading the Target data again to the microcontroller, in order to receive the correct real position from the needed sensor. Loading the data into the microcontroller is a fast operation and usually takes a few time to be completed (about 10 seconds).

3.7 Electronic Connections

To do the control of the exoskeleton, an additional circuit (Figure 3.22) is needed to supply each SMA wire with the precise power, and starting from the PWM signal generated by the STM32F4 microcontroller. This circuit will be connected to the power supply from one side to be provided with the necessary input voltage and will be also connected to the microcontroller from another side. This circuit was designed and made in the RoboticsLab at the Carlos III University of Madrid.

This power electronics card contains the PWM buffer that is needed to receive the PWM signal from the microcontroller. The PWM buffer receives 2 PWM signals since the circuit can aliment 2 SMA actuators, and then performs an amplification of the PWM so that it is possible to continue operating with this signal in the rest of the circuit. It also contains an alimenting circuit containing also a voltage regulator for the 2 transistors, where the input voltage will be used also to aliment the SMA actuators, and it's output voltage is always 12 V to aliment the transistors. The transistors are of type MOSFET and work as switches to close the circuit that that supplies power to the actuators. Since each actuator is connected directly to the positive of the power supply, the transistors close the circuit through the reference, when a certain input voltage is exceeded.

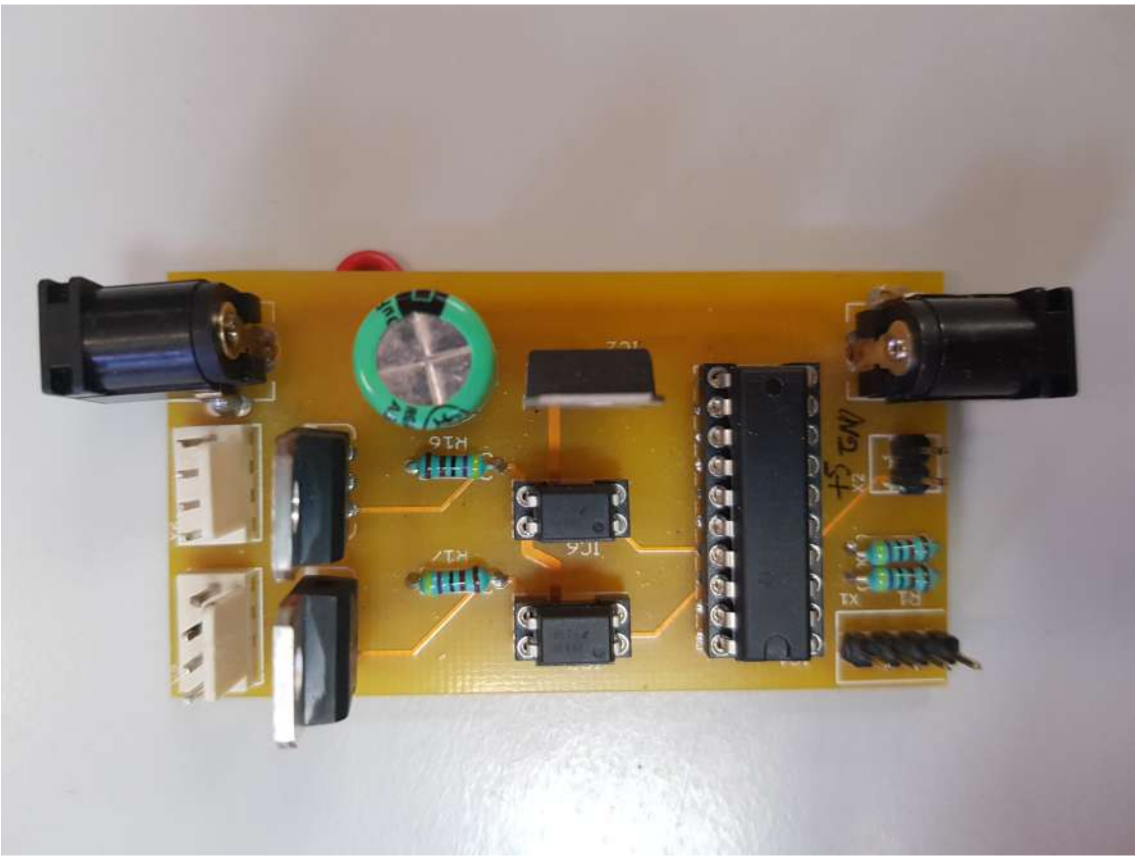
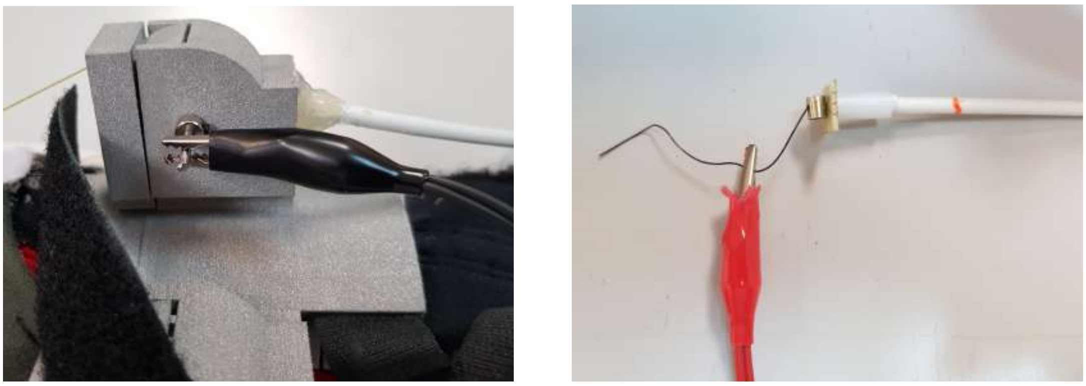


Figure 3.22: Power electronics circuit.



(a) (b)

Figure 3.23: Connection of the SMA actuator to the electronic circuit.

As mentioned above, the input voltage of the alimenting circuit of the power electronic circuit will be used to feed the SMA actuators, so the SMA actuators will be connected to the circuit using crocodiles. One crocodile is connected to the free end of SMA actuator (Figure 3.23b), while the other crocodile is connected to the steel axis (Figure 3.23a). The steel axis is in contact with the aluminum pulley to which the SMA wire is connected, and being the aluminum and steel good conductors of electricity and having a low resistance, they can deliver the voltage to the SMA wire without problems.

The input voltage needed to feed the SMA actuators is calculated according to the characteristics of the SMA flexinol wire used in this work. As specified in the datasheet of the flexinol wire (Appendix A), has a R=4.3 ohms/meter resistance and needs a I= 4 A current to contract, so the voltage needed from the power supply is calculated according to the following:

- For the Flexion-Extension actuators where the length of each actuator is 1.10 m :

$$V = R * I * length = 4.3 ohms/meter * 4A * 1.10m = 18.92V \tag{3.3}$$

- For the abduction-adduction actuators where the length of each actuator is 0.9 m :

$$V = R * I * length = 4.3 ohms/meter * 4A * 0.9m = 15.48V \tag{3.4}$$

3.8 Manufacturing Costs of the Exoskeleton

Fabricating a low-cost device is one of the most important objectives when designing wearable rehabilitation devices, so in this section the costs of the exoskeleton will be listed. The different pieces and parts used in this prototype can be divided into 3 categories, so the costs of each group of pieces will be calculated separately and then the total cost will be calculated.

Piece	**Price(€)**
Piece for EX-ADD-ABD	194,79
Piece for FX	133,6
Hand	52,32
Right tap	54,14
Left tap	54,14
Middle taps (2 taps x 53,89€/tap)	107,78
Pulleys (4 pulleys x 35€/pulley)	140
Shaft collars and screws	6
Steel axis (4 axes x 4cm x 2€/m)	0.32
Total	**742,99**

Table 3.2: Costs of the exoskeleton pieces.

In Table 3.2 the costs of the 3D pieces alongside with the pulleys and other pieces forming the exoskeleton are shown. As mentioned before, these pieces were fabricated in an external company, except for the pulleys that have been fabricated in the technical office of the Carlos III University of Madrid.

Piece	**Price(€)**
SMA wire flexion-extension (2 wires x 6€/m x 1.2m)	14.4
SMA wire adduction-abduction (2 wires x 6€/m x 1m)	12
Teflon tube flexion-extension (2 tubes x 1,40€/m x 1.1m)	3,08
Teflon tube adduction-abduction (2 tubes * 1.40€/tap x 0.9m)	2,52
Bowden cable flexion-extension (2 cables x 1.20€/m x 1.1m)	2,64
Bowden cable adduction-abduction (2 cables x 1.20€/m x 0.9m)	2,16
Total	**36.8**

Table 3.3: Costs of the SMA actuators.

The price per meter and the total cost of each material used to build the SMA based actuators to do each of the 4 movements of the wrist (flexion-extension-adduction-abduction) are shown in Table 3.3. As we can see, these actuators have a very low cost compared to other actuators such as electric motors, and this is one of the advantages of these actuators which help in fabricating low cost wearable devices.

Piece	Price(€)
Microcontroller STM32F407VG	17
Power electronics circuit	20
Cables and wires	10
Sensors (2 sensors x 18.94€/sensor)	37.88
Total	**84.88**

Table 3.4: Costs of the control hardware.

The third group of the parts needed is the control hardware. The costs of the different electronic pieces used in the control of the exoskeleton are shown in Table 3.4. The market price of the commercial products is shown, while for the power electronics circuit that have been developed in the RoboticsLab the price is approximated.

Piece	Price(€)
Exoskeleton pieces	742.99
SMA actuators	36.8
Control hardware	84.88
Glove,belts & forearm protector	19,5
Total	**883.91**

Table 3.5: Total cost of the exoskeleton.

Finally, after taking in consideration all the parts used in the device and summing all the previous calculated costs with the cost of the glove and the forearm protector used in the exoskeleton, the total price of the exoskeleton is **883.91 €** as shown in Table 3.5.

3.9 Weight of the Exoskeleton

Another important aspect to consider is the weight of the exoskeleton, as developing a light-weight device is one of the main objectives when fabricating wearable devices and exoskeletons. Constructing light-weight device consequently makes the device more comfortable for the patient, where the patients are going to put it on their hands. For this reason, this section is dedicated to the weight of the exoskeleton designed.

To determine the weight of the exoskeleton, a very precise balance found in the RoboticsLab is used. The parts that belong to the same group were collected and weighted together. As we can see in Table 3.6 the weight of the pieces fabricated in the external company along with the pulleys and the glove is included in the exoskeleton group, while the second group shows the total weight of the 4 SMA actuators used in the exoskeleton, and the third group shows the weight of the different electronic pieces used to do the control of the exoskeleton.

Component	**Weight(g)**
Exoskeleton	350
SMA actuators	250
Control hardware	200
Total	**800**

Table 3.6: Weight of the developed exoskeleton.

Finally, the total weight of the device is 0.8 Kg and that is what makes this device a light-weight exoskeleton and comfortable for the user, and taking into consideration that the patients will place on their hand only the exoskeleton, where the SMA actuators and most of the control hardware, except for the sensors, will be placed on the table. So the weight of these parts could be subtracted from the weight that will be placed on the hand of the patient. As a conclusion, the total weight that will be placed on the hand of the patient will be **360g** approximately.

Chapter 4

Tests and Experimental Results

After mounting all the pieces of the exoskeleton and connecting all the cables, the next step is to test the functionality of the device. It is necessary to verify the correct functioning of the exoskeleton and to validate the control system of the device for the two degrees of freedom (flexion-extension and ulnar-radial deviation).

As explained in the previous chapter, a regular PID controller will be used for the control of the SMA actuators neglecting the huge effects of hysteresis. Although the SMA actuators are non-linear systems and the PID controllers are linear but they could be adequate in some applications when dealing with non-linear systems. After implementing the control system, it is necessary to adjust the fundamental parameters of the PID controller to avoid overshoots in the response of the system and undesired oscillations in the trajectory. Finally, different experiments on the device will be carried on the hand of a real human to verify the correct functioning of the device in each movement. Tests will be carried on each movement separately and then on the flexion-extension movements together and on the ulnar-radial deviation together and in different positions of the hand.

4.1 Adjusting The PID Controller Parameters

Starting from the theory of the PID controller, the controller output *u(t)* is given by the equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\ d\tau\ + K_d \frac{d}{dt} e(t) \tag{4.1}$$

where:

- K_d is the derivative gain (parameter to be tuned).
- K_i is the integral gain (parameter to be tuned).
- K_p is the proportional gain (parameter to be tuned).

- e is the error, where it is given by the difference between the set point and the process variable.
- t is the instantaneous time.
- τ is the integration variable (takes values from 0 to the present time t).

To find the suitable parameters for the desired control, it is necessary to fix some goals and requirements before proceeding in tuning the parameters. The objectives to be considered while tuning the parameters are:

- System response without undesired overshoot and oscillations.
- Rapid system response to the changes in the reference signal, which means having a response with reduced rise time.
- Error that tends to zero (ideally it should be null).

It is also interesting to consider the effect of increasing each parameter independently on the response of the system. These effects are shown in Table 4.1.

Parameter	**Rise time**	**Overshoot**	**Settling time**	**Stability**	**Steady-State error**
K_p	Decrease	Increase	Small change	Degrade	Decrease
K_i	Decrease	Increase	Increase	Degrade	Eliminate
K_d	Minor change	Decrease	Decrease	Improve if K_d is small	No effect

Table 4.1: Effects of increasing each parameter independently [17][18].

The SMA wires are non-linear systems, and one problem here is that the PID controllers are linear, but their performance in non-linear systems could be variable. In this case the overshoot should be corrected slowly, and the PID should be tuned to be overdamped to reduce or prevent the overshoot, even though this may reduce performance. At this point and taking into consideration the above mentioned objective that have to be satisfied, the adjustment of the parameters will be done by trial and error. Several tests will be carried out while modifying the PID parameters and the input reference for the system until the appropriate parameters that guarantee the previously mentioned objectives are found. In Table 4.2 the values of the fundamental parameters of the PID controllers obtained after many iterations are shown.

PID parameter	**Flexion-Extension**	**Ulnar-Radial deviation**
K_p	32	27
K_i	0	0
K_d	12	8

Table 4.2: Values of the PID controllers parameters .

Since the 2 actuators used for the flexion-extension have different length from the actuators used for the ulnar-radial deviation, different parameters for each case are required to implement the controller. And as observed in the table above, the integral gain is eliminated by setting its value to 0 in both cases, since it destabilizes the system and causes overshoot in the system response.

4.2 Testing The Exoskeleton

After finding the appropriate parameters of the PID controller, different tests will be carried out to check the functionality of the exoskeleton using different types of reference signals and putting the hand in random positions. These tests will be analyzed to check the efficiency of the device and to check what technical aspects could be improved in the future works.

As a first step, the extension and flexion movements will be tested individually and then the 2 actuators will be put in action together and the flexion-extension movements will be tested together, and in the next step the same thing will be done with the ulnar-radial deviation where each movement will be tested individually and then the 2 movements will be tested together. The device will be tested on the hand of a healthy person.

Before starting the tests, the range of motion of each movement should be taken into consideration as mentioned in chapter 3, and recalling the ranges of motion in Table 4.3 . However, the main aim of the rehabilitation therapies is to recover the range of motion in the patient's wrist in ADL range, but it would be also interesting to test the functionality of the device in high ranges of motion.

Movement	**Total Range (degrees)**	**ADL Range (degrees)**
Flexion	90	15
Extension	85	35
Radial deviation	20	15
Ulnar deviation	45	20

Table 4.3: Range of motion of the wrist.

In the case of flexion-extension the angles of the flexion movement will be considered negative while the angles of the extension movement will be considered positive, while in the case of ulnar-radial deviation the angles of the ulnar deviation will be considered positive while the angles of the radial deviation will be considered negative.

4.2.1 Testing The Actuator Of The Extension Movement

The first tests will be done activating only the SMA actuator used to do the extension of the wrist using different types signals as input, to validate its functioning. In these tests we chose to put the forearm parallel to the ground and leaving the palm of the hand free to fall by the effect of the gravity during flexion.

1 - System Response With a Step Input

The objective of this test is to check how the system reacts to a sudden change in the input signal. The test is done by leaving the palm of the hand in a free position at the beginning that was at about -33° (33° in flexion), and then moving it to an upper limit for extension which was chosen to be 82° in this test, and the reason behind choosing this high angle is to verify if the actuator can take the wrist to the maximum position, while in the rehabilitation process normally the angles are limited to lower values. When the wrist reaches 82°, the device is maintained in this position for 15 seconds to analyze the steady state error. After that, the input signal is reduced to 0° and the wrist goes back to this position by the effect of the gravity. In this way the cooling of the SMA wire can be analyzed and the device is forced to maintain the wrist at the point of equilibrium between flexion-extension (0°), and then the input signal is increased to 82° again and the previous sequence is repeated for another 2 cycles while changing the time under which the device is maintained in the same position.

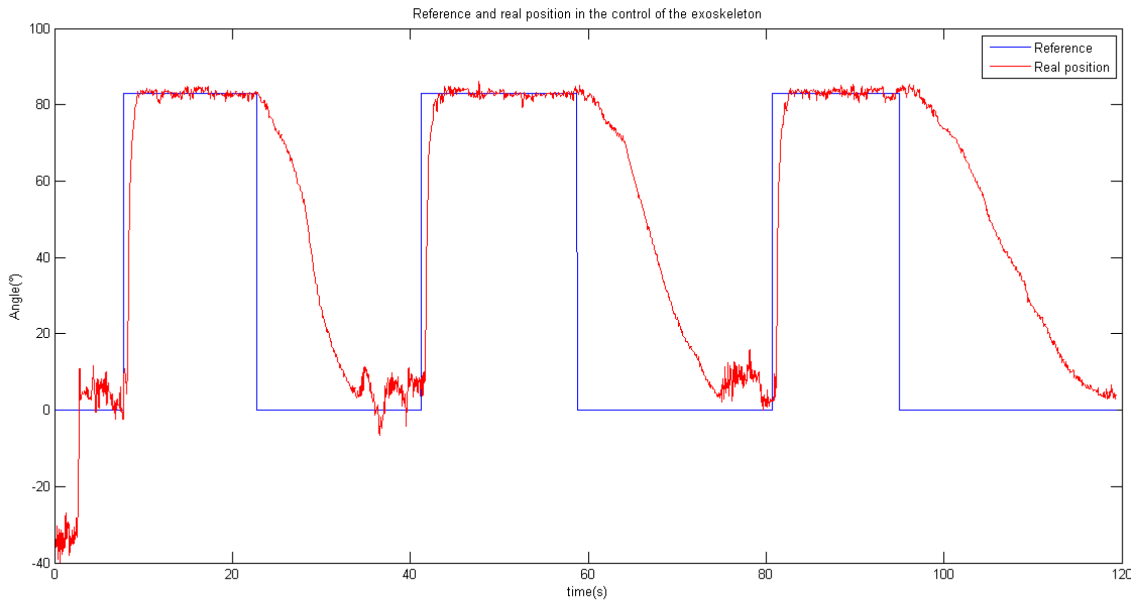


Figure 4.1: System response in extension for step input.

Analyzing Figure 4.1, many points can be discussed. First, a study will be done on the cooling and heating of the actuator. At the beginning, the system was slow to follow the reference, and it took the actuator about 4 seconds to take the wrist to the reference position, and that is explained by the fact that the SMA wire was cold at the beginning and the system needs more time to reach the temperature that causes the transformation from martensite to austenite. When moving then from 0° to 82° in the 3 cycles, the phenomenon explained above is not observed, and it took the actuator less than 2 seconds to take the wrist to the reference position, and this is due to the fact that the SMA wire still accumulates heat. On the other hand, observing the cooling time of the actuator when reducing the reference from

82° to 0°in the first cycle it was approximately 10 seconds, 15 seconds in the second cycle and 20 seconds in the third cycle approximately, and taking into account that the force of gravity applied to the hand takes the wrist back to the position of equilibrium between flexion and extension. This increase in the cooling time after each cycle is caused by the heat stored in the SMA wire after each cycle which makes the system slower after many cycles.

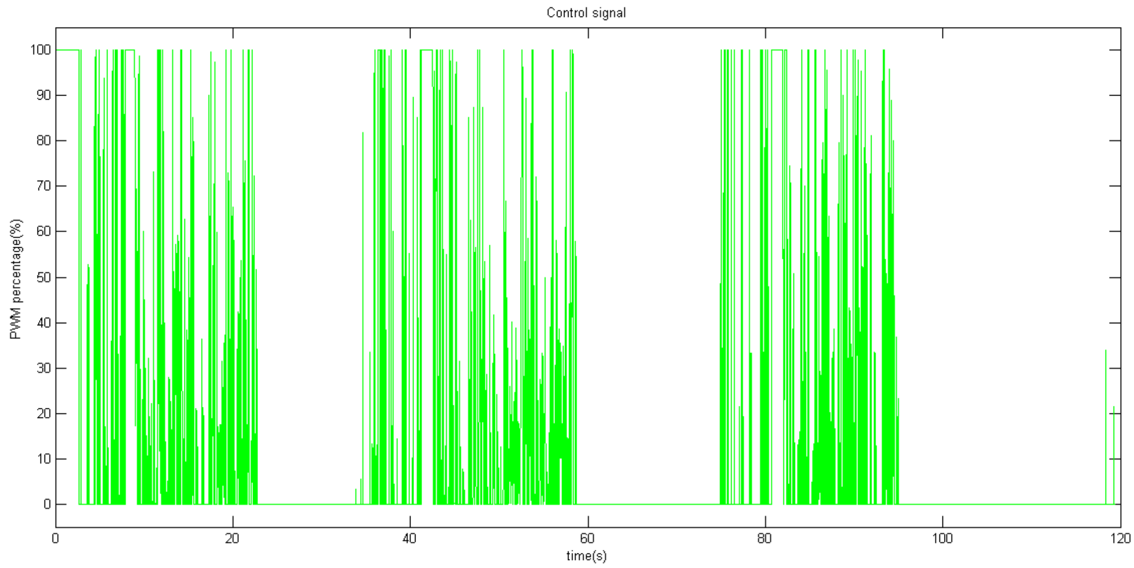


Figure 4.2: Control signal in extension for step input.

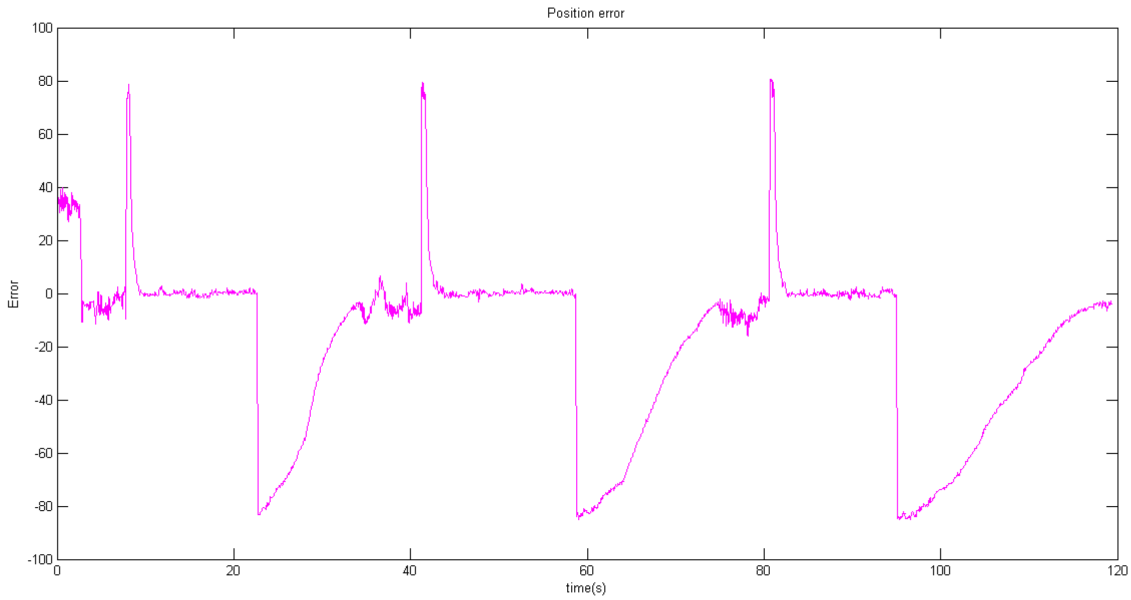


Figure 4.3: System error in extension for step input.

Figure 4.2 shows the control signal in percentage (%) of PWM. It is observed that most of the time the SMA actuators consumes below 60% of the maximum power which is 76 W (19V*4A) to maintain the wrist in the desired position,since the steady state error tends to 0 most of the time, except in some moments where the consumption exceeds the 60% and reaches the maximum sometimes due to the noise of the sensor where the error is not equal to 0 so it forces the actuator to consume more power to take the wrist back to the desired position.

It is also necessary to mention that the steady state error is almost 0 during actuation as seen in Figure 4.3, except at some moments where a small overshoot or a small difference between the reference and the real position is observed, and this is may be caused by the noise of the sensor or by an undesired movement of the wrist of the human.

2 - System Response With a Stair Input

This test aims to check if the system can reach different positions in all the range of angles and to study the cooling and heating of the SMA actuator is done by using a stair input. This test is similar to the previous one but this time we increase the angle gradually after each certain period of time to reach the maximum and then decrease the angle again gradually to bring the wrist back to 0°.

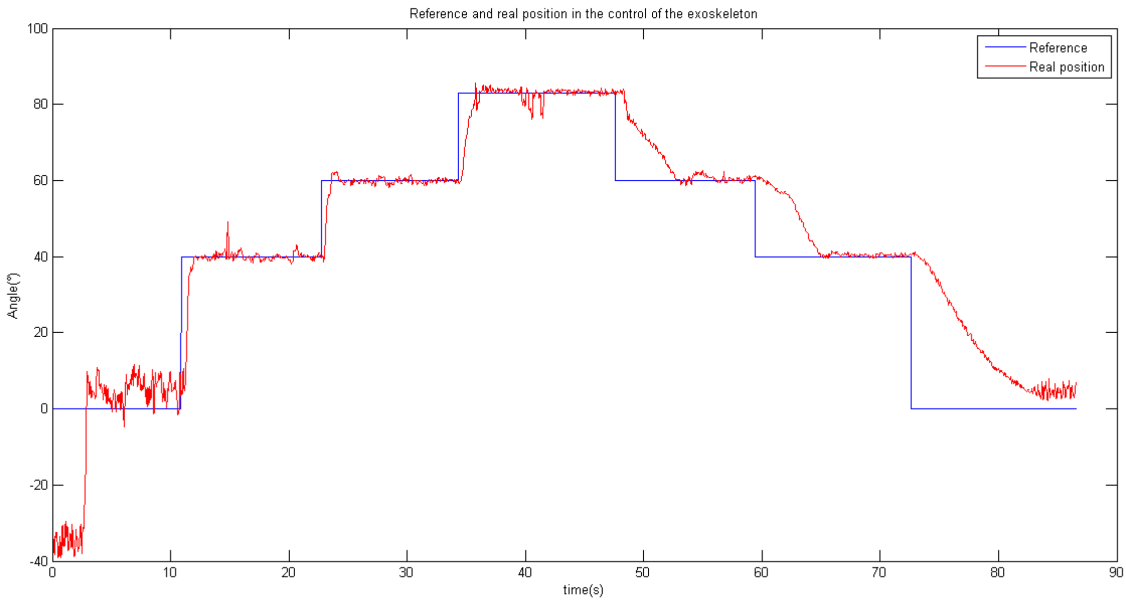


Figure 4.4: System response in extension for stair input.

As noticed in Figure 4.4, at the beginning the phenomenon explained before where the actuator delays 3 seconds to reach the transformation temperature and start actuating. Then taking the wrist to 40°,60° and 80° gradually, the actuator responds quickly to the sudden change of the signal, and the heating time is reduced in each stair in comparison with the previous test since the changes in the reference signal are not so abrupt. On the other hand, it is noticed also how the system is able to follow the reference signal in flexion by the effect of the gravity when decreasing the angles gradually. Notice that the steady state error tends to 0 during actuation as shown in Figure 4.6.

In Figure 4.5 the control signal for stair input is shown, and shows how the actuator consumes power during the test. In the phase of flexion where the actuator is in the cooling phase it is noticed that there is no consumption and the actuator is not actuating, but it consume a small percentage of power when the system reaches the angle of the reference signal in order to keep the wrist in the desired position and to avoid that the system reaches small angles than the one desired and keeping the error near to 0.

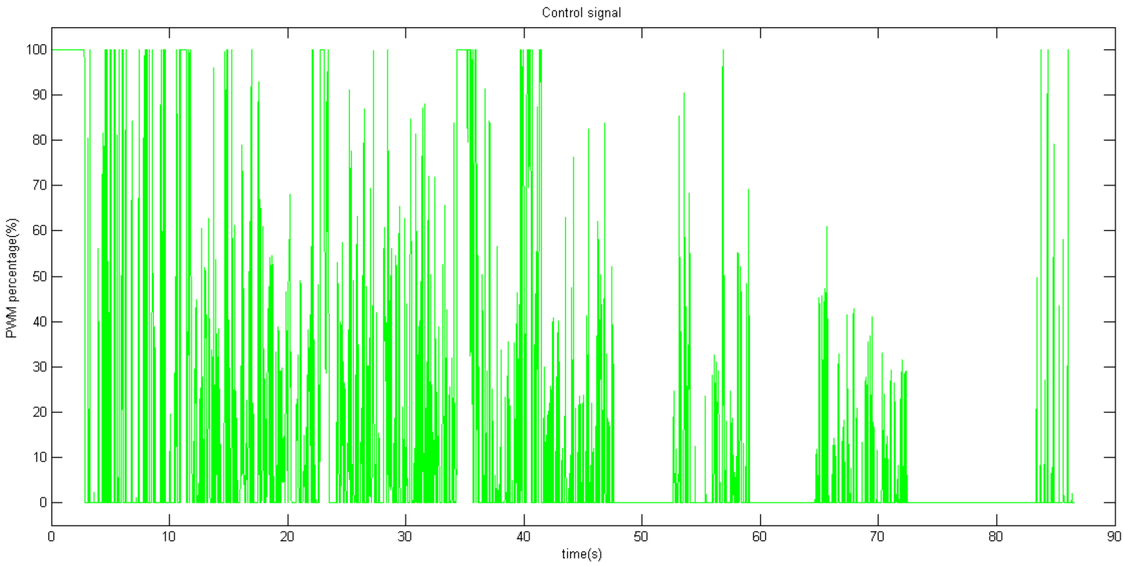


Figure 4.5: Control signal in extension for stair input.

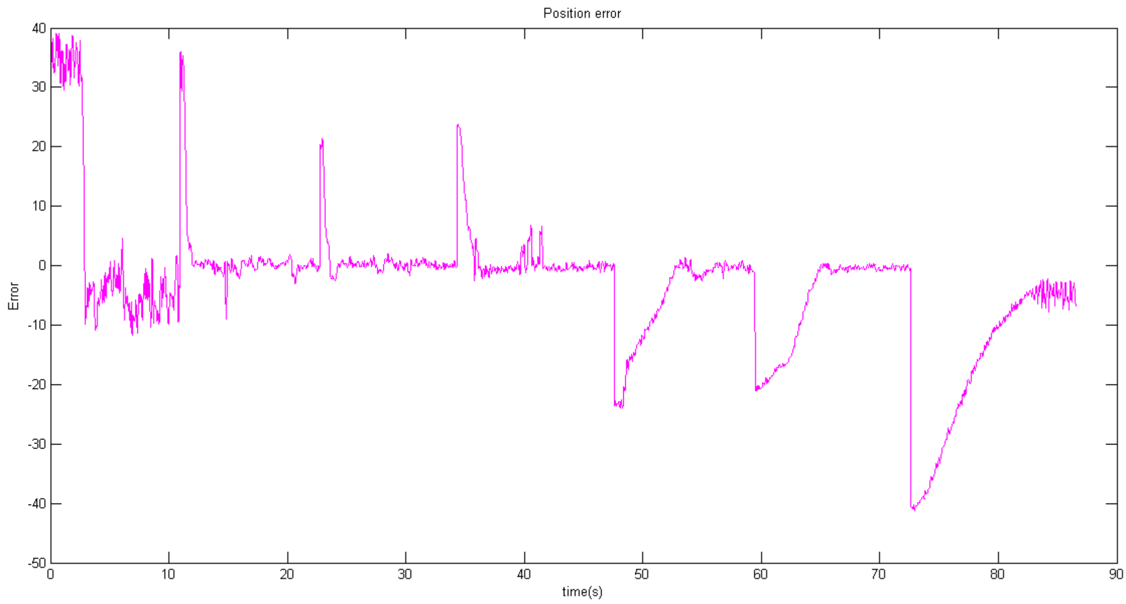


Figure 4.6: System error in extension for stair input.

3 - System Response With a Sinusoidal Input

The last test for the extension actuator is done with a sinusoidal input. In this test it is necessary to choose the correct velocity of the exoskeleton by modifying the frequency of the input signal to ensure smooth movements, since moving very fast can cause an injury to the patient during the rehabilitation process and when moving with a slow speed, the rehabilitation therapy loses its effect and exhausts the patient. For this objective, a sinusoidal signal with a frequency of 0.25Hz, amplitude of 40° and centered in 20° is chosen.

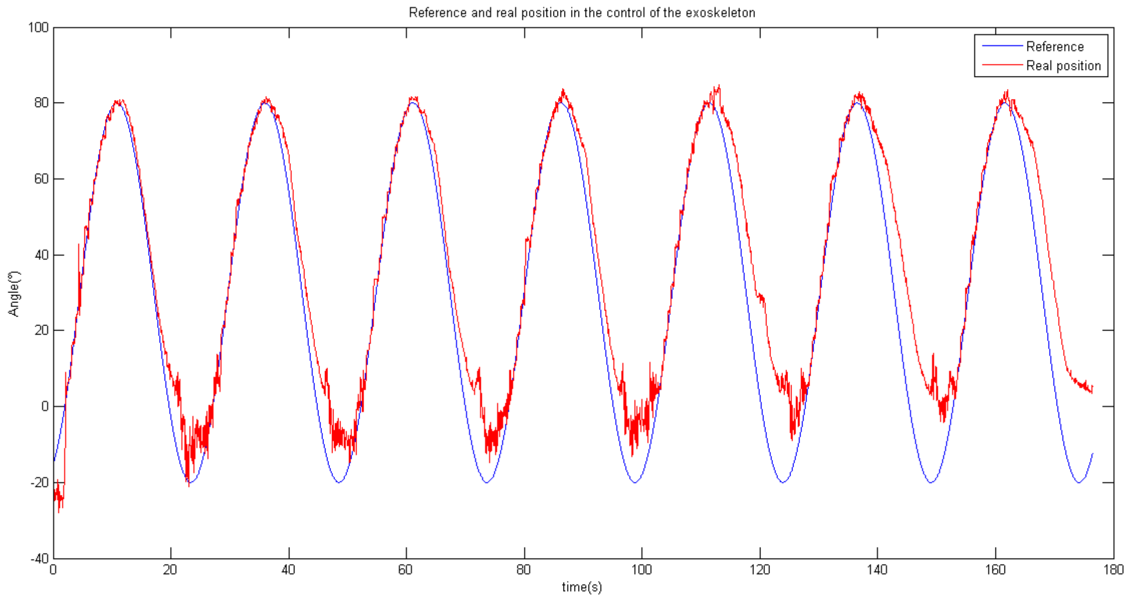


Figure 4.7: System response in extension for sinusoidal input.

In the analysis of Figure 4.7, it is evident that the system follows perfectly the reference signal during extension in the 7 cycles performed and without losing the range of angles of the movement, and during this process the error tends to 0 as shown in Figure 4.9. On the other hand, during flexion the system shows a small delay in the first cycle when following the reference signal because it depends on the cooling time of the extension's SMA actuator, while in the following cycles the delay of the system when following the signal increases due to the increase in the heat stored in the actuator. This increase in the heat storage in the actuator also increases the error after each cycle as can be seen in Figure 4.9 and the system couldn't reach 20° in flexion after the first cycle, and the SMA wire can't recover it's initial form. After these 7 cycles performed it is necessary to wait for 2 or 3 minutes for the SMA wire to recover its initial shape before starting another test in the rehabilitation process.

In Figure 4.8, the control signal in extension for a sinusoidal input is shown. It is evident that the actuator doesn't consume power during flexion while trying to recover its original shape. However, during the extension movement, the SMA actuator consumes 10% and 100% of the maximum power which is equal to 76 W.

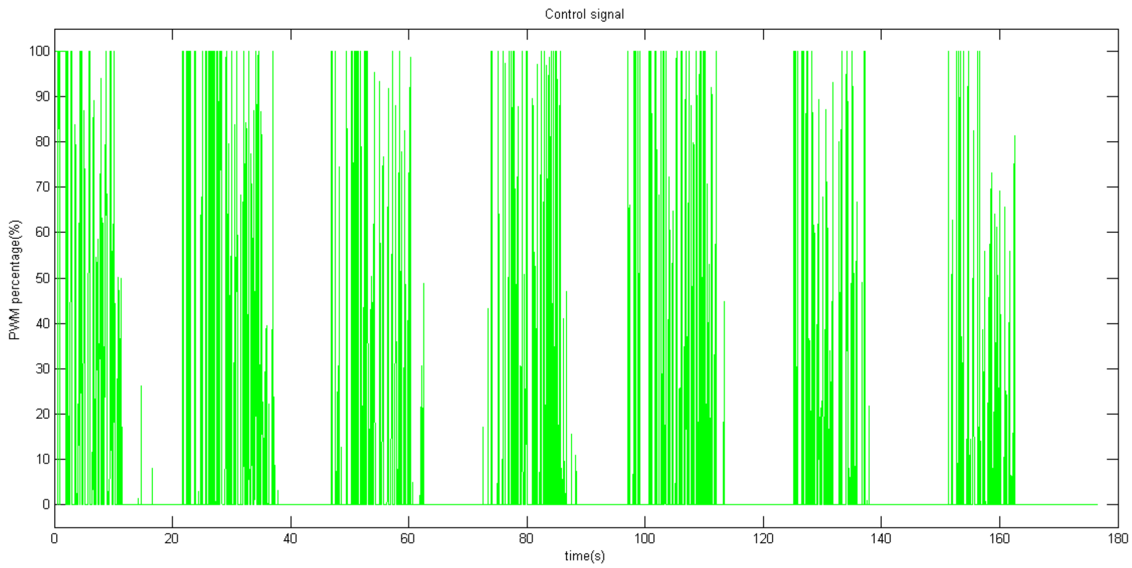


Figure 4.8: Control signal in extension for sinusoidal input.

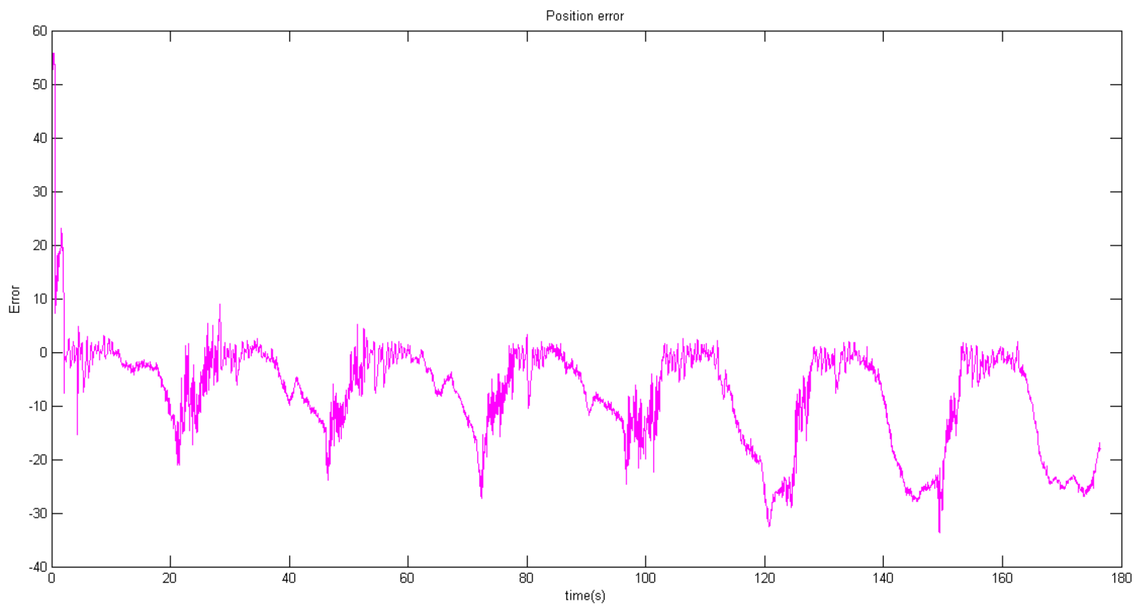


Figure 4.9: System error in extension for sinusoidal input.

4.2.2 Testing The Actuator Of The Flexion movement

The next tests will be performed to test the correct functioning of the actuator used to do the flexion of the wrist, and keeping the hand in the same position as before, where the forearm is parallel to the ground.

1 - System Response With a Step Input.

The first test will be done with a step input. In this test the wrist was left at about -3° at the beginning and then the reference was changed from 0° to -50° (50 degrees in flexion).

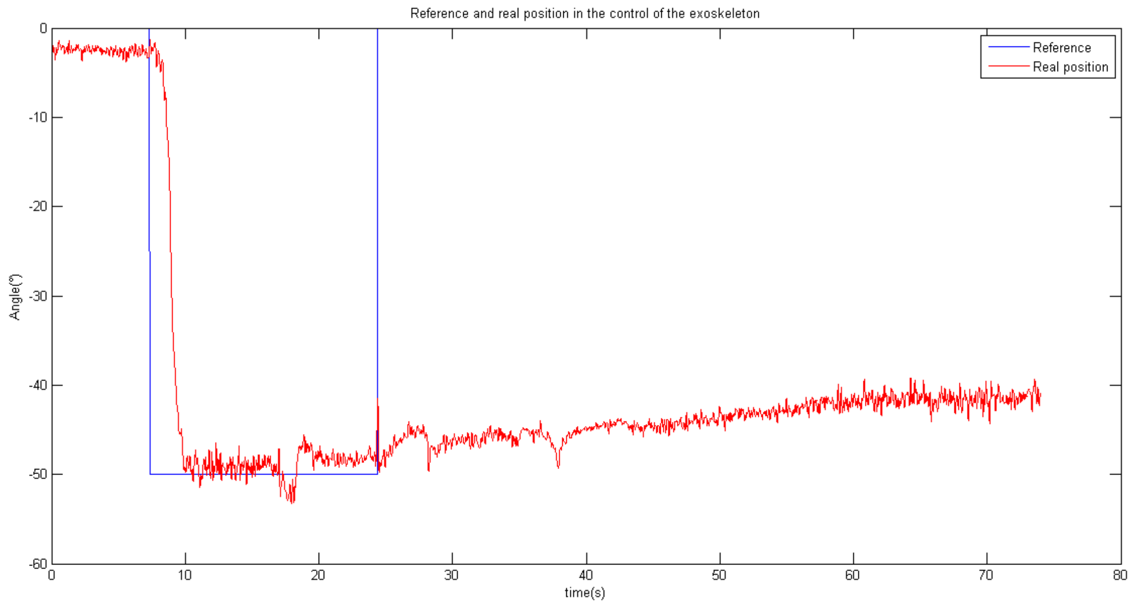


Figure 4.10: System response in flexion for a step input.

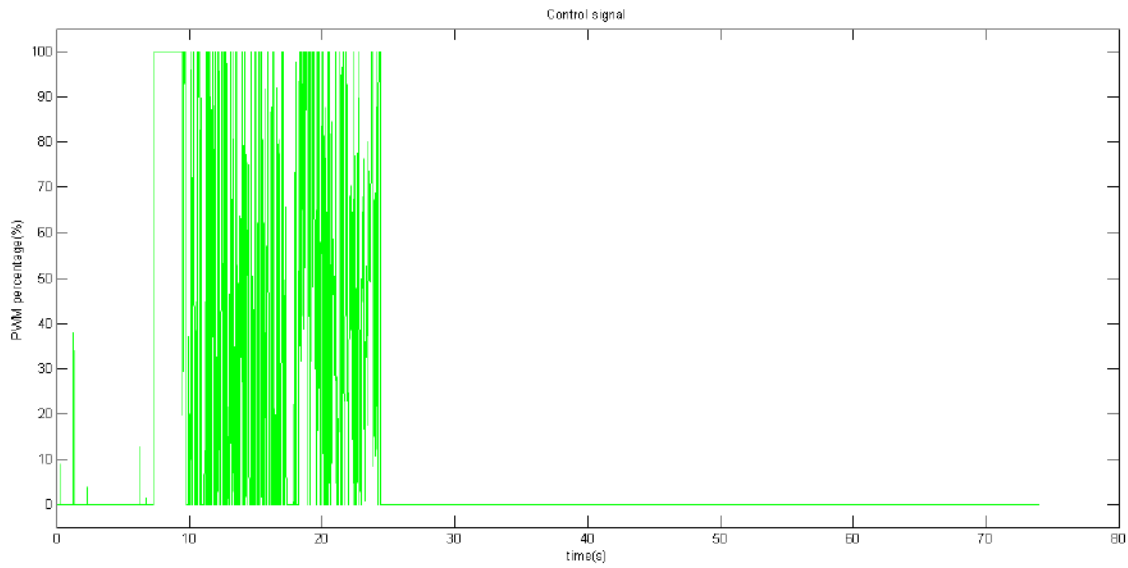


Figure 4.11: Control signal in flexion for a step input.

As shown in Figure 4.10 the system takes about 3 seconds to take the wrist to the desired position since the actuator was cold and it takes time to reach the transformation temperature. The system is then left at -50° for about 20 seconds to analyze the steady state error, and as shown in Figure 4.12 it tends to 0 during actuation. After that the reference signal is taken back to 0 and the hand is left in the free position for about 50 seconds. Obviously, the wrist is not subjected to the gravity force in this case, so it remains in its position and relaxes by about 8° while the SMA actuator is cooling down.

Figure 4.11 represents the control signal in flexion for a step input. It shown that most of the power consumption during actuation is around 60% of the maximum power.

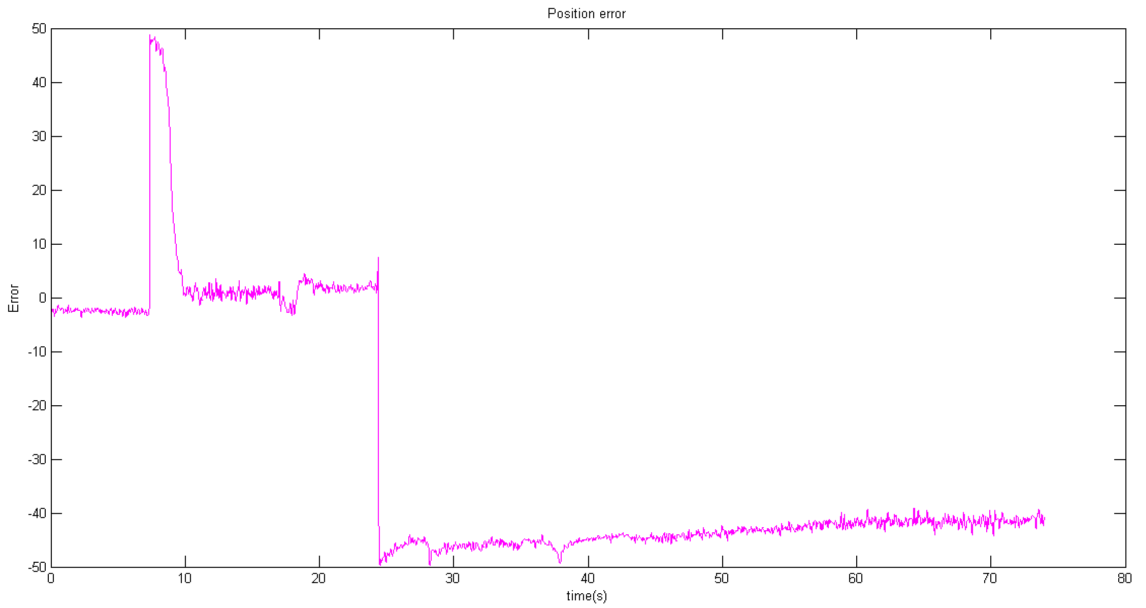


Figure 4.12: System error in flexion for a step input.

2 - System Response for a Sinusoidal Input

The next test will be carried out with a sinusoidal input and the results are similar to the previous test done. A sinusoidal wave with an amplitude of 60°,frequency 0.25 Hz and centered in 0° was chosen. In the first cycle, the wrist was left at about -10° and it takes the system also about 3.5 seconds to reach the transformation temperature and starts actuating and the wrist reaches the desired position and the steady state error tends to -5° as shown in Figure 4.18 due to the delay in the actuation at the beginning so the signal was faster than the system, while in the second cycle the error tend to 0. When the signal goes from -60° to 60° , the wrist relaxes by about 15° in the positive sense while the actuator was cooling down until the second cycle starts and the actuator takes the wrist to -60° . Figure 4.14 shows that the actuator in this case doesn't consume too much power in this case.

As a conclusion, testing the SMA actuator used for flexion alone when the hand is in the position where no gravity force is acting on the system is not effective in the rehabilitation process. Obviously, this test should be carried out when the hand is parallel to the ground and depending on the gravity force for the extension movement, and the results will be similar to the ones obtained in the previous section while testing the SMA actuator for the extension and relying on the gravity force in the flexion phase.

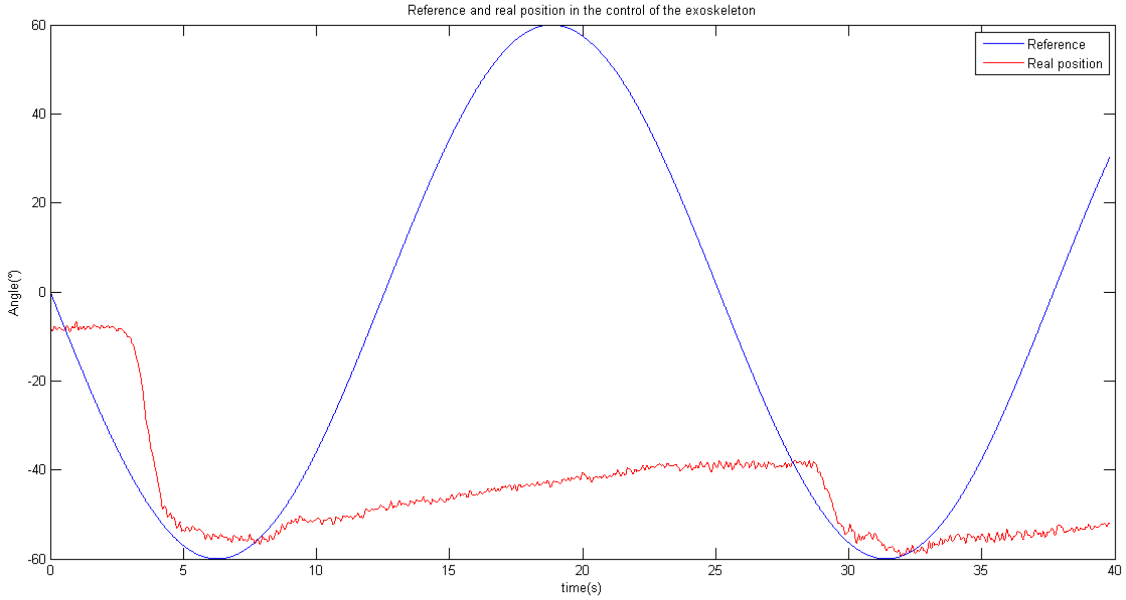


Figure 4.13: System response in flexion for a sinusoidal input.

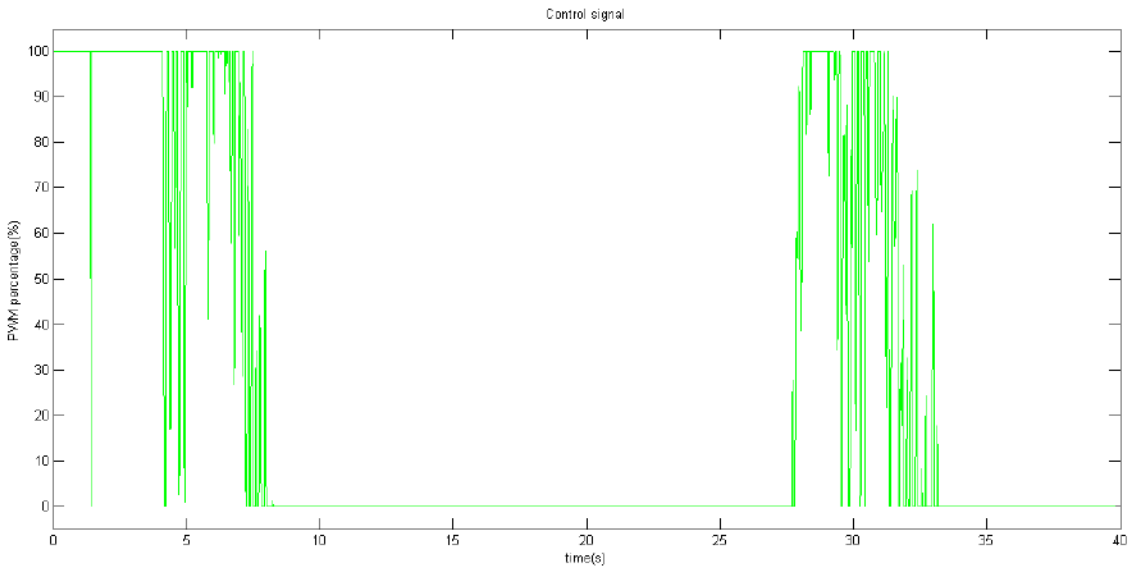


Figure 4.14: Control signal in flexion for sinusoidal input.

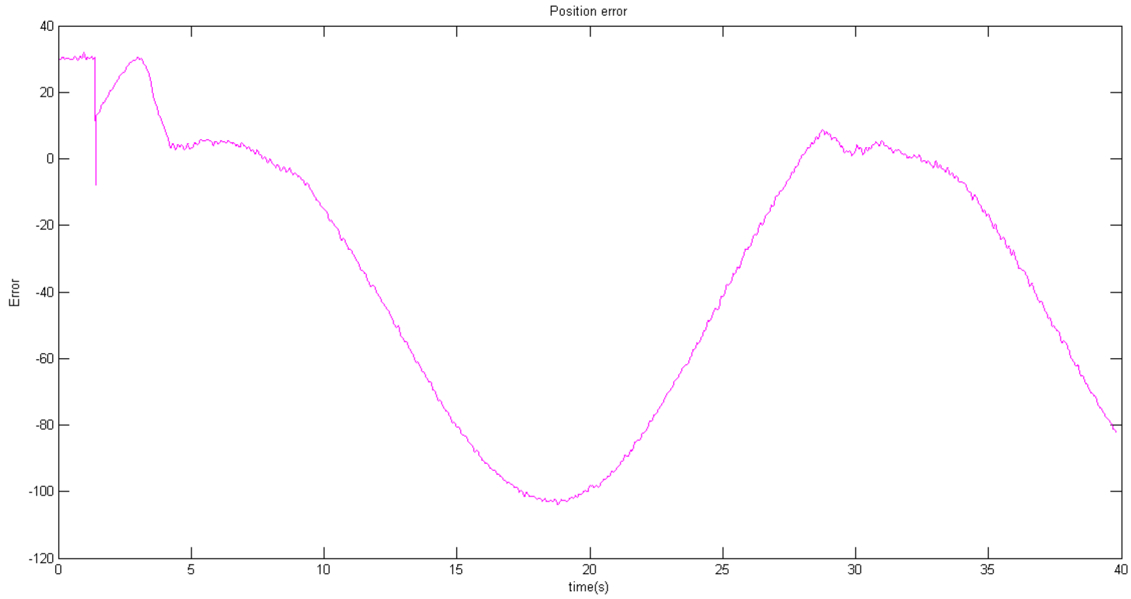


Figure 4.15: System error in flexion for a sinusoidal input.

4.2.3 Testing the Actuators for Flexion-Extension Together

In this part, the 2 actuators used for flexion-extension will be tested together while activating the 2 actuators in the same tests. In this case, the wrist could be fixed in any position as the patient desires during the rehabilitation process so that he/she feels comfortable.

1 - System Response for a Stair Input

This test aims to verify if the system can reach different positions while activating the 2 actuators for flexion-extension together, to study the cooling and heating time of each actuator and to verify that the 2 actuators are not activated in the same time. In this test the angles were chosen between -40° and 30° since this range of angles is the most range used during the rehabilitation therapies. The test starts with the wrist in the -18° position and the reference signal at 10° , then it takes the system about 3.5 seconds to reach 10° after reaching the transformation temperature, then the reference was increased to 30° then the system follows the signal in time and kept for 15 seconds in this position. After this, the reference was decreased to -40° while the extension actuator is deactivated and the second actuator used for flexion is activated after 0.5 seconds of delay to start the flexion movement and take the wrist to -40°. After 10 seconds another cycle was started to test the extension movement and the extension actuator takes the wrist back to 30°. At the end the reference was decreased to -10° , and the wrist goes back to the desired position, but note that the wrist goes a little bit below -10° in this case due to gravity effect as shown in Figure 4.16. The steady state error tends to 0 during actuation as noticed in Figure 4.18.

Figure 4.17 shows the power consumption of each actuator during the rehabilitation process, where the green color indicates the consumption of the extension actuator and the yellow one shows the consumption of the flexion actuator. It is shown how the 2 actuators are never actuated in the same time and one is activated after 0.5 seconds delay when the other is deactivated, so that one actuator cools down while the other actuates, and most of the power consumption is below 60% of the maximum power available.

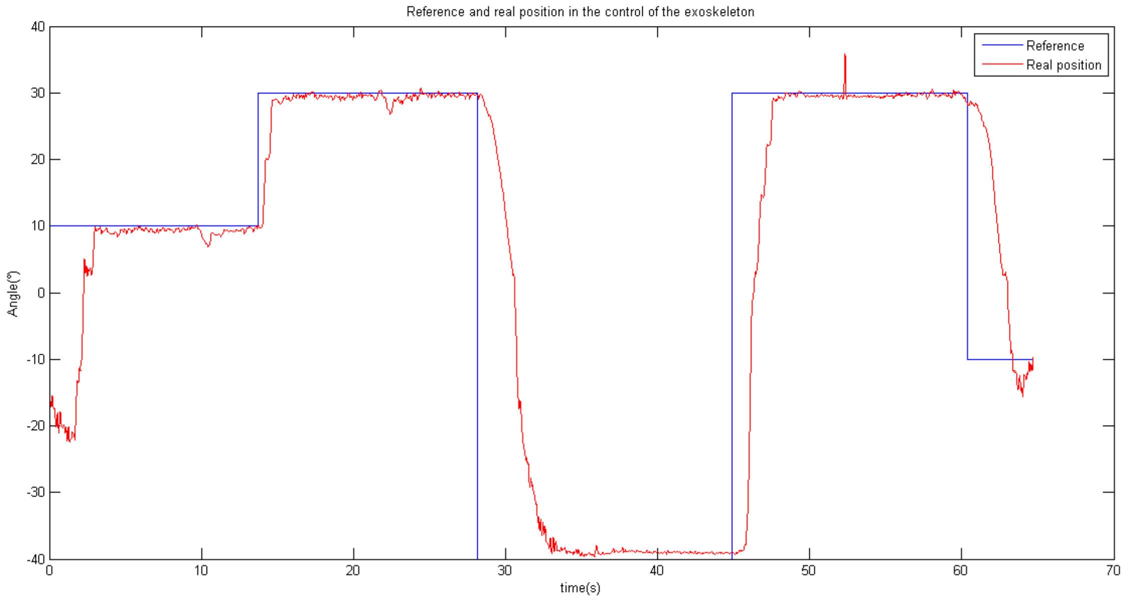


Figure 4.16: System response in flexion-extension for a stair input.

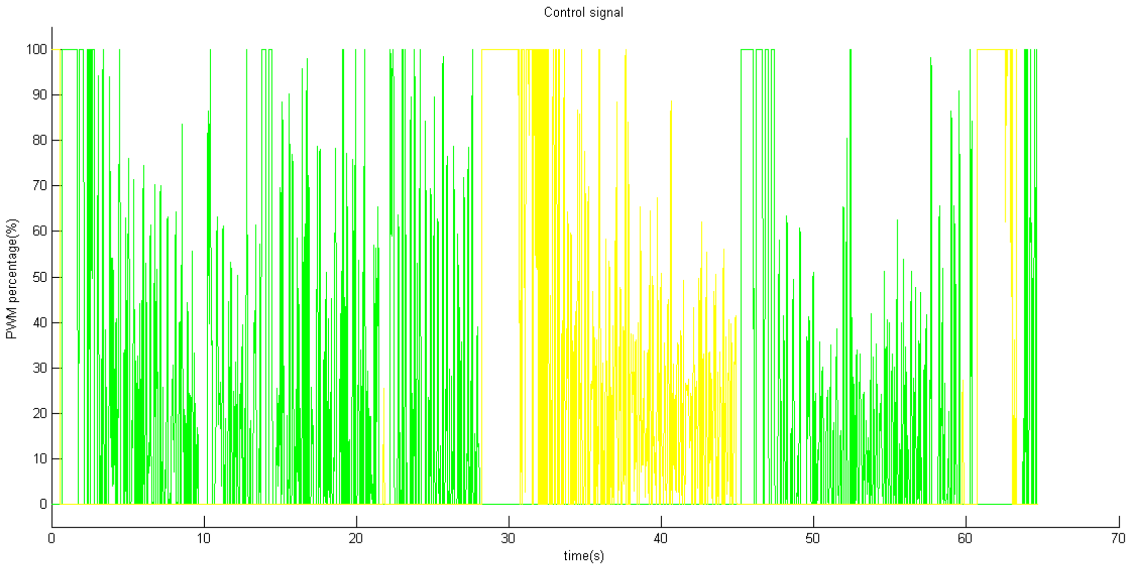


Figure 4.17: Control signals in flexion-extension for a stair input.

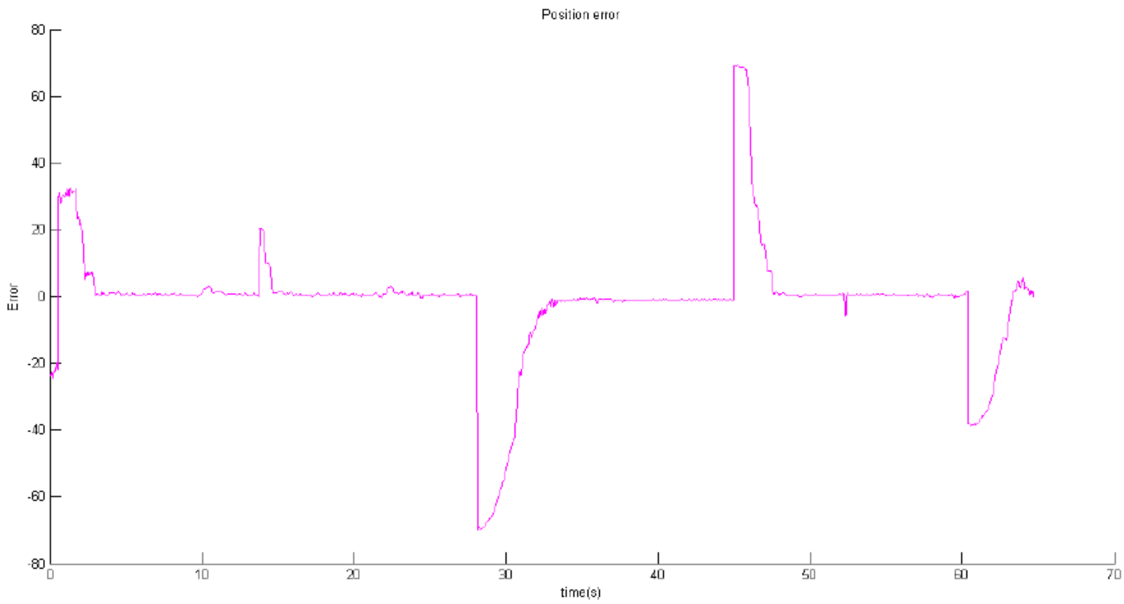


Figure 4.18: System error in flexion-extension for a step input.

To prevent the overheating and the rupture of the actuators, it is better to keep the exercise time under 2.5 minutes, and after several cycles it is necessary to wait 2-3 minutes for the actuators to cool down before starting another rehabilitation exercise.

2 - System Response for a Sinusoidal Input

The second test will be carried out with a sinusoidal input. As explained before it is necessary to adjust the frequency of the signal to have smooth movements, so a sinusoidal wave with an amplitude of 35°,frequency 0.25 Hz and centered in 0° was chosen. In this way, smooth movements are produced, without producing any sudden changes in the movement, which favors the patient's comfort at the time of performing the rehabilitation.

Analyzing the system response shown in Figure 4.19, it is obvious that the system can follow the reference perfectly except for some overshoots obtained during the exercise due to possible undesired movements of the wrist and non-linearities of the SMA actuator, reducing to the minimum the error signal as shown in Figure 4.21. In this case, in comparison with the tests performed for extension with sinusoidal reference and relying on the gravity in the flexion movement, it is observed that by having two actuators, the device is capable of performing the two movements of flexion-extension perfectly, following the reference signal, and therefore, the problem of the cooling time of the actuator is eliminated. It is also true that it is necessary to be cautious and to take precautions to avoid breakage of the actuators, since at the end of the test both actuators will be hot due to the accumulation of heat, and tension occurs between both actuators. However, as it is observed the device is able to perform four cycles in a row in this test without having notions of heat accumulation, and it is necessary to wait for the actuators for about 2-3 minutes at the end of the test to cool down before starting another test.

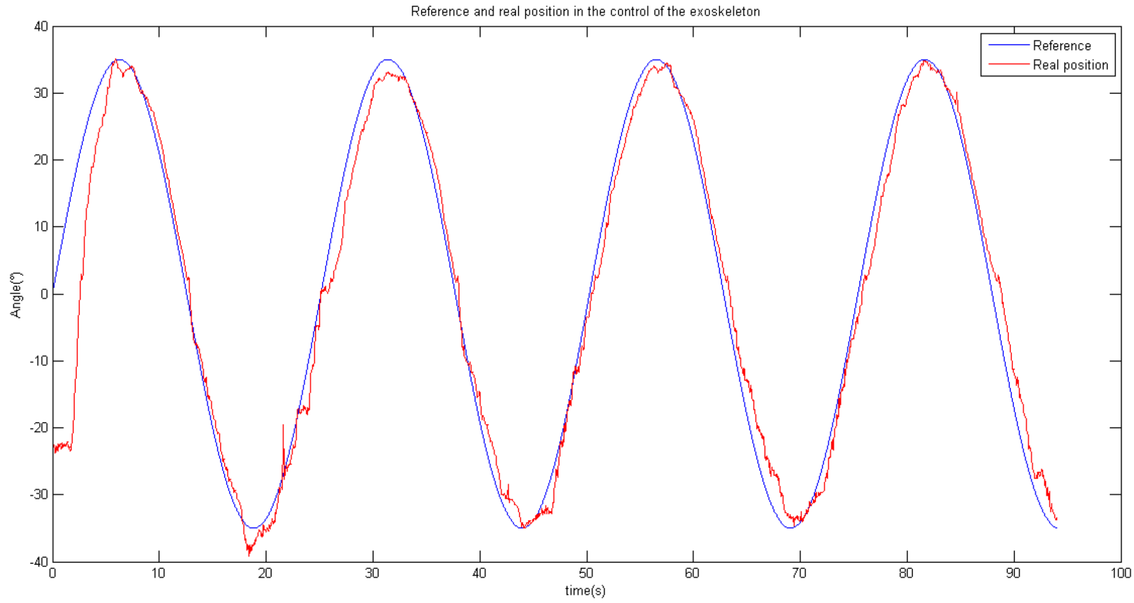


Figure 4.19: System response in flexion-extension for a sinusoidal input.

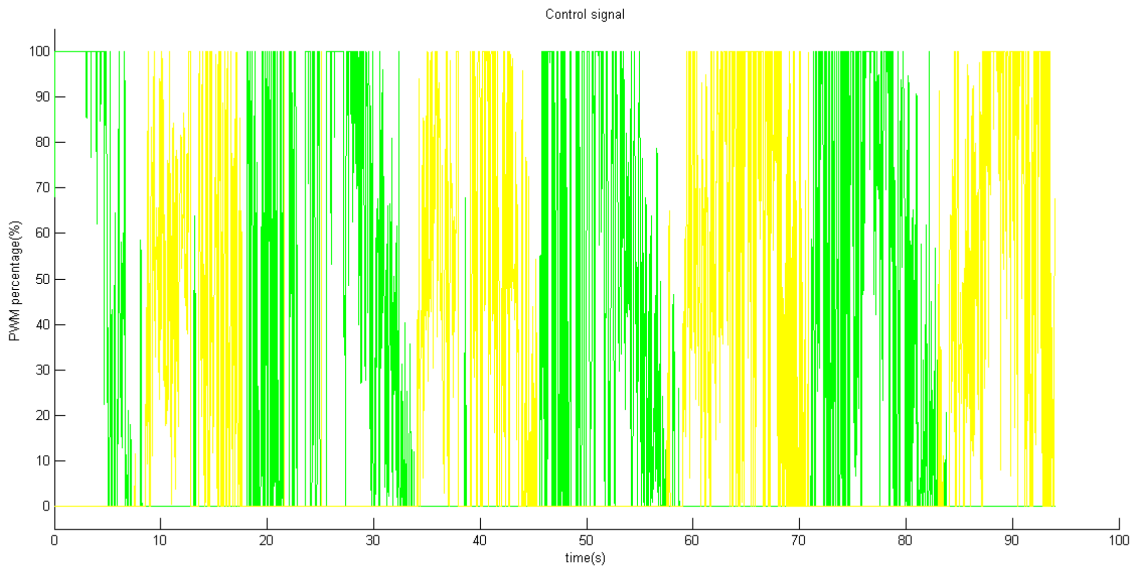


Figure 4.20: Control signals in flexion-extension for a sinusoidal input.

Figure 4.20 shows the control signals generated to carry out the test with a sinusoidal signal. As in the previous test, the coordination between both signals is representative, and the 2 actuators were never activated together at the same time. By analyzing the control in this test, it can be concluded that the control is smoother for a step reference than when a sinusoidal reference is applied, since the power consumption in the first case was lower than the power consumption in the second case. This characteristic is quite important in terms of the temperature reached by the actuators, since there is no over heating or excessive accumulation of heat.

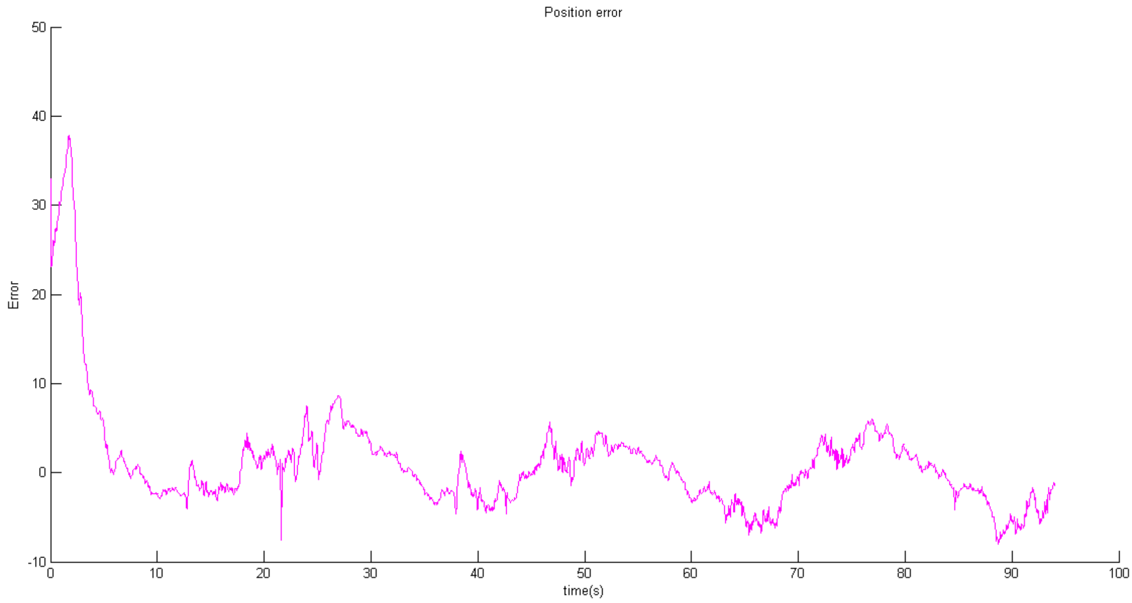


Figure 4.21: System error in flexion-extension for a sinusoidal input.

4.2.4 Testing the Actuator for Ulnar deviation

After testing the device for the first degree of freedom of the wrist, the next step is to test the exoskeleton for the other degree of freedom (ulnar-radial deviation). In this part, the actuator used for the ulnar deviation will be tested alone and without activating the actuator used for the radial deviation, to check its correct functioning before passing to the part where we test the 2 movements together.

1 - System Response for a Sinusoidal Input

The test on the ulnar deviation will be done using a sinusoidal input. The hand was left also parallel to the ground where no gravity effects are acting on the system, and the same sinusoidal signal having an amplitude of 20°,frequency 0.25 Hz and centered in 20° was chosen.

Figure 4.22 shows how the system response in the ulnar deviation for a sinusoidal input. It's obvious how the system follows the reference perfectly in each cycle and keeping the error signal near to 0 as shown in Figure 4.24. The range of angles was chosen to be near to the maximum angle for this movement to verify if the system can reach high ranges of angles and that the movement is not limited to small ranges. However, after each cycle and when the signal reaches the maximum and starts to decrease again, the actuator starts cooling down and the wrist moves by 8° towards the equilibrium position, since the wrist was under the tension of the SMA actuator and it relaxes by a small angle when the actuator is cooling down. Then when the signal increase again the system follows the reference perfectly again.

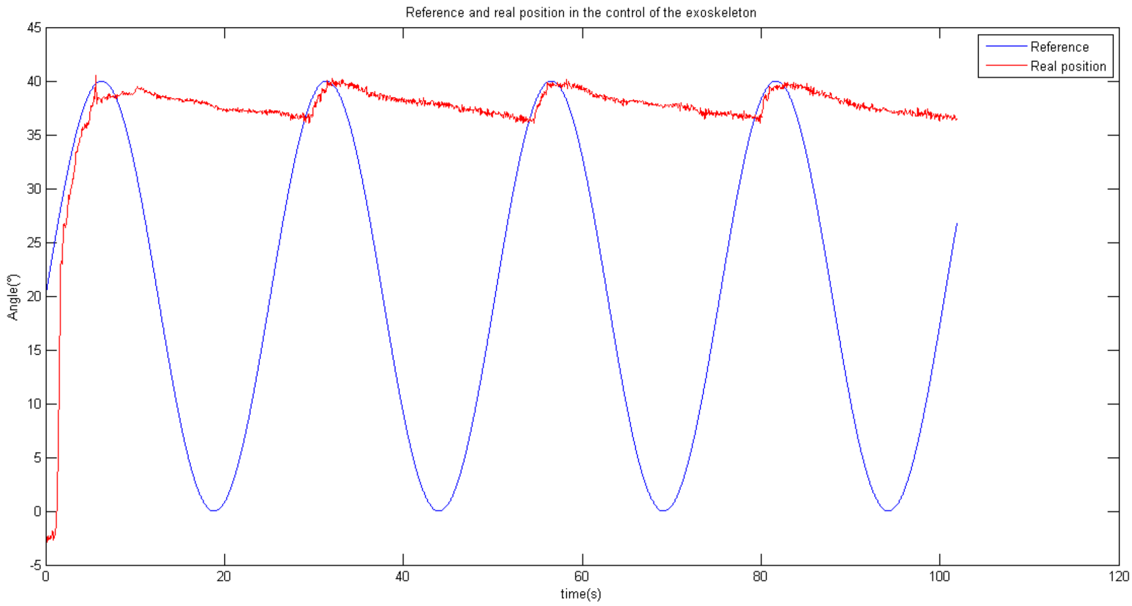


Figure 4.22: System response in ulnar deviation for a sinusoidal input.

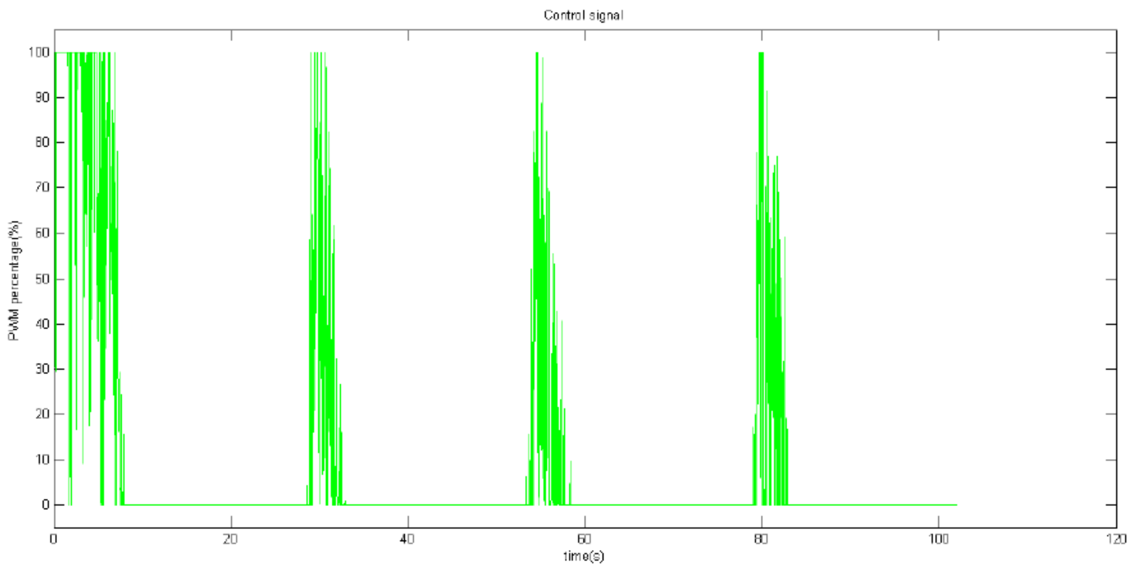


Figure 4.23: Control signal in ulnar deviation for a sinusoidal input.

Figure 4.23 shows the control signal in ulnar deviation in this test. The power consumption reaches 100% at the beginning since the actuator was cold and needed more power to accumulate heat, then the consumption decreases and goes most of the time below 70% of the maximum power available. Testing this actuator alone without activating the other actuator when keeping the hand in a position parallel to the ground where no gravity forces are acting on the opposite movement of the same degree of freedom is not very effective in the rehabilitation process, since the range of movement after the first cycle will be very limited and can't exceed 8° . However, rotating the hand in this case to use the gravity force for the radial deviation is not comfortable for the patient and may cause pain in the elbow.

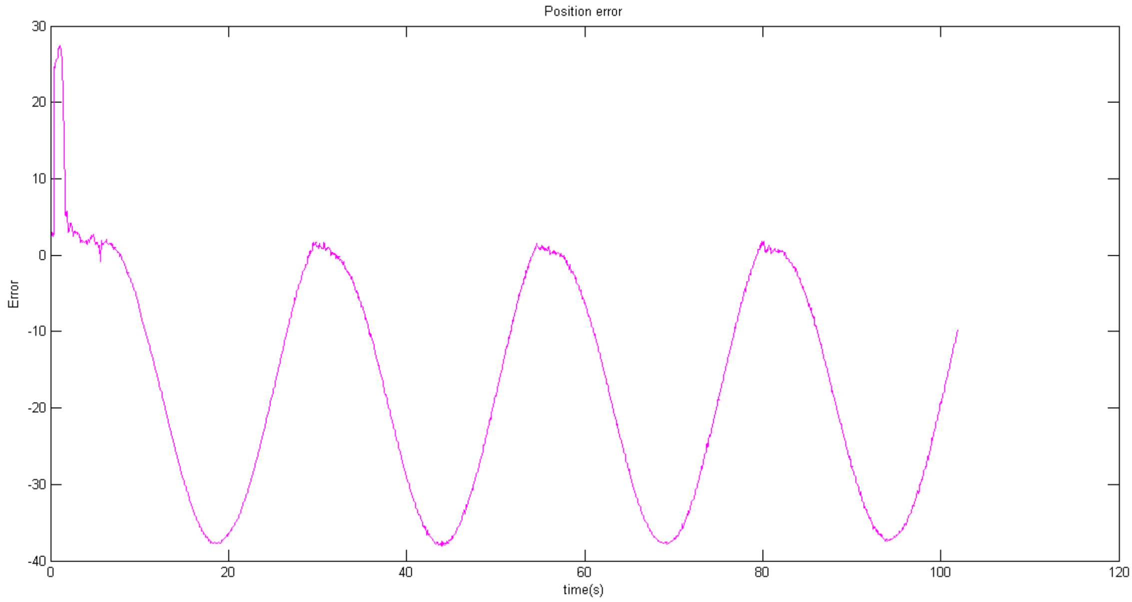


Figure 4.24: System error in ulnar deviation for a sinusoidal input.

4.2.5 Testing the Actuator for Radial deviation

The other movement of the second degree of freedom to test is the radial deviation. The range of angles in this movement is very small and limited to 20°. The wrist will be also put in a position parallel to the ground and no gravity effects will be acting on the system. In this movement, the hand could be rotated about 90° where the ulnar deviation could be done relying on the gravity force and without causing any pain in the elbow of the patient.

1 - System Response for a Step Input

Testing the radial deviation will be done by a stair input. The aim of this exercise is to verify the control of the system and to verify the correct functioning of the device in this case. As shown in Figure 4.25 the reference starts from 0° then it is reduced to -5° (5° in radial deviation) then gradually after sometime to -10° and to -15° . It is clear how the system can follow the reference in time and how the steady state error tends to 0 during actuation as shown in Figure 4.27 and the actuator works perfectly. The range of movements was chosen to reach the maximum in this case to check if the device can reach high range of angles as explained before, while in the real rehabilitation process the therapy will be limited to about -10° in this case.

Figure 4.26 shows the control signal in radial deviation for a stair input, and shows when the actuator is being activated. The power consumption in this case was high compared with the power consumption in the other movements. However, as explained before this test is not very effective for the real rehabilitation therapy since no forces can take back the wrist to the equilibrium position, and aims only to verify the correct functioning of the system.

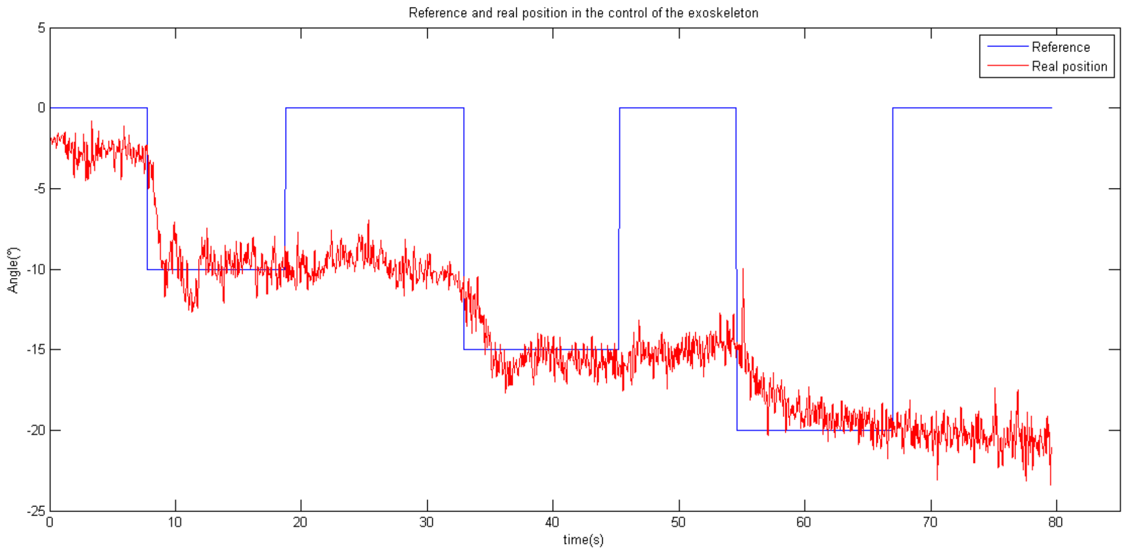


Figure 4.25: System response in radial deviation for a stair input.

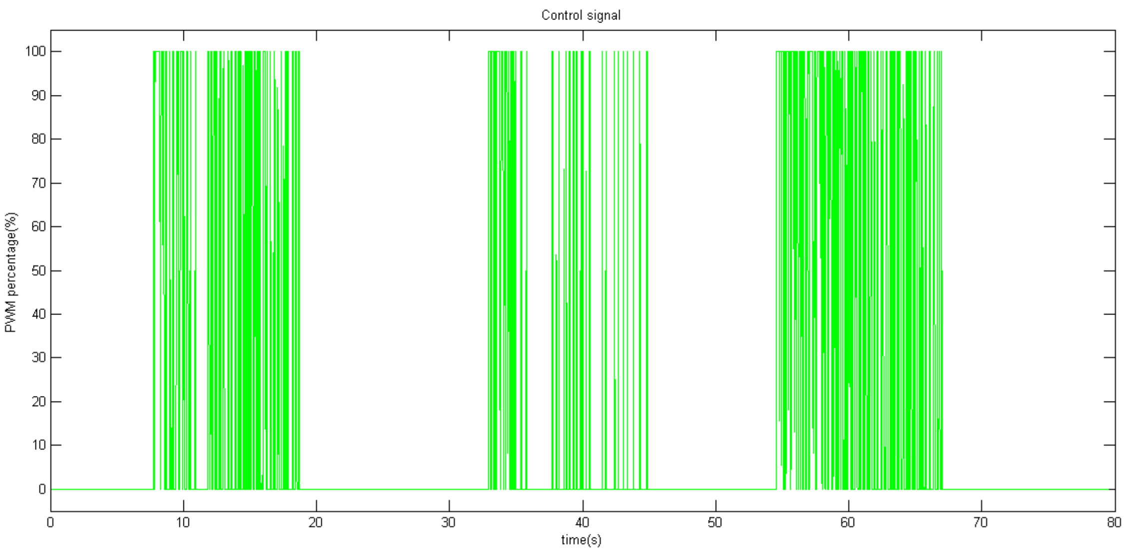


Figure 4.26: Control signal in radial deviation for a stair input.

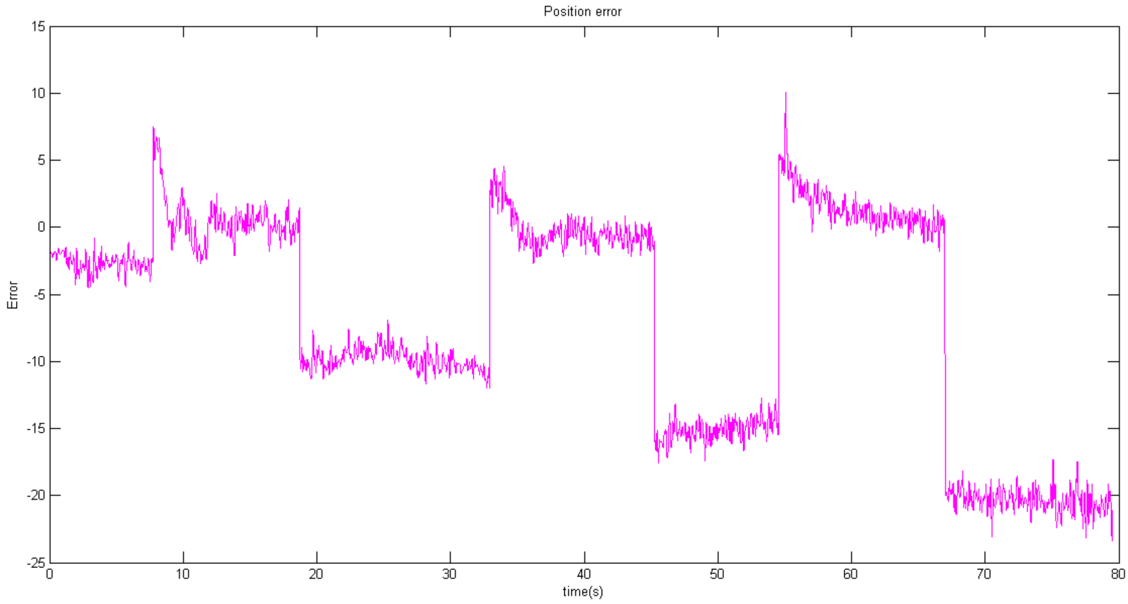


Figure 4.27: System error in radial deviation for a stair input.

4.2.6 Testing The Ulnar-Radial Deviation Together

The last tests will be done to study the behaviour of the 2 actuators of the ulnar-radial deviation when activated together, and to verify the control of the system.

1 - System Response for a Stair Input

In this test a stair input is used. As shown in Figure 4.28, the test consists of performing an ulnar deviation movement up to 45° and then activating the second SMA actuator to move the wrist in the direction of the radial deviation to -15° in the first cycle and to -10° in the second cycle. In this way, the exoskeleton is completely controlled and the response of the system does not depend on the cooling time of the SMA wire. For this reason, the response of the system is rapid both in ulnar and radial deviation, being the establishment time for both movements of approximately 2.5 seconds in the first cycle since the actuators were cold. Since the main purpose is to avoid the overheating of the SMA wires and therefore avoid the breakage of the actuators, it is advised to keep the exercise time below 3 minutes. However, the steady state error tends to 0 as shown in Figure 4.30.

Figure 4.29 shows the control signal in ulnar-radial deviation for the stair reference used. After analyzing this figure, the coordination between the control signal for ulnar deviation and the control signal for radial deviation can be noticed, and the two signals were never active simultaneously and between the deactivation of a signal and the activation of the other one there is a point of inflection in which the two actuators are deactivated. This phenomenon occurs with the purpose that the actuator that has been deactivated, cools down and in this way the tension between the 2 actuators is avoided. However, the power consumption by the actuators in this case is moderate and most of the time it is around 60% of the maximum power available, which means that the actuators were not overheated.

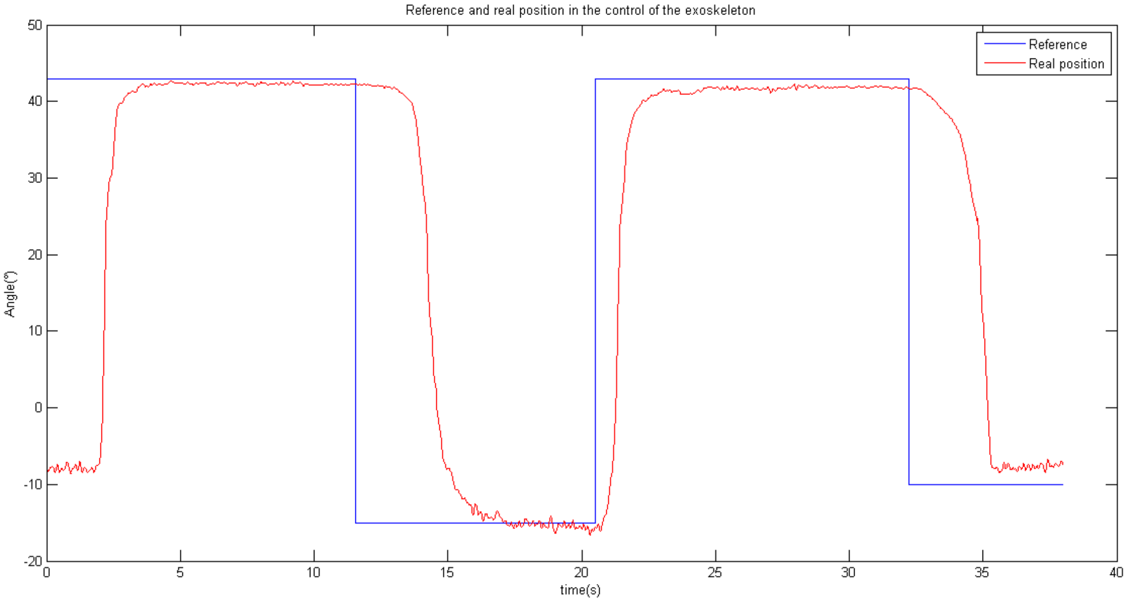


Figure 4.28: System response in ulnar-radial deviation for a stair input.

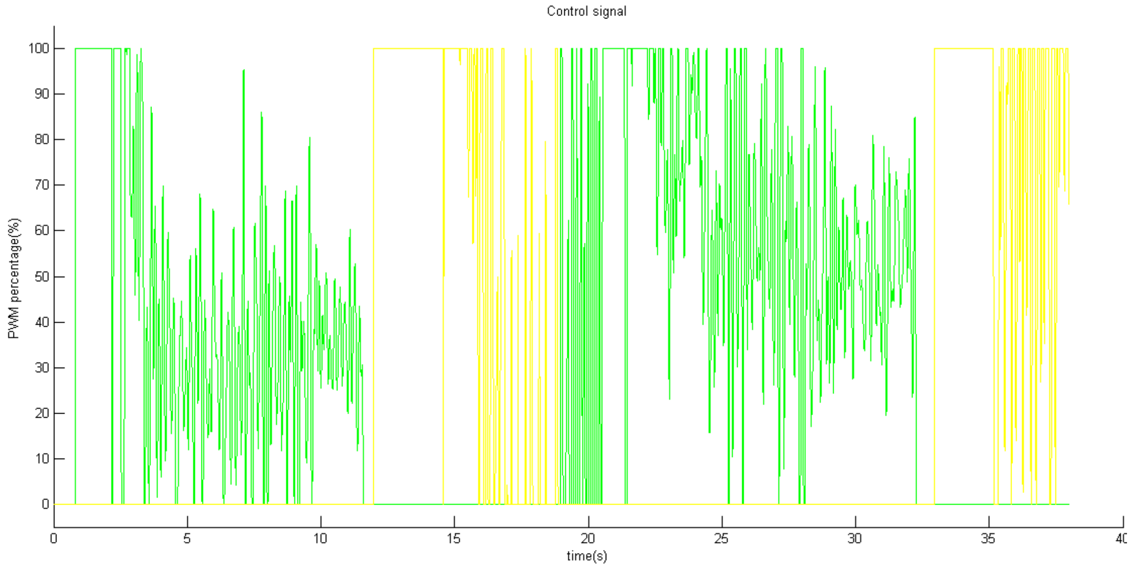


Figure 4.29: Control signal in ulnar-radial deviation for a stair input.

This exercise shows how the 2 actuators worked perfectly when activated together and shows the good coordination between them, therefore this test will be effective in the real rehabilitation therapy and won't create any problem or danger for the patient. Note that after performing this exercise for longer periods it is necessary to wait about 2-3 minutes for the actuators to cool down before starting another one.

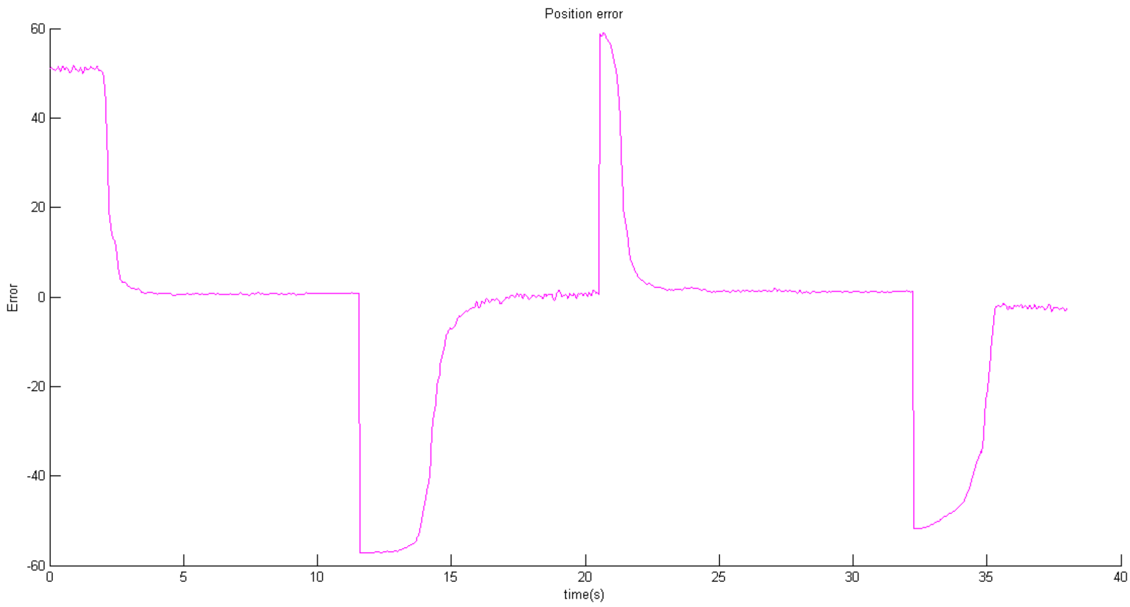


Figure 4.30: System error in ulnar-radial deviation for a stair input.

2 - System Response for a Sinusoidal Input

The last test on the ulnar-radial deviation will be carried out with a sinusoidal input. The system response is shown in Figure 4.31. In this case the error is greater than in the previous case as shown in Figure 4.33. The larger error in this case may be caused by some non-linearities introduced by the actuator.

As in the previous test, the coordination between the 2 actuators during the exercise is perfect as can be seen in Figure 4.32 and the 2 actuators were never activated at the same time. In this case the actuators show a higher power consumption which can overheat the actuators and may lead to their breakage if many cycles are performed.

In comparison with the previous test, it is better to use the step input in the rehabilitation therapy since it produces lower error and near to 0 since it presents a smoother movement and the system can follow the signal perfectly. Also the system consumed less power than in this case.

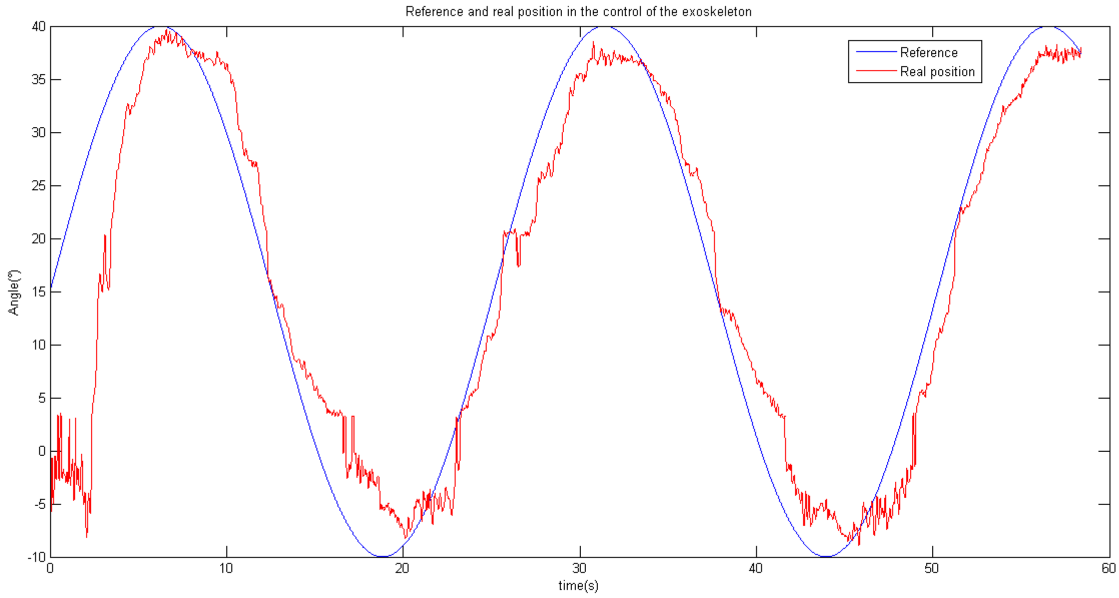


Figure 4.31: System response in ulnar-radial deviation for a sinusoidal input.

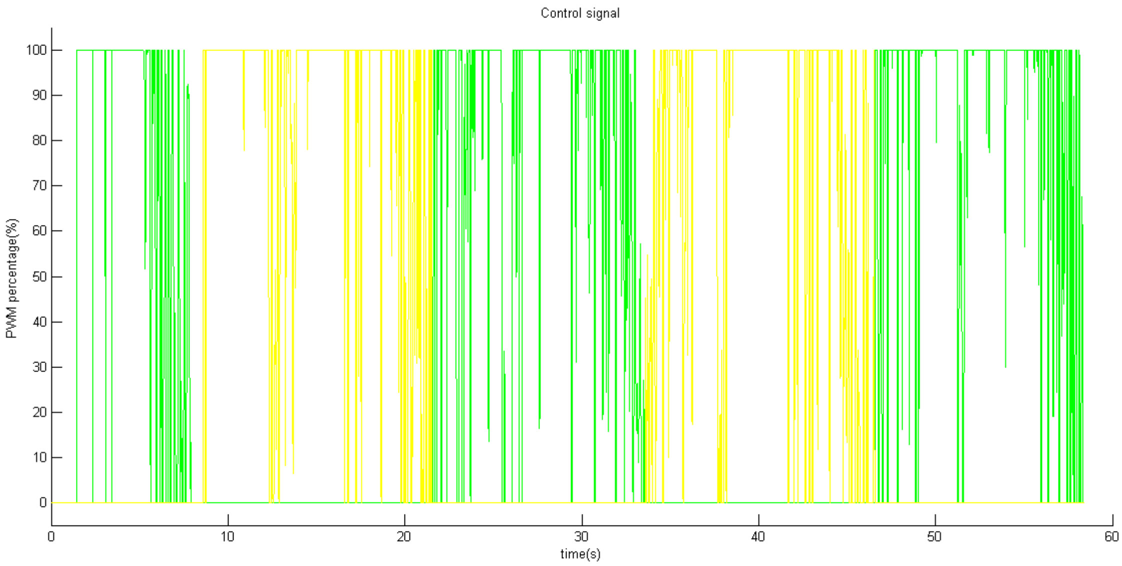


Figure 4.32: Control signal in ulnar-radial deviation for a sinusoidal input.

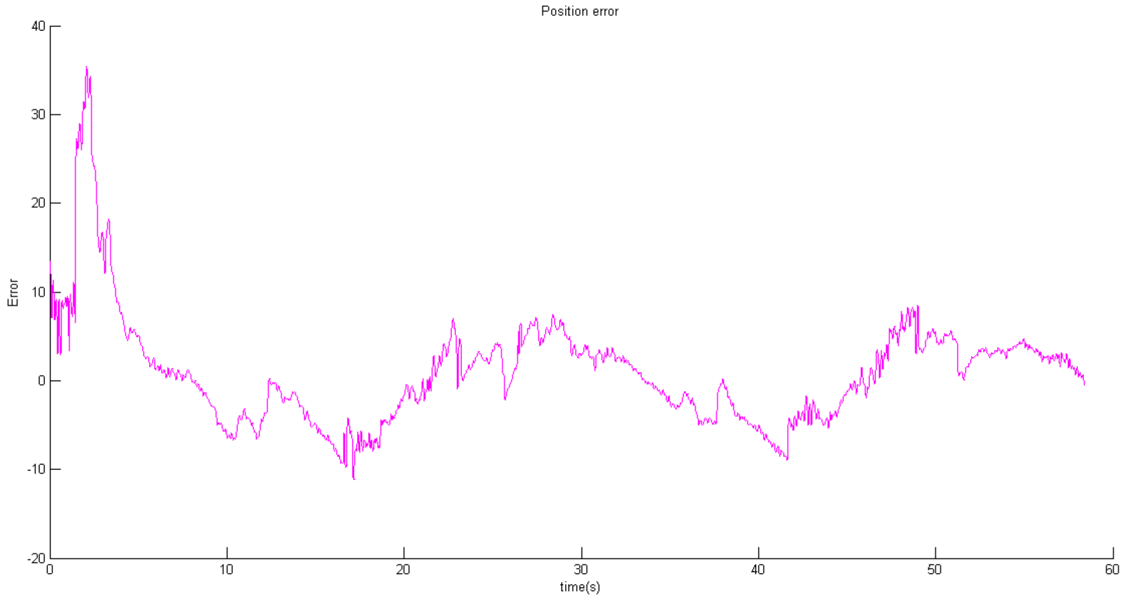


Figure 4.33: System error in ulnar-radial deviation for a sinusoidal input.

Chapter 5

Conclusions and Future Works

Finally, in this section, the conclusions that have been reached at the end of this project will be explained and discussed. And then some future works will be proposed, with the purpose of improving the negative points that have been found in this device during the work on this project.

5.1 Conclusions

The design proposed in this project arises from a previous prototype of a wrist exoskeleton. From the conclusions and problems arising in the previous prototype, a new design has been made, trying to eliminate all the problems found in the previous device. Therefore, in this work, a functional wrist exoskeleton actuated by SMA actuators has been developed and tested. The modifications done provided the following advantages:

- In the previous prototype, the flexion movement could be only done bye the gravity force without using an actuator for this movement and depending on the cooling time of the actuator used for extension, which obliges the patient to put the wrist in a position parallel to the ground, which may bother the patient. In this device, an SMA actuator has been added for the flexion movement and worked perfectly during the testing.

- The total cost of the exoskeleton has been reduced from 986 euros to 883 euros, which is still an acceptable price.

- The total weight of the exoskeleton has been slightly reduced from 960g to 800g, but the weight of the exoskeleton that will be put on the wrist has been slightly increased from 350g to 360g which is still acceptable from the point of view of patient's comfort. Since the actuators are flexible, they can be wound up and placed on the table where the rehabilitation therapy will be performed, and the same thing for the electronics used to control the device.

- In the previous prototype, during ulnar-radial deviation, an extra upwards movement was noticed with each of these movements, which may cause a harm in the wrist of the patient. In this device the SMA actuators to produce these movements have been repositioned correctly and the problem was eliminated.

- The material that has been chosen for the manufacture of the most of the parts of the device, has been a mixture of polyamide with aluminum powder, except for one piece which was made from polyamide and for the pulleys that were made from pure aluminum. This materials provides rigidity to the device and at the same time is lightweight, looking at all times for the purpose of manufacturing a portable and lightweight device.

- Shape-memory-alloy based actuators, provide the advantage of lightness compared to the rest of actuators that are used in the development of exoskeletons, being the most used electric motors. The set of actuators used in the wrist exoskeleton prototype barely reach 250 g. Despite the low weight of the actuators, the relationship between torque-weight is excellent.

- Along with the lightness of the actuators, another main advantages of the shape memory alloys is their silent behavior and their low cost. The weight and the absence of noise are two requirements of the devices for hospital environments and especially to favor the comfort of the users. Besides they have a low cost 6 euros/m, which helps to design a low cost device.

- SMA wires require good electric and thermal isolation, so the threads were introduced in teflon tubes that electrically isolate the wires and support a high temperature range.

- The actuators used in the previous prototype were very long, 2.2m extension actuator and 1.7m each one of the actuators used for ulnar-radial deviation. In this project, the lengths of the actuators were reduced to the half approximately (to 1.10 m and 0.9 m respectively) by using double groove pulleys.

- The design of a functional prototype that meets the requirements mentioned at the beginning of this work has been achieved. The device is portable, light, safe, noiseless, and has a low cost, always focusing on the comfort and convenience of the user and without causing any injuries to the patients.

- Comparing the results obtained with a single actuator and those obtained with two actuators in antagonist mounting, it can be concluded that the antagonist assembly provides benefits, since the slow cooling problems are avoided and therefore, all movements are completely controlled. As a disadvantage of the antagonist assembly, it can be said that the main problem that presents, corresponds to consider the coordination that must exist in the control of both actuators to avoid overheating in the wires, and therefore the breakage of the SMA wires. But after the tests done on the device, the coordination between each 2 actuators of the same degree of freedom was perfect and the 2 actuators were never activated at the same time.

- The idea of using double groove pulleys to reduce the length of the SMA actuators has been proved to work perfectly, even though the SMA actuators are rigid, they were fixed perfectly by screws in the pulleys and they never went out from the pulleys while testing the device.

Finally, the main aim of this project was to build a prototype of a robotic exoskeleton for the rehabilitation of the wrist, fulfilling the main objectives set at the beginning of this project. Currently the exoskeleton can realize data acquisition of the sensors signals (in position), which can be used by the doctor to evaluate the patient and rehabilitation in a passive mode. The proposed design can be improved and some problems have been detected that needs to be solved, since being a prototype, it is necessary to analyze the advantages and disadvantages to improve the design and finally get a wrist exoskeleton that can be marketed. The device can not be used in the active rehabilitation tasks.

5.2 Future Works

In this last section we will describe the improvements that could be introduced to the device in the future to improve the design of the exoskeleton, with the aim of eliminating the disadvantages detected in the prototype developed in this project, and improving the characteristics of this device.

- The diameter of the double groove pulley could be increased so that the SMA actuators' length could be reduced more and more which will make the device more comfortable.

- It would be interesting to integrate pressure sensors to the exoskeleton, and combine the use of the device with the reading of the electromyography signals generated by the muscles of the patient, so that the intention of movement generated by the patient can be detected.

- The sensor signal reading could be improved by replacing the flexible sensors by another sensor type (Hall effect sensors for example) to make the real position signal more precise and to have smoother and more precise movements.

Finally, the work on a device for the rehabilitation of the wrist will continue, and always looking to improve the characteristics of the device to and keeping in mind that it should be safe and comfortable for the user.

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Appendix A

Technical Characteristics of SMA Flexinol Wires

FLEXINOL®

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Technical Characteristics of FLEXINOL® Actuator Wires

Flexinol® Actuator Wires are small diameter wires which contract like muscles when electrically driven. Smaller than motors or solenoids, cheaper and generally easier to use, these wires perform physical movement across an extremely wide variety of applications.

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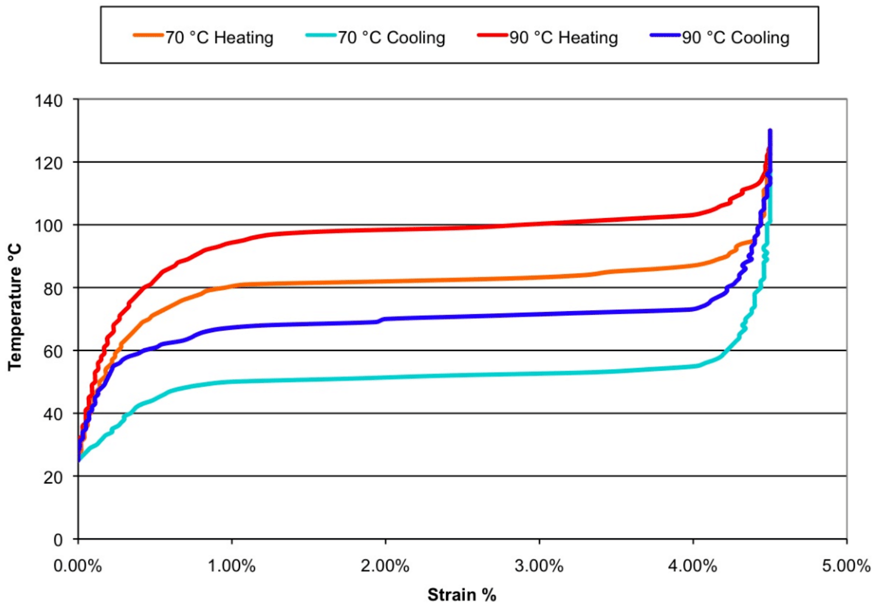
FLEXINOL®

DYNALLOY, Inc.
Makers of Dynamic Alloys

NICKEL - TITANIUM ALLOY PHYSICAL PROPERTIES

1. Density	0.235 lb/in^3 (6.45 g/cm^3)
2. Specific Heat	0.20 BTU/lb * °F (0.2 cal/g * °C))
3. Melting Point	2370 °F (1300 °C)
4. Latent Heat of Transformation	10.4 BTU/lb (5.78 cal/g)
5. Thermal Conductivity	10.4 BTU/hr * ft * °F (0.18 W/cm * °C)
6. Thermal Expansion Coefficient	
Martensite	3.67x10^{-6}/°F (6.6x10^{-6}/°C)
Austenite	6.11x10^{-6}/°F (11.0x 10^{-6}/°C)
7. Poisson Ratio	0.33
8. Electrical Resistivity (approx.)	
Martensite:	32 micro-ohms * in (80 micro-ohms * cm)
Austenite:	39 micro-ohms * in (100 micro-ohms * cm)



Typical Temperature vs. Strain Characteristics for Dynalloy's standard 158°F (70°C) "LT" and 194°F (90°C) "HT" Austenite start temperature alloys, at 172 MPa

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Introduction

Flexinol® is a trade name for shape memory alloy actuator wires. Made of nickel-titanium these small diameter wires contract like muscles when electrically driven. This ability to flex or shorten is characteristic of certain alloys that dynamically change their internal structure at certain temperatures. The idea of reaching higher temperatures electrically came with the light bulb, but instead of producing light these alloys contract by several percent of their length when heated and can then be easily stretched out again as they cool back to room temperature. Like a light bulb both heating and cooling can occur quite quickly. The contraction of Flexinol® actuator wires when heated is opposite to ordinary thermal expansion, is larger by a hundredfold, and exerts tremendous force for its small size. The underlying technology that causes the effect is discussed in Section 5. The main point is that movement occurs through an internal "solid state" restructuring in the material that is silent, smooth, and powerful.

This effect can be used in many ways. The list of viable applications is too long for any single listing. A safe assumption is that any task requiring physical movement in a small space with low to moderate cycling speeds is something that most likely will be better done with actuator wires. Many of the tasks currently being done with small motors or solenoids can be done better and cheaper with Flexinol® actuator wires. Since the actuator wires are much smaller for the work they do a number of new products and improved designs on existing products are readily accomplished.

For new users of Flexinol® actuator wires, Dynalloy, Inc. strongly recommends that an overview of what can be done first be established. This can be done by obtaining one of the Dynalloy, Inc. kits, which is made for such familiarization. Secondly, new users should consider obtaining from Dynalloy, Inc. or other consultants a "Proof of Concept" working model. This is not only useful as an internal marketing and sales tool. It also helps the new user to see how those with more experience approach the specific task in hand. Knowing this provides immeasurable insight into how to proceed and helps reduce the redundancy of reinventing existing techniques. One can always improve on existing methods and sufficient legal and other safeguards can be readily employed to ensure protection of proprietary ideas.

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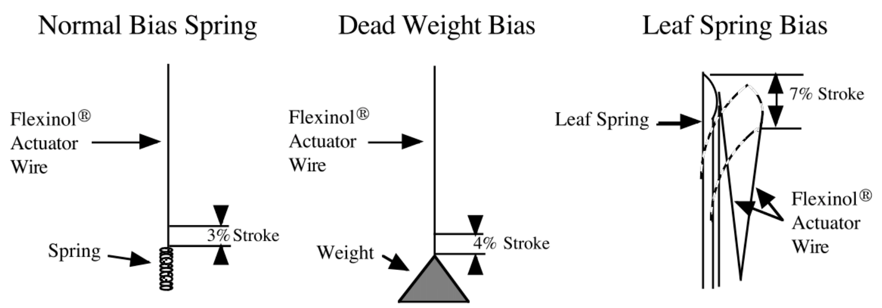
Section 1. Movement

The movement or stroke of Flexinol® actuator wire is measured as a percentage of the length of the wire being used and is determined, in part, by the level of stress one uses to reset the wire, or to stretch it in its low temperature phase. This opposing force, used to stretch the wire, is called the bias force. In most applications, the bias force is exerted on the wire constantly, and on each cycle as the wire cools, this force elongates it. If no force is exerted as the wire cools, very little deformation or stretch occurs in the cool, room temperature state and correspondingly very little contraction occurs upon heating. Up to a point the higher the load the higher the stroke. The strength of the wire, its pulling force and the bias force needed to stretch the wire back out are a function of the wire size or cross sectional area and can be measured in pounds per square inch or “psi”. If a load of 5,000 psi (34.5 MPa) is maintained during cooling, then about 3% memory strain will be obtained. At 10,000 psi (69 MPa), about 4% results, and with 15,000 psi (103 MPa) and above, nearly 5% is obtained. However, there is a limit to how much stress can be applied.

Far more important to stroke is how the wire is physically attached and made to operate. Dynamics in applied stress and leverage also vary how much the actuator wires move. While normal bias springs that increase their force as the Flexinol® actuators contract have only 3-4% stroke, reverse bias forces which decrease as the actuator wires contract can readily allow the wire to flex up to 7%. Mechanics of the device in which it is used can convert this small stroke into movements over 100% of the wires' length and at the same time provide a reverse bias force. The stress or force exerted by Flexinol® actuator wires is sufficient to be leveraged into significant movement and still be quite strong. Some basic structures, their percent of movement, and the approximate available force they offer in different wire sizes are as follows:



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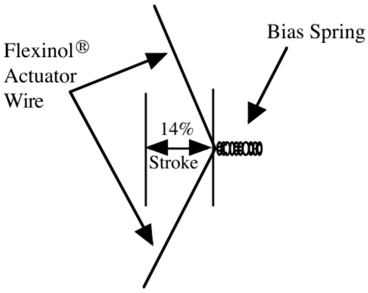
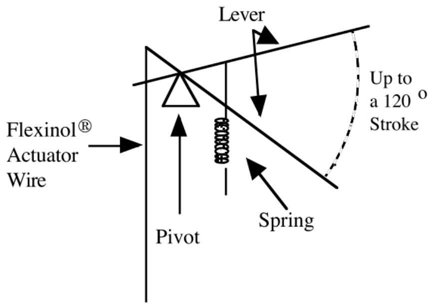
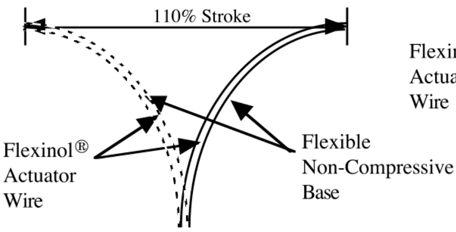
Right Angle Pull



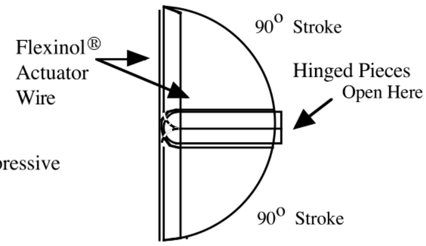
Simple Lever



Adjusting Curvature



Clam Shell



Stroke and Available Force Table

	Approx. Stroke	0.003" Wire (0.076 mm)	0.006" Wire (0.15 mm)	0.010" Wire (0.25 mm)
Normal Bias Spring	3%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Dead Weight Bias	4%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Leaf Spring Bias	7%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Right Angle Pull	14%	0.04 lb (20 g)	0.18 lb (83 g)	0.51 lb (232 g)
Simple Lever (6:1 ex)	30%	0.024lb (11 g)	0.10 lb (47 g)	0.29 lb (133 g)
Adjusting Curvature	110%	0.006 lb (3 g)	0.026 lb (12 g)	0.075 lb (34 g)
Clam Shell	100%	0.007 lb (3.2 g)	0.028 lb (13 g)	0.082 lb (37 g)

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Section 2. Electrical Guidelines

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If Flexinol® actuator wire is used in the appropriate conditions, then obtaining repeatable motion from the wire for tens of millions of cycles is reasonable. If higher stresses or strains are imposed, then the memory strain is likely to slowly decrease and good motion may be obtained for only hundreds or a few thousands of cycles. The permanent deformation that occurs in the wire during cycling is heavily a function of the stress imposed and the temperature under which the actuator wire is operating. Flexinol® wire has been specially processed to minimize this straining, but if the stress is too great or the temperature too high, some permanent strain will occur. Since temperature is directly related to current density passing through the wire, care should be taken to heat, but not overheat, the actuator wire. The following charts give rough guidelines as to how much current and force to expect with various wire sizes.

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Pull Force* pounds (grams)	Cooling Deformation Force* pounds (grams)	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)
0.001 (0.025)	36.2 (1425)	0.02 (8.9)	0.008 (3.6)	45	0.18	0.15
0.0015 (0.038)	22.6 (890)	0.04 (20)	0.016 (8)	55	0.24	0.20
0.002 (0.050)	12.7 (500)	0.08 (36)	0.032 (14)	85	0.4	0.3
0.003 (0.076)	5.9 (232)	0.18 (80)	0.07 (32)	150	0.8	0.7
0.004 (0.10)	3.2 (126)	0.31 (143)	0.12 (57)	200	1.1	0.9
0.005, (0.13)	1.9 (75)	0.49 (223)	0.20 (89)	320	1.6	1.4
0.006 (0.15)	1.4 (55)	0.71 (321)	0.28 (128)	410	2.0	1.7
0.008 (0.20)	0.74 (29)	1.26 (570)	0.50 (228)	660	3.2	2.7
0.010 (0.25)	0.47 (18.5)	1.96 (891)	0.78 (356)	1050	5.4	4.5
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1.13 (512)	1500	8.1	6.8
0.015 (0.38)	0.21 (8.3)	4.42 (2004)	1.77 (802)	2250	10.5	8.8
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	3.14 (1424)	4000	16.8	14.0

* The Heating pull force is based on 25,000 psi (172 MPa), which for many applications is the maximum safe stress for the wire. However, many applications use higher and lower stress levels. This depends on the specific conditions of a given design. The cooling deformation force is based on 10,000 psi (70 MPa), which is a good starting point in a design. Nonetheless, this value can also vary depending on how the material is used.

** The contraction time is directly related to current input. The figures used here are only approximate since room temperatures, air currents, and heat sinking of specific devices vary. On small diameter wires (<= 0.006" diameter) currents that heat the wire in 1 second can typically be left on without over-heating it.

*** Approximate cooling time, at room temperature in static air, using a vertical wire. The last 0.5% of deformation is not used in these approximations.

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Section 3. Cycle Time

The contraction of the Flexinol® actuator wire is due solely to heating and the relaxation solely to cooling. Both contraction and relaxation are virtually instantaneous with the temperature of the wire. As a result mechanical cycle speed is dependent on and directly related to temperature changes. Applying high currents for short periods of time can quickly heat the wire. It can be heated so fast in fact that the limiting factor is not the rate at which heating can occur but rather the stress created by such rapid movement. If the wire is made to contract too fast with a load, the inertia of the load can cause over stress to the wire. To perform high speed contractions inertia must be held low and the current applied in short high bursts. Naturally, current which will heat the wire from room temperature to over 212 °F (100 °C) in 1 millisecond, will also heat it much hotter if left on for any length of time.

While each device has quite different heat sinking and heating requirements, a simple rule of thumb test can be used to prevent overheating. Measuring the actual internal temperature of the wire across such short time periods is somewhat problematic, however, one can tell if the actuator wire is overheated simply by observing if the wire immediately begins to cool and relax when the current is shut off or not. If it does not begin to relax and elongate under a small load promptly, when the power is cut, then the wire has been needlessly overheated and could easily be damaged. Simple visual observation is all that is needed to design measured heating circuitry.

Flexinol® actuator wire has a high resistance compared to copper and other conductive materials but is still conductive enough to carry current easily. In fact one can immerse the wire in regular tap water and enough current will readily flow through it to heat it. All of the conventional rules for electrical heating apply to the wire, except that its resistance goes down as it is heated through its transformation temperature and contracts. This is contrary to the general rule of increased resistance with increased temperature. Part of this drop in resistance is due to the shortened wire, and part is due to the fact that the wire gets thicker as it shortens, roughly maintaining its same three-dimensional volume. It makes no difference to the wire whether alternating current, direct current, or pulse width modulated current is used.

Again relaxation time is the same as cooling time. Cooling is greatly affected by heat sinking and design features. The simplest way to improve the speed of cooling is to use smaller diameter wire. The smaller the diameter the more surface to mass the wire has and the faster it can cool. Additional wire, even multiple strands in parallel, can be used in order to exert whatever force is needed. The next factor in improving the relaxation or cooling time is to use higher temperature wire. This wire contracts and relaxes at higher temperatures. Accordingly the temperature differential between ambient or room temperature and the wire temperature is greater and correspondingly the wire will drop below the transition temperature faster in response to the faster rate of heat loss.

Other methods of improved cooling are to use: forced air, heat sinks, increased stress (this raises the transition temperature and effectively makes the alloy into a higher transition temperature wire), and liquid coolants. Combinations of these methods are also effective. Relaxation time can range from several minutes (i.e. delay switches) to fractions of milliseconds (i.e. miniature high speed pumps) by effective and proper heat sinking. The following page gives some idea of the effect these various methods have.

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Relative Effects of Cooling Methods

	Improvement in Speed
Increasing Stress	1.2:1
Using Higher Temperature Wire	2:1
Using Solid Heat Sink materials	2:1
Forced Air	4:1
Heat Conductive Grease	10:1
Oil Immersion	25:1
Water with Glycol	100:1

*These improvements are not accumulative on the same basis when used together.

Better cooling methods are likely to require more current or heat to move and/or hold the wire in an "on" position. In some cases one may wish to quickly turn the wire on (that is electrically heat it until it contracts) then hold it on for some time. This will likely require a two-step driving current with a larger current to heat the wire and a reduced current to keep it hot without overheating it. There are a number of simple circuits, which will do this.

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Section 4. Miscellaneous

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Cutting - Flexinol® actuator wire is a very hard and anti-corrosive material. It is so hard that cutting it with cutters designed to cut copper and soft electrical conductors will damage the cutters. If you plan to do much work with Flexinol® actuator wires a good high quality pair of cutters like those used to cut stainless steel wires will be a good investment.

Attaching - Attaching Flexinol® actuator wires to make both a physical and an electrical connection can be done in several ways. It can be attached with screws, wedged onto a PC board, glued into a channel with conductive epoxies, and even tied with a knot. The simplest and best way is usually by crimping or splicing. With crimping machines both electrical wires and hooks or other physical attachments can be joined at once. Flexinol® wires tends to maintain the same volume, so when they contract along their length, they simultaneously grow in diameter. This means the wires expand inside the crimps and hold more firmly as the stress increases through pulling. While this works to the advantage in crimps it can be a disadvantage if glues or solder is used, as the material tends to work itself loose in those cases. Flexinol® wire is a very strong material and is not damaged by the crimping process. Dynalloy, Inc. can provide wire that is already crimped at specified intervals. One can then solder or spot-weld to the crimps if such manufacturing methods are preferred.

Accompanying Materials - Flexinol® actuator wires work by internal resistance or other heating methods. Their temperature is often over 212 °F (100 °C) and they often apply pressure with a high force over a small area of the device they are attached to, so it is a good idea to use temperature resistant materials in connection with them. Such materials if used in direct contact with the wire will also need to be non conductive so as to not provide an electrical path around the Flexinol® actuator wire. Silicone rubber, Kapton (used to make flexible circuit boards), ceramics, and glass are good examples.

Strain Reliefs - Over stress can damage Flexinol® wires by permanently stretching (or elongating) them or by reducing the stroke over which they contract. To prevent this one should design products with strain reliefs in them. Care should also be taken to prevent manual interference with their contraction or movement as this can over stress the wire. In other words if the device gets stuck and cannot move or is forced backwards while operating a problem can be created breaking or adversely affecting the actuator wires' performance. Protective measures against this should be used.

Reverse Biases - Although Flexinol® actuator wire moves about 4.5% when lifting a weight or when contracting against a constant force, one can improve this stroke by designing mechanisms which have a reverse bias force. The bias force is the force that elongates the wire in its rubber-like martensitic phase. A reverse bias force is one that gets weaker as the stroke gets longer. This can be done with leaf springs or with designs that give the Flexinol® actuator wires a better mechanical advantage over the bias spring or force as the stroke progresses.

Performance Margins - Although very stable compared to other similar alloys Flexinol® actuator wires will permanently stretch out or strain with large cycles strokes and high stresses. At stresses below 15,000 psi (103 MPa), permanent strain will remain less than 0.5% strain even after hundreds of thousands of cycles. At 20,000 psi (138 MPa), perhaps 1% permanent strain will occur after 100,000 cycles, and with higher stresses proportionally more will occur.

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Section 4. Miscellaneous cont'd.

Good engineering design dictates that one should take into account the amount of memory strain, possible small decreases in the amount of that strain during operation, and some permanent deformation of the wire during cycling if the design is to meet expectations. Pushing all performance aspects of the wire to the limit from the outset of its cycling is likely to lead to disappointment at an early stage in the product life.

Longevity Testing - Flexinol® actuator wire can be over stressed and damaged even though it seems to be working. Much like actual muscles can be strained when called upon to do work above their actual capacity. The device may work in such a way that it is difficult to calculate the actual stresses involved. A good suggestion is to perform life cycle tests before assuming that a device which has worked a few times will continue to work millions more times. Fatigue which is damaging to Flexinol® actuator wire will usually show up in the form of wire elongation or reduced stroke within the first few hundred strokes. As one works with the material a "feel" for what is "working" will develop. The best rule of thumb is to use enough Flexinol® actuator wire to be sure one is well within the parameters in which it can work.

Precise Positioning - Given close temperature control under a constant stress one can get quite precise position control. Control in microns or less is to be expected. The problem is precise temperature control. The temperature is determined by an equilibrium between the rate of heating and the rate of cooling. Heating by electricity makes control of that easy, but the cooling is dynamically affected by changes in room temperature, airflow and so on. In practical terms this means that precise control is usually not feasible unless one can control the heat loss or has dynamic feedback through a closed loop system and can use this to control the heating rate.

Contact Dynalloy, Inc. Freely - There is no practical way for the authors to include everything that has been learned or will be learned in this short document. We have thousands of customers who call and contribute to our general understanding of typical application solutions. In most cases, we have already encountered problems which seem new to the first time user, so whenever possible we are happy to pass on these suggestions and be of help. We want your project to succeed, so please do not hesitate to call for assistance.

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Section 5. Underlying Technology

Flexinol® is a trade name for very high performance, shape memory alloy, actuator wires. Made of nickel-titanium these small diameter wires have been specially processed to have large, stable amounts of memory strain for many cycles. In other words, they contract like muscles when electrically driven. This ability to flex or shorten is characteristic of certain alloys that dynamically change their internal structure at certain temperatures. Flexinol® wires contract by several percent of their length when heated and then easily elongate again by a relatively small load when the current is turned off and they are allowed to cool.

The function of the Flexinol® wire is based on the shape memory phenomenon which occurs in certain alloys in the nickel-titanium family. When both nickel and titanium atoms are present in the alloy in almost exactly a 50%/50% ratio, the material forms a crystal structure which is capable of undergoing a change from one crystal form to another (a martensitic transformation) at a temperature determined by the exact composition of the alloy. In the crystal form that exists above the transformation temperature (the austenite) the material is high strength and not easily deformed. It behaves mechanically much like stainless steel. Below the transformation temperature, though, when the other crystal form (the martensite) exists, the alloy can be deformed several percent by a very uncommon deformation mechanism that can be reversed when the material is heated and transforms. The low temperature crystal form of the alloy will undergo the reversible deformation fairly easily, so the "memory" strain can be put into the material at rather low stress levels.

The resultant effect of the shape memory transformation of the Flexinol® wire is that the wire can be stretched about 4-5% of its length below its transformation temperature by a force of only 10,000 psi (69 MPa) or less. When heated through the transformation temperature, the wire will shorten by the same 4-5% that it was stretched, and can exert stresses of at least 25,000 psi (172 MPa) when it does so. The transformation temperature of the NiTi alloys can be adjusted from over 212 °F (100°C) down to cryogenic temperatures, but the temperature for the Flexinol® actuator wire has been chosen to be 140 – 230 °F (60 - 110 °C). This allows easy heating with modest electrical currents applied directly through the wire, and quick cooling to below the transformation temperature as soon as the current is stopped. Heating with electrical current is not required, but it is perhaps the most convenient and frequently used form of heat.

Flexinol® actuator wires' prime function is to contract in length and create force or motion when it is heated. There are limits, of course, to how much force or contraction can be obtained. The shape memory transformation has a natural limit in the NiTi system of about 8%. That is the amount of strain that can occur in the low temperature phase by the reversible martensitic twinning which yields the memory effect. Deformation beyond this level causes dislocation movement throughout the structure and then that deformation is not only non-reversible but degrades the memory recovery as well. For materials expected to repeat the memory strain for many cycles, it is best to utilize a cyclic memory strain of no more than 4-5%, and that is what is recommended with Flexinol® actuator wire.

The force that the Flexinol® actuator wire can exert when heated is limited by the strength of the high temperature austenitic phase. The phase transformation, or crystal change, that causes the memory effect has more driving force than the strength of the parent material, so one must use care not to exceed that yield strength. The yield strength of Flexinol®'s high temperature phase is over 50,000 psi (345 MPa), and on a single pull the wire can exert this force. To have repeat cycling, however, one should use no more than 2/3 of this level, and forces of 20,000 psi (138 MPa) or below give the best repeat cycling with minimal permanent deformation of the wire.

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ACTUATOR WIRE

A SOLID STATE ACTUATOR THAT MOVES BY "MOLECULAR RESTRUCTURING"!

FOR BETTER MECHANICAL PERFORMANCE...

- In really tight places - Flexinol® actuator wires are smaller by far than alternatives. At least 1,000 times smaller than solenoids for the same work done.
- To simplify designs - Flexinol® actuator wires can often be used "as is", eliminating gear boxes, housings, bearings, and so on. Their flexible forgiving performance is easier to work with.
- In corrosive environments - Flexinol® actuator wires' high corrosion resistance really pays off.
- To reduce noise levels - Flexinol® actuator wires' movement by molecular restructuring is both electrically and acoustically quiet.
- To lower costs - Flexinol® actuator wires are inexpensive to buy and cost less to use in many applications. A nice combination for that bottom line.

SAMPLE APPLICATIONS

ELECTRONICS
Micro Circuit Breakers
PC Mount Relays
Chassis Temp. Controls
Electronic Locks
PC Mount Pilot Valves
Mechanical Latches
Subminiature Door Openers
Micro Manipulators
Retrofit Switch to Relay
Micro Clutches
Spring Loaded Releases
Board Temperature Sensors
"Clean" Actuators
Remote Switch Controllers
Read/Write Head Lifters

MEDICAL
Intravenous Med. Controllers
Steerable Catheters
Prosthetic Limbs
Surgical Instruments
Braille Displays
Vacuum Test Manipulators
Micro Pumps
Blood Pressure Test Valve
Exoskeletal Assistance

AUTOMOTIVE
Door Locks
Environmental Controls
Gear Changing Triggers
Clutch Engagement Triggers
Mirror Controls
Heater Cutoff/Sensors
Pneumatic Valve
Remote Latches
Remote Releases
Alarm Devices

APPLIANCES
Moving Louvers
Spring Releases

Door Openers
Electronic Locks
Mechanical Volt. Regulator
Mechanical Curr. Regulator
Motor Protectors
Box Temperature Control
Overheating Controllers
Hair Dryer Cutoff/Sensors
Safety Cutoffs

MISCELLANEOUS
Ultralight Remote Control
Mechanical Scanners
Camera Manipulators
Magnetic Free Positioners
Manipulator Safety
PC Cutoffs
Fiber Gate
Camera Shutters
Cuckoo Clocks
Alarm Devices Light
Light Fiber Switches
Smart Materials
Mechanical IC's
Robotic Limbs

Flexinol® Actuator Wires are small diameter wires which contract like muscles when electrically driven. Smaller than motors or solenoids, cheaper and generally easier to use, these wires perform physical movement for an extremely wide variety of applications.

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Appendix B

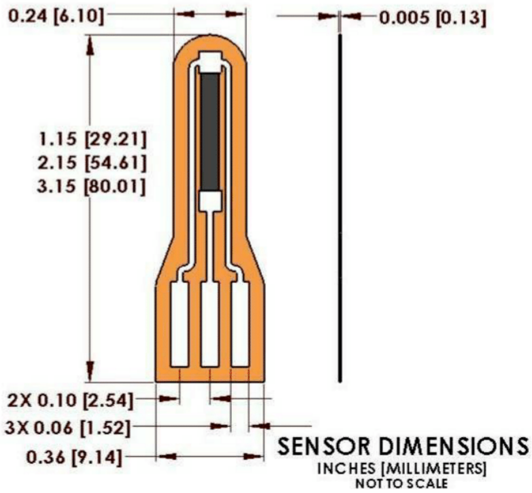
Bi-Directional Bend Sensor Specification Sheet

BI-DIRECTIONAL BEND SENSOR® SPECIFICATION SHEET

Flexpoint's Bi-Directional Bend Sensor® now gives you the ability to use one sensor to measure movement, or flow, in either direction! The single layer Bend Sensor® product allows for the measurement of mechanical movement, air flow, water flow, or even vibration. It can be used as a range of motion sensor, or as a very durable, very reliable switch in most harsh environments.

The Bend Sensor® Advantages:

- Single layer construction
- No sensor ventilation needed
- Excellent in harsh environments
- Durable; Robust
- Cost Effective



The stock product BEND SENSORS® are available in 1", 2" and 3" lengths. Custom sensor designs can be produced to meet customer requirements.

Part Number	Sensor Length	Resistance*	Weight
1100-0000	1.15"	5.0kn - 14.0kn	0.04 grams
2200-0000	2.15"	19.0kn - 46.0kn	0.09 grams
3300-0000	3.15"	32.0kn - 65.0kn	0.13 grams

- Resistance values will be higher when using a protective overlaminate.

AVERAGE % RESISTANCE CHANGE

Resistance changes of 100% or more when bent around a 3" diameter mandrel.

LIFE CYCLE

Greater than 2,000,000 Cycles t
Sensors were bent around a 0.25" radius at 2 cycles/second.

TEMPERATURE RANGE

-40°C to +90°C t
Indicates the extreme limits of testing to date. Bend Sensors are operational even outside these limits.

HUMIDITY RANGE

0% to 100% Humidity t
Indicates the extreme limit of testing to date.

HYSTERESIS

7% tt

RESOLUTION

Less than 1° of Bend (may be significantly less depending on electronics).

ENVIRONMENTS TESTED USING OVERLAMINATE

Water, soapy water, ammonia, cola drink, tea, alcohol, coffee, urine type solution, oil, gasoline.

VOLTAGE

5 vDC to 12 vDC typical

MINIMUM BEND RADIUS

Minimum bend radius is determined by application requirements and limits of the substrate.

t values may drift slightly over a high number of cycles or large changes in temperature and humidity.

tt values may increase and be time dependent when using adhesives.

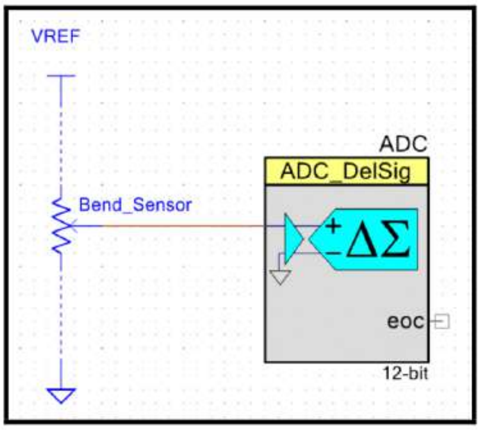
All values are taken statistically at a 95% confidence level. Specifications are derived from specific laboratory testing conditions. All numbers are given for guidelines only and individual results may vary due to specific application restraints and conditions.

US Pat. Nos. 5,157,372; 5,309,135. Other patents pending.

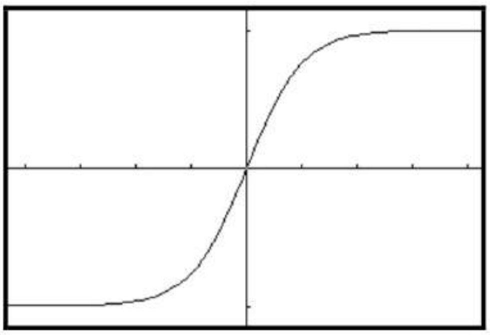
Flexpoint Sensor Systems, Inc.
106 West 12200 South • Draper, UT 84020
Ph: (801) 568-5111 • Fax: (801) 568-2405
www.flexpoint.com • info@flexpoint.com

Bi-directional Bend Sensors®:

Flexpoint also makes Bi-directional Bend Sensors®. When bent in one direction one sensor increases in resistance while the other decreases in resistance. This allows for deflection to be measured in either direction. Bi-directional Bend Sensors® share one common pin. Therefore they can be measured individually using many of the above methods as long as the common pin can be tied to VREF or ground. The Bi-directional Bend Sensor® can also be used in a voltage divider circuit using each side as the top and bottom resistor. This looks similar to a potentiometer schematic:



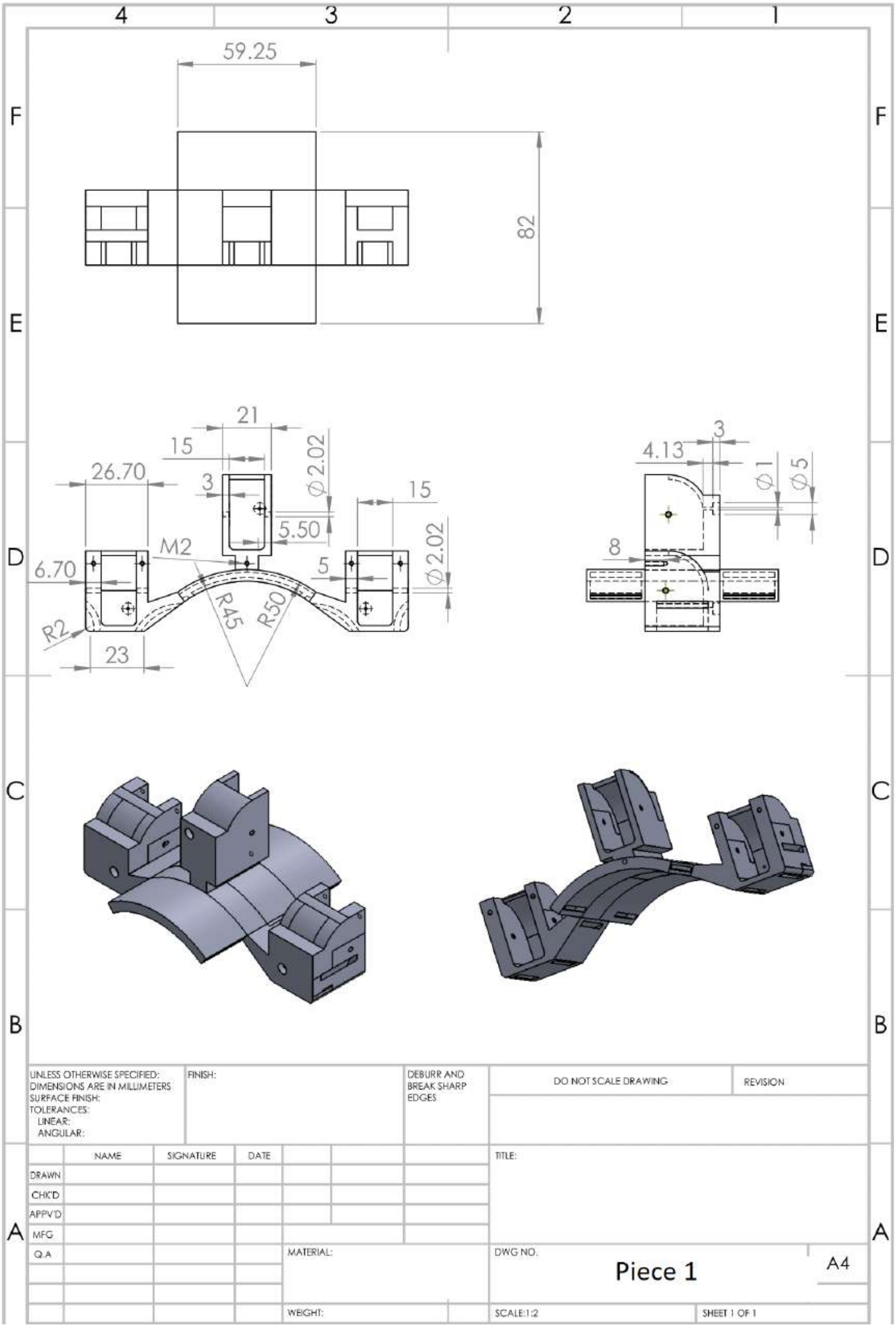
In this configuration the voltage that the ADC will measure will increase or decrease depending on the direction the Bend Sensor® is bent. Because each individual Bend Sensor® cannot go to zero ohms of resistance the response curve looks similar to a hyperbolic tangent function:



There is however a linear region near the center of the curve (VREF / 2).

Appendix C

2D Planes of the Exoskeleton Pieces



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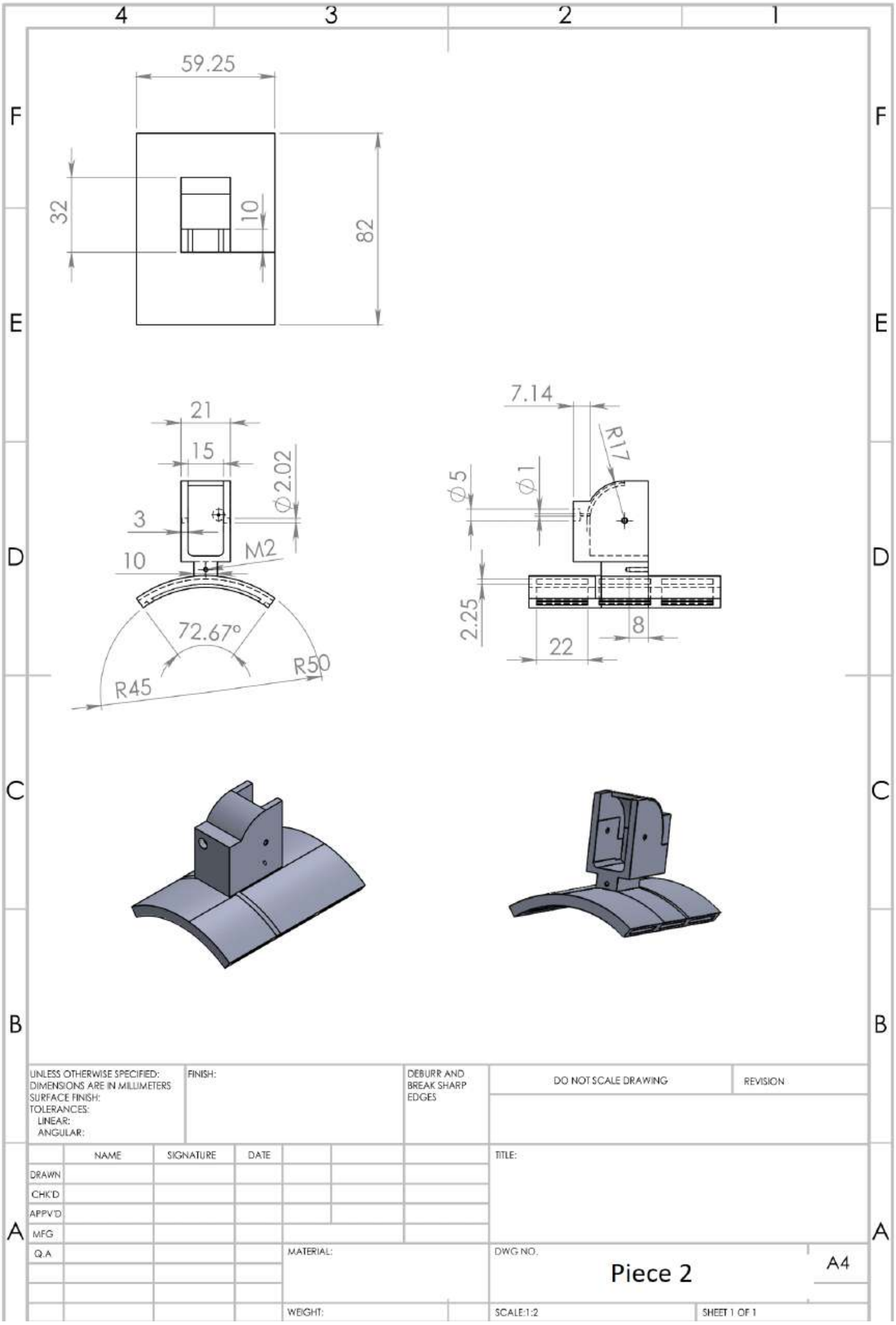
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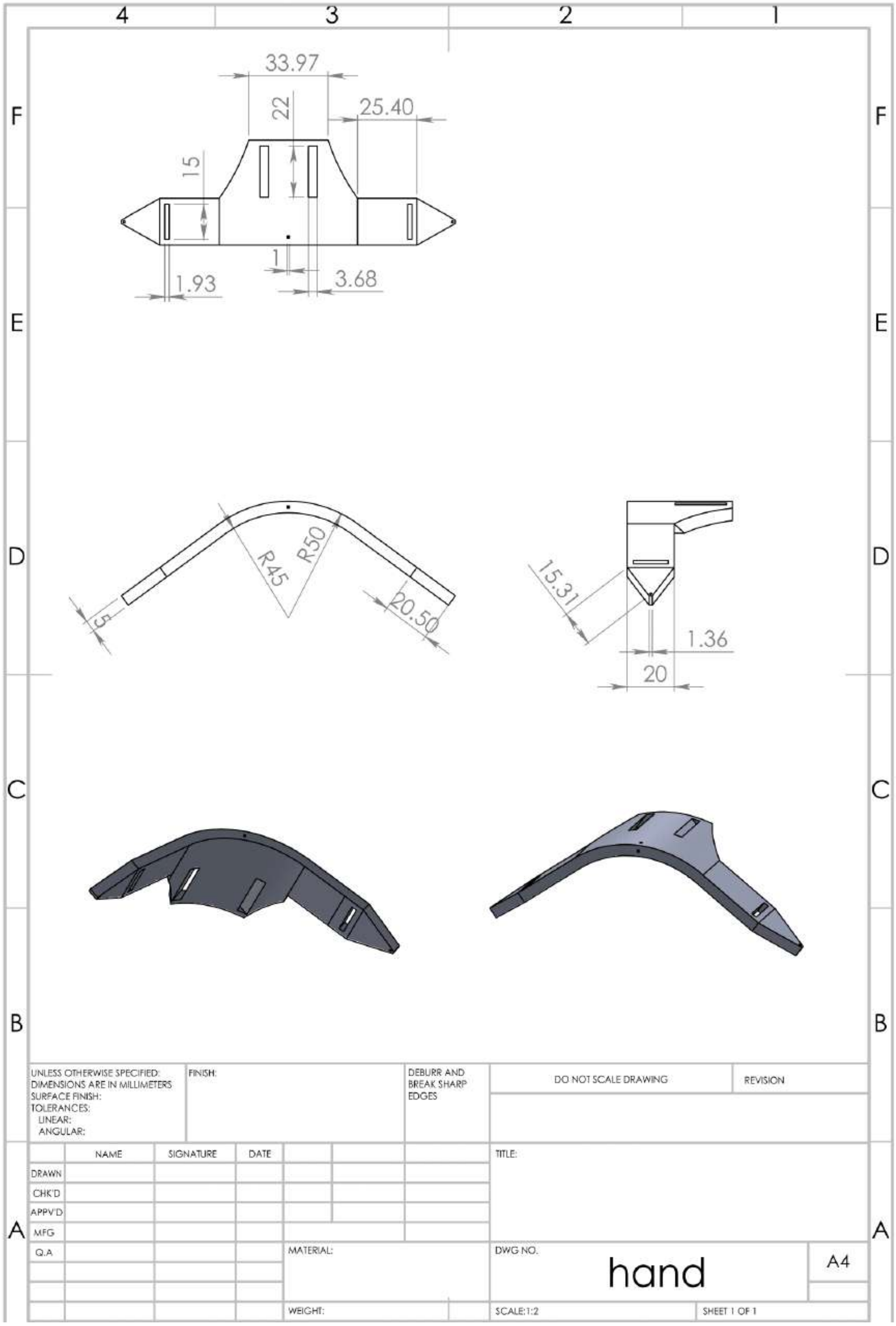
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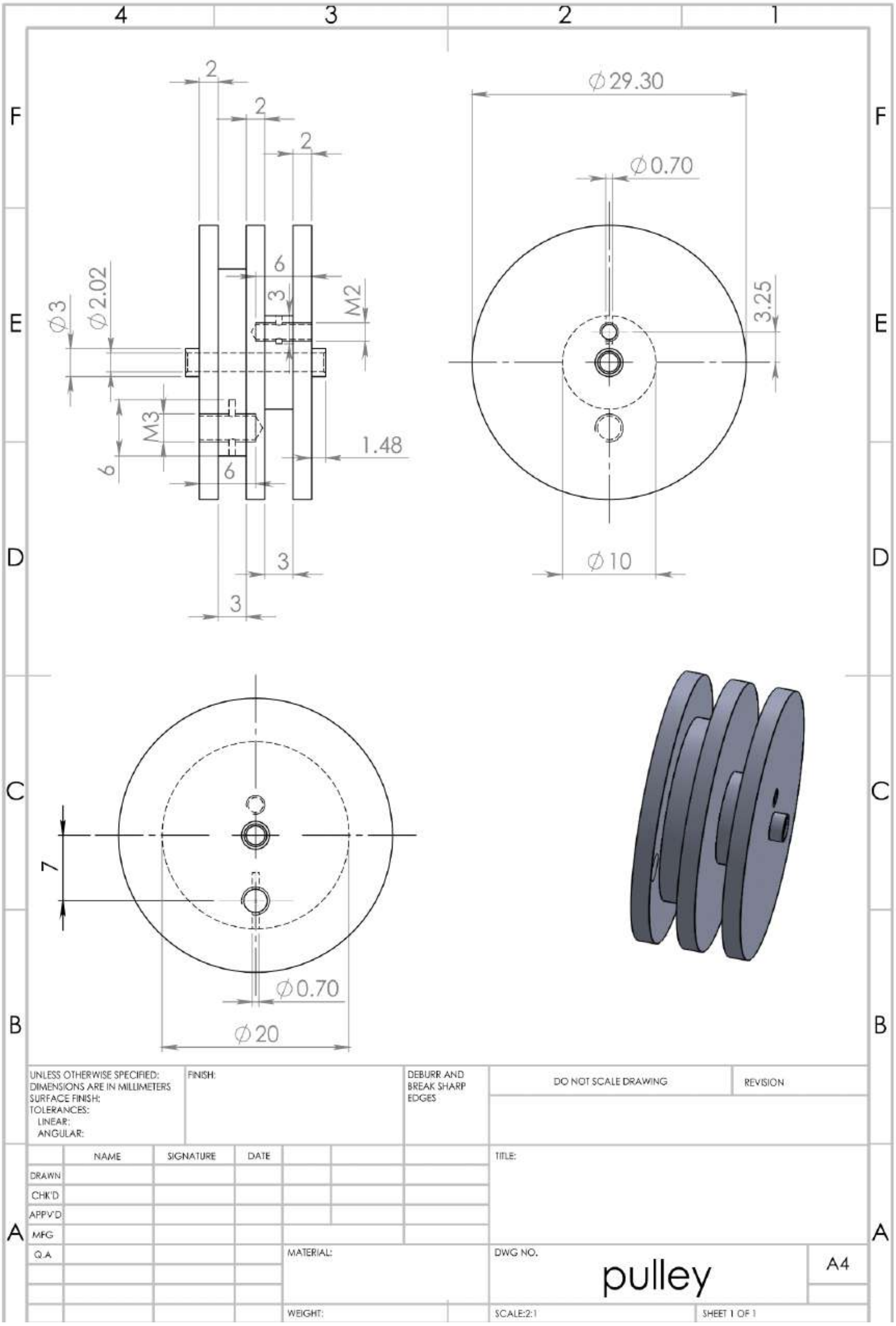
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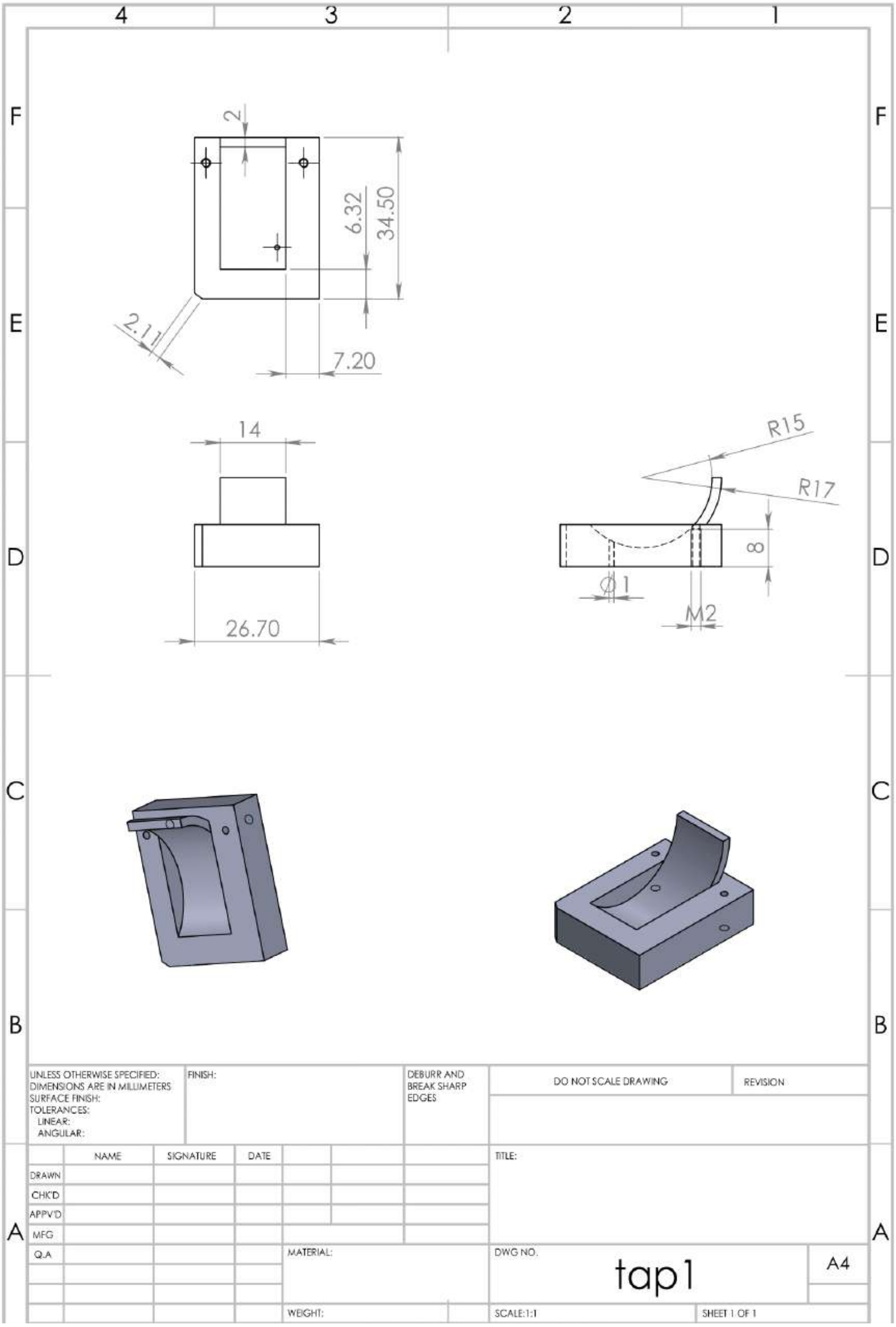
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TOLERANCES:
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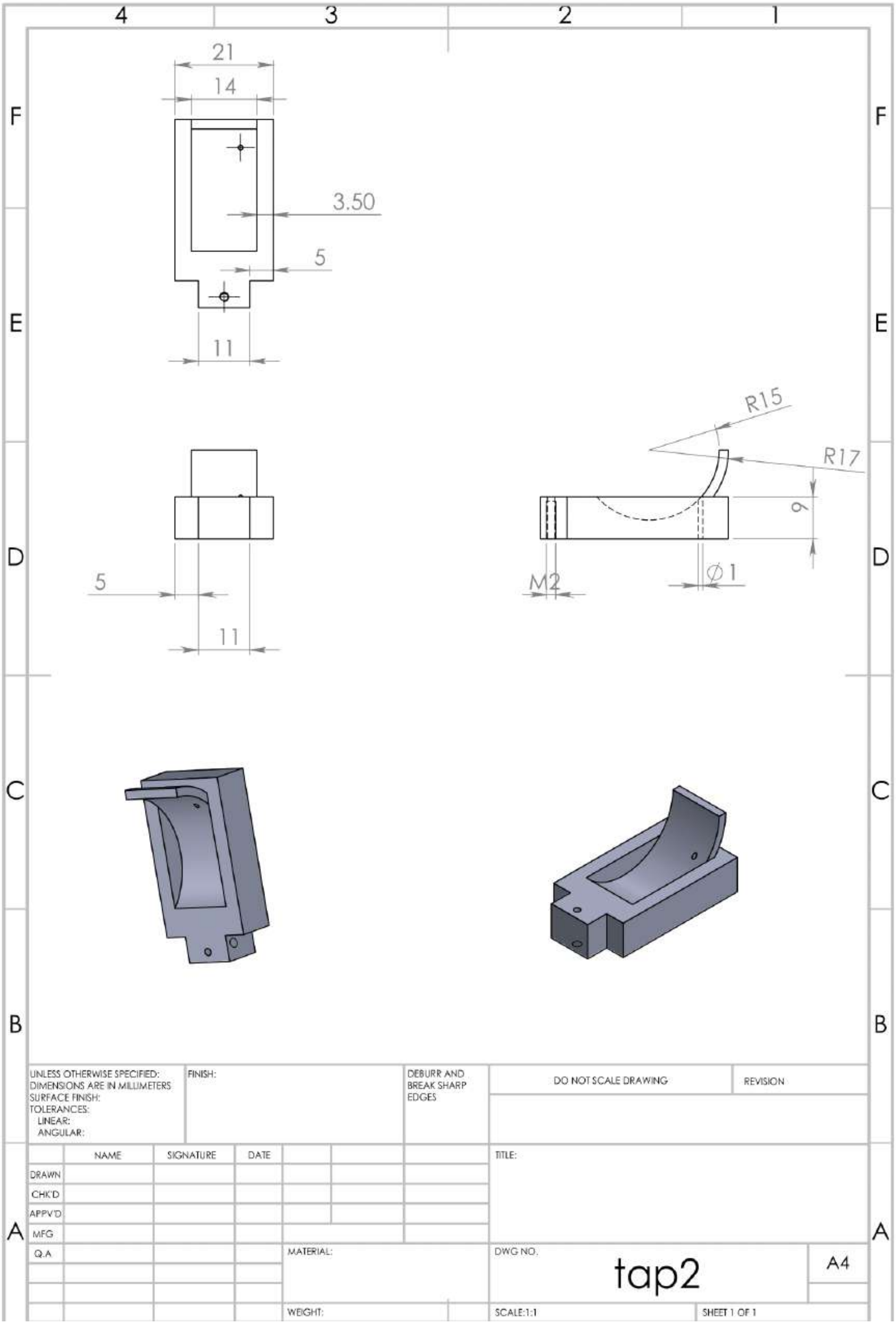
ANGULAR:
FINISH:
DEBURR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
tap1
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1


4
3
2
1
F
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21
14
3.50
5
11
R15
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11
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
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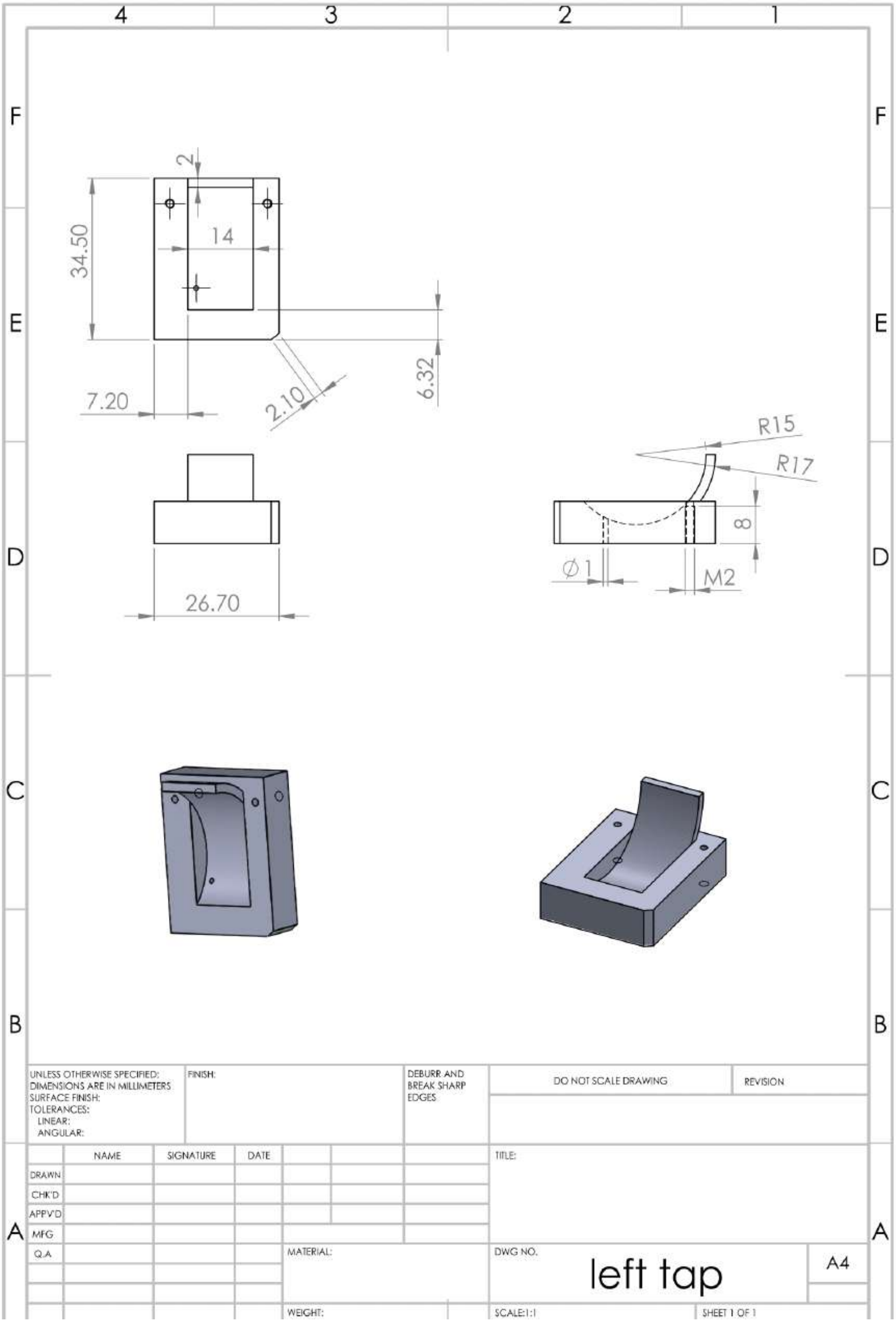
FINISH:
DEBURR AND
BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
tap2
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1


2
14
34.50
7.20
2.10
6.32
26.70
R15
R17
8
Ø1
M2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
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DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
left tap
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1