



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

OPEN DESIGN OF AN ACTUATED ARM ORTHOSIS USING 3D PRINTING TECHNOLOGY FOR PATIENTS WITH PROGRESSIVE MUSCULAR DYSTROPHY

CONSTANZA JAVIERA VILLANUEVA CASADO

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:

MIGUEL TORRES TORRITI

Santiago de Chile, November, 2017

© MMXVII, CONSTANZA JAVIERA VILLANUEVA CASADO



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

OPEN DESIGN OF AN ACTUATED ARM ORTHOSIS USING 3D PRINTING TECHNOLOGY FOR PATIENTS WITH PROGRESSIVE MUSCULAR DYSTROPHY

CONSTANZA JAVIERA VILLANUEVA CASADO

Members of the Committee:

MIGUEL TORRES TORRITI

DANI GUZMAN CARMINE

CARMEN SOLARES CANAL

SERGIO GUTIÉRREZ CID

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Santiago de Chile, November, 2017

© MMXVII, CONSTANZA JAVIERA VILLANUEVA CASADO

Gratefully to my family

ACKNOWLEDGEMENTS

Thanks to CEDETI-UC for supporting the project and giving the opportunity to develop a technological solution that I hope will help many children with muscular dystrophies. Special thanks to Professor Ricardo Rosas, Doctor Raúl Escobar, Carmen Solares and Nayadet Lucero, for their good-natured advice and help through various stages of the project. I also want to thank the patients and their families that volunteered in the experimental validation of the different orthoses designs, for their time and generous willingness to participate in the project.

I wish thank also the National Commission for Scientific and Technological Research of Chile (Conicyt) and the Office of Graduate Studies and Research of the Pontificia Universidad Católica de Chile (VRI-UC) for their funding. This work was supported by the graduate scholarship CONICYT-PCHA/MagisterNacional/2015/22151368 and VRI Interdisciplinario 2014.

I would like to express my gratitude to my advisor, Professor Miguel Torres, for his guidance through the project, support and open-mindedness.

Thanks to my friends of the Robotics and Automaton Laboratory (RAL) for helping me when I was troubled. Everyone had always a positive attitude and was eager to help each other. Many thanks to Jorge Reyes for his help during the printing process of the prototype.

I am also grateful to different professors of the Electrical Engineering Department, who helped me through the process of developing this thesis. Special thanks to Professor Dani Guzman for his support.

Finally, I would like to thank my family for their affection, care and advice, with their motivation I was able to fulfill this process. Special thanks to my boyfriend, for always being there for me. My love to all of them.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iv
LIST OF FIGURES	vii
LIST OF TABLES	xi
ABSTRACT	xii
RESUMEN	xiii
1. INTRODUCTION	1
1.1. Motivation	1
1.2. Problem Description	2
1.3. Objectives	3
1.4. Hypothesis	3
1.5. Existing Approaches	4
1.6. Contributions	9
1.7. Thesis Outline	10
2. FACTS AND PRELIMINARY RESULTS	11
2.1. Muscular Dystrophies	11
2.2. A first approximation to a solution	13
2.2.1. Articulated Armrest	13
2.3. Lessons Learned: 3D printing basics and tips	16
3. ANALYSIS AND DESIGN OF THE ORTHOSIS	20
3.1. Passive Orthosis	20
3.1.1. Mechanical Structure	20
3.1.2. Passive Gravity Compensation	23
3.1.3. Passive Orthosis Design Presentation	26
3.2. Active Orthosis	30

3.2.1.	Selection of the Actuator	30
3.2.2.	A Study of a Compliant Solution	32
3.2.3.	Active Orthosis Design Presentation	42
4.	IMPLEMENTATION AND TESTING METHODOLOGY	52
4.1.	Functional Evaluation Test	52
5.	EXPERIMENTAL RESULTS	56
5.1.	Preliminary Patient Testing	56
5.2.	Passive Mechanism Testing and Results	59
5.3.	Active Mechanism Testing and Results	61
5.4.	Summary of Results	62
6.	CONCLUSION AND FUTURE RESEARCH	64
6.1.	Results Discussion and General Remarks	64
6.2.	Recommendations for Future Research	66
	REFERENCES	68
A.	ADDITIONAL RESOURCES	73
A.1.	Makerbot Desktop 3.10.0.1364 Printing Settings	73
A.2.	Matlab Simulations Code for Gravity Compensation	79
A.3.	Matlab Simulations Code for Compliant Study	84
A.4.	CAD Drawings	97
A.4.1.	General View and Exploded View	97
A.4.2.	Detailed Drawings	99
A.5.	Detailed Costs	110
A.6.	Servomotor datasheet	111
A.7.	Arduino	115
A.8.	Additional Printing References	120
A.9.	CEDETI Functional Evaluation Guide	129

LIST OF FIGURES

1.1	Upper extremity, motor driven, exoskeleton.	5
1.2	CAREX: cable-driven upper ARm EXoskeleton.	5
1.3	Planar MEDARM prototype.	6
1.4	Active A-Gear.	6
1.5	Wilmington Robotic Exoskeleton, patient using the first prototype and a SEA prototype	7
1.6	Small patient using 3D printed version of WREX.	8
1.7	3D printed version of WREX prototype.	9
2.1	CAD model of the articulated armrest.	14
2.2	3D printed articulated armrest.	15
2.3	SMA patient with the articulated armrest fixed to wheelchair armrest.	15
2.4	Makerbot Desktop, infill preview	18
2.5	Makerbot Desktop, raft preview	18
2.6	Makerbot Desktop, general view	19
3.1	Joint configuration for orthosis.	21
3.2	Simple four-link bar mechanism.	21
3.3	Four-link parallelogram range of movement.	22
3.4	Change of limit angle with distance w	23
3.5	Four-link bar detailed diagram and forces diagram.	24
3.6	Rubber band length for variations on elevation angle θ	25
3.7	Torque variations for different configurations of rubber bands.	26
3.8	Torque variations for different number of rubber bands.	26
3.9	CAD model of passive design, various views.	27

3.10 Forearm holder.	29
3.11 Second link.	29
3.12 Net torque load at elevation joint: $\tau_l - \tau_e$	31
3.13 Compliant behavior of an actuator.	33
3.14 SEA Model representation.	35
3.15 SEA modification to a pulley system.	36
3.16 Simulation of the SEA pulley system, with sinusoidal reference.	39
3.17 Simulation of the SEA pulley system with an obstacle, with sinusoidal reference.	40
3.18 CAD model of active design, various views.	42
3.19 Shoulder vertical shaft comparison, section view	43
3.20 Elbow vertical shaft in passive and active design, section view.	44
3.21 Second arm horizontal shaft in passive and active design, section view.	45
3.22 First arm horizontal shafts in active design, section view.	46
3.23 Servomotor attachment to orthosis, front view.	47
3.24 Servomotor attachment to orthosis, isometric view.	47
3.25 Forearm holder modified.	48
3.26 Second link modified.	48
3.27 Wheelchair attachment of the Orthosis.	49
3.28 Arduino Blue-tooth App screenshot in Joypad mode.	50
4.1 Objects used for the functional evaluation.	54
5.1 Patients using the orthosis in different tests.	57
A.1 Makerbot Desktop Software, general view.	73
A.2 Makerbot Desktop Software, printing preview.	73
A.3 Makerbot Desktop Software, detailed printing preview.	74
A.4 Views of the CAD model	97

A.5	Exploded view of the CAD model, includes all parts to assemble	98
A.6	Aluminum squared tube anchor	99
A.7	Counterweight socket	100
A.8	Rubber band anchor	100
A.9	Elbow interior assembly	101
A.10	Elbow outer assembly	101
A.11	Forearm holder	102
A.12	Forearm socket	102
A.13	Forearm socket aluminum	103
A.14	Main link 1	103
A.15	Main link 2	104
A.16	Main link 3	104
A.17	Aluminum squared tube for arm	105
A.18	Aluminum squared tube for counterweight	105
A.19	Aluminum squared tube for forearm	106
A.20	Servomotor holder	106
A.21	Servomotor movable holder	107
A.22	Servomotor pulley axis	107
A.23	Bushing	108
A.24	Vertical link at elbow	108
A.25	Vertical link at forearm	109
A.26	Vertical link at shoulder	109
A.27	Arduino schematic connection for HC-06 Bluetooth Module	115
A.28	Thing: Aluminum squared tube anchor	120
A.29	Thing: Counterweight socket	121

A.30 Thing: Rubber band anchor	121
A.31 Thing: Elbow interior assembly	122
A.32 Thing: Elbow outer assembly	122
A.33 Thing: Forearm holder	123
A.34 Thing: Forearm socket	123
A.35 Thing: Forearm socket aluminum	124
A.36 Thing: Main link 1	124
A.37 Thing: Main link 2	125
A.38 Thing: Main link 2	125
A.39 Thing: Servomotor holder	126
A.40 Thing: Servomotor movable holder	126
A.41 Thing: Bushing	127
A.42 Thing: Vertical link at elbow	127
A.43 Thing: Vertical link at forearm	128
A.44 Thing: Vertical link at shoulder	128

LIST OF TABLES

3.1	Supplies in passive orthosis.	28
3.2	Supplies in active orthosis.	51
4.1	Functional Evaluation Test: tasks and evaluation.	55
5.1	Scores of the Functional Evaluation Test for patient 1 with no orthosis.	58
5.2	Scores of the Functional Evaluation Test for patient 2 with no orthosis.	58
5.3	Functional Evaluation for patient 1 with passive orthosis mechanism.	60
5.4	Functional Evaluation for patient 2 with passive orthosis mechanism.	60
5.5	Scores of the Functional Evaluation Test for patient 1 with active orthosis mechanism.	61
5.6	Scores of the Functional Evaluation Test for patient 2 with active orthosis mechanism.	62
5.7	Scores summarized of the Functional Evaluation Test for both patients.	63
A.1	Device Settings	75
A.2	Infill	75
A.3	Model Properties	75
A.4	Extrusion Speeds	76
A.5	Raft	77
A.6	Supports and Bridging	77
A.7	Right Extruder, left is the same	78
A.8	Passive Orthosis Detailed Costs	110
A.9	Active Orthosis Detailed Costs	111

ABSTRACT

Patients with progressive muscular dystrophies (PMD) are not able to complete regular daily activities by themselves. Arm orthoses are used to help them fulfill simple tasks and thus try to improve their quality of life. However, the cost and usability of existing commercial orthoses makes them prohibitive for many people. Hence, this work proposes an open-design of an actuated orthosis that can be fabricated using the evermore popular 3D printing technology. The orthosis has three passive joints and one actuated joint. This document presents a full review of the design of the mechanism, as well as the experimental evaluation of the device. The results show that the orthosis helps patients to complete activities that would otherwise require posture compensation. An orthosis with a low-cost actuator system can support motion only of patients that retain some minimum strength, especially at their shoulder, and that have not completely lost mobility of the arm. Patients with a more advanced muscular degeneration would require a similar orthosis, but with higher torque and more expensive actuators. Nonetheless, the proposed low-cost arm exoskeleton can be used to improve self-esteem and self-sufficiency in patients with PMD in early stages of the disease, as well as reducing additional muscle stress from over-compensatory movements.

Keywords: open, design, open-design, actuator, arm, orthosis, orthoses, 3d, printing, medicine, progressive muscular dystrophy, duchenne, atrophy, spinal, compliance.

RESUMEN

Los pacientes con distrofia muscular progresiva (DMP) no son capaces de realizar actividades cotidianas por su propia cuenta. Las órtesis de brazo se utilizan para ayudarlos a realizar tareas sencillas y de esta manera tratar de mejorar su calidad de vida. Sin embargo, el costo y usabilidad de las órtesis comerciales existentes las hace prohibitivas para muchas personas. Por lo tanto, este trabajo propone diseñar una órtesis con actuadores, siguiendo el concepto de diseño abierto, u *open-design* por su nombre en inglés, que se fabrica empleando la cada vez más popular tecnología de impresión 3D. La órtesis tiene tres articulaciones pasivas y una articulación actuada. Este documento presenta una revisión completa del diseño del mecanismo, así como la evaluación experimental del dispositivo. Los resultados muestran que la órtesis ayuda a los pacientes a completar actividades que requerirían la compensación corporal de la postura de no contar con la órtesis. Un sistema de órtesis con actuador de bajo costo solo puede apoyar el movimiento articular de pacientes que mantengan una cierta fuerza mínima, particularmente en el hombro, y no hayan perdido la movilidad completa del brazo. Pacientes con una degeneración muscular más avanzada requerirían una órtesis similar, pero con actuadores de mayor toque, y por lo tanto de mayor costo. No obstante, el exoesqueleto para brazos de bajo costo que se propone puede utilizarse para mejorar la autoestima y autosuficiencia de pacientes con DMP en etapas tempranas de la enfermedad, así como también para ayudar a reducir el estrés muscular adicional por el exceso de movimientos corporales para generar posturas compensatorias.

Palabras Claves: open-design, actuador, brazo, órtesis, 3d, impresión, medicina, distrofia muscular progresiva, duchenne, atrofia espinal, compliance.

1. INTRODUCTION

Muscular dystrophy makes patients unable to move their limbs freely at young ages. Arm orthoses are built with the objective of helping children to complete daily activities by themselves, improving self-esteem and autonomy. Most orthoses are complex, expensive, and conceived for rehabilitation rather than home-use. The widespread availability of 3D printing creates a good opportunity for building modular and adaptable orthoses that suit the needs of each patient at a lower cost. Nowadays, there also exist many different options to include small actuators or motors in the design of active orthosis, which are commonly referred to as exoskeletons. In this work, the words *orthosis* and *exoskeleton* will be used interchangeably.

1.1. Motivation

Muscular dystrophies have an average incidence of 1 in 3500 newborns with an associated low life expectancy. Being diagnosticated at early stages of life, these types of diseases render children unable to walk at young ages, and impair the upper limbs' movement. This situation entails psychological and social problems to the family and patient, that make their life harder each day as the disease progresses.

To improve the patient's quality of life, orthoses that help the person to regain some autonomy and in turn improve the mood and self-esteem, have been proposed. Unfortunately, there does not exist a commercial actuated orthosis, and the only commercial orthoses are passive, limited in the range of ages for which they have been designed (do not grow with the child) and high-priced. Furthermore, passive orthoses cannot be programmed to perform some common object handling tasks, such as when eating or brushing their teeth. On the other hand, employing a robotic arm that responds to user commands, while technically feasible is even more costly and may requires a longer process of calibration and customized setup for each user's specific needs.

An affordable and adaptable solution is peremptory. Today such a solution is possible thanks to the open design movement and ideas, which facilitate the usage and sharing of

software and hardware designs for free. The absence of an obligation to pay a monetary compensation for a design to the author, and the growth of Internet as a platform that facilitates sharing information have promoted the development of an active community that shares their open design hardware projects. On the other hand, 3D printers have become easily available thanks to the open design movement, thus enabling more people to build prototypes or even finished products at home, without requiring specialized machine shops.

1.2. Problem Description

Since patients with progressive muscular dystrophy have a decreased range of motion of the upper limb, this thesis proposes the design and construction of an arm orthosis. The mechanism must be able to support arm weight of the patient, alleviating muscle exhaustion when doing daily activities, such as lifting cutlery or picking and placing objects that would be typically found on a desk.

This thesis proposes the use of 3D printing technology to manufacture the main structure of the mechanism making possible the adaptability and scalability of the orthosis at a low cost, requiring only certain pieces of the design to be changed so that the orthosis fits the person as the patient grows up.

A special effort has been made to produce a design that uses commercial-of-the-shelf parts and parts that can be manufactured with a 3D printer. The option of adding actuated joints to the orthosis has also been considered as part of the design. While adding actuators to the design increases the cost, adding actuated joints can allow to mitigate muscular stress even further. However, in addition to the selection of the right actuator, other factors, such as the selection of the power supply, the user input, and the control strategies, become crucial in an active orthosis. An actuated orthosis should have some level of compliance to deliver natural continuous movements, and at the same time protect the user of collisions.

The proposed design has been made publicly available for free with all the schematics and instructions, so that anyone can build it, thus helping also lower income families that cannot afford commercial designs.

1.3. Objectives

The objective of this thesis is to produce and test an open design of a low-cost arm orthosis for patients with some type of neuromuscular disease. The open design will emphasize modularity, adaptability, simplicity and re-usability in order to create an orthosis that can easily be modified according to the patient's needs. To this end, special emphasis will be placed on developing a design that relies on commercial of the shelf components and 3D printed parts as much as possible.

The specific objectives are:

- (i) To design and build the simplest possible passive orthosis.
- (ii) To test the simple orthosis in order to identify failures and refine the design.
- (iii) To design and build an active orthosis to improve the patient's motor capacity.
- (iv) To test the passive and an active orthosis designs in a set of tasks that include activities of daily life.
- (v) To publish the building instructions on a free access website, as well as the blueprints of the entire project.

1.4. Hypothesis

The main hypotheses of this thesis can be summarized in:

- The new 3D printing technologies, which have become popular in recent years among the rapid prototyping community, make it possible to easily implement modular and modifiable arm orthoses at a low cost for people with progressive muscular dystrophies.

- Including a servomotor and a compliance mechanism can improve the range of motion, while reducing the effort required by the user and protecting the person from collision and the rigidity of traditional servomotors.
- The open design arm orthosis would help people to carry out activities of daily living, such as eating or picking objects, without requiring compensatory torso and head movements that can aggravate the progression of the dystrophy.

1.5. Existing Approaches

An orthosis or exoskeleton differs from a prosthesis, which is a common generic term, in which the second one is a replacement for a body member, whereas the first supports a certain part of the body. As stated by the International Organization for Standardization (IOS) an orthosis is “an externally applied device used to modify the structural and functional characteristics of the neuromuscular and skeletal system”.

Orthoses can be used in different parts of the body, from fingers to the vertebral column. Most used orthoses are the ones that restrict movement, thus correcting shape or function of the body, or reducing the pain of a lesion (Bunch & Keagy, 1976). They can go from a sling or sprint to a more complex body jacket to stabilize fractures of the spine.

Aiding rehabilitation is another use of orthoses. Controlling, guiding and assisting movement in general or at a particular joint. Lower-limb orthoses play a crucial role in gait rehabilitation. For stroke rehabilitation, robotic orthoses help the therapist to work with the patient at different paces, guiding their movements at every point of the desired trajectory needed to reinforce their muscles. Appropriate coordination of joints angles is needed to recover upper-limb functionality and range of motion (Kwakkel, Kollen, & Krebs, 2007).

Early rehabilitation manipulators started mid 1960's. In works such as (Pignolo, 2009) and (Hillman, 2004), an extended review of rehabilitation robotics can be found. Different types of actuation in orthoses or exoskeletons have been researched. Electromechanical actuators such as motors, are more widely used, for example in (Moubarak, Pham,

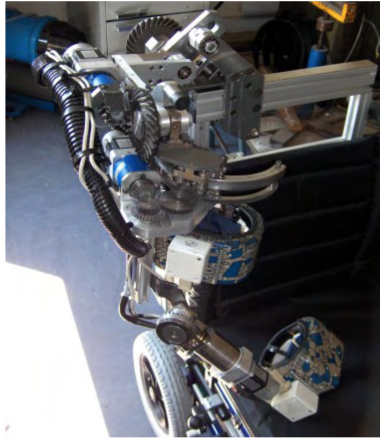


FIGURE 1.1. Upper extremity, motor driven, exoskeleton, retrieved from (Moubarak et al., 2010).



FIGURE 1.2. CAREX: cable-driven upper ARM EXoskeleton, retrieved from (Mao et al., 2015).

Moreau, & Redarce, 2010), where gravity compensation is achieved through motor torque applied directly to the joint. Other mechanisms use cable driven actuators such as (Mao, Jin, Dutta, Scholz, & Agrawal, 2015) and (Ball, Brown, & Scott, 2007).

Different strategies for control are used in each exoskeleton. EMG (Electromyography) is widely used for controlling robotics, (Desplenter, Lobo-Prat, Stienen, & Trejos, 2016), but has a slow learning curve in patients. In (Wolbrecht, Leavitt, Reinkensmeyer,

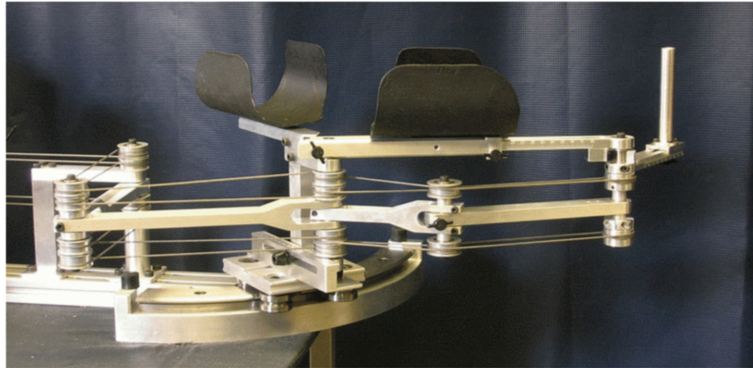


FIGURE 1.3. Planar MEDARM prototype, retrieved from (Ball et al., 2007).

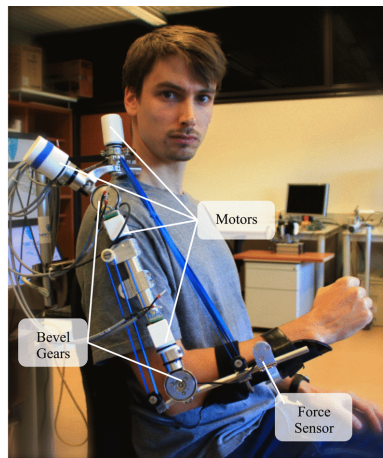


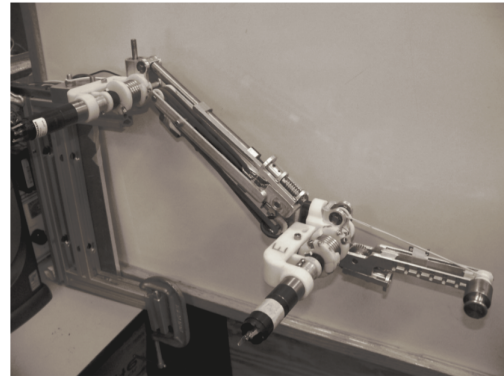
FIGURE 1.4. Active A-Gear, retrieved from (Kooren et al., 2016).

& Bobrow, 2006) a pneumatic orthosis is controlled with MEMS accelerometers with a Kalman filter to provide smooth trajectories for patients.

But, exoskeletons are not only made for rehabilitation purposes. A wide variety of orthoses are built to help patients with neuromuscular diseases complete activities of daily living. In (Kooren et al., 2016), a 5 DOF exoskeleton is designed specifically for Duchenne patients, which is driven by DC motors and in (Koo et al., 2009) a hybrid orthosis is built to provide passive assistance in the horizontal plane movement and active in the vertical plane.



(A) Patient using WREX prototype, retrieved from (Rahman et al., 2000).



(B) WREX SEA prototype, retrieved from (Ragonesi et al., 2011).

FIGURE 1.5. Wilmington Robotic Exoskeleton, patient using the first prototype and a SEA prototype

One commercially available exoskeleton, specially used by muscular dystrophy patients is the WREX. The Wilmington Robotic Exoskeleton started in (Rahman, Ramanathan, Seliktar, & Harwin, 1995), as a passive mechanism for gravity compensation. In (Rahman, Sample, Seliktar, Alexander, & Scavina, 2000) an exoskeleton was build, which worked using linear elastic elements to balance for the effects of gravity and is adjusted according to the patient.

Modifications of the WREX mechanism had been made by the authors and third parties. A more extended test of the mechanism is shown in (Rahman, Sample, & Seliktar, 2004), and the same structure is used in (Sanchez et al., 2004, 2005) as base for a pneumatic actuated version for rehabilitation purposes. More studies over the WREX mechanism can be found in (Rahman et al., 2006, 2007). Later on, an actuated version of the WREX was proposed (Ragonesi, Agrawal, Sample, & Rahman, 2011), in which they included SEA actuators to achieve a more compliant solution.

In the case of neuromuscular disease, each patient has a different range of movement and strength depending on the stage of their disease. When strength fails in their shoulder and elbow, the movement with WREX would be impossible as the force required to overcome frictional and balancing forces could not be provided by the patient.



FIGURE 1.6. Small patient using 3D printed version of WREX, retrieved from (JavelinTechnologies, 2013).

Nevertheless, WREX is a patented device (Rahman & Sample, 2004), with a web price of over 4000 US. Making it not an affordable solution to most patients. Especially considering that kids usually upgrowth orthoses very fast, needing external help since the early stages of the disease, when they are around 10. All the more, muscular weakness of DMD and SMA patient is progressive, which means the passive mechanism will mostly stop working correctly at a certain point of the dystrophy progress.

The Wilmington Center uploaded a video where a simplified version of the orthosis is build based on 3D printed parts (JavelinTechnologies, 2013). The patient shown in the video is a small girl with Arthrogryposis Multiplex Congenita (AMC). It is characterized by severe joint contractures and muscle weakness, but with non-progressive symptoms. Typical treatment of AMC includes occupational therapy, physical therapy, splinting and surgery.

As force requirements for AMC syndrome do not increase with time, an adaptable solution with 3D printing is most suitable. Since 3d printing can be easily accessed by regular people, modification as the kid grows is easy and not as expensive compared to metallic machined pieces. But, plastic is not so rigid, hence it can't support as much weight and heavier structures may collapse after some use. Despite the disadvantages, 3D printing is a good prototyping material proposed as a cheaper solution for building arm orthosis with high adaptability.



FIGURE 1.7. 3D printed version of WREX prototype, retrieved from (JavelinTechnologies, 2013).

1.6. Contributions

The original and novel contributions presented in this thesis are:

- (i) The design of a simple passive arm orthosis based on a four-link bar mechanism that can be built using commercial-of-the-shelf components.
- (ii) The design of an active arm orthosis that draws on ideas of the previous design and includes a servomotor on the shoulder joint.
- (iii) The evaluation of the designed orthoses applying a *Functional Evaluation Test* on volunteer patients.
- (iv) The publication of the CAD models, 3D printer files, drawings, blueprints and assembly instructions of the orthoses under a free and open source scheme at http://ral.ing.puc.cl/arm_orthosis.htm, i.e. anyone is freely licensed to use, copy, study, and change the design in any way, which has been openly shared so that people are encouraged to improve it and keep contributing the community. The project is also available in the Thingiverse website at <https://www.thingiverse.com/thing:2674114>.

1.7. Thesis Outline

This thesis is organized as follows. Chapter 2 describes further muscular dystrophies and the implications of the diseases, proposes a first approximation to the orthosis, and states a set of lessons learned and important recommendations regarding 3D printing. In Chapter 3 the complete design and analysis of the passive and active mechanism is presented. A description of the testing methodology is described in Chapter 4. Results of the testing with the mechanism is presented in Chapter 5. Finally, in Chapter 6, the conclusions of this work are presented and further research topics are proposed.

2. FACTS AND PRELIMINARY RESULTS

In this chapter, a review of the muscular dystrophies and the symptoms is presented, to further understand the lives of the patients and their needs. Then a first approach to a solution is presented and the preliminary results are discussed. At last, a summary of 3D printing knowledge and tips is stated, as lessons learned from the previous work.

2.1. Muscular Dystrophies

There are more than 30 types of Neuromuscular Disorders (Emery, 2002). Although most of them are rare, the sum of patients with a certain type of disorder may be compared to numbers of more known syndromes such as Parkinson disease. Neuromuscular disorders mostly affect the muscles, creating a progressive weakening and breakdown of them, but may also carry effects that damage organs. The life expectancy is usually low, and patients die before their thirties in most cases when organs are compromised.

General symptoms of these disorders include:

- Progressive muscular weakness
- Inability to walk
- Limited range of movement
- Scoliosis (curvature of the spine)
- Respiratory difficulty

Diagnosis of Neuromuscular Disorders (NMD) is made early on, between the age of 3 to 5, especially identifiable when the gait problems start to show. Most of NMD are genetic and may or not be inherited from the parents, as can also be result of a mutation on early stages of the pregnancy.

Although most NMD do not compromise the brain, and so children have normal cognitive development, their lives are far from normal. By the age of 8 to 10, most of the patients will be using a wheelchair and have notorious problems to complete everyday

activities. The psychological consequences affect the families, thus having to bear with an extra weight besides medical costs of the disease.

There are two most common NMD: Duchenne Muscular Dystrophy (DMD) and Spinal Muscular Atrophy (SMA). The first one has an incidence of 1 in 3500 male births (Emery, Muntoni, & Quinlivan, 2015). DMD syndrome is X-linked recessive, thus affecting males and females are only carriers. SMA has an incidence of 1 in 5000 newborns, affecting both girls and boys (Lunn & Wang, 2008).

Both syndromes have similar development in terms of how the progressive muscular weakness is shown. First legs are affected, forcing use of a wheelchair. Then the arms are affected, going from proximal to distal decay, meaning that the weakness goes from their shoulders and towards their elbows, and finally affecting their wrists and fingers. At early stages, movement is restricted by the shoulder range of motion, and as the disease progresses the movement becomes more limited.

Besides the muscular weakness, the organs begin to degenerate too. In many cases a respiratory therapy is needed, including non-invasive ventilation and in extreme cases tracheostomy is the only option to prevent pulmonary muscles to weaken even more. Physical and occupational therapy helps to slow down the progressive degradation. Orthopedic surgery may be needed in cases where the spine is compromised in order to improve the quality of life.

Low doses of Corticosteroids may help maintain muscle tone. But overall, there is no cure for NMD. Nowadays there's been shown improvement of symptoms for certain DMD mutations with the use of exon skipping treatment (Dunckley, Manoharan, Villiet, Eperon, & Dickson, 1998). The treatment causes cells to skip over faulty or misaligned sections of genetic code, leading to a truncated but still functional protein despite the genetic mutation, being the mutated protein the main source of the disease. Despite results, further clinical studies are needed.

Most treatments are oriented to improve the quality of life, for the patient and for the family (Chen & Clark, 2007). Helping the kids to complete daily activities more

easily and without compromising even more their muscles is very important for their own health. Physical therapy focuses on improving the movement of upper-limbs, with one objective being that the patient can feed themselves, thus improving the patient autonomy and quality of life.

2.2. A first approximation to a solution

After understanding patients needs, a simple approximation to the problem arose. Multiple meetings with the project partners were held, which included the Occupational Therapist that treated the patients, as well as the head doctor in charge of their medical treatment.

The main problem is to counter the effects of gravity when patients move their limb in the vertical plane, lifting the arm from rest position. The same applies when the patient elevates their forearm with the elbow lean on a surface. Depending on the dystrophy's progression, different patients may or may not be able to achieve the second movement by themselves.

To address the patients lack of strength, an articulated armrest mechanism is proposed. The idea is to give the arm and forearm a lifted surface to rest that would enable the patient to bring the hand closer to the mouth, being able to feed themselves without compensatory movement. But, not only elevating the arm is enough, it also requires having a joint for the elbow to rotate and move the hand away from the table, where the plate of food is, to the mouth.

2.2.1. Articulated Armrest

The designed structure has three main parts, as depicted in Fig. 2.1. The CAD model was done in Autodesk Inventor. The lower horizontal level is used as support of the entire mechanism and also enables the structure to be mounted on a wheelchair armrest or table.

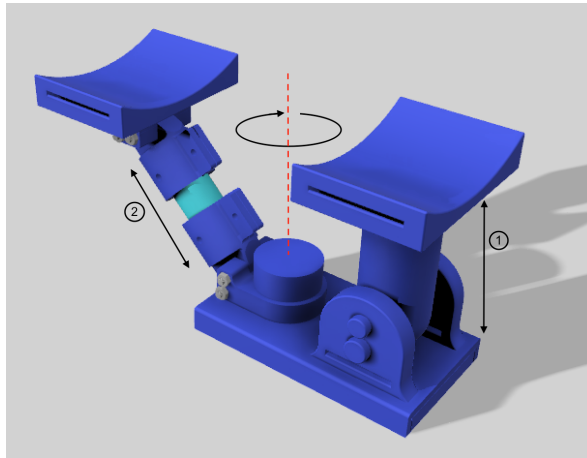


FIGURE 2.1. CAD model of the articulated armrest.

A two-piece arrangement works as the articulated armrest (1). Height can be adjusted screwing the upper segment into the vertical one. A rotational joint enables the forearm to rotate if the elbow is aligned with the axis of the armrest.

The third part consist in a set of pieces joined by screws that supports the forearm (2), the segment is at 45° angle and the length is adjusted by a piece of PVC pipe cut to the desired distance. The forearm can be fixed to the support by Velcro strips.

Most of the pieces can be 3D printed. The printer used in the articulated armrest was the FlashForge Creator Pro. The PVC pipe was chosen to add steadiness as the material is more rigid than standard 3D printing filaments such as ABS. Real screws are used, as small pieces in the printer, even with complete fill, are not resistant enough. A 3D printed version of the structure is shown in Fig. 2.2.

The mechanism proposed enables the user to raise their arm segment to a desired height and move it over the horizontal plane. Testing was carried out with two patients, one with DMD and other with SMA. Both had different complexities and the progressive dystrophy was not equal, but neither of them was able to raise the arm because of shoulder muscles having low to none strength in them, making their problematic comparable in terms of the solution presented.



FIGURE 2.2. 3D printed articulated armrest.



FIGURE 2.3. SMA patient with the articulated armrest fixed to wheelchair armrest.

Conclusions of these tests were that the structure was not comfortable to use on a daily basis. Since the rotational axis was built of 3D printed parts without a smooth shaft, rotation of the second segment was hard to achieve due to friction that could not be overcome by the patients. A main concern of parents and patients was that, in order to let the user feed themselves, a higher dish would be needed, or a higher table, making things more difficult to the patient rather than helping. Both patients could compensate

movement in order to be able to feed themselves even if it meant to lean over the table with neck flexion.

Even if the results were not entirely positive, a more deep understanding of the needs and restrictions of the patient were acknowledged. A joint for the elevation of both shoulder and elbow were needed in order for the patient to have a more fluent and easier movement of the mechanism.

2.3. Lessons Learned: 3D printing basics and tips

One of the objectives of this thesis is to use 3D printing to build most pieces of the desired mechanism. 3D printing is an additive manufacturing process that creates a physical object from a digital design. In order to successfully print a component, considerations in the design and printing process are important. A set of different parameters can be chosen in most 3D printing software. A list of these and their implications are listed below.

- **Resolution:** is adjusted by the layer height. A Smaller number, means better resolution and a smoother surface will be achieved. But increasing the resolution also increases the printing time as more steps and layers are built in the Z axis.
- **Infill:** Two parameters define the infill. The first is the percentage of infill. A 100% means a full solid piece. The second parameter is the shape of infill, such as honeycombs or diamonds. Depending on the piece being printed, between 25% and 40% of fill will give enough support. Normally any type of filling would work, but if there are narrow walls, special care should be taken in order to achieve proper filling. (Fig. 2.4)
- **Orientation:** Since printing is constructed upon layers, orientation of the piece within the machine is crucial to achieve proper resistance. Shear and axial forces, as well as bending moment will be affected by the layer composition. If the structure is under a bending moment is important that layers are perpendicular to the axis of rotation in order to improve resistance.

- Support: When printing parts that have holes through them, or a roof type of structure, support underneath is needed to properly hold the upper structure in place. If the object is spherical or in a 45° angle, no support is needed. Since Supports uses a lot of material that is later removed is important to have it in mind and position the piece to minimize waste if needed.
- Raft: this structure is used to fix the printed piece to the printing bed. Two considerations are important in this case. First, is the raft radius that contours the piece. With a bigger radius, a better adhesion is achieved, thus avoiding warping of the printing corners. Warping can compromise both the end result and the printing process as well, since the piece could be separated from the bed and dragged around by the extruder if not adhered to the platform. Second, is the thickness of the raft. If it is thicker, more material is wasted, but the bed temperature does not affect the final piece, which enables the Raft to be peeled off easily afterwards. (Fig. 2.5)

Other set of parameters are needed to be defined as well. Temperature of the platform and extruder will depend on the material, common materials include ABS and PLA. For this thesis, only ABS was used. Bed temperature was set to 125 °C and extruder to 240 °C.

Each printer has different parameters that can be modified. During this project two similar printers were used: FlashForge Creator Pro, as presented before, and for the rest a Makerbot Replicator 2X was used. The software used to slice the digital model was Makerbot Desktop, compatible with both printers, a screenshot of the software is shown on Fig. 2.6. There are multiple softwares available for the slicing process that can be used with different printers, a suitable one should be found for the requirements of each project.

Feed rate, which is the speed with which the extruder moves over and across the printing bed, will partially define the printed piece resolution. When printing a small piece low speeds are recommended in order to give each layer enough time to cool down and avoiding a melted finish. Successfully printing small parts could also be achieved

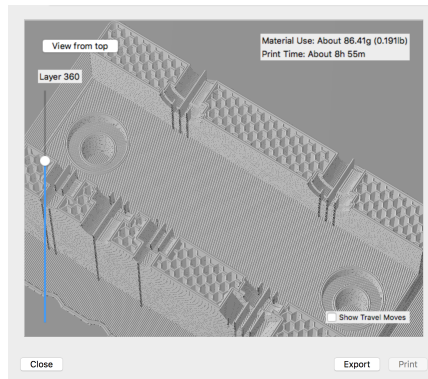


FIGURE 2.4. Makerbot Desktop, infill preview

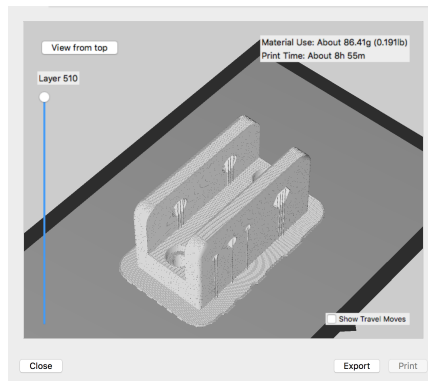


FIGURE 2.5. Makerbot Desktop, raft preview

by printing more than one part in the same bed, distancing them as much as possible. Different pieces are not recommended to be printed together, as the movement between parts could make them be lifted from the surface if the Raft is not well selected.

In order to print, a CAD model need to be imported to the printing software. Design of the 3D model also has several considerations to take in account. The crucial factor is to consider the expansion and contraction of the plastic when printing. The precision of most machines is below the millimeter, but deviations occur due to the temperature phenomenon, changing the final precision.

When printing a part with a hole, the diameter of the hole will most likely be reduced due to the printing process. So, when printing a piece that will fit or slide in other, a

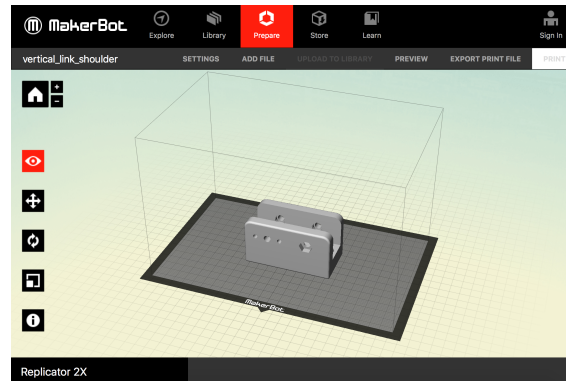


FIGURE 2.6. Makerbot Desktop, general view

tolerance of 0.2 to 0.5 mm should be taken in consideration. All of the tips and constrains mentioned above were considered when designing the following versions of the orthosis.

Additional resources about the settings chosen to print components of the project can be found in the Appendix A.1 and A.8.

3. ANALYSIS AND DESIGN OF THE ORTHOSIS

After the first tests were carried out, it was clear that a more complex solution was needed. Drawing on ideas of the WREX orthosis presented in (JavelinTechnologies, 2013), a model adapted to the patients characteristics is proposed as a starting point.

In this section the passive and active mechanism will be presented. An analysis of the primary structure and passive gravity compensation is first described, followed by the first design presentation. Preliminary drawbacks are identified and modifications are transferred to the following design.

The active orthosis is proposed at the end of this chapter, emphasizing in mechanical modifications carried out, and motor mounting. This section also analyzes the implementation of compliant motion for the orthosis.

3.1. Passive Orthosis

First a passive mechanism similar to the WREX was designed. Given the base structure to be followed in the design process, an analysis of the main components follows. The analysis will derive in relevant parameters that will be implemented in the final design.

3.1.1. Mechanical Structure

The structure has four degrees of freedom. Two for the shoulder and two for the elbow, as depicted in Fig. 3.1. The joints allow full range of movement given that the shoulder is not fixed and that wrist can be rotated.

Joints 1 and 3 move the arm in the horizontal plane, which is not affected by gravity and limb weight. Most of the force needed to raise the arm must be applied at joint 2, and slightly less at joint 4. Raising the arm is one of the main difficulties most dystrophy patients have because the progressive degeneration of muscles starts at the torso and continues towards the hands. The lack of force required to raise the arm must be provided by the mechanism.

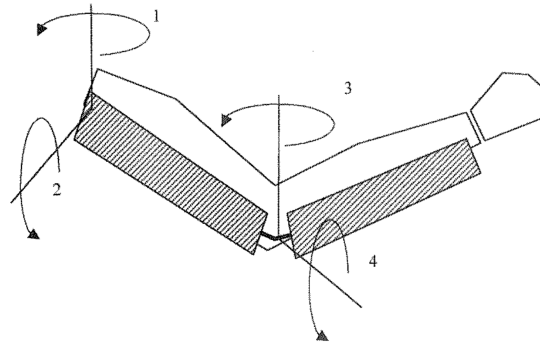
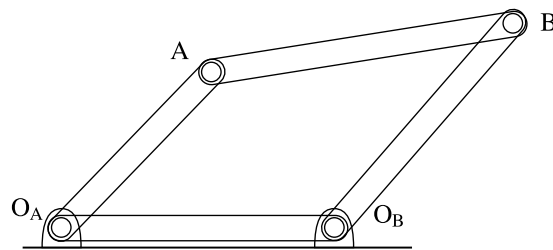


FIGURE 3.1. Joint configuration for orthosis, retrieved from (Rahman et al., 2000).



$O_A O_B$	—	Frame
$O_A A$	—	Rocker
AB	—	Coupler
$O_B B$	—	Follower

FIGURE 3.2. Simple four-link bar mechanism.

For joints 1 and 3, a regular rotational joint is proposed. For joints 2 and 4 a specific structure is described as follows. A four-link system, that creates each link of the orthosis is used. A simple four-link bar system is shown in Fig. 3.2 with each link name listed below. A detailed study of four-link bar systems can be found on (Natesan, 1994).

In the orthosis case, the frame is in vertical position as well as the coupler. Fixing the distance of both links to the same value, and let the rocker and follower have the same length, the system would be called a parallelogram linkage, shown in Fig. 3.3. The structure fixes the angle of each link to be both parallel and fixes in a vertical position the

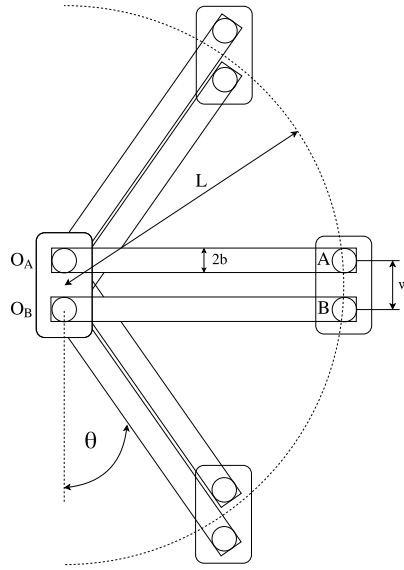


FIGURE 3.3. Four-link parallelogram range of movement.

coupler angle, enabling the user to move the segment without changing the whole structure angle.

An important parameter from the parallel bar design is the limit angle when the follower and rocker touch each other and so limits the movement range of the arm.

$$\theta_{lim} = \arcsin \left(\frac{2b}{w} \right) \quad (3.1)$$

Equation 3.1 shows the limit angle of the structure, where only the link bar width and distance AB determines the angle. In Fig. 3.3 the shown θ represents the limit angle.

Given that the width of the link bar ($2b$) is predefined and equal to 20 mm, Fig. 3.4 shows a plot of the relation between the angle limit and the distance w . Normal movement of the orthosis is expected to be $\theta = 90^\circ \pm 60^\circ = 30^\circ$ to 150° at joints 2 and 4, thus fixing $w = 5$ cm where the limit is $\sim 24^\circ$. The length of the rocker and follower links should match the patient distance between shoulder and elbow joint.

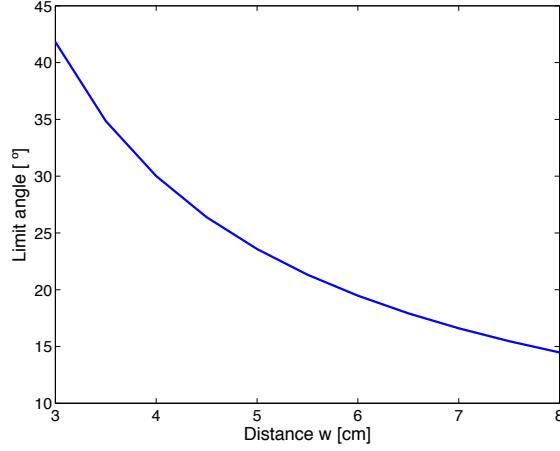


FIGURE 3.4. Change of limit angle with distance w .

3.1.2. Passive Gravity Compensation

To achieve gravity compensation without including an actuator, potential energy in springs is used. The passive compensation system, explained further in (Rahman et al., 2000), uses rubber bands as a way to compensate for the arms weight.

The structure uses the four-link bar system described in the previous section, shown in Fig. 3.5 (A). The blue line represents a rubber band that is positioned in the rotation axis of the vertical segments. The length of the rubber band is $x(\theta)$. In Fig. 3.5 (B), the structure is presented in a different angle, showing how the complete system behaves, adding also forces and torques representations.

A weight m in the second vertical link of the structure, as presented in the figures, represents the arm weight of the patient. The torque with respect to the rotational axis (O_A) of the first link is given by:

$$\tau_g = L m g \sin(\theta) \quad (3.2)$$

$$\tau_e = F_e \sin(\alpha) \quad (3.3)$$

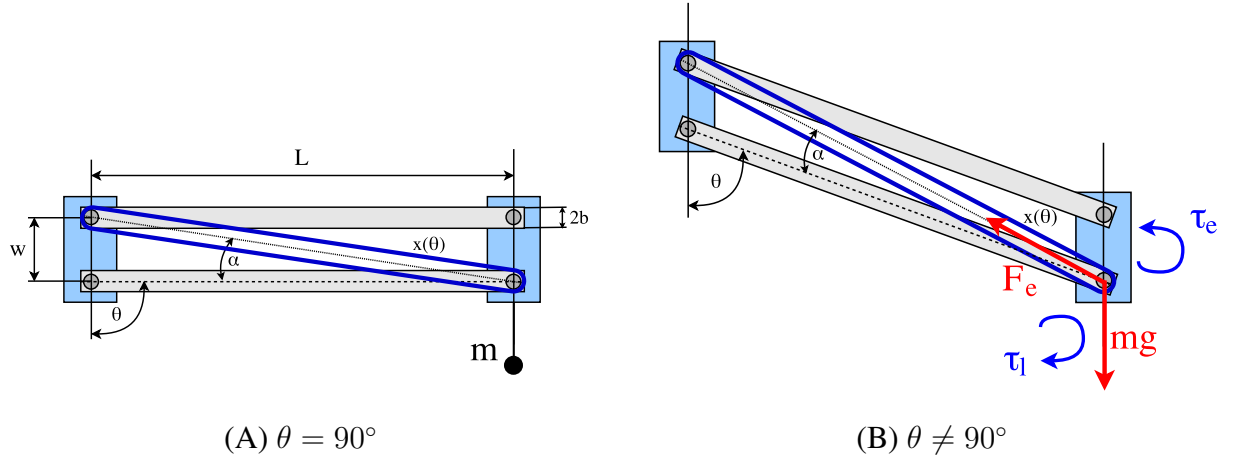


FIGURE 3.5. Four-link bar detailed diagram and forces diagram.

On the other hand, the torque of the rubber band with respect to the same axis is defined by equation 3.3, where α is the angle between the axis of the rubber band and the lever arm of the torque.

Where F_e is the force of the rubber band. Hooke's laws states that $F_e = k_e x$. Considering the geometry of the mechanism is possible to obtain an expression for the length of the rubber band in terms of θ as:

$$x(\theta) = \sqrt{L^2 + 2 L w \cos(\theta) + w^2} \quad (3.4)$$

Fig. 3.6 shows that for the full angle range of the mechanism, as stated before, the difference in x goes between 35 to 25 cm, achieving max stretching when the orthosis is closer to the body, at low values of θ .

Analyzing the geometry of the mechanism, it is also possible to obtain the angle α in terms of θ as:

$$\alpha(\theta) = \arccos \left(\frac{L^2 + x(\theta)^2 - w^2}{2 L x(\theta)} \right). \quad (3.5)$$

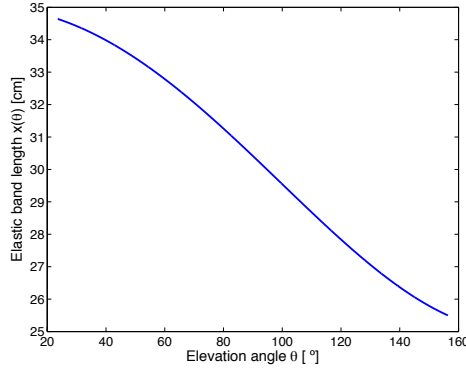


FIGURE 3.6. Rubber band length for variations on elevation angle θ .

If the natural length of the rubber band is x_0 , the torque produced by the rubber band as function of θ will be given by

$$\tau_e(\theta) = L k_e (x(\theta) - x_0) \sin(\alpha(\theta)) \quad (3.6)$$

The shape of the torque curves τ_g and τ_e with respect to the elevation angle θ is similar, as shown in Fig. 3.7. Different sets of rubber bands configurations are used, such as different natural length or number of bands and combinations of both. In Fig. 3.8 a fixed natural length of 5 cm is selected, similar to desktop rubber bands, with an elastic constant of $k_e = 20\text{N/m}$, and different number of rubber bands n_e are used in each curve.

The numerical evaluation for a given set of parameters shows that curve $\tau_e, n_e = 29$ partially matches the arm torque due to gravity τ_g . No integer number of rubber bands matches 100% the torque curve produced by the effect of gravity on the arm. But, considering that most of the movement that will be carried out by patients will not require to raise the arm more than 100° , the solution is feasible to cancel the gravity induced arm torque.

Another method of compensating gravity effects is to use a counterweight. As the rubber bands, both need to be tuned to the patient and the desired weight to carry. Both methods will be tested out, the rubber band as presented before, and the counterweight as a weight aligned with the rotational axes of the shoulder and elbow.

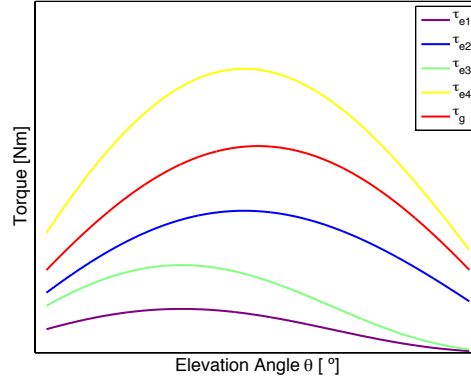


FIGURE 3.7. Torque variations on the shoulder joint against elevation angle of the arm (θ) for different rubber band configurations, number of bands and natural length.

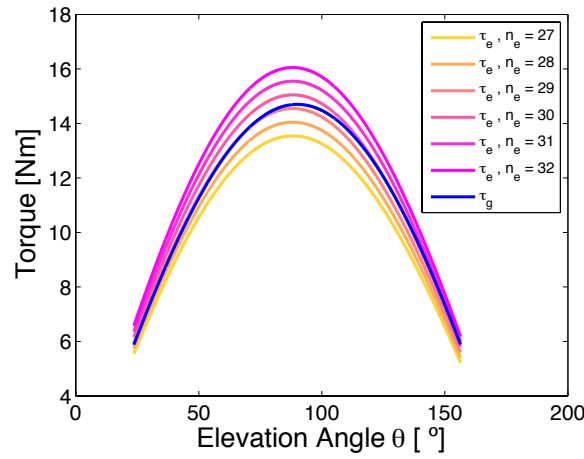


FIGURE 3.8. Torque variations on the shoulder joint against elevation angle of the arm (θ), for different number of rubber bands, given a fixed natural length.

3.1.3. Passive Orthosis Design Presentation

Based in the structure presented before, a full design of the passive mechanism is presented as follows. The four-link system, as in Fig. 3.3, is used as the main link of the orthosis, between shoulder and elbow.

All blue parts in Fig. 3.9 are 3D printed coupling elements. The rocker and follower elements of the four-linkage are squared aluminum tubes, that give more resistance to the structure rather than long printed pieces. Restrictions of size are usual when using a 3D

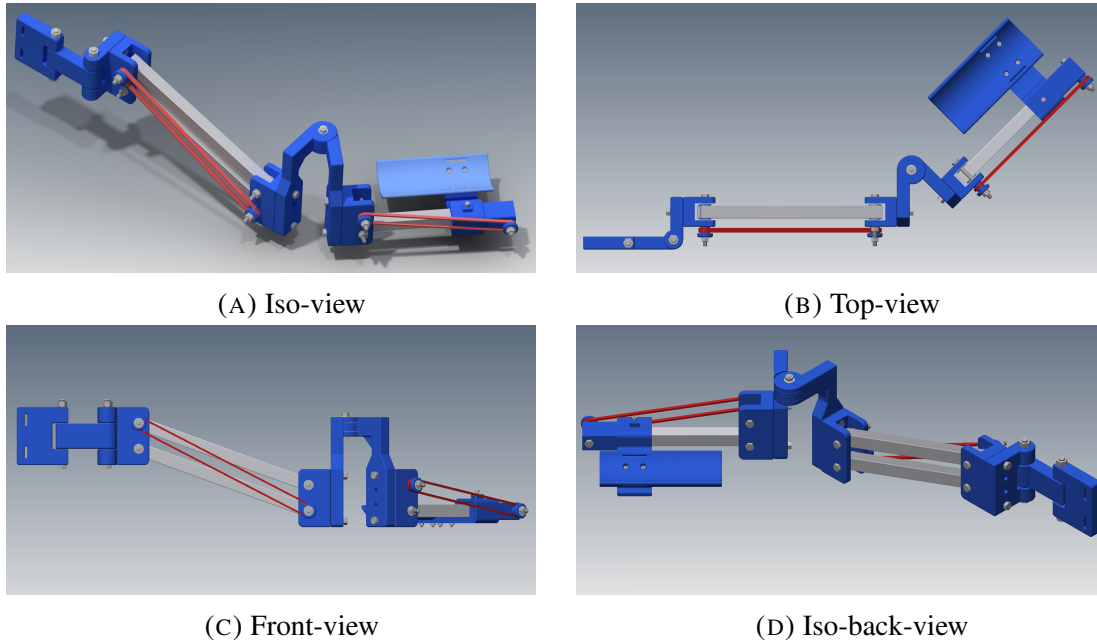


FIGURE 3.9. CAD model of passive design, various views.

printer, so if a piece is bigger than the bed size a couple mechanism would be needed. Using a two-piece-part would decrease the resistance of the longer links, so a one-piece-solution is preferred.

A very small number of parts needs to be purchased to assemble the design together with the 3D printed components. The most basic version does not employ bearings. Only standard commercial bolts and nuts are required. These serve both as fastening elements and as axes at each joint. A detailed list of components can be found in the Appendix A.5 and a summary is shown in Table 3.1.

The rubber bands are positioned as shown in the Fig. 3.9 by the red elements, and enables the mechanism to counteract gravity in the arm and forearm. The rotational joints are unrestricted and can move freely. Since, gravity only affects vertical movements, rotations in the horizontal plane do not need compensation.

The system is attached to the user wheelchair by a set of clamps that fix the orthosis position to the backrest. Customization of the wheelchair connection depend on the

Part Type	Specs	Quantity
3D printed	different for each part	25
Rubber Bands	15 cm diameter	multiple
Aluminum squared tube	20x20mm squared tube	3
Hex Screw Inch	1/4" x diff length	14
Hex Nut Inch	1/4" thread size	14
Hex Screw Inch	3/8" x 3 1/2"	2
Hex Nut Inch	3/8" thread size	2
Washer Inch	1/4" bore size	14
Washer Inch	3/8" bore size	2
Socket Screw Metric	M4 x diff length	4
Hex Nut Metric	M4 thread size	4

TABLE 3.1. Supplies in passive orthosis.

wheelchair model. It is important that the mechanism height is aligned with the patient's shoulder. To adjust the user's arm to the orthosis, an forearm rest is used, and the forearm is fixed to position with Velcro strips.

The average cost of the passive orthosis mechanism is 65.28 USD, where 36 USD is from 3D printing material, and 29.28 USD is from commercial components. A cost of printing could be included considering that a total amount of 60 hours was required to fully print the mechanism. Including printing cost, at an average cost of 3.2 USD per hour of printing, with 192 USD solely in printing, the total value of the mechanism adds to 221.28 USD.

3.1.3.1. Drawbacks

The main drawback of the passive design of the orthosis was identified to be the rigid rotation of most of the axes, due to friction between the metallic shafts and plastic support. Although some friction was expected, the magnitude of it did not allow patients, with little strength in the shoulder joint to elevate or rotate the orthosis about the shoulder axes.

The rubber bands also presented an unexpected drawback. Since a set of rubber bands were stacked in the supports, not all of them were completely perpendicular to the axes of rotation, resulting in new forces with a component perpendicular to the plane of the

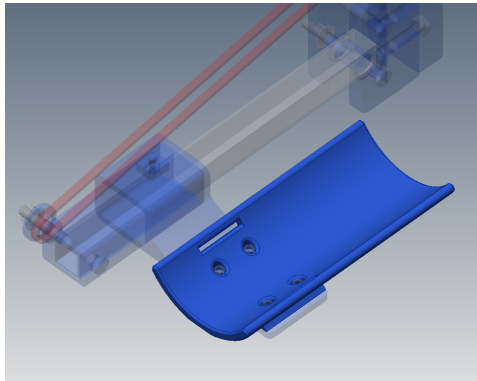


FIGURE 3.10. Forearm holder.

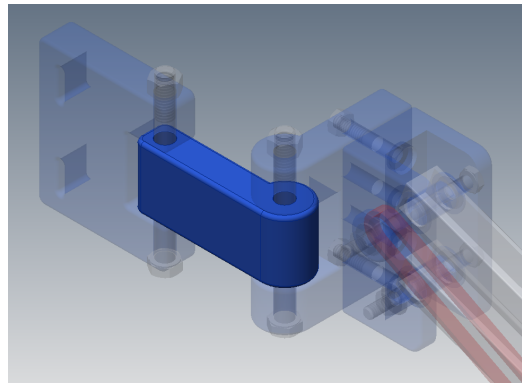


FIGURE 3.11. Second link.

vertical element, thus creating additional friction on the joint. Adding more rubber bands enabled more compensation to be achieved, but made the mechanism stiffer with each new addition.

Other minor modifications were identified, such as design of the armrest being uncomfortable to certain wrist movements; shown in Fig. 3.10. Another problem is the linkage length of the connection between the piece fixing the orthosis to the wheelchair and the frame of the shoulder system; shown in Fig. 3.11. The linkage allows the patient to properly adjust the position of the orthosis to the movement performed. A short linkage restricts some of the desired trajectories. Each drawback will be addressed with a solution in the presentation of the final design.

3.2. Active Orthosis

One of the objectives of the project has been to upgrade the previously presented orthosis and to include active actuation. Results of testing the mechanism, as presented in a following chapter, illustrates the proposed theory that passive compensation would not be enough to enable the patient to move their arm when the dystrophy is in a final stage. Thus, the need of a motor is addressed in the following section.

3.2.1. Selection of the Actuator

There exist different types of actuators that could be chosen for the proposed orthosis. Electric and pneumatic actuators are most commonly used in robotic devices. Electric actuators have more availability as well as different models; and costs associated with, to choose from.

DC motors are widely used in robotic systems. A DC motor is a rotatory electrical machine that converts the electrical energy of a direct current into mechanical energy. A DC motor requires an electronic circuit to control the speed and direction of rotation. The DC motors can be applied from small toys to large robotic arms.

Small servomotors are commonly used as actuators in amateur or do-it-yourself (DIY) robotics. A servomotor is a DC motor with sensor feedback that allows to control its angular position. The input is just a control signal that represents the angle of the output shaft. A servomotor is selected as the shoulder actuator because angular position control is desired.

When selecting a motor for a specific application it is important to select the one that meets the required torque and speed specifications. In general, low-cost servomotors have low-rotational speeds. However, the most important requirement is the loading torque capacity of the servomotor, since in this context it is not required that orthosis moves the arm at a high speed. The rotation speed of standard servomotors is similar to the human arm rotation speed in daily activities. Therefore, the choice of the servomotor must focus on the force requirements.

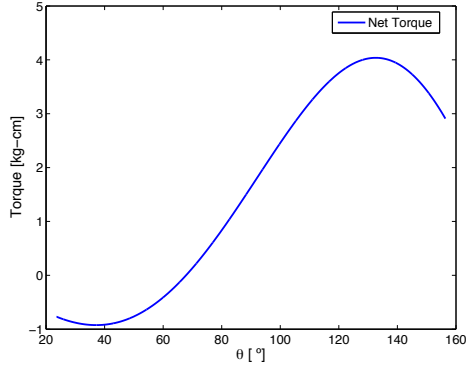


FIGURE 3.12. Net torque load at elevation joint: $\tau_l - \tau_e$.

For torque estimation a notion of load requirement is indispensable. The actual load that the orthosis must lift is the arm weight plus some small objects. To define the load, the therapist working with patients defined that arm weight of a child around 5% of body mass. A 60 kg kid would have an arm weight of around 3 kg. Equivalent static torque, assuming a 60 cm arm length with load represented in the middle of it, would be approximately 8.8 Nm.

For servomotors the torque requirement for the arm load is established as high torque, as 8.8 Nm is equivalent to almost 90 kg-cm. Most of-the-shelf servomotors are around 15 kg-cm. Servomotors with high torque capabilities are over 400 USD or need really high gear ratios to achieve it.

But, the passive mechanism can be used to reduce load demand of the servomotor. A small analysis of the effectiveness of the elastic power to compensate arm weight follows. The best case presented in Fig. 3.8 was achieved using 29 rubber bands. A closer look at the difference of torque between arm weight torque and elastic torque is shown in Fig. 3.12.

From Fig. 3.12, it can be seen that in the worst case, the rubber bands would need 4 kg-cm to compensate gravity when the arm is lifted above the horizontal plane.

Finally, from commercially available servomotors the Pololu Servo; Power HD Ultra-High-Torque, High-Voltage Digital Giant Servo HD-1235MG, was selected. Selected servomotor has a stall torque of 40 kg-cm at 7.4 V and speed of 0.18 sec/60°. For around 60 USD, Pololu's servomotor has a high capability with a rather compact case.

The torque of the selected servomotor enables the system to work with different configurations of rubber bands or counterweight; as well as using a low gear reduction, 1:2, to increase the torque applied without compromising the range of movement but enabling full arm weight compensation. Details of the selected servomotor can be found in the Appendix A.6.

3.2.2. A Study of a Compliant Solution

The traditional premise for good robot design has been “Stiffer is better” for years (Williamson, 1995). A stiffer type of control enables a precise position control, increasing the stability and end-point position error under load disturbances.

Interaction of robots with humans and with non-controlled environments are the next step that designers and engineerings are working to overcome. To properly interact in non-controlled scenarios the robots are being designed towards a more natural behavior, where compliance is as important as position control.

Contact with hard, unexpected, surfaces is a major problem when a robot is instructed to conduct a certain trajectory. In a regular stiff system, upon an obstacle, only two possible situations exist: The system is stronger than the obstacle, breaking through it in order to reach its objective position; or the system force is not enough and the electronics commands the motors to increase their torques, to the point where irreversible damage can be made to them.

In order to improve performance in the new robotic challenges, compliance has been added in most robotics systems, even if it is as simple as adding compliant or elastic covering to the end-point of the actuator.

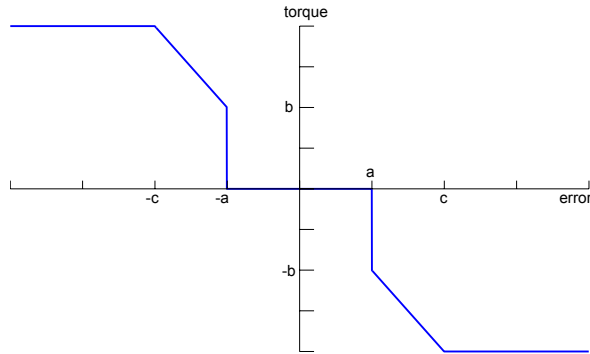


FIGURE 3.13. Compliant behavior of an actuator.

Compliant behavior enables the system to react when an unexpected obstacle is encountered, or to allow some degree of slack under external force. The second action has been used to create reference trajectories from user-defined positions, that are followed by the end-point in such a way the robot has some freedom to yield upon applied external forces by turning off motor torques for errors below some threshold.

In Fig. 3.13, the curve represents the torque of an actuator that has a compliant response. When the error; in position, angle or other measured variable, is greater than a certain threshold; in the plot $[-a, a]$, the torque response of the actuator increases or decreases to counteract the effect of the external variable, with a certain minimal value given by $-b$ and b .

The torque of any actuator has a limit; in the plot of Fig. 3.13, when the error is greater than $[-c, c]$, the torque saturates, which could be represented by the actuator being stiff to error increments. The compliant actuator is not stiff to an error increment, neither is completely flexible as to let the error increase indefinitely, the behavior can be suited to the application.

There are typically two types of compliant solutions implement in robotic systems, a mechanical and an electrical approach. In the mechanical solution, a compliant spring-damper element is between the actuator and the body of the device. In the electrical solution, current control is used to measure force control in the motor axis, enabling the system to know when an obstacle is obstructing the desired trajectory, modifying the control loop.

A mechanical type of compliant system is the **Series Elastic Actuator** (SEA) as presented by (Williamson, 1995). In the cited work, elasticity is added to a classic robotic system to achieve a more accurate and stable force control solution, enabling the system to act more naturally. The human body has a low stiffness and low bandwidth, but can easily interact with hard surfaces and react over an external force.

Most electric motors used in robotics have some gear, or several, in order to generate large forces at low speed. But gears add backlash, friction, noise and torque ripple to the system, making it harder to achieve proper force control.

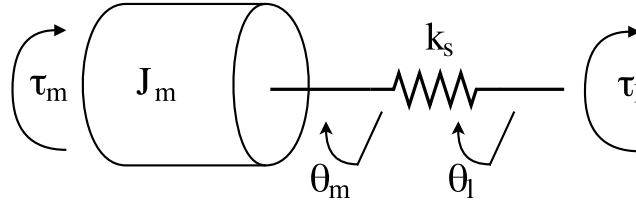
To counter the effects of the gears, and in essence separate the load from the motor, an elastic element is added between the load and motor gear, as seen in Fig. 3.14. One direct effect of the SEA configuration is that the series elasticity is a low-pass filter to shock loads, thereby reducing peak gear forces. In the presented model the elasticity is a torsional spring.

As depicted in the Fig. 3.14, the angle of the motor θ_m and load θ_l are measured before and after the elasticity k_s . The output force is proportional to the position difference across the series elasticity, multiplied by its spring constant; transforming the force control problem into a position control one, which greatly improves force accuracy.

By applying Newton's Laws

$$\tau_m + k_s(\theta_l - \theta_m) = J_m \ddot{\theta}_m \quad (3.7)$$

$$-k_s(\theta_l - \theta_m) = \tau_l \quad (3.8)$$



$$\begin{aligned}
 \tau_m &= \text{motor torque} \\
 J_m &= \text{motor inertia} \\
 k_s &= \text{spring elastic constant} \\
 \theta_m &= \text{motor movement angle} \\
 \theta_l &= \text{load movement angle} \\
 \tau_l &= \text{load torque}
 \end{aligned}$$

FIGURE 3.14. SEA Model representation.

Taking Laplace transform, an expression relating both torques can be found:

$$\tau_m(s) = \left(1 + \frac{J_m}{k_s}s^2\right)\tau_l(s) + J_ms^2\theta_l(s) \quad (3.9)$$

If the output of the actuator is assumed clamped ($\ddot{\theta}_l = 0$), then the transfer function between the output torque τ_l , and motor torque τ_m is

$$\frac{\tau_l}{\tau_m}(s) = \frac{1}{1 + s^2 J_m/k_s} \quad (3.10)$$

And for the impedance of the system

$$Z(s) = \frac{\tau_l}{\theta_l}(s) = \frac{-s^2 J_m}{1 + s^2 J_m/k_s} \quad (3.11)$$

The equations 3.10 and 3.11 define the model of the plant of the SEA model. The objective of the SEA model is to precisely control the force on the load, including the series elasticity to enable the system more human-like movements.

DC motors are preferred to use in the case of SEA actuators, but in this thesis a servomotor is proposed to be used. In order to apply the Series Elasticity to the prototype, modifications to the original system are needed.

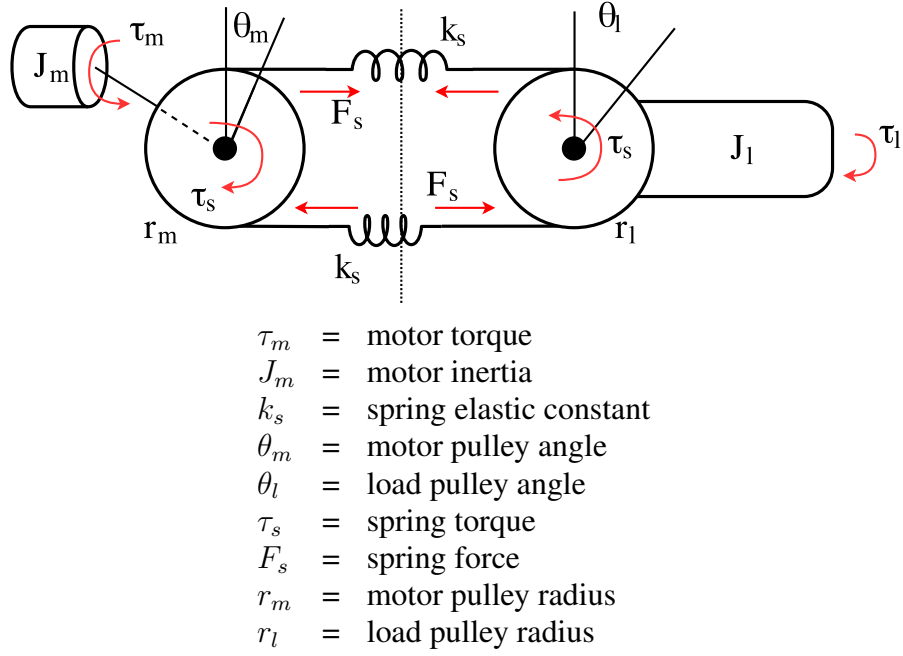


FIGURE 3.15. SEA modification to a pulley system.

The proposed solution employs pulleys with linear springs. The pulley makes the system behave as the original model, transforming linear elasticity into torsional torque. A representation of the modified system can be seen in Fig. 3.15.

The equations of the pulley SEA system can be directly derived from the Fig. 3.15 and are similar to Eqs 3.7 and 3.8.

$$\tau_m + 2k_s(\theta_l r_l - \theta_m r_m)r_m = J_m \ddot{\theta}_m \quad (3.12)$$

$$\tau_l + 2k_s(\theta_l r_l - \theta_m r_m)r_l = J_l \ddot{\theta}_l \quad (3.13)$$

Additional terms can be seen in the equations. For instance, the radius of the pulleys (r_m , r_l) is important as it defines the torque applied by the spring force. The load inertia J_l is also added to represent the actual load of the system. The servomotor enables us to

directly modify the angle of it, thus θ_m is the manipulated variable in the system, rather than τ_m .

Unlike some of the existing work in the literature that deals with torque control in SEAs for manipulators, which assume that the load is clamped, here it is necessary to assume that the gravitational load which produces a torque offset is zero and that the only torque on the load side is due to the inertial load. This condition with null gravitational torque is equivalent to a fully balanced system with zero external net torque acting on it and is necessary in order to correctly simulate the system. Otherwise, the continuous offset makes not possible to stabilize the torque error because the load continuously stretches the springs.

The objective in the actuated exoskeleton is to provide the user with a way to control the position, or trajectory, of the shoulder elevation θ_l , through the command of the servomotor. The angle of the pulley in both ends the spring needs to be measured to control the orthosis movement; since the servomotor is directly controlled through angle target, θ_m is set by the system and only a reading of θ_l is added.

To simulate the system, a state space model will be used. The following variables are defined:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \theta_l \\ \dot{\theta}_l \end{bmatrix} \quad \mathbf{u} = \begin{bmatrix} u \end{bmatrix} = \begin{bmatrix} \theta_m \end{bmatrix} \quad \mathbf{y} = \begin{bmatrix} \theta_l \end{bmatrix}$$

Following the state space model the system can be defined: assuming there is no external torque applied to the load ($\tau_l = 0$), it can be isolated from Eq. 3.13

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\theta}_l \\ \ddot{\theta}_l \end{bmatrix} = \mathbf{f}(\mathbf{x}, \mathbf{u}) = \begin{bmatrix} x_2 \\ \frac{1}{J_l} 2kr_l(r_l x_1 - r_m u) \end{bmatrix} \quad (3.14)$$

There is no need to analyze Eq. 3.12, because it is assumed the servomotor will go to the desired θ_m when indicated, regardless of external factors. Using a classic control

scheme of a PID controller for the manipulated variable and as reference θ_l , the system can be simulated. For the full code see Appendix A.3.

Using the in-built PID Tuner in MATLAB, the system PID is chosen. The function returns the parameters K_p , K_i and K_d of the PID that, for a given bandwidth, achieve balance between reference tracking and disturbance rejection. The response of the system can be easily modified using the functions `pidTune`, to create the system, and `pidTuner`, to graphically see the response of the system to a step input. The constants used in the following simulations are selected using this methodology and are:

$$K_p = 12 \quad K_i = 0.9 \quad K_d = 5$$

To simulate the system according to a real life situation, sinusoidal references are to be used. A sinusoid represents the user moving up and down his arm. The zero angle will represent the arm being parallel to the ground, in a horizontal position.

The first simulation of the systems shows that the servomotor can follow the reference with a small error bandwidth. As seen in Fig. 3.16, the system has a little overshoot in the servomotor angle, to start moving the load downwards, since there is no effect of gravity, as it is compensated by the external force, the motor needs to make additional effort to overcome the load inertia.

Even so, the system does not have detectable cumulative error, and the range is below 1 degree, which at a distance of 80 cm, where the hand is, is less than 1 cm. As expected, the difference in angle of load and motor increases at the beginning, showing the delay that the springs provoke in the system. Nonetheless, the system is able to follow the reference.

For a second simulation, the user trajectory will be obstructed by an obstacle. As is the previous simulation, the user has pre-instructed the servomotor with a sinusoidal reference, similar to the one used before, but with a bigger amplitude. In the trajectory, an obstacle will be present during a set period of time, but the reference will keep the

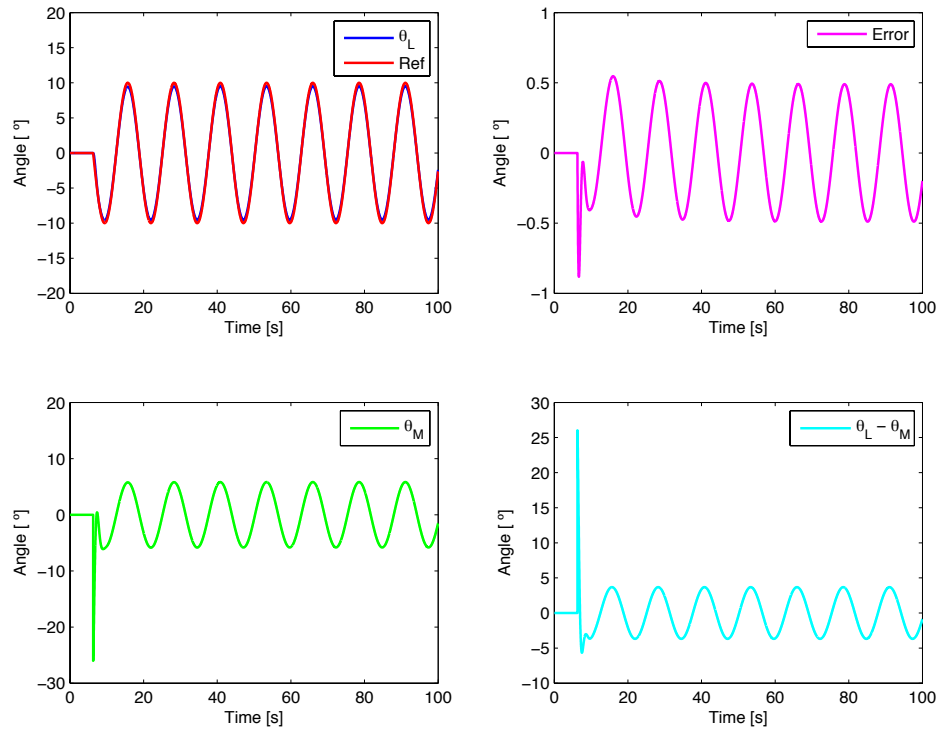


FIGURE 3.16. Simulation of the SEA pulley system, with sinusoidal reference.

sinusoidal movement, simulating that the user does not react to the obstacle by himself . The obstacle can be a table or any other kind of restriction.

If there is an obstruction in the trajectory on a regular pulley system, the error will increase and thus instructing the motor to move to minimize the difference between the load angle and reference. Doing so, the system will enter an oscillation state and lose control over the movement, which could cause damage to the user.

But, in the proposed SEA pulley system, the springs acts as a damper, allowing the program to understand there is actually an obstacle in the trajectory, rather than a real error increase. Physical restrictions are added to the mathematical model. The strings have a maximum stretching and compression, which implies in a maximum difference that can be allowed between the load and motor angle.

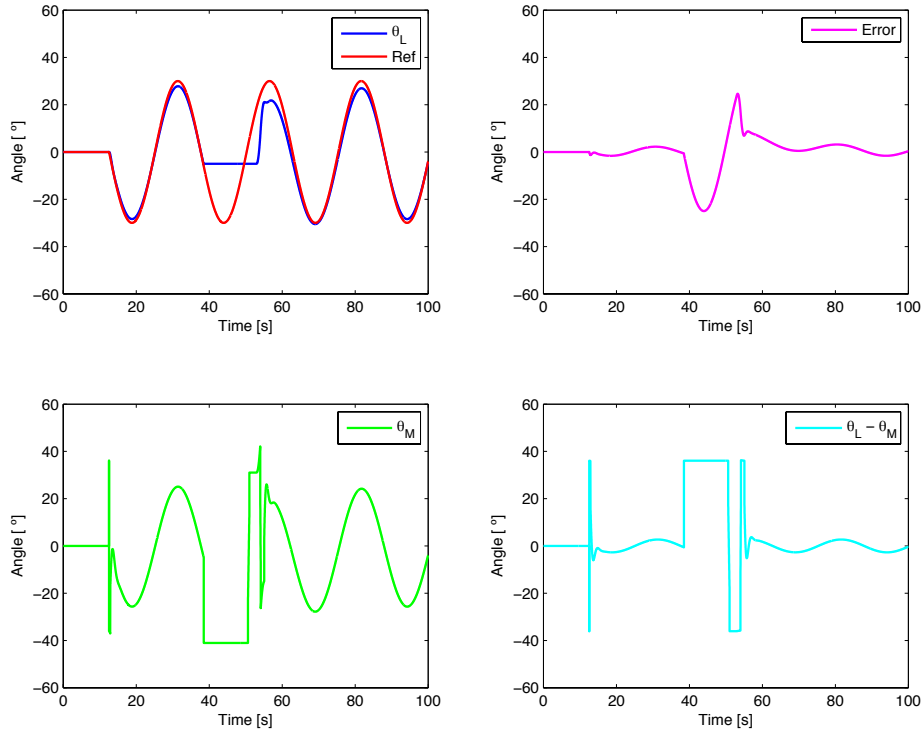


FIGURE 3.17. Simulation of the SEA pulley system with an obstacle, with sinusoidal reference.

$$\Delta\theta_{max} = \frac{\max[\Delta x_{spring}]}{r_{pulley}}$$

In the study case, the maximum $\Delta\theta_{max}$ is around 36° . In order to represent an obstacle during the simulation, after the state transition, the calculated state of the system is fixed to a certain position and zero speed, instead of letting the space model calculate them. In Fig. 3.17, is shown that the red reference continues to move, while the blue line, θ_L , is fixed in -5° for a given time. Position and speed of the system is then released to be calculated by the state space model to continue the loop.

Initial movement of the motor is more aggressive than before, having a positive and negative peak to follow the reference, but with no overshoot in θ_L . It is to be noted that the amplitude of the sinusoid in Fig. 3.17 is bigger than in Fig. 3.16, but the system can keep up with the reference.

When the obstacle appears, the error increases negatively, which makes the servomotor reach the maximum difference between load and motor due to the springs. Instead of overshooting and oscillating, the servomotor saturates its position, as long as the difference is bigger than half $\Delta\theta_{max}$. Since the springs act compressing and stretching, both take action at the same time, thus the restriction is selected as half $\Delta\theta_{max}$, enabling both springs to take part of the system equally.

Doing so, as can be seen in the cyan line (θ_{LM}), the angle is saturated and it prevents the system to oscillate, even when the error moves, increasing or decreasing. When the state is released to its natural behavior, θ_m oscillates but the state has no reflection of it and the movement in the user perspective is soft. Different simulations performed showed similar results, with more or less overshoot depending on when the state is released, but with the same kind of accomplishment.

The proposed pulley SEA systems seems to be a feasible solution for adding compliance to the system. But, several assumptions are used in the simulations that in the real case are difficult or impossible to achieve.

It is assumed that the load is actually gravity balanced. But, to get a perfectly balanced system, there are a lot of variables that had been left aside, such as friction, gear backlash, torque ripple, etc. Load variation would also affect the system, which can be represented by the user picking up objects of different weights or drinking from a cup, thus changing the load.

With a minimal deviation of compensated load, the term eliminated, τ_l , enters the equation; the system can't be initially balanced and naturally falls, due to gravity, and the motor can not actuate over the load. The springs chosen can't stand the load by themselves, as a small constant k_s is needed for them to be sensitive to small obstacles, represented in trajectory error.

To counter the effect of gravity, the springs would need to be able to create a higher torque and force, increasing the length of how much the springs can stretch and compress could increase their effect and pull up the load countering the gravity. It would also require

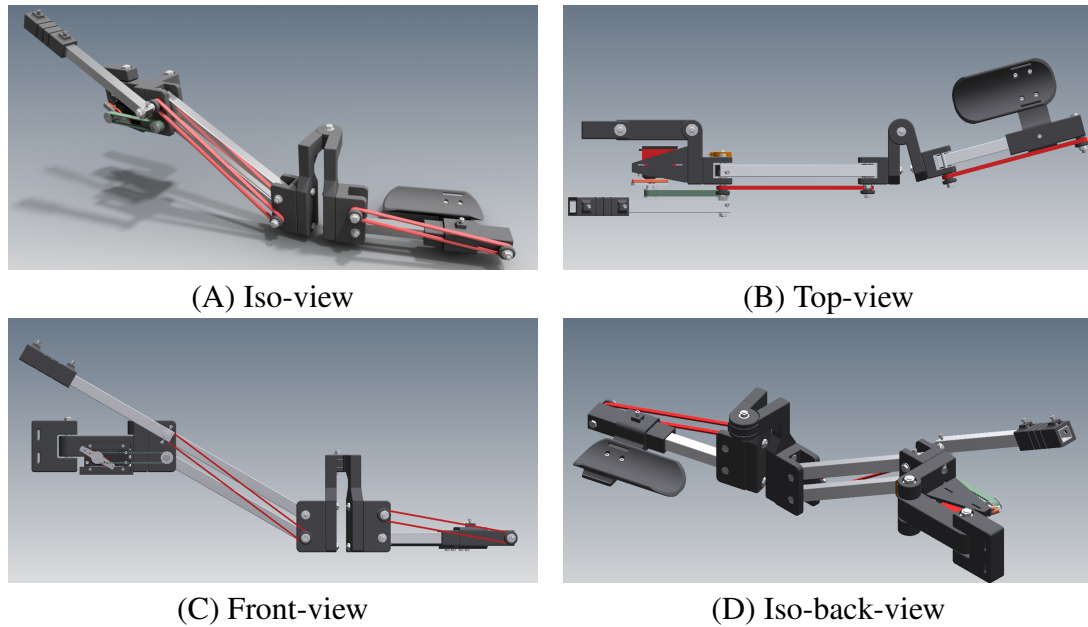


FIGURE 3.18. CAD model of active design, various views.

software modifications for the error to differentiate when there is an obstacle present and when the non-balanced system is affect it.

But, enabling the springs to induce a higher torque provokes a substantial change in the design. The pulleys must be separated over the length of the initial mechanism, making the orthosis over-cramped to the purpose of this thesis. The system is a good solution and easy to construct in terms of compliance, but it is not ideal for the objectives of this project.

3.2.3. Active Orthosis Design Presentation

The second and final version of the orthosis is presented in this section. The system is very similar, to the first passive orthosis design, but several changes were made and are to be pointed out. Basic materials remain the same, here 3D printed parts are presented in black and the aluminum squared tubes are used as well.

As seen in Fig. 3.18 the four-link system is used in the arm segment and a simplified version of it is used in the forearm segment, as presented in the previous , passive orthosis,

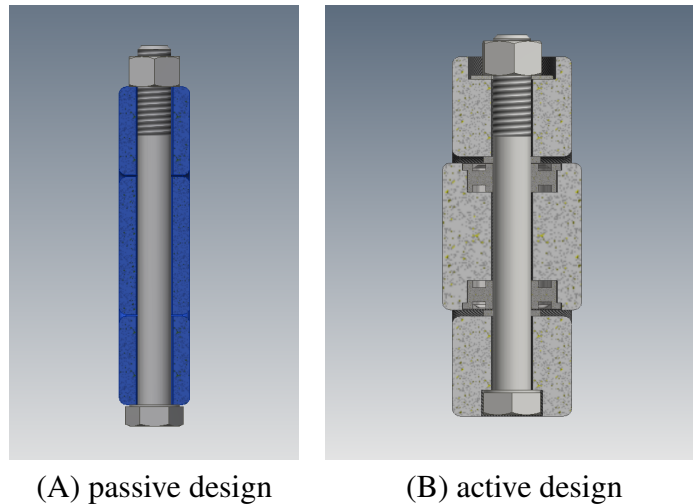


FIGURE 3.19. Shoulder vertical shaft comparison, section view

design. The active orthosis design includes the addition of a counterweight link attached to the superior axis of the vertical elevation of the shoulder.

To address the presented drawbacks of the passive orthosis design, as mentioned in section 3.1.3.1, important changes were made. A main problem identified was the stiffness presented in the rotation of most axes. To improve the smoothness of the rotation, bearings were used in every plastic piece that included a rotating axis.

In the passive orthosis design, as seen in Fig. 3.19 (A), the axis rotates being supported directly by the plastic piece. In the new design, two bearings are added for each shaft, as can be seen in Fig. 3.19 (B). In both figures, the vertical rotation axis presented is the main vertical shaft for the shoulder, allowing movement in the horizontal plane.

Adding the bearings in any of the rotation axes significantly made the movement of those axes smoother, even with load. A bearing spacer was also added to minimize friction between the bearing and the plastic piece.

A total of three horizontal rotation axes are present in the orthosis, two for the shoulder and one in the elbow. The changes to the axes are shown in figures 3.20 (A) and 3.20 (B), in which the active design includes bearings and spacers in the vertical shaft.

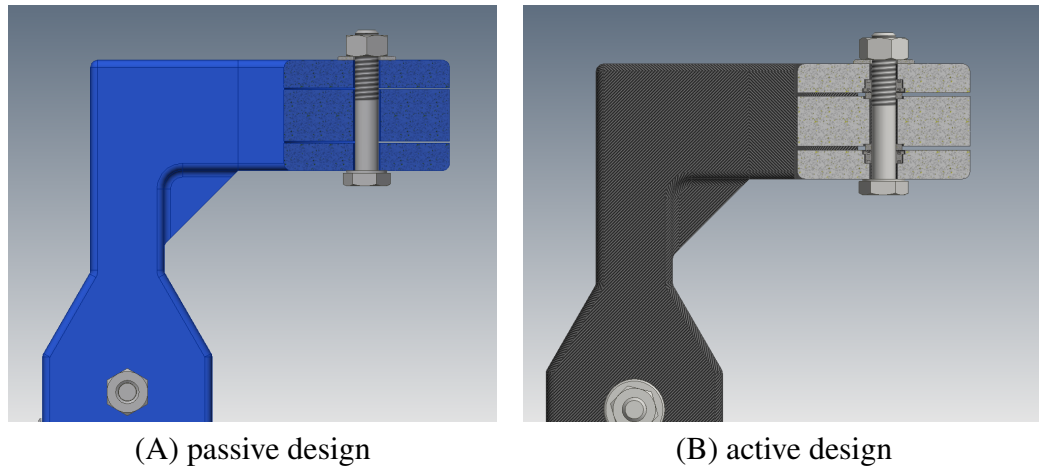


FIGURE 3.20. Elbow vertical shaft in passive and active design, section view.

For the vertical rotation axes, with a total of 6 horizontal shafts in the design, bearings and spacer are also added, but the design for the vertical axes is different because all the pieces includes a squared aluminum tube as a linkage instead of another plastic piece. In the first passive design the three pairs of axes used the same pieces, as presented in Fig. 3.21 (A).

The active orthosis includes a bushing, a two piece sleeve plain flanged bearing, that was inserted in the aluminum squared tube, so that the metallic shaft did not have direct contact with the tube. The solution is employed in both pairs of elbow shafts, second arm shaft and forearm. The modified version, with bearings and spacers, is shown in Fig. 3.21 (B).

A drawback found in the previous design was that the rubber bands interfered in an unexpected way, adding friction to the elevation axes. The forces created by the rubber bands rotated the tube within the plastic parts, which made them touch against each other, thus increasing friction.

A smaller deviation of the position of the aluminum tube was ensured in the active design thanks to printing variations and the addition of new parts, such as bearings and

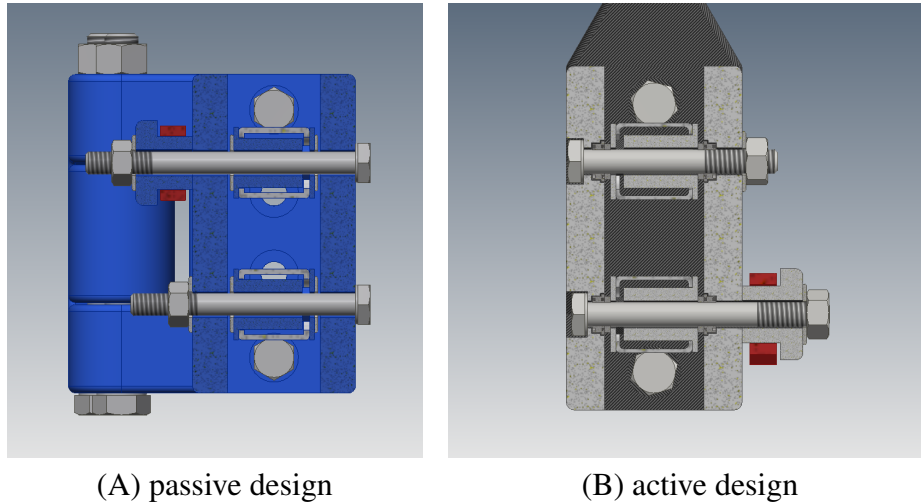


FIGURE 3.21. Second arm horizontal shaft in passive and active design, section view.

spacers. The tube was tightly fixed within the plastic part, thus preventing it from turning within the plastic part. This in turn contributed to keeping the rubber band forces perpendicular to the motion axis and prevent the additional friction forces.

Other modifications made to the design consisted in fixing the axis of each linkage to the tubular bars in order to transmit the motion of the servomotor and the counterweight action to the main links. Fixing the tube directly was not possible because the thin aluminum tube is too weak for a bolt to work as set screw. Therefore, a printed part was designed to fit inside the square tube to add thickness to the part, while at the same time have a thread for the bolt. The thread cannot be printed because the resolution of the 3D printer is insufficient and the material is not resistant enough. However, it is possible to add a thread to a printed part using a nut fixed to the part. The space for the nut was designed to hold the nut tightly. The tube was fixed to the axis using cap head bolts.

The servomotor transmits its movement to the shoulder joint through a dented belt between the two pulleys. The pulley at the shoulder joint is fixed to its axis using the printed part attached to the aluminum profile. For the counterweight to work correctly it is necessary that its orientation is always parallel to the arm's elevation angle. The axis that

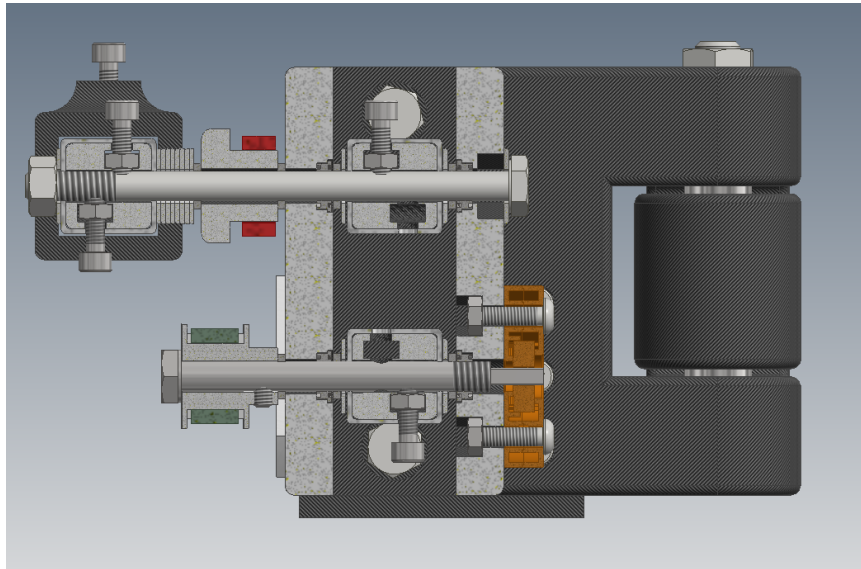


FIGURE 3.22. First arm horizontal shafts in active design, section view.

the counterweight and the four-link system share is fixed to each part using the printed parts and cap bolts, thus ensuring they move together.

The shoulder joint is shown in Fig. 3.22. The designed piece that fixes the tube to the shaft is present in three of the tubes ends, two for the counterweight and one for the servomotor. The joint is completed with the addition of bearings and spacers in each shaft.

The last main modification made to the active design is the inclusion of the servomotor and pulley system. The pulley uses a set screw to fix its rotation to the axis, and the same was needed to fix the rotation of the servomotor to the pulley. Both pulleys were connected through a timing belt. The system details are shown figures 3.23 and 3.24.

The servomotor fixing system is composed of seven pieces. The servomotor and its metallic horn, the aluminum manufactured shaft, the pulley and belt, and two printed pieces. In figures 3.23 and 3.24 the red outlined part is used to fix the system to the orthosis link, and the blue outlined part is used to fix the servomotor to the previous piece. Slots are used to adjust the fixture and fix the distance between the pulleys. When installing the system, the belt is positioned when both pulleys are closer to each other, and once

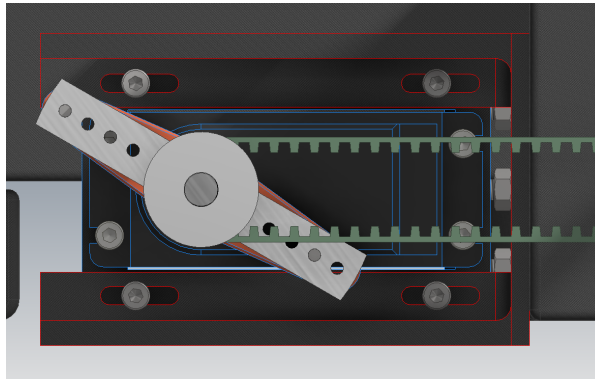


FIGURE 3.23. Servomotor attachment to orthosis, front view.

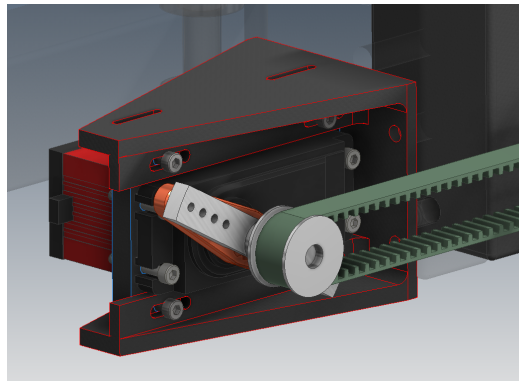


FIGURE 3.24. Servomotor attachment to orthosis, isometric view.

installed, the belt is stretched using the slots to pull apart both pulleys and fixing the final position of the servomotor.

Finally, small details mentioned in the drawbacks of the passive design are addressed. The design of the forearm rest is modified in order to make it more comfortable, as seen in Fig. 3.25. The length of the linkage, shown in Fig. 3.26, connecting the wheelchair fixture and main frame of the shoulder joint is increased, allowing a more natural movement of the system.

Details of every component of the design can be found in the Appendix A.4. The system is attached to the user's wheelchair with clamps as seen in Fig. 3.27 and customization

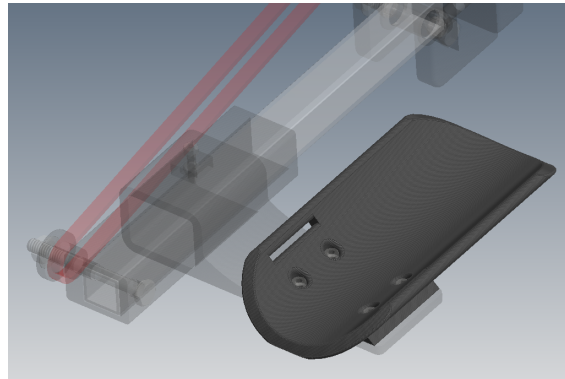


FIGURE 3.25. Forearm holder modified.

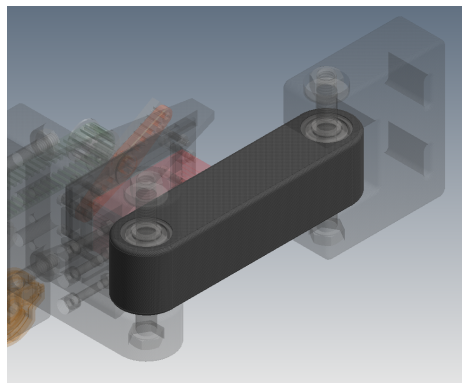


FIGURE 3.26. Second link modified.

of the fixing linkage part may be needed. Additional modifications may be needed according to the patients age, adjusting the length of the aluminum tubes to suit the user's arm size.

In order to control the servomotor an Arduino board is selected, specifically the Arduino Uno. To control the servomotor, three wires are provided, two for power supply and one for position control. Servomotor must be powered from a source different from the Arduino itself for voltage and current requirements. Control position is achieved through a PWM, which commands the servomotor to a move to a fixed angular position, between 0 and 180. The control loop is done within the servomotor; since the only requirement established is to achieve a certain position, the internal PID of the servomotor is determined to be enough.

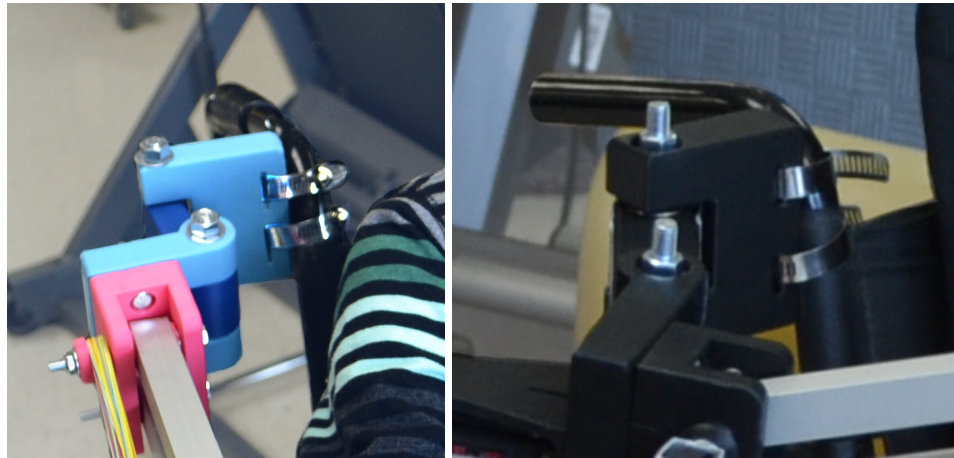


FIGURE 3.27. Wheelchair attachment of the Orthosis.

The user must input a command to the Arduino controlled servomotor of either the position desired, or the step direction. The communication with the Arduino board is achieved through a Bluetooth connection, using an Arduino HC-06 Serial Bluetooth Module. The module is connected to an App on an Android Smartphone, any App can be used, the one presented here is “Arduino Bluetooth controller” by Giumig Apps.

The Bluetooth App connects to the HC-06 and then enables the user to select the desired mode: Command Line Input, ON/OFF Switch and Joypad mode. The module sends the Arduino a serial character in any mode, the Arduino code reads the Serial bus and execute a predetermined instruction. To carry out the tests, the Joypad mode is selected, and different instructions are added to each button. A screenshot of the Smartphone App is shown in Fig. 3.28.

Up and Down buttons are programmed to command the servomotor to increase or decrease its position in one step. Step size is fixed through Square, Triangle and X buttons, to 5° , 10° and 15° respectively. Start button is fixed to take the servomotor to a horizontal position, i.e. 90° and Circle to a fixed angle. Customization of the instructions are made by changing the character sent by the App and the instruction in the Arduino code itself. Code implemented can be found in the Appendix A.7.

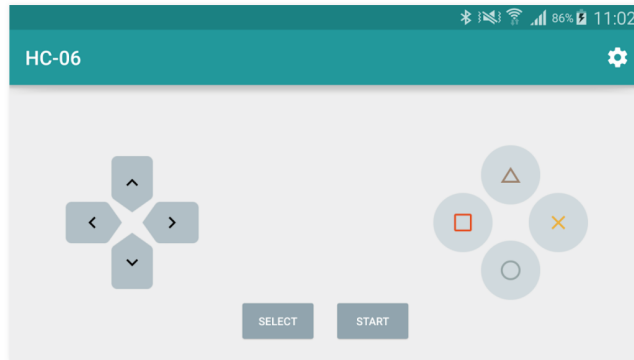


FIGURE 3.28. Arduino Blue-tooth App screenshot in Joypad mode.

The Table 3.2 shows a summary of the parts needed to build the active orthosis, additional to the stated items the user needs a 7.5 VDC power supply and a Smartphone.

Approximately 1 kg of ABS plastic is used to print the total amount of pieces, including the use of both Raft and Support when needed. To fully print the active orthosis mechanism a total of 85 hours are used, considering that a high resolution and at least a 40% of infill is chosen, slowing down the printing process. The cost of the 3D printed parts can be considered including the printing cost per hour, at 3.2 USD, which adds a total of 272 USD. Detailed cost of the parts used can be found in the Appendix A.5, and the total cost, including printing material is around 422 USD. Including the printing cost, total cost of the mechanism is of 694 USD.

Part Type	Specs	Quantity
3D printed	different for each part	27
Rubber Bands	15 cm diameter	multiple
Aluminum Squared Tube	20x20mm squared tube	4
Hex Screw Inch	1/4" x diff length	14
Hex Nut Inch	1/4" thread size	13
Hex Screw Inch	3/8" x 3 1/2"	2
Hex Nut Inch	3/8" thread size	2
Washer Inch	1/4" bore size	26
Washer Inch	3/8" bore size	2
Socket Screw Metric	M4 x diff length	14
Socket Screw Metric	M3 x diff length	8
Button Screw Metric	M4 x 16 mm	2
Button Screw Metric	M3 x 8 mm	2
Hex Nut Metric	M4 thread size	16
Hex Nut Metric	M3 thread size	8
Bearing	1/4" bore size	12
Bearing	3/8" bore size	4
Spacer	1/4" bore size	15
Spacer	3/8" bore size	4
Power Servo	Pololu High Torque	1
Metal Horn	Aluminum	1
Potentiometer	Vex Robotics	1
Dented Pulley	1/4" bore size	2
Dented Belt	teeth matching pulley	1
Servo Pulley Axis	Aluminum CNC	1
Arduino Board	Arduino Uno	1
Bluetooth Module	HC-06	1

TABLE 3.2. Supplies in active orthosis.

4. IMPLEMENTATION AND TESTING METHODOLOGY

This chapter explains the implementation of the proposed designs and the methodology employed to test the performance of the orthoses and to verify the hypothesis.

Volunteer patients of the pediatric neuromuscular disease care group of the *Centro Médico UC* were invited to participate in the testing of the orthosis as part of the Interdisciplinary VRI UC project. The set of patients were also part of a study carried out by *CEDETI UC*, that is reviewing the progress of the disease, with therapists, kinesiologists and a medical doctor from the *Centro Médico UC*.

To quantify the results of the study, *CEDETI UC* has developed a Functional Evaluation Test. The test consists in a series of tasks that measure the patients upper body motor condition. The document that *CEDETI UC* developed has a detailed guide on how to prepare the materials for the test, how to evaluate each task, the score given the performance of the patient, and a detailed description of the tasks to be carried out. The functional evaluation test was chosen to assess how the proposed orthosis is able to help patients to complete daily life activities using the passive and active mechanisms.

4.1. Functional Evaluation Test

The test has been developed to quantify the degree of development of a neuromuscular disorder in a patient. It is especially useful for assessing the functionality of children or adults at developmental stages of the disease which requires them to use a wheelchair because of becoming unable to walk.

The test includes a set of tasks for a valid upper limb function evaluation. Which assigns a numerical score that is easy to compare between different subjects or between tests done on the same patient. The score gives the therapist not only information of the development of the disorder, but also of the effectiveness of the physical treatment given to improve muscular conditions.

The test comprehends a total of 21 tests or actions that the subject must try to complete. The activities are separated in four groups.

- Proximal Shoulder Mobility Criteria: The patient must move one arm at a time, from rest position (on a table) to a raised arm with the elbow at eyes' height. Tasks differ between flexion and abduction movement of the shoulder joint.
- Elbow Mobility Criteria: Movements that require elbow movement for different kinds of tests. They may or not require shoulder movement. The activities may require a weight to move over the table and with arm extension.
- Hand and Wrist Mobility Criteria: The activities measure mostly the ability to grasp objects and move them over a table, with more accurate trajectories.
- Instrumental Functionality: Movements that are usually done in the daily living are studied in this section. Self-feeding being one of the most important for therapists. The activities tested usually use all joints together.

The achievement of each activity is measured in a scale from 0 to 5. Each test has a specific definition for each score, but in general, the achievement criteria is whether or not the patient compensates the movement with the rest of the body or whether both hands are used to finish the task, when normally one hand should be enough. Also, different weights are used to measure the weakness or strength of the muscles. Tools used in the test can be seen in Fig. 4.1.

CEDETI carries out the complete test to the patients they are working with at the *Centro Médico UC*. The patients are evaluated each time they visit, together with the standard evaluation, which includes physical exams and a lung function test.

To evaluate the performance of the orthosis, a subset of tests of the Functional Evaluation Test is employed. The complete document and the application test can be found in Appendix A.9. The tests selected were those in which the exoskeleton may aid the subject, and do not interfere with the person's movements, such as when putting on a t-shirt. The activities selected are described in the Table 4.1, with the different criteria for each level of achievement. Test are to be carried out in three different scenarios:

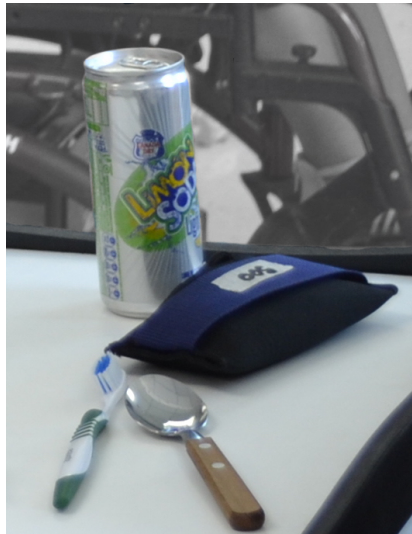


FIGURE 4.1. Objects used for the functional evaluation.

- Without exoskeleton
- With passive exoskeleton (rubber bands power)
- With active exoskeleton with servomotor and counterweight

Comparison of the performance in each case is easy to analyze because of the evaluation scores. The table must be filled by the same therapist in order to maintain evaluation consistency. The total sum of points achieved in each subset of tasks will give a number that allows easy comparison between scenarios and patients. Tests must be carried out with rest between scenarios so that the user can recover from effort needed to complete each task.

Task	0	1	2	3	4	5	Points
Flex shoulder to raise elbow to shoulder height	Not achieved	Achieved without additional weight	Achieved with a weight of 200 gr	Achieved with a weight of 500 gr	Achieved with a weight of 700 gr	Achieved with a weight of 1000 gr	
Flex shoulder to raise elbow to face height	Not achieved	Achieved without additional weight	Achieved with a weight of 200 gr	Achieved with a weight of 500 gr	Achieved with a weight of 700 gr	Achieved with a weight of 1000 gr	
Move a weight across a surface	Cannot move weight	Raises and moves a weight of 50 gr	Raises and moves a weight of 100 gr	Raises and moves a weight of 200 gr	Raises and moves a weight of 250 gr	Raises and moves a weight of 500 gr	
Take spoon to mouth	Not achieved	Grasping spoon on table but does not move it	Spoon reaches mouth, but with neck flexion and other hand reinforcement	Spoon reaches mouth, but with neck flexion and elbow compensation	Spoon reaches mouth, but with neck flexion	Spoon reaches mouth, without elbow support and neck flexion	
Brushing teeth	Not achieved	Grasping toothbrush on table but does not move it	Toothbrush reaches mouth, but with neck flexion and other hand reinforcement	Toothbrush reaches mouth, but with neck flexion and elbow compensation	Toothbrush reaches mouth, but with neck flexion	Toothbrush reaches mouth, without elbow support and neck flexion	
Takes can with liquid to mouth	Not achieved	Capable of grasping can on table but not move it	Takes can to mouth with compensation and other hand reinforcement	Takes can to mouth without compensation but with other hand reinforcement	Takes can to mouth with compensation and no elbow support	Takes can to mouth without compensation and no elbow support	

TABLE 4.1. Functional Evaluation Test: tasks and evaluation.

5. EXPERIMENTAL RESULTS

The final prototype was installed and tested with two patients. In order to improve the process, only the modified active orthosis was used in the tests, both in passive-only (disabling the servomotor action) and active mode, thus including improvement of presented drawbacks of the passive-only mechanism.

From the set of patients the Center was working with, only two of them were able to properly use the mechanism, at the time of the final testing. Some patients have small to no dysfunction at all, some of them had a really advanced stage of the disease, which impede them to rotate the elbow joint by themselves, joint that is not additionally supported by the orthosis. Patients with wrist problems, that requires a certain position of the wrist to have grasping, were also discarded. Progression of the dystrophy is different in each patient.

The tests done with the two patients are shown in Fig. 5.1. Fig. 5.1.(A) and (B) shows patient 1 using the orthosis with passive compensation; in (B), the patient is holding a small weight used in the tests. Fig. 5.1.(C) and (D) shows patient 2 using the orthosis with the passive compensation. Fig. 5.1.(E) shows patient 1 using the orthosis with the active compensation, lifting a can to the mouth. Fig. 5.1.(F) shows patient 2 using the orthosis with the active mechanism, holding the Smartphone that controls the servomotor.

5.1. Preliminary Patient Testing

In order to have a good comparison of performance, the tests were first carried out in the first scenario, where the patient must perform the activities described in the previous section without the exoskeleton. Results of the preliminary tests are shown in the tables 5.1 & 5.2.

With a maximum of 30 points, the first patient has 13 against 9 points of the second one. Both subjects use compensation to complete general activities, such as eating and lifting objects. Compensatory movement may include flexing the neck towards a table,



(A)



(B)



(C)



(D)



(E)



(F)

FIGURE 5.1. Patients using the orthosis in different tests.

making a downward movement, or using the spine to curve the body and compensate the height of the object being moved.

Compensatory motions may seem natural, but when they are constantly used to achieve an activity that usually does not require that muscles, it generates an additional stress in

No Orthosis	Patient 1	
Task	Result	Points
Flex shoulder to raise elbow to shoulder height	Not achieved	0
Flex shoulder to raise elbow to face height	Not achieved	0
Move a weight across a surface	Raises and moves a weight of 250 gr	4
Take spoon to mouth	Spoon reaches mouth, but with neck flexion and elbow compensation	3
Brushing teeth	Toothbrush reaches mouth, but with neck flexion and elbow compensation	3
Take can with liquid to mouth	Take can to mouth without compensation but with other hand reinforcement	3
Total Points		13

TABLE 5.1. Scores of the Functional Evaluation Test for patient 1 with no orthosis.

No Orthosis	Patient 2	
Task	Result	Points
Flex shoulder to raise elbow to shoulder height	Not achieved	0
Flex shoulder to raise elbow to face height	Not achieved	0
Move a weight across a surface	Raises and moves a weight of 50 gr	1
Take spoon to mouth	Spoon reaches mouth, but with neck flexion and elbow compensation	3
Brushing teeth	Toothbrush reaches mouth, but with neck flexion and elbow compensation	3
Take can with liquid to mouth	Take can to mouth with compensation and other hand reinforcement	2
Total Points		9

TABLE 5.2. Scores of the Functional Evaluation Test for patient 2 with no orthosis.

them. For therapist, the more compensatory movements the patient does, the harder is to treat properly the muscles being affected by the dystrophy, as they shorten them without proper use. Spine compensation usually carries out a lot of pain, especially when the patient is also affected by scoliosis or a similar spine condition.

Neither of the patients was able to use the shoulder joint to raise the arm, as shown by the scores in tables 5.1 and 5.2, but they are able to complete the other activities. Both patients could eat using special cutlery normally. In the weight lifting trial, each subject took the weights across the table from one side to the other without restrictions in the minimum or maximum height, using compensation and elbow support to raise the weight.

5.2. Passive Mechanism Testing and Results

The passive compensation mechanism was then attached to the wheelchair and the forearm is fixed to the forearm support with Velcro strips. Rubber bands are added to each segment of the device; at first the forearm section with the elbow rested on a surface until natural weightless feel is achieved.

Rubber bands in the arm section are added with the whole arm in suspension and until the elevation of the arm is parallel to the floor or a little less, depending on the patient and activities to be completed.

The evaluation results for patients 1 and 2 are summarized in tables 5.3 and 5.4. A considerable progress was made by patient 1, increasing the score from 13 to 23. Patient 2 presented the same total score, however, variations in individual scores were found.

Most of the score of patient 1 is due to scoring points in the first tasks, for which a lot of shoulder strength was required, but was now supported by the orthosis. The achieved support helped to increase some scores in the next tasks, for which little or no compensation was needed to complete the activity. Patient 1 was very comfortable using the orthosis, which helped to reduce significantly neck bending that aggravates the scoliosis.

The second patient did not find the orthosis as comfortable as the first one. In fact, he needed extra encouragement to complete the tests. The arm weight for patient 2 was larger than the previous one, and had less strength in the shoulder and elbow joint. In this case, the results did not improve significantly compared to the previous one.

The results of the previous test made it foreseeable that the patient would not be able to fulfill properly some of the second tests. The orthosis only supports weight in the

Passive Orthosis	Patient 1	
Task	Result	Points
Flex shoulder to raise elbow to shoulder height	Achieved with a weight of 500 gr	3
Flex shoulder to raise elbow to face height	Achieved with a weight of 200 gr	2
Move a weight across a surface	Raises and moves a weight of 250 gr	4
Take spoon to mouth	Spoon reaches mouth, without elbow support and neck flexion	5
Brushing teeth	Toothbrush reaches mouth, without elbow support and neck flexion	5
Take can with liquid to mouth	Takes can to mouth with compensation and no elbow support	4
Total Points		23

TABLE 5.3. Functional Evaluation for patient 1 with passive orthosis mechanism.

Passive Orthosis	Patient 2	
Task	Result	Points
Flex shoulder to raise elbow to shoulder height	Not achieved	0
Flex shoulder to raise elbow to face height	Not achieved	0
Move a weight across a surface	Raises and moves a weight 200 gr	3
Take spoon to mouth	Spoon reaches mouth, but with neck flexion and other hand reinforcement	2
Brushing teeth	Toothbrush reaches mouth, but with neck flexion and other hand reinforcement	2
Take can with liquid to mouth	Takes can to mouth with compensation and other hand reinforcement	2
Total Points		9

TABLE 5.4. Functional Evaluation for patient 2 with passive orthosis mechanism.

vertical axis, which requires the patient to do all the work to move along the horizontal plane, plus having to balance the arm in the desired vertical position with a small amount of shoulder or elbow torque. The condition of the dystrophy in patient 2 developed faster than the patient 1, thus adding difficulties to the tests.

The passive mechanism did not allow patients to fulfill completely all the tasks all the tasks. This was in part due to the inability of patients to freely move the shoulder joint, even though most of the arm weight is being countered by the force of the rubber bands.

5.3. Active Mechanism Testing and Results

The servomotor added to the elevation axis of the shoulder joint should enable the patient to control the elevation position of the orthosis when the system is fully balanced by the counterweight, which is easily modifiable with the presented solution.

The results summarized in tables 5.5 and 5.6 were not as expected. The first patient scored 22 points, a point below the 23 from the passive test, and the second patient scored 7 points, two points below.

Active Orthosis		Patient 1	
Task	Result	Points	
Flex shoulder to raise elbow to shoulder height	Achieved with a weight of 200 gr	2	
Flex shoulder to raise elbow to face height	Achieved with a weight of 200 gr	2	
Move a weight across a surface	Raises and moves a weight of 250 gr	4	
Take spoon to mouth	Spoon reaches mouth, without elbow support and neck flexion	5	
Brushing teeth	Toothbrush reaches mouth, without elbow support and neck flexion	5	
Take can with liquid to mouth	Takes can to mouth with compensation and no elbow support	4	
Total Points			22

TABLE 5.5. Scores of the Functional Evaluation Test for patient 1 with active orthosis mechanism.

Unfortunately, the mechanical system to transmit the servomotor movement to the arm turned out to be a limiting aspect due to traction issues which did not allow to properly turn the pulley to raise the arms when it was commanded to the servomotor. It was hard to

Active Orthosis		Patient 2	
Task	Result	Points	
Flex shoulder to raise elbow to shoulder height	Achieved without additional a weight	1	
Flex shoulder to raise elbow to face height	Not achieved	0	
Move a weight across a surface	Raises and moves a weight of 50 gr	1	
Take spoon to mouth	Spoon reaches mouth, but with neck flexion and other hand reinforcement	2	
Brushing teeth	Toothbrush reaches mouth, but with neck flexion and other hand reinforcement	2	
Take can with liquid to mouth	Capable of grasping can on table but not move it	1	
Total Points			7

TABLE 5.6. Scores of the Functional Evaluation Test for patient 2 with active orthosis mechanism.

complete all the tests, as sometimes the orthosis would slip and was hard to control for the patient. The slip would happen more often with the second patient, as he was older and heavier than the first one, thus straining more the device.

Small improvements were shown in some of the tests, but the general result was a smaller score in both patients than the scenario with the passive mechanism.

5.4. Summary of Results

In Table 5.7 a summary of the results with both patients in the different scenarios, with the final score of the Functional Evaluation, is presented. For the first patient there was a considerable improvement from the no orthosis scenario to using the device, in both passive and active case. The second patient had problems to use the orthosis and the score did not improved from his scores without the mechanism.

The tested patients presented a similar initial state of dystrophy when the project started. The progression of the disease turned out to be very different for each participant, since at the moment of the final testing, the condition of patients was quite different.

	Patient 1	Patient 2
No Orthosis	13	9
Passive Orthosis	23	9
Active Orthosis	22	7

TABLE 5.7. Scores summarized of the Functional Evaluation Test for both patients.

The design required some minimal strength to be able to move the mechanism about the balanced position, even with the addition of the servomotor on the shoulder axis.

Despite each patient's limitations, the mechanism can be used to complete activities of daily living, especially in early stages of the disease, when the person still has enough strength to move the rubber band balanced device.

To tackle muscle weakness in advanced stages of dystrophy, bigger motors are necessary because counterweight or passive spring compensation is insufficient. Additional motors give the user more control of the mechanism, but increases the cost of it. Adding more motors would also improve results when the dystrophy has further progressed.

6. CONCLUSION AND FUTURE RESEARCH

6.1. Results Discussion and General Remarks

In order to provide a low-cost solution to the mobility limitations of patients with neuromuscular degenerative diseases, an open design of an arm orthosis has been developed. The design takes advantage of the growing popularity and availability of 3D printers, as well as commercial-of-the-shelf components. Three designs of different complexity were studied: a simple articulated armrest, a passive exoskeleton and an active version of it.

The results show that a simple 1-DOF articulated armrest is not useful for patients with muscular dystrophy. Nonetheless, the results allowed us to establish a set of criteria to be considered in the articulated versions of the orthosis. A better understanding of the 3D printing process, its capabilities and limitations has been developed through the design iterations. For example, printing orientation, internal density, and part thickness are key to a successful manufacturing of the parts and ensuring the mechanical strength requirements. Including these aspects is fundamental for a feasible prototype, both in terms of its manufacturability and its capability to satisfy the operational specifications.

The proposed passive exoskeleton draws on ideas of the original WREX orthosis, which was modified to meet the low-cost and open design goals. The proposed design employs aluminum squared tubes to add stiffness to the structure and provide an increased level of modularity, i.e. the tubes can easily be replaced to fit different arm sizes and extend the age range for which the design can be used, in contrast to the original WREX 3D printed design which was designed for a 5 year old girl. A metallic commercial WREX device has an elevated cost, and the period that the exoskeleton can help the patient will vary from one to another. Considering the evolution of the disease, additional support will be needed, and within a couple of months the orthosis could become useless. Therefore, designing an orthosis that can grow with the person is highly desirable.

The main framework of the passive exoskeleton consists of a four-link bar system, that keeps vertical links parallel, constraining the movement of the mechanism. The four-link bar system is essential when using spring or rubber bands to passively compensate gravity. The analysis of the mechanism's force balance equations under different amounts of elastic force shows that passive gravity compensation is possible and allows the person to reduce the force required to maintain the arm in some position in spite of the arm's gravity force. However, the experimental evaluation of the passive orthosis reveals that gravity compensation does not act equally across the full range of arm motion, and therefore, in certain positions the person requires an additional force to lower the arm. Another limitation of the low-cost passive orthosis design is in the increased friction between the plastic parts of the joints due to the lack of bearings and spacers.

The second orthosis design proposes an active orthosis, which includes a servomotor on the shoulder's elevation axis to help the patient to move the orthosis, because the passive design does not provide enough compensation, especially at the ends of the motion range. The shoulder joint was identified during the experimental evaluation of the first design to be the weakest joint, especially when the person tried to raise the arm. The second design also includes bearings in each joint to decrease the friction that was present in the former design and provide better support to each axis. Unlike the passive orthosis, which requires the person to employ more force to move the arm, the active orthosis reduces the effort required.

However, the compliance system could not be implemented since the simulations of the theoretical performance of the compliant actuator show that a perfect cancellation of the gravity force is required to achieve compliance. In practice, what happens is that the servomotor needs to continuously apply a torque to cancel the load of the arm. This in turn causes the linear springs to be stretched to its limit, thus canceling also the compliant behavior that was sought.

A solution to this problem is to add a counterweight, but since the arm does not have a constant inertia matrix, a fixed counterweight does not fully solve the problem. Therefore,

a truly compliant orthosis would require active current compensation and torque feedback in the servomotor control loops. While this is possible to achieve in high end industrial and research robots, the cost and complexity makes such a design unfeasible. Increasing the spring constants to the point the compliant joint becomes an almost rigid joint obviously does not solve the problem as well. Hence, compliance in a low-cost DIY orthosis design should be discarded with the current actuator and sensor costs.

The design of the actuated mechanism was completed with an average cost of 422 USD in parts, which raises to 694 USD including the printing costs. Compared to commercially available orthoses, the mechanism has a low cost and is easy to assemble and modify. Adjustments of the design could be needed to fit the size of different arms, and the addition of the active support is optional in the final design.

Testing of the device was carried out with two patients, with Spinal Muscular Atrophy and Duchenne Muscular Dystrophy, respectively. General results show that 3D printing can be used to prototype a functional orthosis that may help in some activities of everyday life's, helping the patient to reduce compensatory body movements to achieve specific tasks.

When the stage of muscular dystrophy is advanced, more than one joint needs to be actuated, and elevation support for the shoulder joint is not enough to carry out most of the activities. A simple orthosis design like the presented in this thesis is especially useful during early stages of the disease, when self-esteem of the child can be greatly improved by helping them to be self-sufficient. Additionally, the proposed orthosis allows the patients to do some tasks without affecting their muscles further because of over-compensatory movements that would aggravate the condition caused by the disease.

6.2. Recommendations for Future Research

Improving the orthosis performance can be achieved by including a transversal shoulder actuator and an elbow motor. This unfortunately would increase the cost and complexity of the design to the point in which it stops being a DIY-project. Improving quality of

life may require a completely different approach using an assistive robotic arm controlled by the patient instead of an exoskeleton. Although this will be more expensive than the current orthosis design, it could be more effective along the whole evolution of the various types of degenerative muscular diseases and a variety of patients. On the other hand, a small external SCARA-type robot with servomotors could be built using high-torque RC servomotors, whose price has slightly decreased in recent years due to the rise of hobby robotics.

Despite the limitations of the presented compliant solution, it could be useful to study other type of problems, where a balanced system is present at all times, or variations of load are minimal. Most of the innovative robotic manipulator designs are pursuing full compliance to allow collaborative human-robot interaction. Turning the current orthosis design into a compliant mechanism is technically possible if the servomotors are replaced with regular DC motors with current feedback to implement torque control loops nested within the position control loops.

Future steps should consider an extended longitudinal study of the device with a controlled group of patients in order to fully understand how the orthosis can help avoid premature degeneration of the muscles due to over-compensation stress in activities of daily living. Patients would have to use the device for a sufficiently long period of time in order to obtain statistically significant results between the pilot and control groups. One challenge of progressive muscular dystrophies is that every patient is affected differently and the progression of the disease varies from one patient to another.

REFERENCES

- Ball, S. J., Brown, I. E., & Scott, S. H. (2007, Aug). A planar 3dof robotic exoskeleton for rehabilitation and assessment. In *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (p. 4024-4027). doi: 10.1109/IEMBS.2007.4353216
- Bunch, W. H., & Keagy, R. D. (1976). *Principles of orthotic treatment*. Mosby.
- Chen, J.-Y., & Clark, M.-J. (2007). Family function in families of children with duchenne muscular dystrophy. *Family & community health*, 30(4), 296–304.
- Desplenter, T., Lobo-Prat, J., Stienen, A. H. A., & Trejos, A. L. (2016, July). Extension of the wearme framework for emg-driven control of a wearable assistive exoskeleton. In *2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)* (p. 288-293). doi: 10.1109/AIM.2016.7576781
- Dunckley, M. G., Manoharan, M., Villiet, P., Eperon, I. C., & Dickson, G. (1998). Modification of splicing in the dystrophin gene in cultured mdx muscle cells by antisense oligoribonucleotides. *Human Molecular Genetics*, 7(7), 1083. Retrieved from <http://dx.doi.org/10.1093/hmg/7.7.1083> doi: 10.1093/hmg/7.7.1083
- Emery, A. E. (2002). The muscular dystrophies. *The Lancet*, 359(9307), 687–695.
- Emery, A. E., Muntoni, F., & Quinlivan, R. C. (2015). *Duchenne muscular dystrophy*. OUP Oxford.
- Hillman, M. (2004). Rehabilitation robotics from past to present—a historical perspective. *Advances in Rehabilitation Robotics*, 25–44.

JavelinTechnologies. (2013, Jun). *Youtube*. [Video]. Retrieved from <https://www.youtube.com/watch?v=Pqsd2tm0HdQ>

Koo, B., Montes, J., Gamarnik, V., Yeager, K., Marra, J., Dunaway, S., ... others (2009). Design and evaluation of a hybrid passive and active gravity neutral orthosis (gno). In *Engineering in medicine and biology society, 2009. embc 2009. annual international conference of the IEEE* (pp. 1573–1576).

Kooren, P. N., Lobo-Prat, J., Keemink, A. Q. L., Janssen, M. M., Stienen, A. H. A., de Groot, I. J. M., ... Koopman, B. F. J. M. (2016, June). Design and control of the Active A-Gear: A wearable 5 DOF arm exoskeleton for adults with Duchenne muscular dystrophy. In *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)* (p. 637-642). doi: 10.1109/BIOROB.2016.7523697

Kwakkel, G., Kollen, B. J., & Krebs, H. I. (2007). Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabilitation and neural repair*.

Lunn, M. R., & Wang, C. H. (2008). Spinal muscular atrophy. *The Lancet*, 371(9630), 2120–2133.

Mao, Y., Jin, X., Dutta, G. G., Scholz, J. P., & Agrawal, S. K. (2015, Jan). Human movement training with a cable driven arm exoskeleton (carex). *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 23(1), 84-92. doi: 10.1109/TNSRE.2014.2329018

Moubarak, S., Pham, M. T., Moreau, R., & Redarce, T. (2010). Gravity compensation of an upper extremity exoskeleton. In *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE* (pp. 4489–4493).

Natesan, A. K. (1994). Kinematic analysis and synthesis of four-bar mechanisms for straight line coupler curves.

Pignolo, L. (2009). Robotics in neuro-rehabilitation. *Journal of rehabilitation medicine*, 41(12), 955–960.

Ragonesi, D., Agrawal, S., Sample, W., & Rahman, T. (2011, Aug). Series elastic actuator control of a powered exoskeleton. In *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (p. 3515-3518). doi: 10.1109/IEMBS.2011.6090583

Rahman, T., Ramanathan, R., Seliktar, R., & Harwin, W. (1995). A simple technique to passively gravity-balance articulated mechanisms. *Journal of Mechanical Design*, 117(4), 655–658.

Rahman, T., & Sample, W. (2004, November 23). *Orthosis device*. Google Patents. Retrieved from <https://www.google.com/patents/US6821259> (US Patent 6,821,259)

Rahman, T., Sample, W., Jayakumar, S., King, M. M., Wee, J. Y., Seliktar, R., ... Clark, A. (2006). Passive exoskeletons for assisting limb movement. *Journal of rehabilitation research and development*, 43(5), 583.

Rahman, T., Sample, W., & Seliktar, R. (2004). 16 design and testing of wrex. In *Advances in rehabilitation robotics* (pp. 243–250). Springer.

Rahman, T., Sample, W., Seliktar, R., Alexander, M., & Scavina, M. (2000). A body-powered functional upper limb orthosis. *Journal of rehabilitation research and development*, 37(6), 675.

Rahman, T., Sample, W., Seliktar, R., Scavina, M. T., Clark, A. L., Moran, K., ... others (2007). Design and testing of a functional arm orthosis in patients with neuromuscular diseases. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 15(2), 244–251.

Sanchez, R., Reinkensmeyer, D., Shah, P., Liu, J., Rao, S., Smith, R., ... Bobrow, J. (2004, Sept). Monitoring functional arm movement for home-based therapy after stroke. In *The 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Vol. 2, p. 4787-4790). doi: 10.1109/IEMBS.2004.1404325

Sanchez, R., Wolbrecht, E., Smith, R., Liu, J., Rao, S., Cramer, S., ... Reinkensmeyer, D. J. (2005, June). A pneumatic robot for re-training arm movement after stroke: rationale and mechanical design. In *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.* (p. 500-504). doi: 10.1109/ICORR.2005.1501151

Williamson, M. M. (1995). *Series elastic actuators*. (Tech. Rep.). DTIC Document.

Wolbrecht, E. T., Leavitt, J., Reinkensmeyer, D. J., & Bobrow, J. E. (2006, Aug). Control of a Pneumatic Orthosis for Upper Extremity Stroke Rehabilitation. In *2006 International Conference of the IEEE Engineering in Medicine and Biology Society* (p. 2687-2693). doi: 10.1109/IEMBS.2006.259941

APPENDIX

APPENDIX A. APPENDIX

A.1. Makerbot Desktop 3.10.0.1364 Printing Settings

Makerbot Desktop is the software that Makerbot printers use to connect directly to the printer. The software enables the user to import a 3D file, usually in STL format. A general screen capture of it can be seen in Fig. A.1.

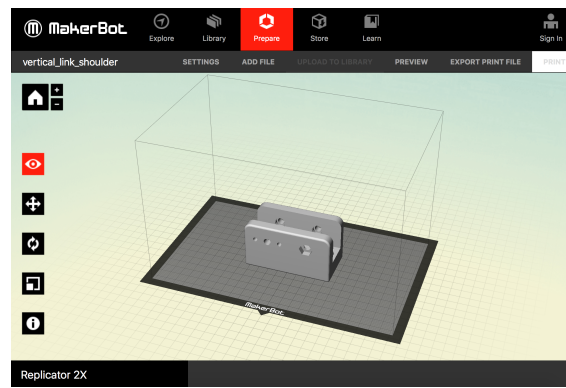


FIGURE A.1. Makerbot Desktop Software, general view.

Once the solid is oriented and positioned on the platform, the printing setting can be defined. A complete set of the settings used in most of the impressions of this thesis can be seen in Tables A.1 through A.7. Other screen captures of the software can be seen in Fig. A.2 and A.3, where details as the raft, support and infill can be appreciated.

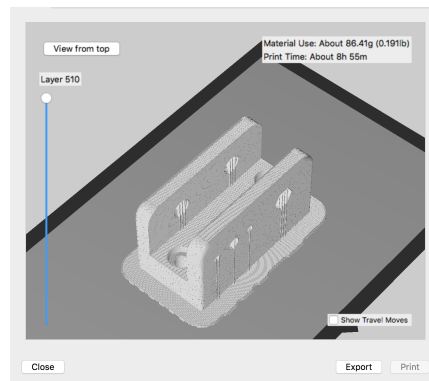


FIGURE A.2. Makerbot Desktop Software, printing preview.

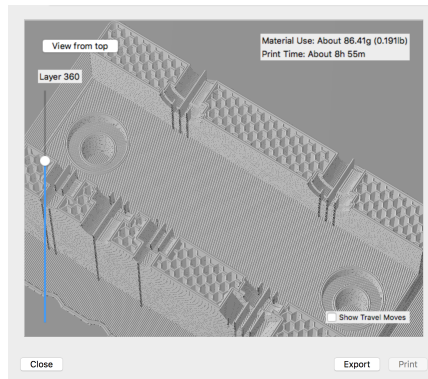


FIGURE A.3. Makerbot Desktop Software, detailed printing preview.

Device Settings	
Extruder Temperature	240 ° C
Platform Temperature	110 ° C
Travel Speed	80 mm/s
Z-axis Travel Speed	23 mm/s
Minimum Layer Duration	5.0 s

TABLE A.1. Device Settings

Infill	
Infill Density	40%
Infill Layer Height	0.20 mm
Infill Pattern	Hexagonal

TABLE A.2. Infill

Model Properties	
Layer Height	0.10 mm
Number of Shells	2
Roof Thickness	0.80 mm
Floor Thickness	0.80 mm
Coarseness	0.00010 mm
Fixed Shell Starting Point	Uncheck
Fixed Shell Starting Point	Check
Shell Starting Point	215 °

TABLE A.3. Model Properties

Extrusion Speeds		
Bridges		
Filament Sooling Fan Speed	0.5	
Print Speed		40 mm/s
First Layer		
Filament Cooling Fan Speed	0.5	
Print Speed		30 mm/s
First Layer Raft		
Filament Cooling Fan Speed	0.5	
Print Speed		40 mm/s
Floor Surface Fills		
Filament Cooling Fan Speed	0.5	
Print Speed		90 mm/s
Infill		
Filament Cooling Fan Speed	0.5	
Print Speed		90 mm/s
Insets		
Filament Cooling Fan Speed	0.5	
Print Speed		90 mm/s
Outilines		
Filament Cooling Fan Speed	0.5	
Print Speed		40 mm/s
Raft		
Filament Cooling Fan Speed	0.5	
Print Speed		10 mm/s
Raft Base		
Filament Cooling Fan Speed	0.5	
Print Speed		10 mm/s
Roof Surface Fills		
Filament Cooling Fan Speed	0.5	
Print Speed		90 mm/s
Sparse Roof Surface Fills		
Filament Cooling Fan Speed	0.5	
Print Speed		90 mm/s

TABLE A.4. Extrusion Speeds

Raft	
Raft to Model Spacing	0.35 mm
Raft Margin	4.0 mm
Base Layer	
Minimum Base Patter Gap	0 mm
Base Pattern Spacing	0.8 mm
Base Pattern Length	15.0 mm
Base Layer Angle	0
Base Layer Density	0.70
Base Extrusion Width	2.5 mm
Base Layer Height	0.40 mm
Number of Base Layers	2
Interface Layers	
Interface Layer Angle	45
Interface Layer Density	0.30
Interface Extrusion Width	0.40 mm
Interface Layer Height	0.27 mm
Number of Interface Layers	2
Surface Layers	
Number of Surface Layer Shells	2
Surface Layer Angle	0
Surface Layer Height	0.20 mm
Number of Surface Layers	1

TABLE A.5. Raft

Supports and Bridging	
Support	Check
Leaky Connections	Check
Aling Support	Check
Extra Support	Uncheck
Support Density	0.20
Support Margin	0.5 mm
Support to Model Spacing	0.4 mm
Support Roof to Model Spacing	0.4 mm
Support Angle	68
Support Layer Height	0.20 mm
Breakaway Support	Uncheck
Maximum Bridge Length	40.0 mm
Support Bridges	Check

TABLE A.6. Supports and Bridging

Right Extruder	
Filament Diameter	1.77 mm
Retraction Distance	1.3 mm
Retraction Speed	25 mm/s
Restart Speed	25 mm/s
Extra Restart Distance	0.0 mm/s
Extra Restart Speed	25 mm/s

TABLE A.7. Right Extruder, left is the same

A.2. Matlab Simulations Code for Gravity Compensation

```
1 %%Modelacion del sistema de barrar paralelas con elasticos
2
3 clc; clear all; close all;
4
5 %Constantes:
6 L=0.300;
7 w_fijo=0.050;
8 b=0.010;
9 m=5;
10
11 x_d=sqrt(L^2-w_fijo^2); %para beta = 90
12 theta_min_r = (acos(x_d/L));
13 disp('Theta donde resorte es horizontal: ')
14 disp(rad2deg(theta_min_r))
15
16 %Variables
17 k_fijo=50;
18 k=k_fijo:50:k_fijo*10;
19
20 %x_0 = 0.060:0.020:0.250;
21 x_0 = [0.250 0.100];
22 x_0_fijo=0.20;
23
24 theta_lim = (asin(2*b/w_fijo));
25 disp('Theta donde topan las barras para w=5cm : ')
26 disp(rad2deg(pi/2-theta_lim))
27
28
29 %Variaciones de w para ver angulo de tope de barras:
30 w=0.030:0.005:0.08;
31
32 theta_lim_w = (asin(2*b./w));
33 figure
34 set(gcf,'Color',[1,1,1])
35 set(gca,'FontSize',14)
36 alldatacursors = findall(gcf,'type','hggroup')
37 set(alldatacursors,'FontSize',18)
38 plot(w.*100,rad2deg(theta_lim_w),'Linewidth',2)
39 %title('Distancia entre ejes v/s ngulo m ximo estructura', 'FontSize', 16)
40 xlabel('Distance w [cm]', 'FontSize', 16)
41 ylabel('Limit angle [ ]', 'FontSize', 16)
42 print -depsc
43
44 theta=[theta_lim:0.001:pi-theta_lim];
45
46 %Largo del resorte
47 x=sqrt(L^2+2*L*w_fijo*cos(theta)+w_fijo^2);
48 figure
49 set(gcf,'Color',[1,1,1])
50 set(gca,'FontSize',14)
51 plot(rad2deg(theta), x.*100,'Linewidth',2)
52 %set(gca,'Xdir','reverse')
53 %title('Estiramiento del resorte', 'FontSize', 16)
54 xlabel('Elevation angle \theta [ ]', 'FontSize', 16)
55 ylabel('Elastic band length x(\theta) [cm]', 'FontSize', 16)
56 print -depsc
57
```

```

58 %%
59 %Angulo del resorte respecto a vertical
60 beta = acos((-L^2+x.^2+w_fijo^2)/(2*w_fijo*x));
61
62 figure
63 set(gcf,'Color',[1,1,1])
64 plot(rad2deg(theta), rad2deg(beta),'Linewidth',2)
65 %set(gca, 'Xdir', 'reverse')
66 title('Relaci n del angulo de la estructura y del resorte para w=5cm')
67 xlabel(' ngulo de la estructura')
68 ylabel(' ngulo del resorte ')
69
70 %Angulo del resorte y de la barra
71 alpha = acos((L^2+x.^2-w_fijo^2)/(2*L*x));
72 figure
73 set(gcf,'Color',[1,1,1])
74 plot(rad2deg(theta), rad2deg(alpha),'Linewidth',2)
75 %set(gca, 'Xdir', 'reverse')
76 title('Angulo del resorte respecto a la barra de torque')
77 xlabel(' ngulo de la estructura')
78 ylabel(' ngulo del resorte ')
79
80 torque_r = zeros(length(theta), length(k));
81 torque_m = zeros(length(theta));
82 N = size(torque_r,2);
83
84 figure
85 hold on
86 for i=1:N
87
88 [ torque_r(:,i) , torque_m ,~] = torque_resorte( L,w_fijo,b,k(i),x_0_fijo,m ,theta);
89 plot(rad2deg(theta),torque_r(:,i),'Color',[1,(N-i)/N,i/N],'Linewidth',2)
90 legendInfo{i} = [ 'N-{e} = ' num2str(k(i)/k_fijo)]; %Numero de elasticos
91
92 end
93 %set(gca, 'Xdir', 'reverse')
94 set(gcf,'Color',[1,1,1])
95 xlabel('\theta [ ]')
96 %ylim([0 18])
97 ylabel('Torque [Nm]')
98 title('Variaci n en cantidad de el sticos de k=50 para x0 = 20 cm')
99 plot(rad2deg(theta),torque_m,'-b','Linewidth',2)
100 legendInfo{i+1} = [ '\tau_{b_r_a_z_o}']; %Numero de elasticos
101 legend(legendInfo,'Location','northeastoutside')
102 box on
103 hold off
104
105
106 %% % Caso de variaci n de x_0 para k=250 -> 5 elasticos
107 % CASO DOBLE ANALISIS
108
109 torque_r_x = zeros(length(theta), length(x_0));
110 N = size(torque_r_x,2);
111
112 figure
113 %subplot(1,2,1)
114 hold on
115 for i=1:N
116 [ torque_r_x(:,i) , torque_m ,~] = torque_resorte( L,w_fijo,b,k_fijo*10,x_0(i),m ,theta);
117 plot(rad2deg(theta),torque_r_x(:,i),'Color',[1,(N-i)/N,0,i/N],'Linewidth',2)

```

```

118 %legendInfo{i} = ['N_e=5, x_0=' num2str(x_0(i)*100) 'cm'];
119 legendInfo{i} = ['E ' num2str(i)];
120 end
121
122 for i=1:N
123 [ torque_r_x(:,i) , torque_m ,~] = torque_resorte( L,w_fijo ,b,k_fijo*20,x_0(i),m ,theta);
124 plot(rad2deg(theta),torque_r_x(:,i),'Color',[i/N,1,(N-i)/N],'Linewidth',2)
125 %legendInfo{N+i} = ['N_e=10, x_0=' num2str(x_0(i)*100) 'cm']; ; %Numero de elasticos
126 legendInfo{N+i} = ['E ' num2str(N+i)]; %Numero de elasticos
127 end
128
129 %set(gca, 'Xdir', 'reverse')
130 set(gcf,'Color',[1,1,1])
131 set(gca,'xtick',[])
132 set(gca,'ytick',[])
133 set(gca,'FontSize',14)
134 xlabel('\theta [ ]')
135 %ylim([0 18])
136 ylabel('\tau [Nm]')
137 %title('Variaci n de x0 con k fijo , 5 el sticos ')
138 plot(rad2deg(theta),torque_m,'-r','Linewidth',2)
139 legendInfo{2*N+1} = ['\tau_a_r_m'];
140 legend(legendInfo,'Location','northeast')
141 box on
142 hold off
143 print -depsc
144
145 % figure
146 % %subplot(1,2,2)
147 % hold on
148 % for i=1:N
149 % [ torque_r_x(:,i) , torque_m ,x_r,~] = torque_resorte( L,w_fijo ,b,k_fijo*5,x_0(i),m);
150 % resorte = x_r./x_0(i);
151 % plot(rad2deg(theta),resorte,'Color',[1,(N-i)/N,i/N],'Linewidth',2)
152 % legendInfo{i} = ['x_0 = ' num2str(x_0(i)*100) 'cm']; ;
153 % end
154 % set(gcf,'Color',[1,1,1])
155 % xlabel('\theta [ ]')
156 % ylabel('x/x_0')
157 % title('Proporci n de estiramiento a largo natural')
158 % %plot(rad2deg(theta),torque_m,'-b','Linewidth',2)
159 % %legendInfo{i+1} = ['Torque brazo']; %Numero de elasticos
160 % %legend(legendInfo,'Location','northeast')
161 % box on
162 % hold off
163
164
165 %% Simulacion mas real...
166
167 %Variables
168 k_fijo=20; %elastico de escritorio
169 k=27*k_fijo:20:k_fijo*32;
170
171 %x_0 = 0.060:0.020:0.250;
172 x_0 = [0.250 0.100];
173 x_0_fijo=0.05;
174
175 theta=[theta_lim:0.001:pi-theta_lim];
176
177 torque_r = zeros(length(theta), length(k));

```

```

178 torque_m = zeros(length(theta));
179 N = size(torque_r,2);
180
181 figure ,
182 hold on
183 for i=1:N
184
185 [ torque_r(:,i) , torque_m ,~] = torque_resorte( L,w_fijo ,b,k(i),x_0_fijo ,m ,theta);
186 plot(rad2deg(theta),torque_r(:,i),'Color',[1,(N-i)/N,i/N],'Linewidth',2)
187 legendInfo{i} = ['n_{e} = ' num2str(k(i)/k_fijo)]; %Numero de elasticos
188
189 end
190 %set(gca, 'Xdir', 'reverse')
191 set(gcf,'Color',[1,1,1])
192 set(gca,'FontSize',14)
193 xlabel('Elevation Angle \theta [ ]','FontSize', 18)
194 ylim([0 18])
195 ylabel('Torque [Nm]','FontSize', 18)
196 %title('Variaci n en cantidad de el sticos de k=20 para x0 = 5 cm','FontSize', 18)
197 plot(rad2deg(theta),torque_m,'-b','Linewidth',2)
198 legendInfo{i+1} = ['\tau_{a-r-m}']; %Numero de elasticos
199 legend(legendInfo,'Location','northeast','FontSize', 10)
200 box on
201 hold off
202 print -depsc
203
204 %% Hagamos un grafico para demostrar la eleccion del motor dado un
205 % caso de estudio
206
207 torque_r = zeros(length(theta));
208 torque_m = zeros(length(theta));
209 k_fijo = 29*20;
210
211 %El motor tiene 40 kg-cm en el mejor caso
212 T_motor = ones(size(theta))*(40/10.197);
213
214 [ torque_e , torque_m ,~] = torque_resorte( L,w_fijo ,b,k_fijo ,x_0_fijo ,m ,theta);
215
216 figure
217 hold on
218 plot(rad2deg(theta),torque_e,'-b','Linewidth',2)
219 %set(gca, 'Xdir', 'reverse')
220 set(gcf,'Color',[1,1,1])
221 set(gca,'FontSize',14)
222 xlabel('\theta [ ]','FontSize', 16)
223 ylim([0 18])
224 ylabel('Torque [Nm]','FontSize', 16)
225 %title('Variaci n en cantidad de el sticos de k=50 para x0 = 20 cm')
226 plot(rad2deg(theta),torque_m,'-r','Linewidth',2)
227 plot(rad2deg(theta),T_motor,'-g','Linewidth',2)
228 %legendInfo{i+1} = ['\tau_{b-r-a-z-o}']; %Numero de elasticos
229 legendInfo = ['\tau_E'; '\tau_{a-r-m}'; 'Servo Torque'];
230 legend(legendInfo,'Location','northeast')
231 xlim([20 160])
232 box on
233 hold off
234 print -depsc
235
236 figure
237 hold on

```

```

238 plot(rad2deg(theta),(torque_m-torque_e),'-c','Linewidth',2)
239 plot(rad2deg(theta),T_motor,'-g','Linewidth',2)
240 set(gcf,'Color',[1,1,1])
241 set(gca,'FontSize',14)
242 xlabel('\theta [ ]','FontSize',16)
243 ylabel('Torque [Nm]','FontSize',16)
244 legendInfo = ['Net Torque ','Servo Torque'];
245 legend(legendInfo,'Location','northeast')
246 ylim([-0.5 5])
247 xlim([20 160])
248 box on
249 hold off
250 print -depsc
251
252 %%
253 figure
254 hold on
255 plot(rad2deg(theta),(torque_m-torque_e),'-b','Linewidth',2)
256 %plot(rad2deg(theta),T_motor,'-g','Linewidth',2)
257 set(gcf,'Color',[1,1,1])
258 set(gca,'FontSize',14)
259 xlabel('\theta [ ]','FontSize',16)
260 ylabel('Torque [Nm]','FontSize',16)
261 legendInfo = ['Net Torque ','Servo Torque'];
262 legend(legendInfo,'Location','best')
263 %ylim([-0.5 5])
264 xlim([20 160])
265 box on
266 hold off
267 print -depsc
268
269 %%
270 figure
271 hold on
272 plot(rad2deg(theta),10.197*(torque_m-torque_e),'-b','Linewidth',2)
273 %plot(rad2deg(theta),T_motor,'-g','Linewidth',2)
274 set(gcf,'Color',[1,1,1])
275 set(gca,'FontSize',14)
276 xlabel('\theta [ ]','FontSize',16)
277 ylabel('Torque [kg-cm]','FontSize',16)
278 legendInfo = ['Net Torque ','Servo Torque'];
279 legend(legendInfo,'Location','best')
280 %ylim([-0.5 5])
281 xlim([20 160])
282 box on
283 hold off
284 print -depsc

```

A.3. Matlab Simulations Code for Compliant Study

```
1 %Modelacion, asumiendo sistema en equilibrio...
2
3 clc
4 clear all
5 close all
6
7 M = 5; %kg
8 g = 9.8;
9 L = 0.3; %m
10 %w=0.050;
11 %b=0.010;
12
13 k = 0.3*1000;
14
15 r1 = (25.4/2)/1000; %m
16 rm = (25.4/2)/1000; %m
17 J1 = (1/3)*M*L^2;
18
19 %Free Length (L)30.00 mm
20 %Max. Extension (mm)37.99 mm
21 dL = (37.99 - 30)/1000;
22 dtheta_max = dL/r1;
23
24 %Definimos la ecuacion del sistema X_punto = f(x,u)
25 % x1 = theta_L
26 % x2 = theta_L_punto = omega_L
27 % u = theta_M
28 %syms x1
29 %syms x2
30 %syms u
31
32 %F = [ x2 ;
33 %      (1/J1)*2*k*r1*(r1*x1-rm*u) ];
34
35 dt = 0.01;
36 t = dt:dt:100;
37
38 %% Partamos por lo basico, una simulacion, de escalon, con pid
39 Kp = 12;
40 Ki = 0.9;
41 Kd = 5;
42
43 X = zeros(2,size(t,2));
44 L = size(t,2);
45
46 x1_0 = 0;
47 x2_0 = 0;
48 u_0 = 0;
49
50 X(:,1) = [x1_0;x2_0];
51 U = zeros(1,L);
52 U(1) = u_0;
53 u_lim = pi/2;
54 error = 0;
55 error_i = 0;
56 error_d = 0;
57 error_p = 0;
```

```

58 N = 20;
59
60 ref = zeros(1,L);
61 %ref(:) = pi/2+dt;
62 ref(L/10:L) = 30*pi/180; %30 grados en escalon
63
64 for i=2:L
65
66 %Calculo de errores
67 error = ref(i) - X(1,i-1);
68 error_i = error_i + error*dt;
69 error_d = (error-error_p)/dt;%*N/(1+N*dt)*;
70 %Calculo variable manipulada
71 U(i) = Kp*error + Ki*error_i + Kd*error_d;
72 %Saturacion
73 if U(i) > u_lim
74 U(i) = u_lim;
75 elseif U(i) < -u_lim
76 U(i) = -u_lim;
77 end
78
79 %Restriccion de angulos
80 if X(1,i-1)-U(i) > dtheta_max/2
81 U(i) = X(1,i-1)-dtheta_max/2;
82 %display(rad2deg(X(1,i-1)-U(i)),'Atraso')
83 %display(t(i),'t')
84 j = j + 1;
85 elseif U(i)-X(1,i-1) > dtheta_max/2
86 U(i) = X(1,i-1)+dtheta_max/2;
87 %display(rad2deg(-X(1,i-1)+U(i)),'Adelanto')
88 %display(t(i),'t')
89 j = j + 1;
90 end
91
92 %Transicion de estados
93 % X = X(i-1) + F(X(i-1),u(i))*dt
94 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/J1)*2*k*r1*(r1*X(1,i-1)-rm*U(i)) ].*dt;
95
96 %Actualizacion de error
97 error_p = error;
98
99 end
100
101 figure(1)
102 set(gcf,'Color',[1,1,1])
103 set(gca,'FontSize',14)
104 supitle('Escalon, sistema en torno a 0')
105 subplot(2,2,1)
106 hold on
107 plot(t,rad2deg(X(1,:)),'b','Linewidth',1.5)
108 plot(t,rad2deg(ref),'r','Linewidth',1.5)
109 %legendInfo{1} = ['Theta_L'];
110 %legendInfo{2} = ['Ref'];
111 legend('Theta_L','Ref','Location','best')%,'Location','southeastinside')
112 hold off
113 subplot(2,2,3)
114 plot(t,rad2deg(U),'g','Linewidth',1.5)
115 xlabel('Angulo [ ]')
116 legend('Theta_M','Location','best')
117 subplot(2,2,2)

```



```

118 plot(t,rad2deg(ref-X(1,:)), 'magenta', 'Linewidth',1.5)
119 legend('Error', 'Location', 'best')
120 subplot(2,2,4)
121 plot(t,rad2deg(X(1,:)-U), 'cyan', 'Linewidth',1.5)
122 legend('Theta_L - Theta_M', 'Location', 'best')
123 xlabel('Angulo [ ]')
124
125 %% Sistema en torno a 90
126
127 X = zeros(2,size(t,2));
128 L = size(t,2);
129
130 x1_0 = pi/2;
131 x2_0 = 0;
132 u_0 = pi/2;
133
134 X(:,1) = [x1_0;x2_0];
135 U = zeros(1,L);
136 U(1) = u_0;
137 u_lim = pi;
138 error = 0;
139 error_i = 0;
140 error_d = 0;
141 error_p = 0;
142 N = 20;
143
144 ref = zeros(1,L);
145 ref(:) = pi/2;
146 ref(L/10:L) = pi/2+30*pi/180; %10 grados en escalon
147
148 for i=2:L
149
150 %Calculo de errores
151 error = ref(i) - X(1,i-1);
152 error_i = error_i + error*dt;
153 error_d = (error-error_p)/dt;%*N/(1+N*dt)*;
154 %Calculo variable manipulada
155 U(i) = Kp*error + Ki*error_i + Kd*error_d;
156 %Saturacion
157 if U(i) > u_lim
158 U(i) = u_lim;
159 elseif U(i) < 0
160 U(i) = 0;
161 end
162
163 %Transicion de estados
164 % X = X(i-1) + F(X(i-1),u(i))*dt
165 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/J1)*2*k*r1*(r1*X(1,i-1)-rm*U(i)) ].* dt;
166
167 %Actualizacion de error
168 error_p = error;
169
170 end
171
172 figure(2)
173 set(gcf, 'Color', [1,1,1])
174 subplot(2,1,1)
175 plot(t,rad2deg(X(1,:)),t,rad2deg(ref), 'r', 'Linewidth',1.5)
176 title('Escalon, sistema en torno a 90 ')
177 legendInfo{1} = ['Theta_L'];

```

```

178 legendInfo{2} = ['Ref'];
179 legend(legendInfo)%,'Location','southeastinside')
180 subplot(2,1,2)
181 plot(t,rad2deg(U),'g','Linewidth',1.5)
182 legendInfo{1} = ['Theta_M'];
183 xlabel('Angulo [ ]')
184 legend(legendInfo)
185
186 %Por alguna razon se cae al principio y no entiendo porque...
187 %Asumamos que el sistema esta en pi/2 pero en torno a 0...
188
189 %% Sinusoide ...
190
191 Kp = 12;
192 Ki = 0.9;
193 Kd = 5;
194
195 X = zeros(2,size(t,2));
196 L = size(t,2);
197
198 x1_0 = 0;
199 x2_0 = 0;
200 u_0 = 0;
201
202 X(:,1) = [x1_0;x2_0];
203 U = zeros(1,L);
204 U(1) = u_0;
205 u_lim = pi/2;
206 error = 0;
207 error_i = 0;
208 error_d = 0;
209 error_p = 0;
210 N = 20;
211
212 ref = zeros(1,L);
213 %ref(:) = pi/2+dt;
214 ref(629:L) = sin(0.5*t(629:L))*10*pi/180;
215
216 for i=2:L
217
218 %Calculo de errores
219 error = ref(i) - X(1,i-1);
220 error_i = error_i + error*dt;
221 error_d = (error-error_p)/dt;%*N/(1+N*dt)*;
222 %Calculo variable manipulada
223 U(i) = Kp*error + Ki*error_i + Kd*error_d;
224 %Saturacion
225 if U(i) > u_lim
226 U(i) = u_lim;
227 elseif U(i) < -u_lim
228 U(i) = -u_lim;
229 end
230
231 %Transicion de estados
232 % X = X(i-1) + F(X(i-1),u(i))*dt
233 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/Jl)*2*k*r1*(r1*X(1,i-1)-rm*U(i)) ].*dt;
234
235 %Actualizacion de error
236 error_p = error;
237

```

```

238 end
239
240 %plot(t,X(2,:))
241
242 figure(3)
243 set(gcf,'Color',[1,1,1])
244 subtitle('Sinusoide , sistema en torno a 0')
245 subplot(2,2,1)
246 hold on
247 plot(t,rad2deg(X(1,:)),'b','Linewidth',1.5)
248 plot(t,rad2deg(ref),'r','Linewidth',1.5)
249 %legendInfo{1} = ['Theta_L'];
250 %legendInfo{2} = ['Ref'];
251 legend('Theta_L','Ref','Location','best')%,'Location','southeastinside')
252 hold off
253 subplot(2,2,3)
254 plot(t,rad2deg(U),'g','Linewidth',1.5)
255 xlabel('Angulo [ ]')
256 legend('Theta_M','Location','best')
257 subplot(2,2,2)
258 plot(t,rad2deg(ref-X(1,:)),'magenta','Linewidth',1.5)
259 legend('Error','Location','best')
260 subplot(2,2,4)
261 plot(t,rad2deg(X(1,:)-U),'cyan','Linewidth',1.5)
262 legend('Theta_L - Theta_M','Location','best')
263 %xlabel('Angulo [ ]')
264
265 figure(7)
266 set(gcf,'Color',[1,1,1])
267 set(gca,'FontSize',14)
268 %subtitle('Sinusoide con obstaculo')
269 subplot(2,2,1)
270 hold on
271 plot(t,rad2deg(X(1,:)),'b','Linewidth',1.5)
272 plot(t,rad2deg(ref),'r','Linewidth',1.5)
273 ylim([-20 20])
274 box on
275 %legendInfo{1} = ['Theta_L'];
276 %legendInfo{2} = ['Ref'];
277 legend('\theta_L','Ref')%,'Location','best')%,'Location','southeastinside')
278 hold off
279 subplot(2,2,3)
280 plot(t,rad2deg(U),'g','Linewidth',1.5)
281 ylim([-30 20])
282 %xlabel('Angulo [ ]','FontSize',16)
283 legend('\theta_M')%,'Location','best')
284 subplot(2,2,2)
285 plot(t,rad2deg(ref-X(1,:)),'magenta','Linewidth',1.5)
286 %ylim([-40 40])
287 legend('Error')%,'Location','best')
288 subplot(2,2,4)
289 plot(t,rad2deg(X(1,:)-U),'cyan','Linewidth',1.5)
290 %ylim([-40 40])
291 legend('\theta_L - \theta_M')%,'Location','best')
292 %xlabel('Angulo [ ]')
293 [ax1,h1]=suplabel('Time [s]');
294 [ax2,h2]=suplabel('Angle [ ]','y');
295 set(h1,'FontSize',14)
296 set(h2,'FontSize',14)
297 print -depsc

```

```

298
299
300 %% Sinusoide... con restriccion de angulos
301
302 Kp = 12;
303 Ki = 0.9;
304 Kd = 5;
305
306 X = zeros(2,size(t,2));
307 L = size(t,2);
308
309 x1_0 = 0;
310 x2_0 = 0;
311 u_0 = 0;
312
313 X(:,1) = [x1_0;x2_0];
314 U = zeros(1,L);
315 U(1) = u_0;
316 u_lim = pi/2;
317 error = 0;
318 error_i = 0;
319 error_d = 0;
320 error_p = 0;
321 N = 20;
322
323 ref = zeros(1,L);
324 %ref(:) = pi/2+dt;
325 ref(L/10:L) = sin(0.5*t(L/10:L))*10*pi/180; %10 grados en escalon
326 %para referencia bonita 629
327 %Agregar perturbacion a la referencia
328 %ref(L/2:L/2+L/5) = -10*pi/180;
329 j = 0;
330
331 for i=2:L
332
333 %Calculo de errores
334 error = ref(i) - X(1,i-1);
335 error_i = error_i + error*dt;
336 error_d = (error-error_p)/dt;%*N/(1+N*dt)*;
337 %Calculo variable manipulada
338 U(i) = Kp*error + Ki*error_i + Kd*error_d;
339 %Saturacion
340 if U(i) > u_lim
341 U(i) = u_lim;
342 elseif U(i) < -u_lim
343 U(i) = -u_lim;
344 end
345
346 %Restriccion de angulos
347 if X(1,i-1)-U(i) > dtheta_max/2
348 U(i) = X(1,i-1)-dtheta_max/2;
349 %display(rad2deg(X(1,i-1)-U(i)),'Atraso')
350 %display(t(i),'t')
351 j = j + 1;
352 elseif U(i)-X(1,i-1) > dtheta_max/2
353 U(i) = X(1,i-1)+dtheta_max/2;
354 %display(rad2deg(-X(1,i-1)+U(i)),'Adelanto')
355 %display(t(i),'t')
356 j = j + 1;
357 end

```

```

358
359
360 %Transicion de estados
361 % X = X(i-1) + F(X(i-1),u(i))*dt
362 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/J1)*2*k*r1*(r1*X(1,i-1)-rm*U(i)) ].*dt;
363
364 %Perturbacion a la medicion del estado, fijo en posici n
365 if i > 19.9/dt && i < 37.89/dt
366 X(1,i) = -5*pi/180;
367 X(2,i) = 0;
368 end
369
370 %Actualizacion de error
371 error_p = error;
372
373
374 end
375
376 display(k, 'Numero de restricciones de angulo')
377 %plot(t,X(2,:))
378
379 figure(4)
380 set(gcf, 'Color',[1,1,1])
381 subtitle('Sinusoide, sistema en torno a 0, angulo restringido')
382 subplot(2,2,1)
383 hold on
384 plot(t,rad2deg(X(1,:)), 'b', 'Linewidth',1.5)
385 plot(t,rad2deg(ref), 'r', 'Linewidth',1.5)
386 %legendInfo{1} = ['Theta_L'];
387 %legendInfo{2} = ['Ref'];
388 legend('Theta_L', 'Ref')%, 'Location', 'best')%, 'Location', 'southeastinside')
389 hold off
390 subplot(2,2,3)
391 plot(t,rad2deg(U), 'g', 'Linewidth',1.5)
392 xlabel('Angulo [ ]')
393 legend('Theta_M')%, 'Location', 'best')
394 subplot(2,2,2)
395 plot(t,rad2deg(ref-X(1,:)), 'magenta', 'Linewidth',1.5)
396 legend('Error')%, 'Location', 'best')
397 subplot(2,2,4)
398 plot(t,rad2deg(X(1,:)-U), 'cyan', 'Linewidth',1.5)
399 legend('Theta_L - Theta_M')%, 'Location', 'best')
400 %xlabel('Angulo [ ]')
401
402 %plot(t,rad2deg(error_i), 'cyan', 'Linewidth',1.5)
403
404
405
406 %% Sinusoide mas lenta pero alta ... con restriccion de angulos %ploteado
407
408 Kp = 12;
409 Ki = 0.9;
410 Kd = 5;
411
412 X = zeros(2, size(t,2));
413 L = size(t,2);
414
415 x1_0 = 0;
416 x2_0 = 0;
417 u_0 = 0;

```

```

418
419 X(:,1) = [x1_0;x2_0];
420 U = zeros(1,L);
421 U(1) = u_0;
422 u_lim = pi/2;
423 error = 0;
424 error_i = 0;
425 error_d = 0;
426 error_p = 0;
427 N = 20;
428
429 ref = zeros(1,L);
430 %ref(:) = pi/2+dt;
431 ref(12.56/dt:L) = sin(0.25*t(12.56/dt:L))*30*pi/180; %10 grados en escalon
432 %Agregar perturbacion a la referencia
433 %ref(L/2:L/2+L/5) = -10*pi/180;
434 j = 0;
435
436 for i=2:L
437
438 %Calculo de errores
439 error = ref(i) - X(1,i-1);
440 error_i = error_i + error*dt;
441 error_d = (error-error_p)/dt;%*N/(1+N*dt)*;
442 %Calculo variable manipulada
443 U(i) = Kp*error + Ki*error_i + Kd*error_d;
444 %Saturacion
445 if U(i) > u_lim
446 U(i) = u_lim;
447 elseif U(i) < -u_lim
448 U(i) = -u_lim;
449 end
450
451 %Restriccion de angulos
452 if X(1,i-1)-U(i) > dtheta_max/2
453 U(i) = X(1,i-1)-dtheta_max;
454 %display(rad2deg(X(1,i-1)-U(i)),'Atraso')
455 %display(t(i),'t')
456 j = j + 1;
457 elseif U(i)-X(1,i-1) > dtheta_max/2
458 U(i) = X(1,i-1)+dtheta_max;
459 %display(rad2deg(-X(1,i-1)+U(i)),'Adelanto')
460 %display(t(i),'t')
461 j = j + 1;
462 end
463
464
465 %Transicion de estados
466 % X = X(i-1) + F(X(i-1),u(i))*dt
467 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/Jl)*2*k*r1*(r1*X(1,i-1)-rm*U(i)) ].*dt;
468
469 %Perturbacion a la medicion del estado, fijo en posici n
470 if i > 38.5/dt && i < 53/dt
471 X(1,i) = -5*pi/180;
472 X(2,i) = 0;
473 end
474
475 %Actualizacion de error
476 error_p = error;
477

```

```

478
479 end
480
481 display(k, 'Numero de restricciones de angulo')
482 %plot(t,X(2,:))
483
484 figure(5)
485 set(gcf, 'Color', [1,1,1])
486 set(gca, 'FontSize', 14)
487 %suptitle('Sinusoide con obstaculo')
488 subplot(2,2,1)
489 hold on
490 plot(t, rad2deg(X(1,:)), 'b', 'Linewidth', 1.5)
491 plot(t, rad2deg(ref), 'r', 'Linewidth', 1.5)
492 ylim([-60 60])
493 box on
494 %legendInfo{1} = ['Theta_L'];
495 %legendInfo{2} = ['Ref'];
496 legend('\theta_L', 'Ref', 'Location', 'best', 'Location', 'southeastinside')
497 hold off
498 subplot(2,2,3)
499 plot(t, rad2deg(U), 'g', 'Linewidth', 1.5)
500 ylim([-60 60])
501 %xlabel('Angulo [ ]', 'FontSize', 16)
502 legend('\theta_M', 'Location', 'best')
503 subplot(2,2,2)
504 plot(t, rad2deg(ref-X(1,:)), 'magenta', 'Linewidth', 1.5)
505 ylim([-60 60])
506 legend('Error', 'Location', 'best')
507 subplot(2,2,4)
508 plot(t, rad2deg(X(1,:)-U), 'cyan', 'Linewidth', 1.5)
509 ylim([-60 60])
510 legend('\theta_-(L-M)', 'Location', 'best')
511 %xlabel('Angulo [ ]')
512 [ax1, h1] = suplabel('Time [s]');
513 [ax2, h2] = suplabel('Angle [ ]', 'y');
514 set(h1, 'FontSize', 14)
515 set(h2, 'FontSize', 14)
516 print -depsc
517
518 %plot(t, rad2deg(error_i), 'cyan', 'Linewidth', 1.5)
519
520
521 %% Sinusoide mas lenta pero alta... con restriccion de angulos
522 % y si cambiamos los R?
523
524 Kp = 12;
525 Ki = 0.9;
526 Kd = 5;
527
528 X = zeros(2, size(t, 2));
529 L = size(t, 2);
530
531 x1_0 = 0;
532 x2_0 = 0;
533 u_0 = 0;
534
535 X(:, 1) = [x1_0; x2_0];
536 U = zeros(1, L);
537 U(1) = u_0;

```

```

538 u_lim = pi/2;
539 error = 0;
540 error_i = 0;
541 error_d = 0;
542 error_p = 0;
543 N = 20;
544
545 dtheta_max = dL/(2*r1);
546
547 ref = zeros(1,L);
548 %ref(:) = pi/2+dt;
549 ref(12.56/dt:L) = sin(0.25*t(12.56/dt:L))*30*pi/180; %10 grados en escalon
550 %Agregar perturbacion a la referencia
551 %ref(L/2:L/2+L/5) = -10*pi/180;
552 j = 0;
553
554 for i=2:L
555
556 %Calculo de errores
557 error = ref(i) - X(1,i-1);
558 error_i = error_i + error*dt;
559 error_d = (error-error_p)/dt;%N/(1+N*dt)*;
560 %Calculo variable manipulada
561 U(i) = Kp*error + Ki*error_i + Kd*error_d;
562 %Saturacion
563 if U(i) > u_lim
564 U(i) = u_lim;
565 elseif U(i) < -u_lim
566 U(i) = -u_lim;
567 end
568
569 %Restriccion de angulos
570 if X(1,i-1)-U(i) > dtheta_max/2
571 U(i) = X(1,i-1)-dtheta_max;
572 %display(rad2deg(X(1,i-1)-U(i)),'Atraso')
573 %display(t(i),'t')
574 j = j + 1;
575 elseif U(i)-X(1,i-1) > dtheta_max/2
576 U(i) = X(1,i-1)+dtheta_max;
577 %display(rad2deg(-X(1,i-1)+U(i)),'Adelanto')
578 %display(t(i),'t')
579 j = j + 1;
580 end
581
582
583 %Transicion de estados
584 % X = X(i-1) + F(X(i-1),u(i))*dt
585 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/J1)*2*k*2*r1*(2*r1*X(1,i-1)-2*rm*U(i)) ].* dt;
586
587 %Perturbacion a la medicion del estado, fijo en posici n
588 if i > 38.5/dt && i < 53/dt
589 X(1,i) = -5*pi/180;
590 X(2,i) = 0;
591 end
592
593 %Actualizacion de error
594 error_p = error;
595
596
597 end

```



```

598
599 display(k, 'Numero de restricciones de angulo')
600 %plot(t,X(2,:))
601
602 figure(5)
603 set(gcf, 'Color', [1,1,1])
604 subtitle('Sinusoide, sistema en torno a 0, angulo restringido, R = 2in')
605 subplot(2,2,1)
606 hold on
607 plot(t, rad2deg(X(1,:)), 'b', 'Linewidth', 1.5)
608 plot(t, rad2deg(ref), 'r', 'Linewidth', 1.5)
609 %legendInfo{1} = ['Theta_L'];
610 %legendInfo{2} = ['Ref'];
611 legend('Theta_L', 'Ref')%, 'Location', 'best')%, 'Location', 'southeastinside')
612 hold off
613 subplot(2,2,3)
614 plot(t, rad2deg(U), 'g', 'Linewidth', 1.5)
615 xlabel('Angulo [ ]')
616 legend('Theta_M')%, 'Location', 'best')
617 subplot(2,2,2)
618 plot(t, rad2deg(ref-X(1,:)), 'magenta', 'Linewidth', 1.5)
619 legend('Error')%, 'Location', 'best')
620 subplot(2,2,4)
621 plot(t, rad2deg(X(1,:)-U), 'cyan', 'Linewidth', 1.5)
622 legend('Theta_L - Theta_M')%, 'Location', 'best')
623 %xlabel('Angulo [ ]')
624
625 %plot(t, rad2deg(error_i), 'cyan', 'Linewidth', 1.5)
626
627
628 %% rampa?... con restriccion de angulos
629
630 dt = 0.01;
631 t = dt:dt:100;
632
633 Kp = 12;
634 Ki = 10.9;
635 Kd = 5;
636
637 X = zeros(2, size(t,2));
638 L = size(t,2);
639
640 x1_0 = 0;
641 x2_0 = 0;
642 u_0 = 0;
643
644 X(:,1) = [x1_0; x2_0];
645 U = zeros(1,L);
646 U(1) = u_0;
647 u_lim = pi/2;
648 error = zeros(size(t));
649 error_i = zeros(size(t));
650 error_d = zeros(size(t));
651 %error_p = 0;
652 N = 20;
653
654 ref = zeros(1,L);
655 %ref(:) = pi/2+dt;
656 ref(10/dt:30/dt) = 0:(30*pi/180)/(20/dt):30*pi/180; %10 grados en escalon
657 ref(30/dt:L) = 30*pi/180;

```

```

658 %para referencia bonita 629
659 %Agregar perturbacion a la referencia
660 %ref(L/2:L/2+L/5) = -10*pi/180;
661 j = 0;
662
663 for i=2:L
664
665     error = ref(i) - X(1,i-1);
666     if(abs(error) > dtheta_max/5)
667         ref(i) = (X(1,i-1)+ref(i-1))/2 ; %Promedio
668         error = ref(i) - X(1,i-1); %Lo calcula de nuevo
669     end
670
671 %Calculo de errores
672 error(i) = ref(i) - X(1,i-1);
673 error_i(i) = error_i(i) + error(i)*dt;
674 error_d(i) = (error(i)-error(i-1))/dt;%N/(1+N*dt)*;
675 %Calculo variable manipulada
676 U(i) = Kp*error(i) + Ki*error_i(i) + Kd*error_d(i);
677 %Saturacion
678 if U(i) > u_lim
679     U(i) = u_lim;
680 elseif U(i) < -u_lim
681     U(i) = -u_lim;
682 end
683
684 %Restriccion de angulos
685 if X(1,i-1)-U(i) > dtheta_max/2
686     U(i) = X(1,i-1)-dtheta_max/2;
687     %display(rad2deg(X(1,i-1)-U(i)),'Atraso')
688     %display(t(i),'t')
689     j = j + 1;
690 elseif U(i)-X(1,i-1) > dtheta_max/2
691     U(i) = X(1,i-1)+dtheta_max/2;
692     %display(rad2deg(-X(1,i-1)+U(i)),'Adelanto')
693     %display(t(i),'t')
694     j = j + 1;
695 end
696
697 %Transicion de estados
698 %X = X(i-1) + F(X(i-1),u(i))*dt
699 X(:,i) = X(:,i-1) + [ X(2,i-1) ; -(1/Jl)*2*k*rl*(rl*X(1,i-1)-rm*U(i)) ].*dt;
700
701 %Perturbacion a la medicion del estado, fijo en posici n
702 %     if i > 19.9/dt && i < 37.89/dt
703 %         X(1,i) = -5*pi/180;
704 %         X(2,i) = 0;
705 %     end
706
707 %Si la perturbacion es mucha, deber a actualizarse la referencia para
708 %que vuelva gradualmente y no drasticamente a esta el sistema
709 %     if(abs(error) > dtheta_max/2)
710 %         ref(i+1) = (X(1,i)+ref(i))/2 ; %Promedio
711 %     end
712
713 %Actualizacion de error
714 %error_p = error;
715
716 end
717

```

```

718 display(k, 'Numero de restricciones de angulo')
719 %plot(t,X(2,:))
720
721 figure(6)
722 set(gcf, 'Color', [1,1,1])
723 subtitle('Escalon, sistema en torno a 0')
724 subplot(2,2,1)
725 hold on
726 plot(t, rad2deg(X(1,:)), 'b', 'Linewidth', 1.5)
727 plot(t, rad2deg(ref), 'r', 'Linewidth', 1.5)
728 %legendInfo{1} = ['Theta_L'];
729 %legendInfo{2} = ['Ref'];
730 legend('Theta_L', 'Ref')%, 'Location', 'best')%, 'Location', 'southeastinside')
731 hold off
732 subplot(2,2,3)
733 plot(t, rad2deg(U), 'g', 'Linewidth', 1.5)
734 xlabel('Angulo [ ]')
735 legend('Theta_M')%, 'Location', 'best')
736 subplot(2,2,2)
737 plot(t, rad2deg(ref-X(1,:)), 'magenta', 'Linewidth', 1.5)
738 legend('Error')%, 'Location', 'best')
739 subplot(2,2,4)
740 plot(t, rad2deg(X(1,:)-U), 'cyan', 'Linewidth', 1.5)
741 legend('Theta_L - Theta_M')%, 'Location', 'best')
742 %xlabel('Angulo [ ]')
743 %%
744 figure
745 plot(t, rad2deg(error_i), 'cyan', 'Linewidth', 1.5)
746 figure
747 plot(t, rad2deg(error_d), 'cyan', 'Linewidth', 1.5)

```

A.4. CAD Drawings

A.4.1. General View and Exploded View

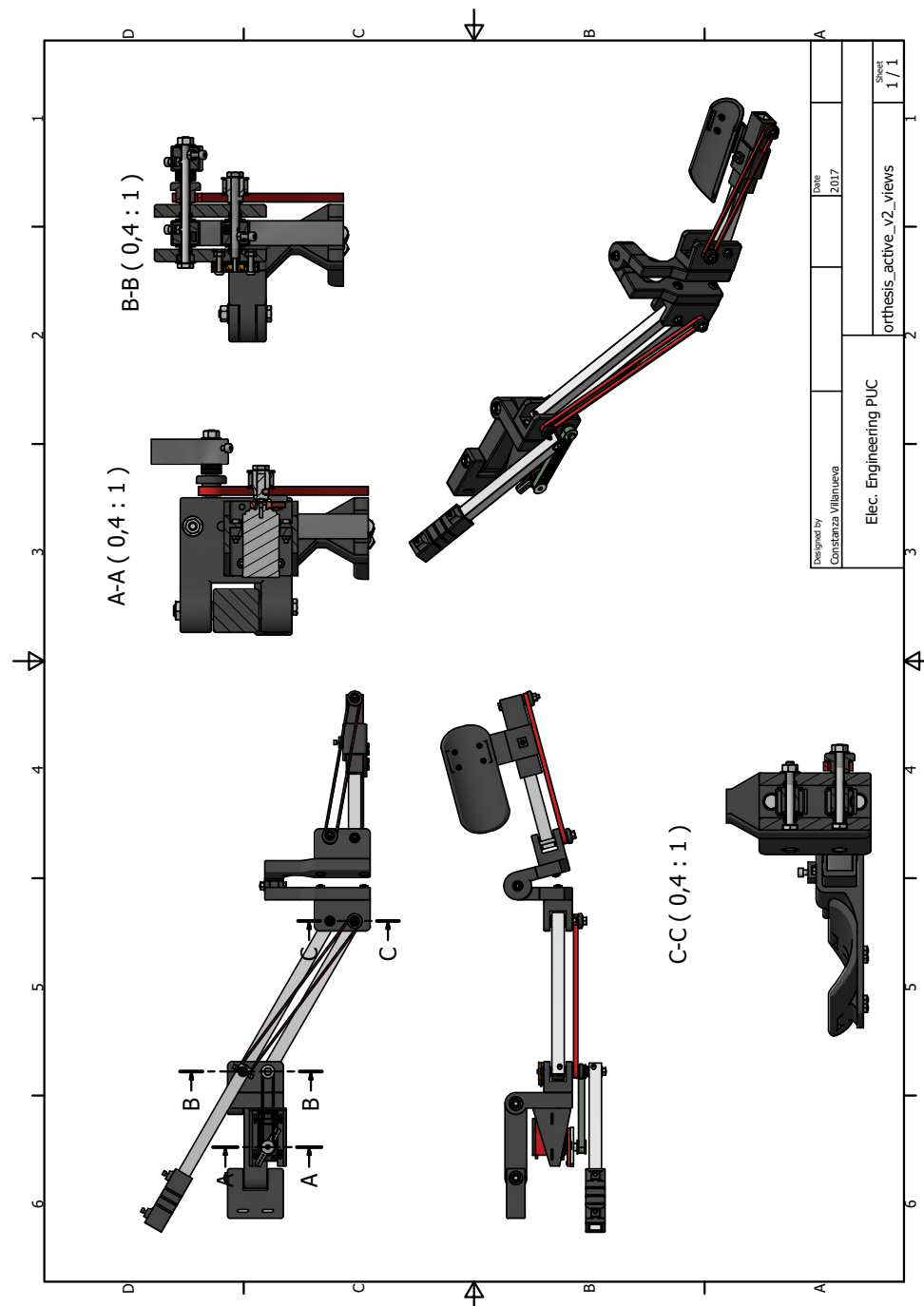


FIGURE A.4. Views of the CAD model



FIGURE A.5. Exploded view of the CAD model, includes all parts to assemble

A.4.2. Detailed Drawings

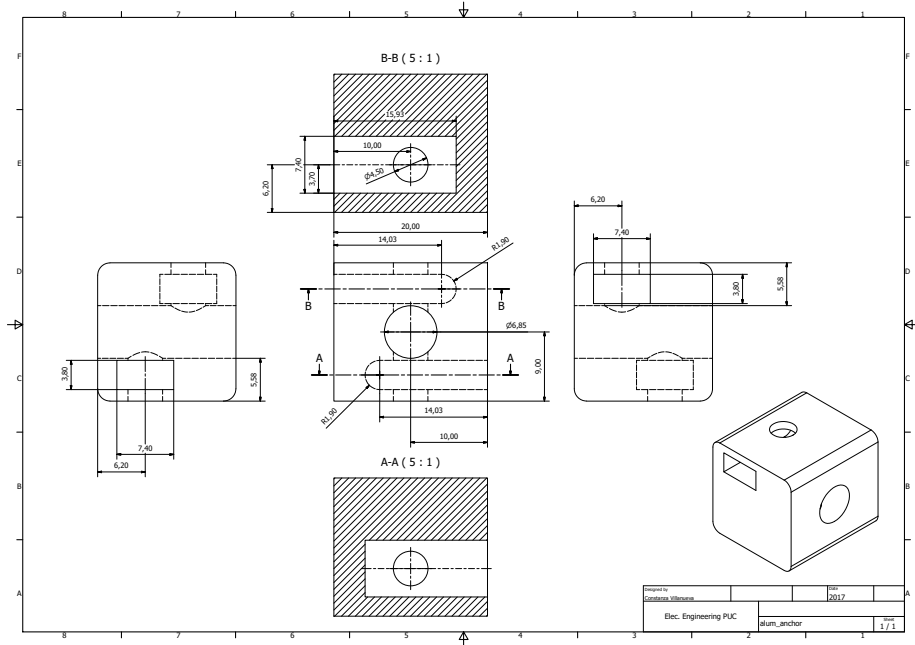


FIGURE A.6. Aluminum squared tube anchor

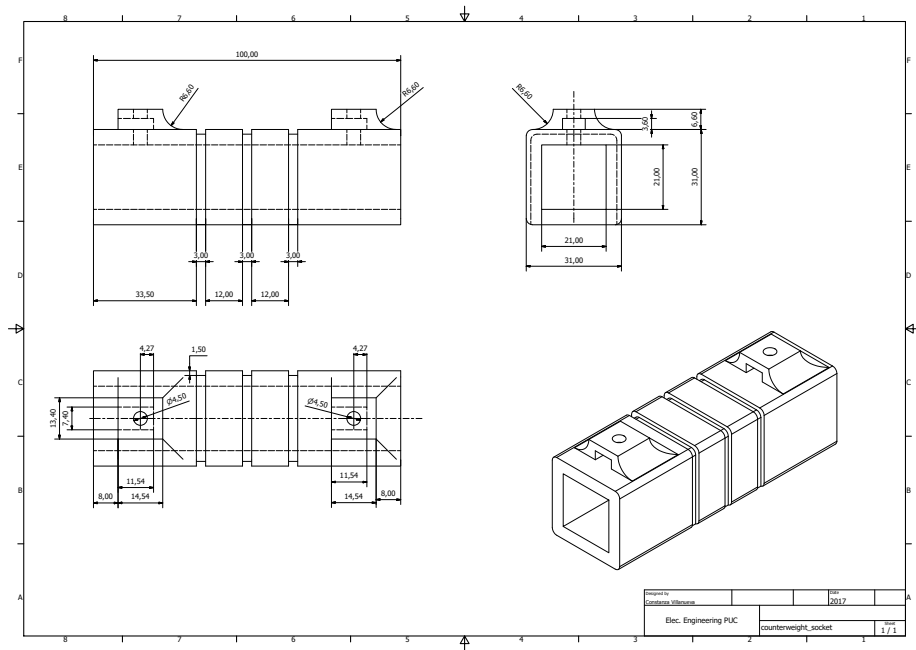


FIGURE A.7. Counterweight socket

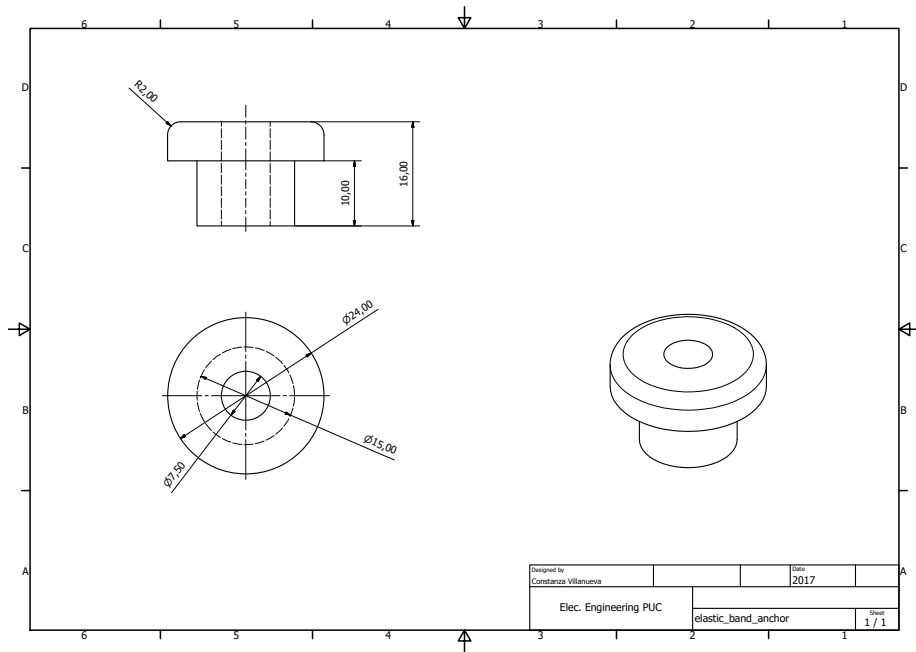


FIGURE A.8. Rubber band anchor

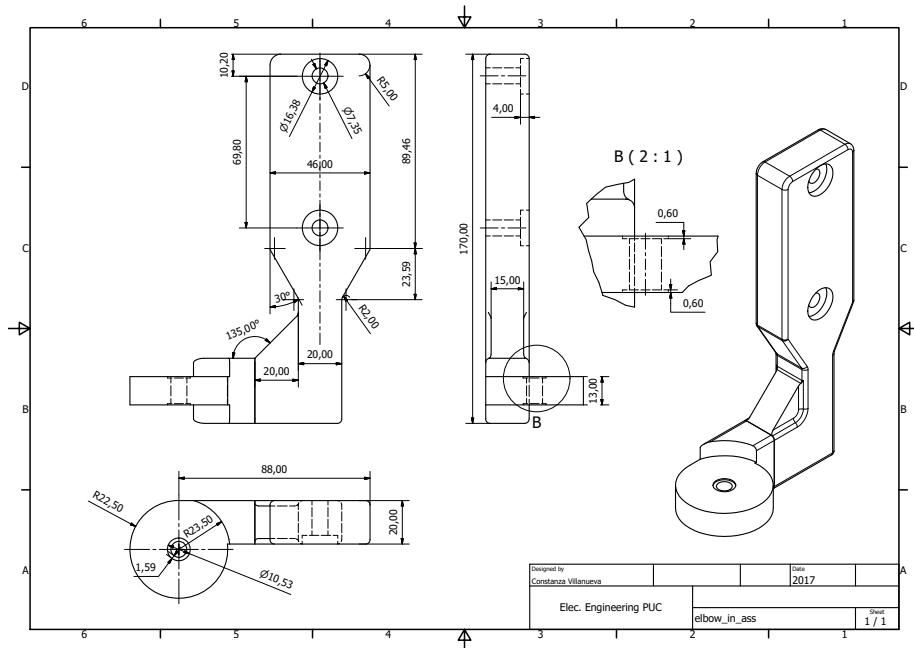


FIGURE A.9. Elbow interior assembly

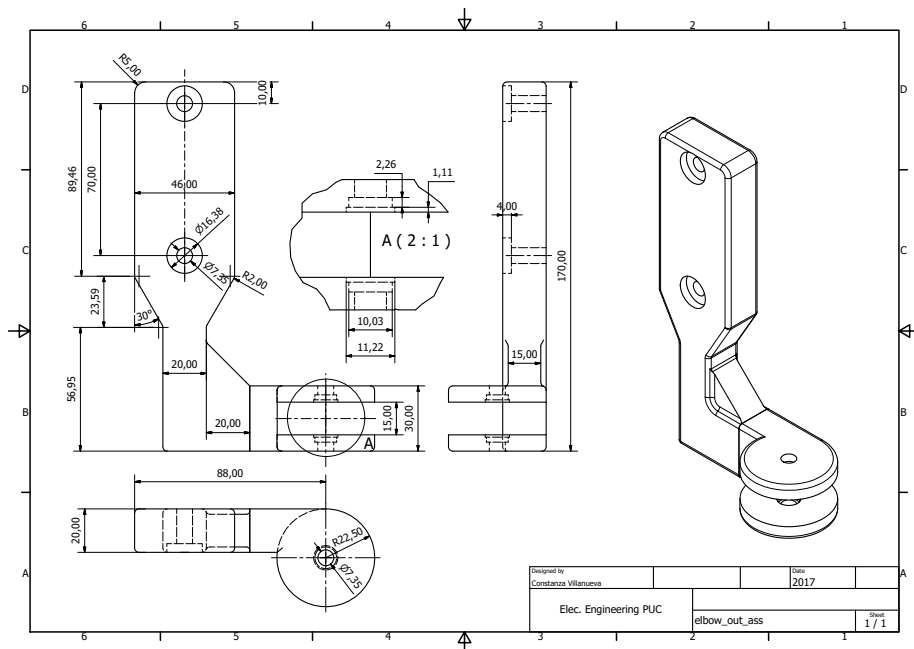


FIGURE A.10. Elbow outer assembly

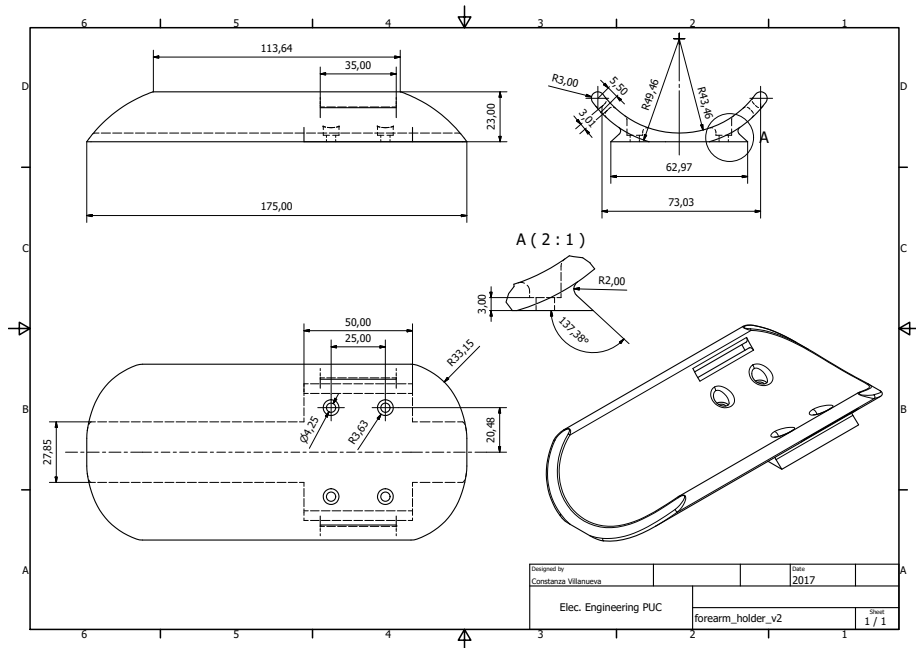


FIGURE A.11. Forearm holder

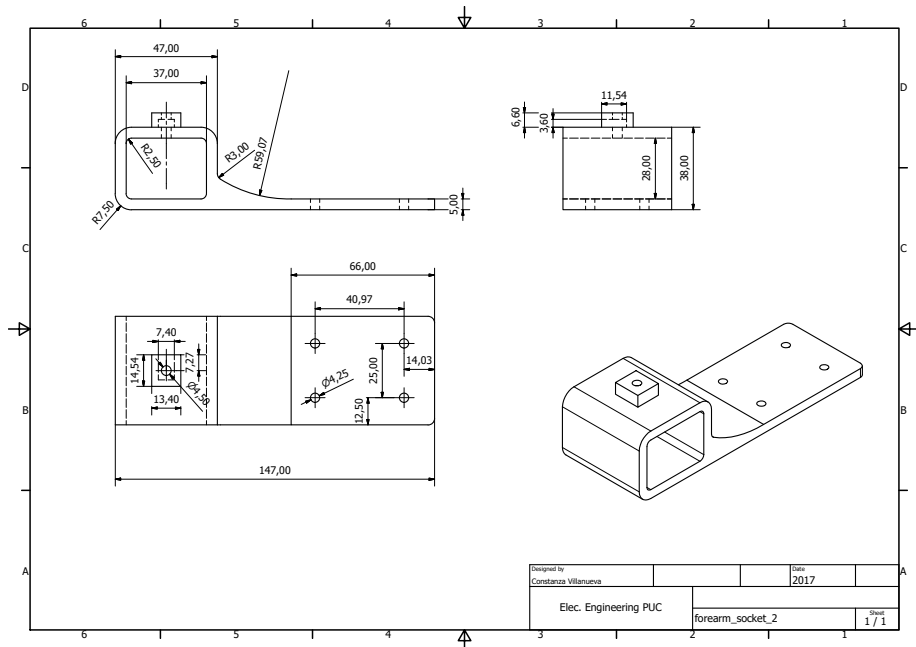


FIGURE A.12. Forearm socket

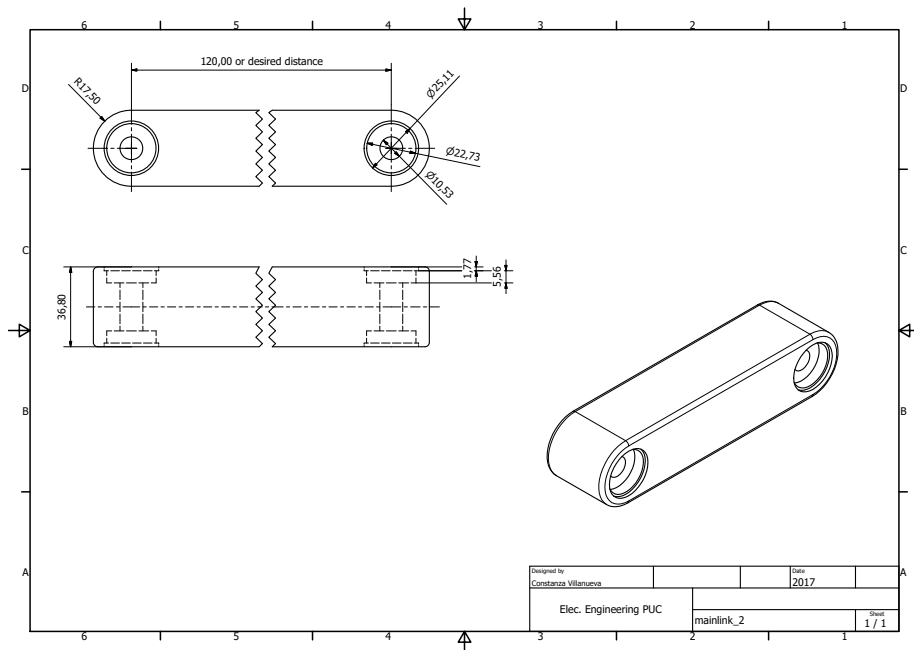


FIGURE A.15. Main link 2

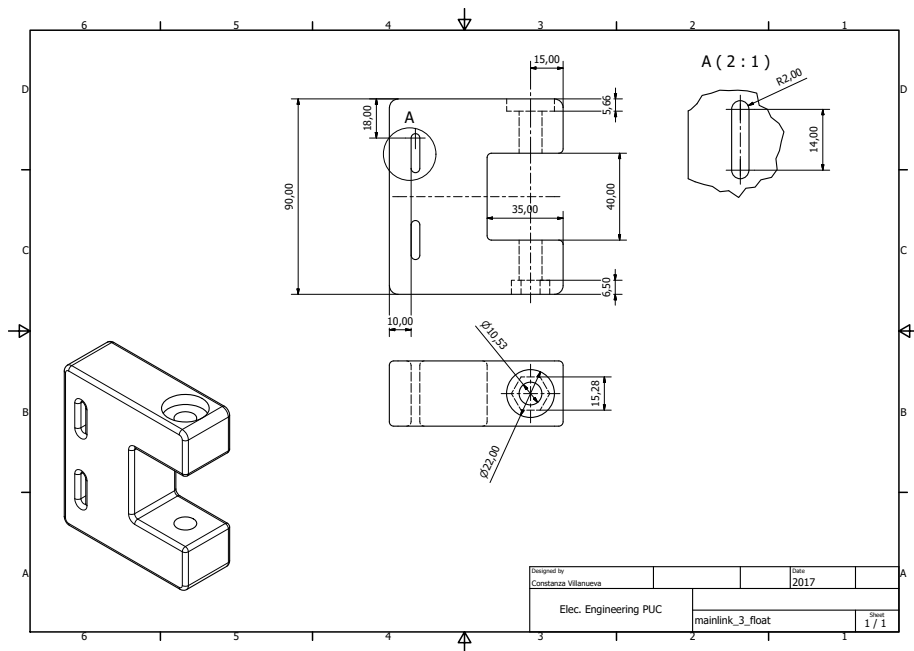


FIGURE A.16. Main link 3

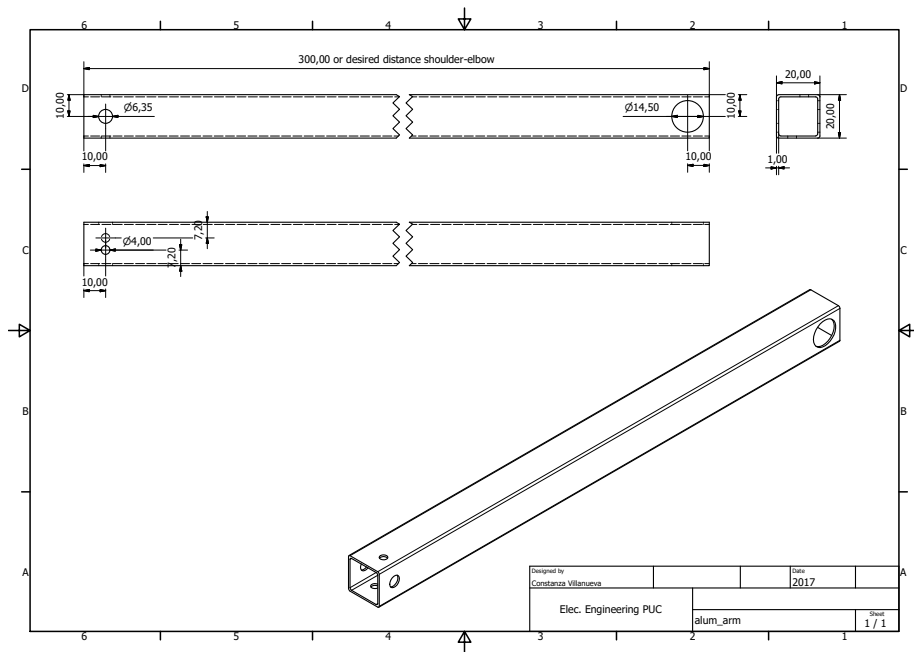


FIGURE A.17. Aluminum squared tube for arm

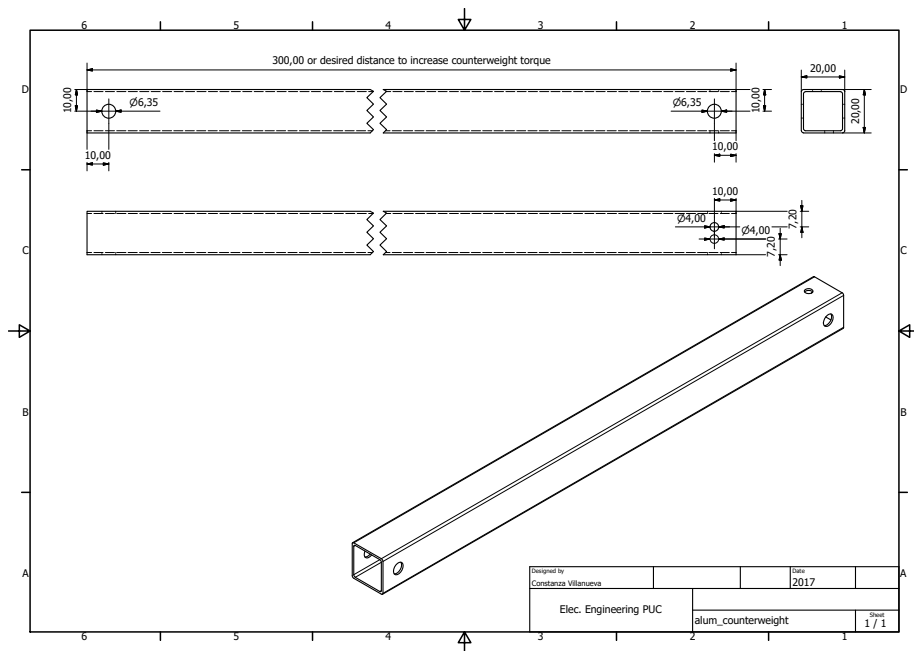


FIGURE A.18. Aluminum squared tube for counterweight

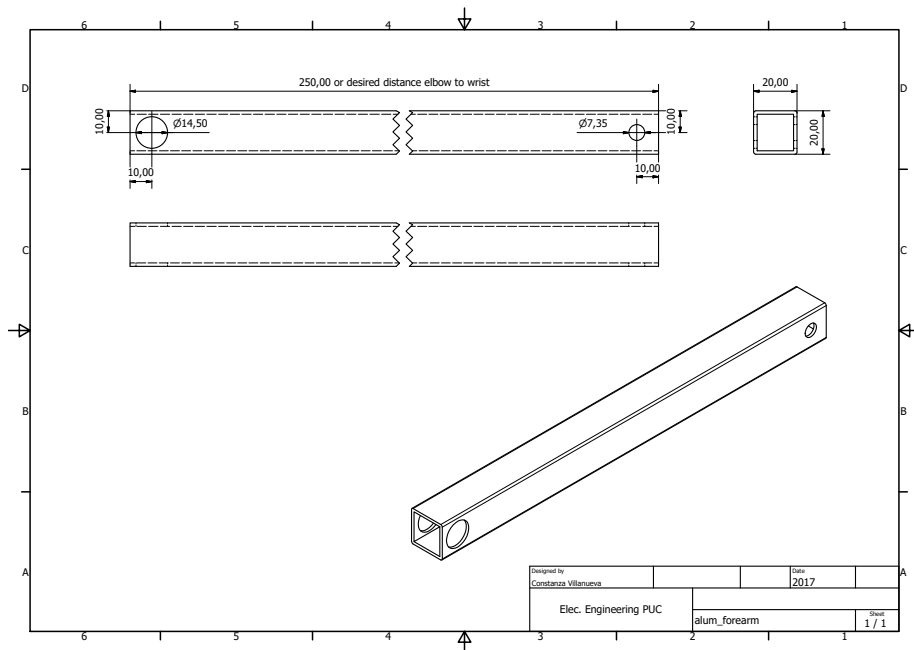


FIGURE A.19. Aluminum squared tube for forearm

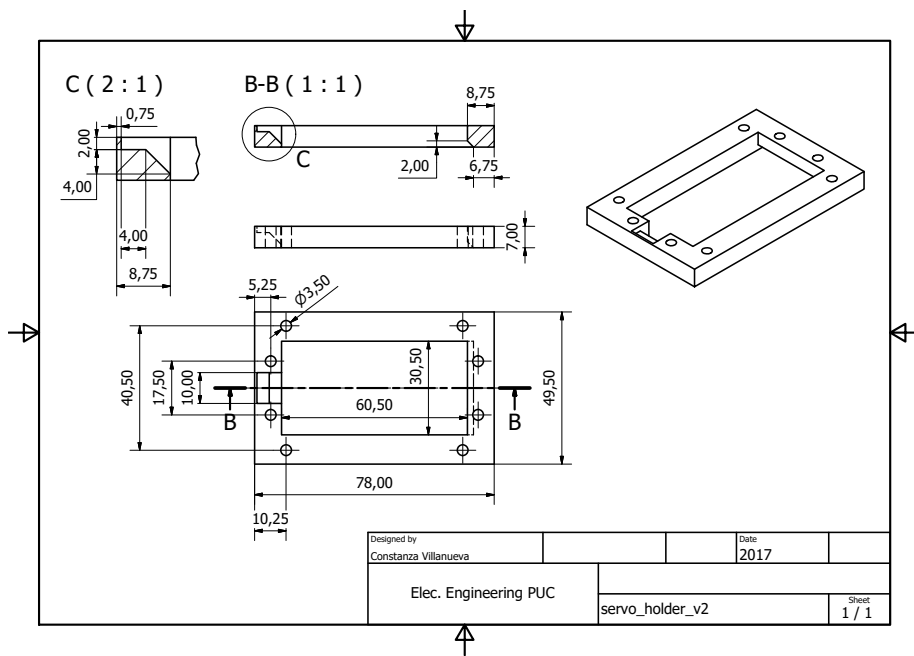


FIGURE A.20. Servomotor holder

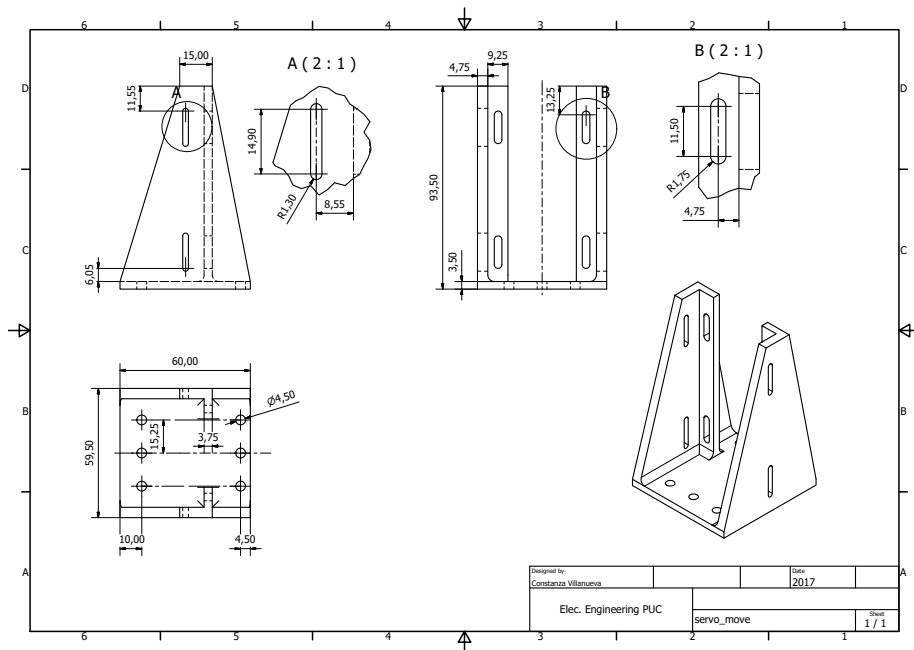


FIGURE A.21. Servomotor movable holder

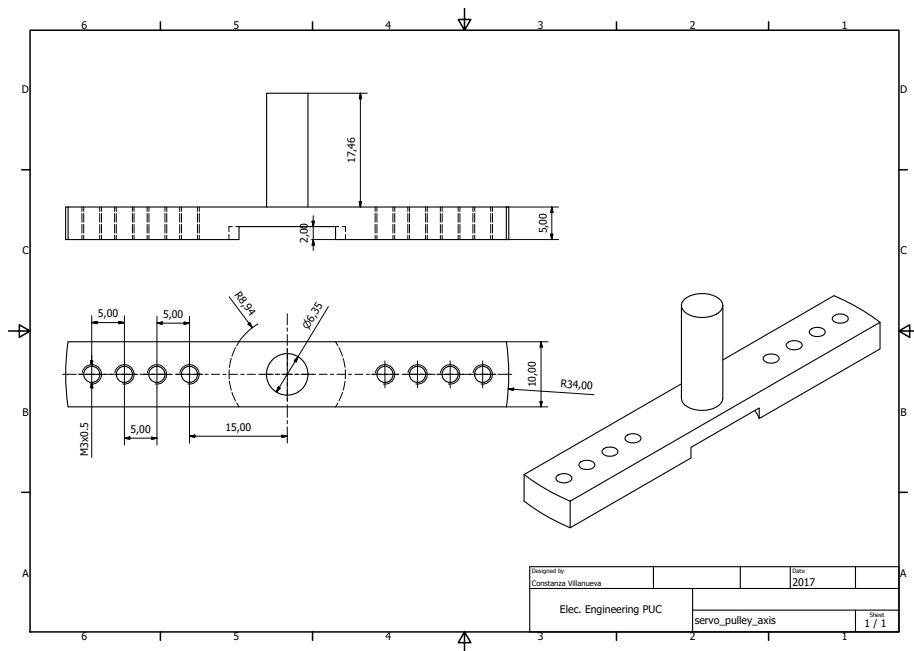


FIGURE A.22. Servomotor pulley axis

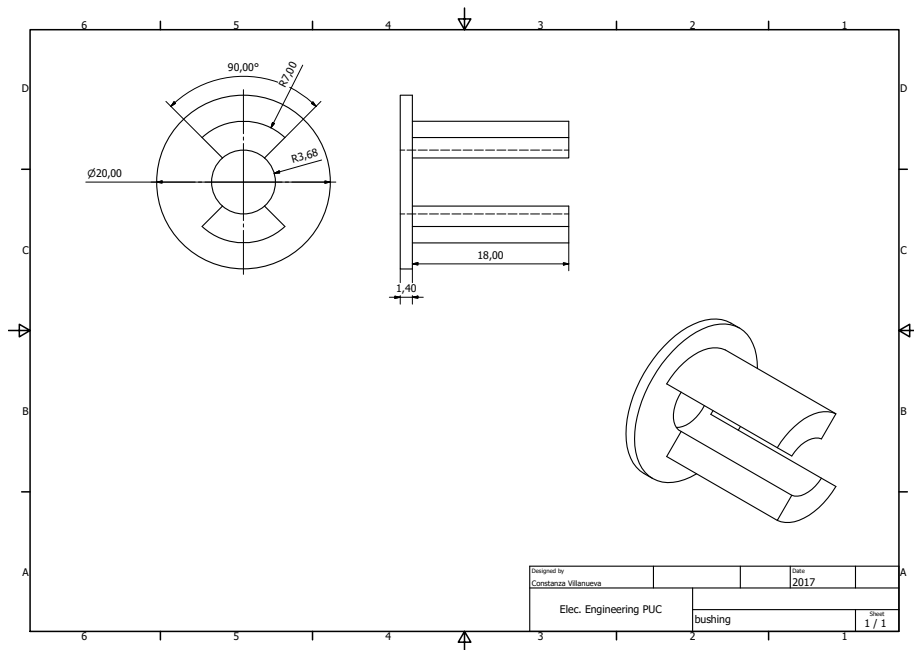


FIGURE A.23. Bushing

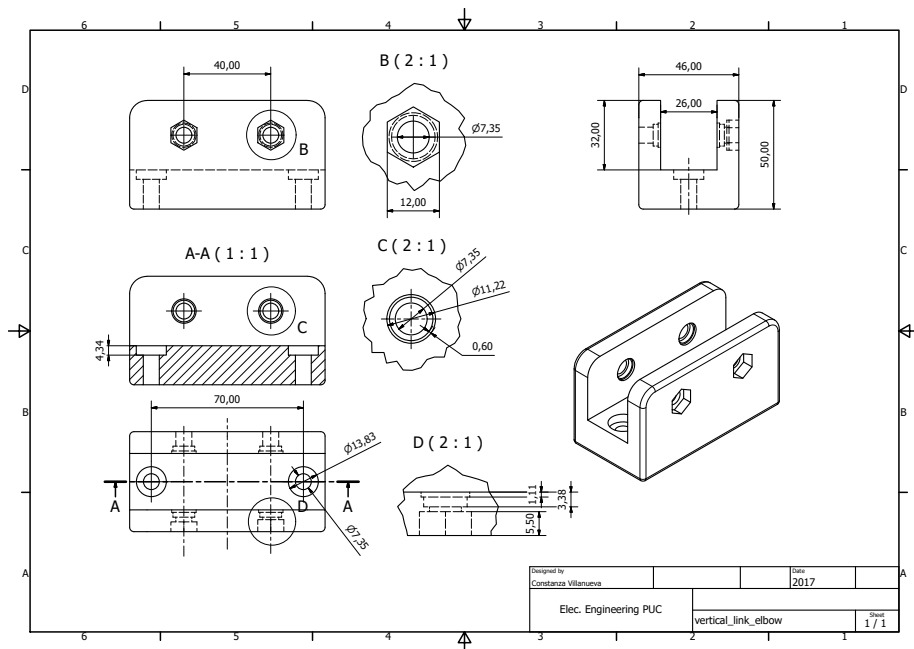


FIGURE A.24. Vertical link at elbow

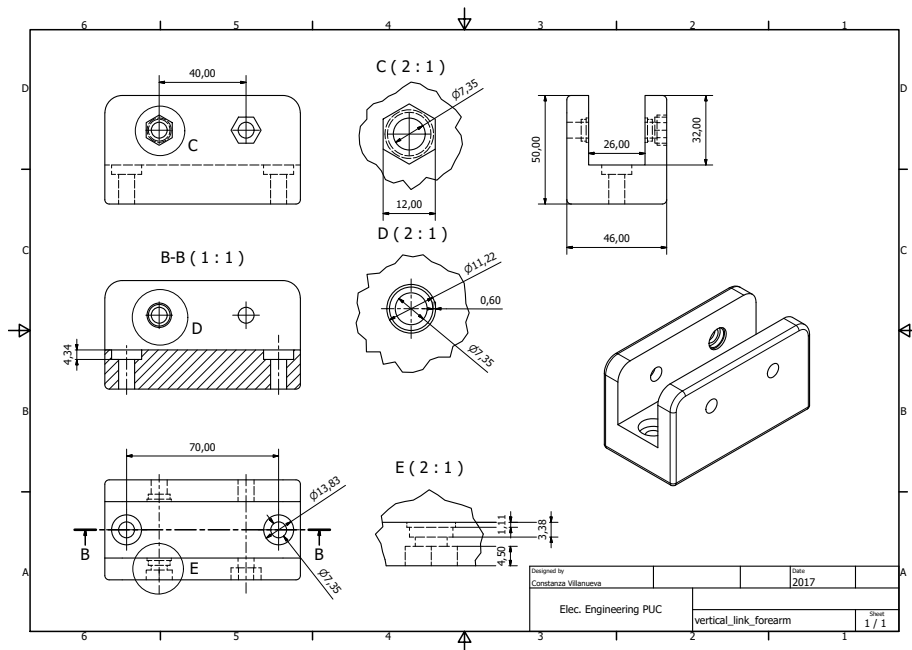


FIGURE A.25. Vertical link at forearm

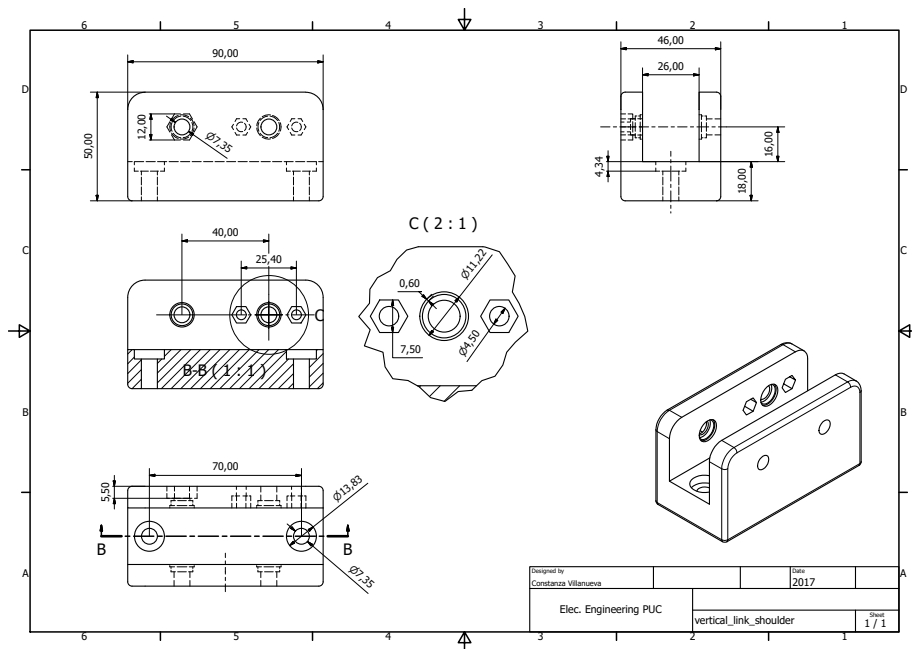


FIGURE A.26. Vertical link at shoulder

A.5. Detailed Costs

Item	Store	Unit Price	Units Used	Final Price
ABS Filament 1kg	Makerbot	US\$ 48.00	0.75	US\$ 36.00
Rubber Bands pack	Jumbo	US\$ 0.44	1	US\$ 0.44
Aluminium Squared Tube 6 mts	Maquimetal	US\$ 14.71	0.14	US\$ 2.08
Hex Screws Inch	Sodimac	US\$ 1.02	16	US\$ 16.35
Hex Nut Inch	Sodimac	US\$ 0.33	16	US\$ 5.29
Washer Inch	Sodimac	US\$ 0.15	16	US\$ 2.35
Socket Screw Metric	RS Components	US\$ 0.59	4	US\$ 2.35
Hex Nut Metric	RS Components	US\$ 0.10	4	US\$ 0.40
TOTAL PRICE				US\$ 65.28

TABLE A.8. Passive Orthosis Detailed Costs

Item	Store	Unit Price	Units Used	Final Price
ABS Filament 1kg	Makerbot	US\$ 48.00	1	US\$ 48.00
Rubber Bands pack	Jumbo	US\$ 0.44	1	US\$ 0.44
Aluminium Squared Tube 6 mts	Maquimetal	US\$ 14.71	0.19	US\$ 2.82
Hex Screws Inch	Sodimac	US\$ 1.02	16	US\$ 16.35
Hex Nut Inch	Sodimac	US\$ 0.33	15	US\$ 4.96
Washer Inch	Sodimac	US\$ 0.15	28	US\$ 4.12
Socket Screw Metric	RS Components	US\$ 0.59	22	US\$ 12.94
Buttton Screw Metric	RS Components	US\$ 0.21	4	US\$ 0.82
Hex Nut Metric	RS Components	US\$ 0.10	24	US\$ 2.40
Bearing 1/4"	SDP-SI	US\$ 6.87	12	US\$ 82.44
Bearing 3/8"	SDP-SI	US\$ 12.60	4	US\$ 50.40
Spacer 1/4"	SDP-SI	US\$ 1.98	15	US\$ 29.70
Spacer 3/8"	SDP-SI	US\$ 3.92	4	US\$ 15.68
Giant Servo HD-1235MG	Pololu	US\$ 59.95	1	US\$ 59.95
Metal Horn	Pololu	US\$ 8.95	1	US\$ 8.95
Potentiometer	VEX Robotics	US\$ 6.50	1	US\$ 6.50
Dented Belt	Olimex	US\$ 10.13	1	US\$ 10.13
Dented Pulley	Olimex	US\$ 11.01	2	US\$ 22.03
Aluminium Stock Custom	Online Metals	US\$ 6.00	1	US\$ 6.00
Arduino Uno	Arduino	US\$ 24.95	1	US\$ 24.95
Bluetooth Module HC-06	Amazon	US\$ 12.00	1	US\$ 12.00
TOTAL PRICE				US\$ 421.59

TABLE A.9. Active Orthosis Detailed Costs

A.6. Servomotor datasheet

1. 使用環境條件

Apply Environmental Condition :

No.	項目	規格
1-1	保存溫度 Storage Temperature Range	-20℃ ~ 60℃
1-2	操作溫度 Operating Temperature Range	-10℃ ~ 50℃
1-3	操作電壓 Operating Voltage Range	6V ~ 7.4V

2. 測試環境

Standard Test Environment :

2-1	測試環境 Standard Test Environment	每一個檢查必須是正常的溫度和濕度進行測量，溫度 $25 \pm 5^{\circ}\text{C}$ ，相對濕度 $65 \pm 10\%$ ，在按照本規範的標準測試條件下判斷特徵。
-----	-----------------------------------	---

3. 外觀檢查

Appearance Inspection :

No.	項目	規格
3-1	外觀尺寸 Outline Drawing	尺寸見附件 Dimension see the attachment
3-2	外觀 Appearance	無損壞，不允許影響功能

4. 電 氣 特 性

Electrical Specification (Function of the Performance) :

No.	Item	6V	7.4V
4-1	空載轉速 Operating speed (at no load)	0.2 sec/60°	0.18 sec/60°
4-2	空載電流 Running current (at no load)	700 mA	900 mA
4-3	停止扭力 Stall torque (at locked)	35kg-cm,	40kg-cm
4-4	停止電流 Stall current (at locked)	7.5A	9.0A
4-5	待機電流 Idle current (at stopped)	10 mA	15 mA

注：项目 4-2 定义平均值时，伺服器无负荷运行

5. 機 械 特 性

Mechanical Specification :

No.	项目	规格
5-1	外觀尺寸 Overall Dimensions	59.5*29 *55
5-2	機構極限角度 Limit angle	180°± 10°
5-3	重量 Weight	165± 1 g
5-4	導線規格 Connector wire gauge	# 28 PVC
5-5	導線長度 Connector wire length	300 ± 5 mm
5-6	舵片規格 Horn gear spline	17T/ ϕ 8.80
5-7	舵片種類 Horn type	半臂，一字
5-8	減速比 Reduction ratio	188: 1



Product Name
数字伺服器 Digital Servo

Model No.
1235MG

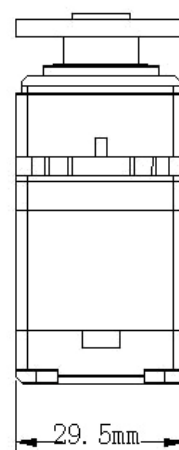
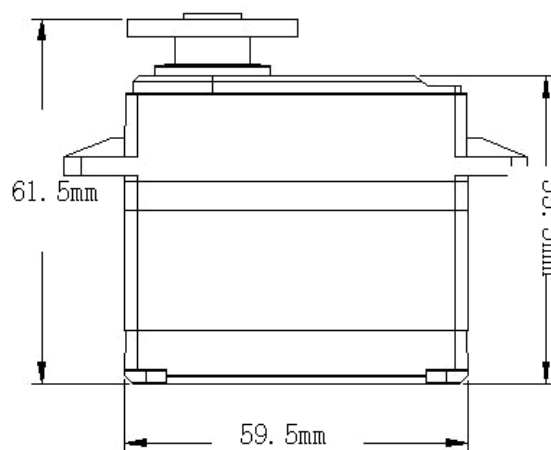
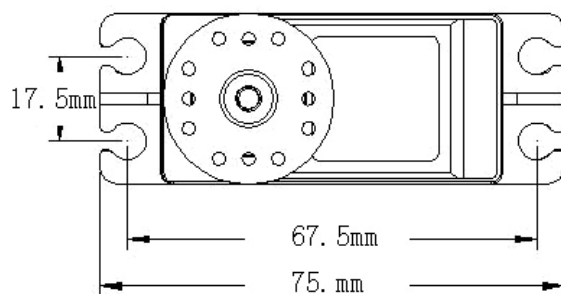
Version
V1

Page
2/3

6. 控制特性

Control Specification :

No.	项目	规格
6-1	控制系统 Control system	改变脉冲宽度 Pulse Width Modification
6-2	放大器種類 Amplifier type	330Hz 数字控制器 330Hz Digital Controller
6-3	操作角度 Operating travel	90° (在 1000→2000 μ sec)
6-4	中立位置 Neutral position	1500 μ sec
6-5	脈波訊號虛位 Dead band width	4 μ sec
6-6	旋轉方向 Rotating direction	逆时针 (在 1500→2000 μ sec) Anticlockwise (when 1500→2000 μ sec)
6-7	脈波寬度範圍 Pulse width range	800→2200 μ sec
6-8	可作動角度範圍 Maximum travel	大约 165°(在 800→2200 μ sec) Approx 165°(when 800→2200 μ sec)



Product Name
数字伺服器 Digital Servo

Model No.
1235MG

Version
V1

Page
3/3

A.7. Arduino

In order to control the active orthosis, a servomotor was installed in the prototype, and to controlled an Arduino was used. Libraries for this system are available free on the Internet and the servomotor controlling is very used. To control the servomotor only a PWM is needed. The library enables the user to only give a position in degrees to the servomotor, while the library manages the interruptions and clocks so the proper PWM is delivered to the servomotor.

To connect the servomotor, only a digital pin was used; it can be any PWM enabled pin of the Arduino board, in this case, pin 9 was used. Power supply to the servomotor is delivered from an external source, since the voltage and current requirements are more that the Arduino can deliver. Grounds of servomotor, power supply and Arduino must be connected.

Communication with the Arduino commanding the servomotor was made through a Smartphone App using Bluetooth communication. The connection of the module used can be seen in the Fig. A.27, retrieved from <https://tinyurl.com/yccmr5vz>. It is important to notice that this connection can not be used while programming the Arduino from a computer over USB.

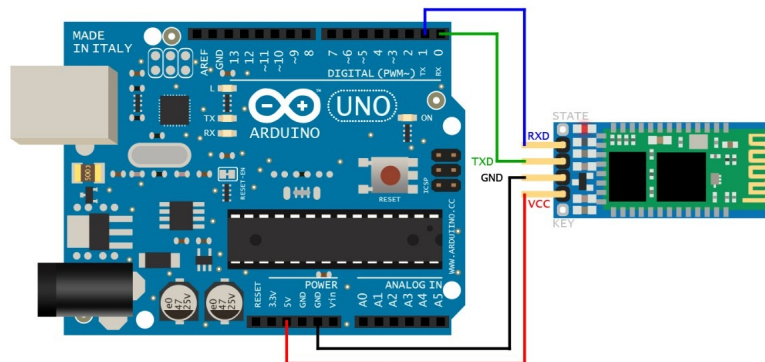


FIGURE A.27. Arduino schematic connection for HC-06 Bluetooth Module

The app can be configured in joypad mode to send serial characters that are processed in the code as specif commands such as moving the servomotor 15 degrees up, or down, or change the increment step, etc. Code used can be found below.

```

1  // #include <Servo.h>
2  #include <VarSpeedServo.h>
3
4  // Servo myservo; // create servo object to control a servo
5  VarSpeedServo myservo;
6
7  int pot = 0; // analog pin used to connect the potentiometer
8  float theta_L;
9  int theta_L_map;
10 int theta_M;
11 int theta_M_servo;
12 int button = 'o';
13 int ref = 0;
14 int delta = 1;
15 int ref_new = 0;
16 boolean pressed = false;
17 int dtime = 30;
18 int Kp = 1;
19 int error = 0;
20
21 void setup() {
22     // put your setup code here, to run once:
23     myservo.attach(9); // attaches the servo on pin 9 to the servo object
24     pinMode(7, OUTPUT); // up button
25     pinMode(6, OUTPUT); // down button
26     pinMode(5, OUTPUT); // ref step 1
27     pinMode(4, OUTPUT); // ref step 2
28     pinMode(3, OUTPUT); // ref step 3
29     Serial.begin(9600);
30 }
31
32 void loop() {
33     // put your main code here, to run repeatedly:
34
35     if(Serial.available() > 0){ // lee el bluetooth y almacena en estado
36         button = Serial.read();
37     }
38     if(button == 's'){ // comienza el servo en 0 grados, aka 90
39         myservo.write(90, 20, true);
40         // delay(15);
41         ref_new = 0;
42         pressed = true;
43     }
44     // else if(button == '1'){ // delta de ref es 1
45         // digitalWrite(5, HIGH);
46         // delay(15);
47         // digitalWrite(5, LOW);
48         // delta = 1;
49         // pressed = true;
50         // dtime = 30;
51         // }
52     else if(button == '2'){
53         digitalWrite(4, HIGH);
54         delay(15);
55         digitalWrite(4, LOW);
56         delta = 5;
57         pressed = true;
58         dtime = 150; // 30*5
59     }
60     else if(button == '3'){

```



```

61         digitalWrite(3,HIGH);
62         delay(15);
63         digitalWrite(3,LOW);
64         delta = 15;
65         pressed = true;
66         dtime = 210;//30*7
67     }
68     else if(button=='t' and pressed==false){ // ir a top 45
69         ref_new = 45;
70         pressed = true;
71     }
72     else if(button=='b' and pressed==false){ // ir a bottom -45
73         ref_new = -45;
74         pressed = true;
75     }
76     else if(button=='u' and pressed==false){ // Subir referencia
77         digitalWrite(7,HIGH);
78         delay(15);
79         digitalWrite(7,LOW);
80         ref_new = ref + delta;
81         pressed = true;
82     }
83     else if(button=='d' and pressed==false){ // Bajar referencia
84         digitalWrite(6,HIGH);
85         delay(15);
86         digitalWrite(6,LOW);
87         ref_new = ref - delta;
88         pressed = true;
89     }
90     else if(button=='p'){ // parar referencia
91         delay(15);
92         pressed = false;
93     }
94
95     Serial.flush();
96
97     theta_L = analogRead(pot); // reads the value of the
98     // potentiometer (value between 0 and 1023)
99     theta_L_map = map(theta_L, 90, 860, -90, 90); // scale it to use it with the
100     // servo (value between 0 and 180)
101
102     if(ref_new > 90){
103         ref_new = 90;
104     }
105     else if(ref_new < -90){
106         ref_new = -90;
107     }
108
109     if( pressed == true ){
110         theta_M = ref_new; //control directo de referencia igual al servo
111         //error = ref_new - theta_L_map;
112         //theta_M = Kp * error;
113     }
114     //aca se puede agregar que si va muy rapido se hacen dos iteraciones
115     // asi se disminuye la velocidad, o se usa la lib de speed
116
117     theta_M_servo = map(theta_M, -90, 90, 0, 180);
118
119     if (theta_M_servo > 180){
120         theta_M_servo = 180;

```

```

119     }
120     else if (theta_M_servo < 0){
121         theta_M_servo = 0;
122     }
123
124     myservo.write(theta_M_servo,10,true);
125     // delay(dtime);
126
127     Serial.print("Theta L: ");
128     Serial.print("\t");
129     Serial.print(theta_L);
130     Serial.print("\t");
131     Serial.print("Theta L Map: ");
132     Serial.print("\t");
133     Serial.print(theta_L_map);
134     Serial.print("\t");
135     Serial.print("Ref: ");
136     Serial.print("\t");
137     Serial.print(ref_new);
138     Serial.print("\t");
139     // Serial.print("Error: ");
140     // Serial.print("\t");
141     // Serial.print(error);
142     // Serial.print("\t");
143     Serial.print("Theta Servo: ");
144     Serial.print("\t");
145     Serial.print(theta_M_servo);
146     Serial.println("");
147
148     ref = ref_new;
149
150 }

```

A.8. Additional Printing References

In this document, it was stated that for optimal performance, printing orientation of the piece on the printing bed should be considered in order to optimize the layer orientation of the piece, improving the stiffness. Orientation will also make a difference when considering adding or not support to certain pieces, and design modifications were considered to not use support in specific situations.

For each piece that was printed, a screenshot of the desirable printing orientation is shown below. This can be easily imported into the Makerbot Desktop Software as .thing file, but this is exclusive to Makerbot printers. For other printers use the picture as reference to orientation. When printing small parts, it is recommended to print more than one at a time, positioning them on the table as separated as possible.

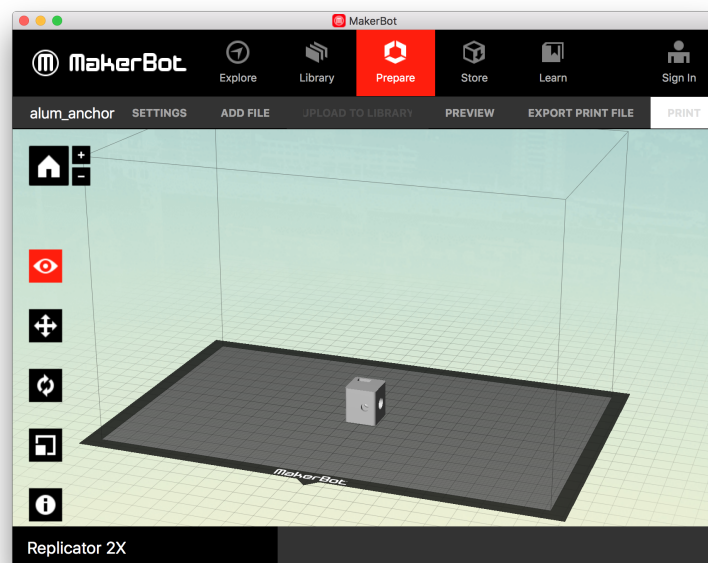


FIGURE A.28. Thing: Aluminum squared tube anchor

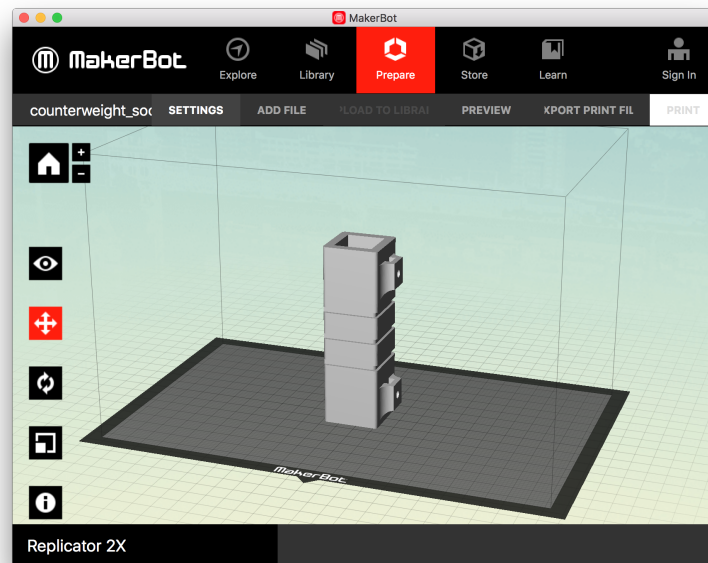


FIGURE A.29. Thing: Counterweight socket

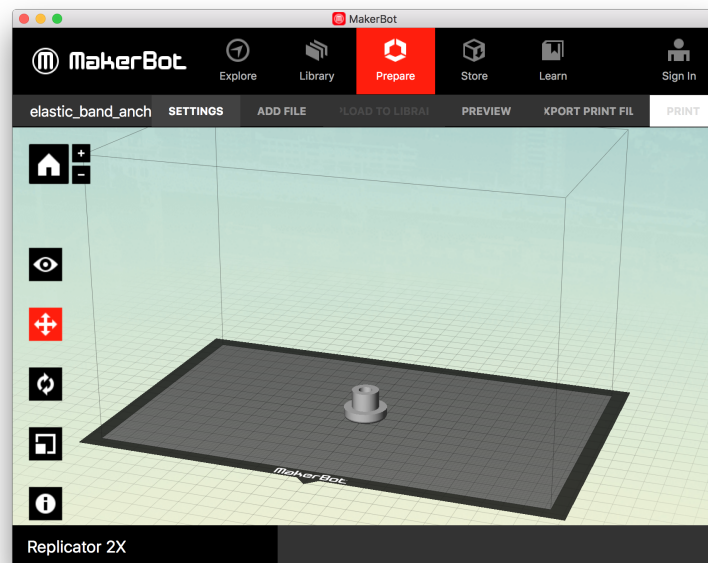


FIGURE A.30. Thing: Rubber band anchor

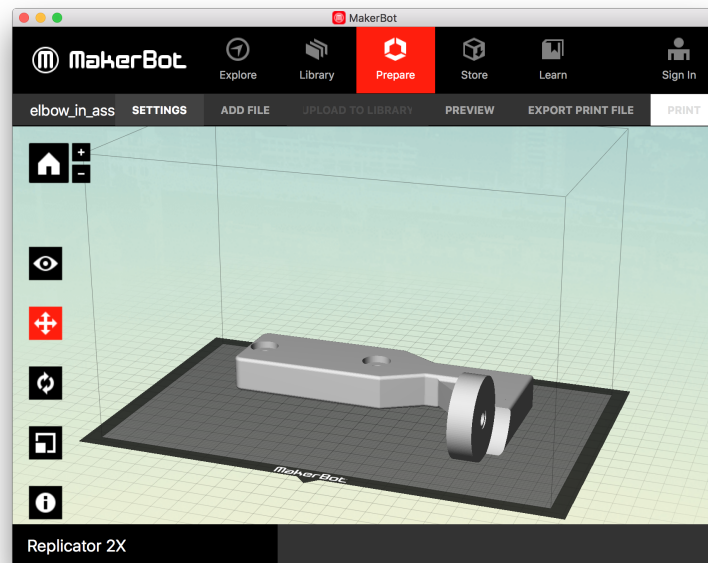


FIGURE A.31. Thing: Elbow interior assembly

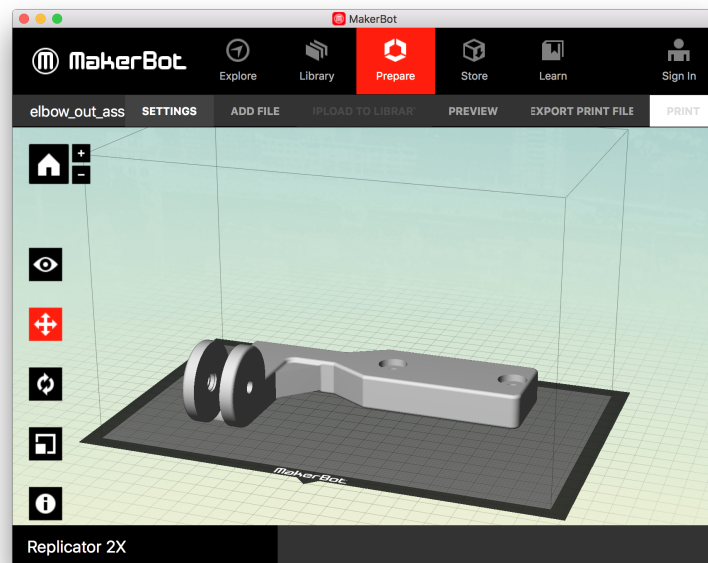


FIGURE A.32. Thing: Elbow outer assembly

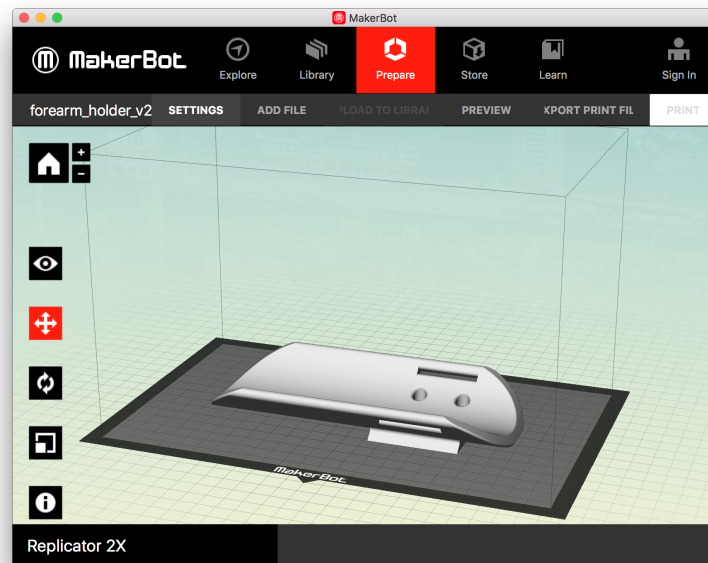


FIGURE A.33. Thing: Forearm holder

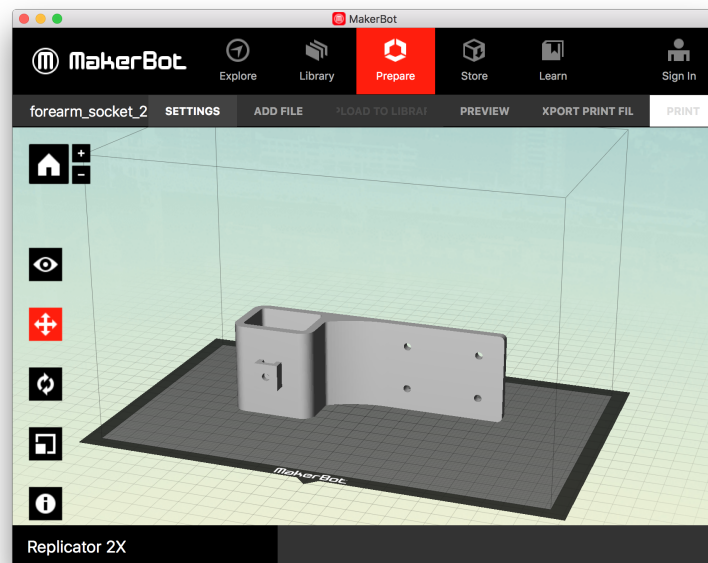


FIGURE A.34. Thing: Forearm socket

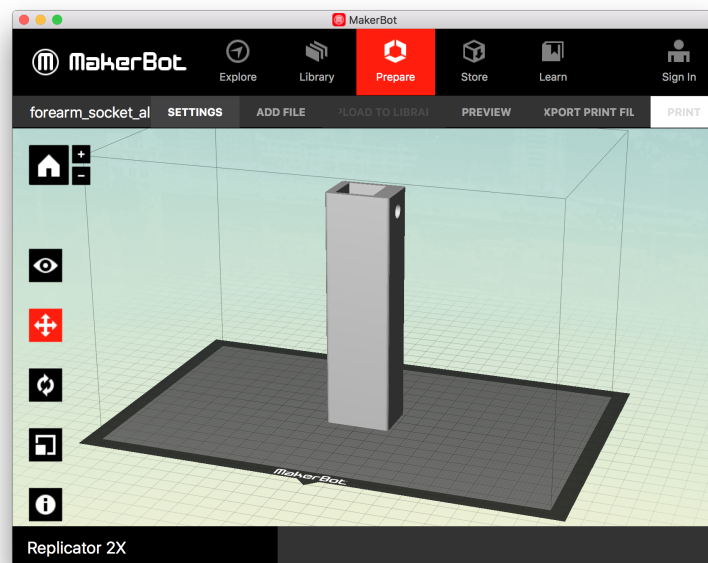


FIGURE A.35. Thing: Forearm socket aluminum

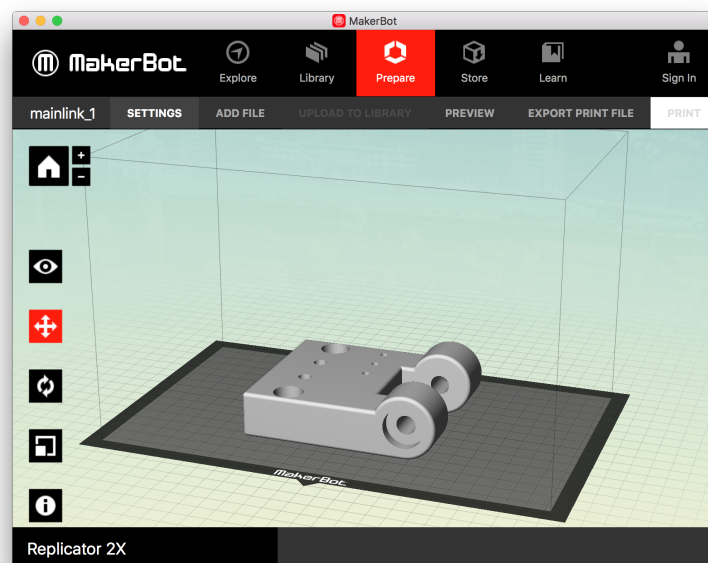


FIGURE A.36. Thing: Main link 1

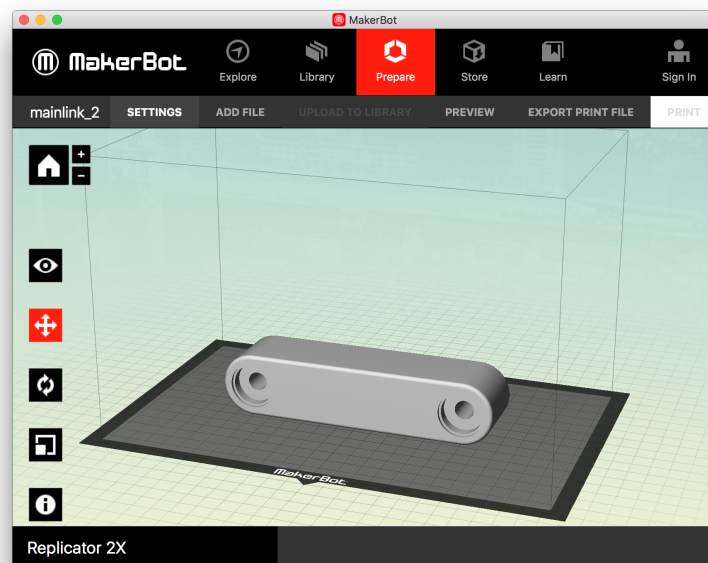


FIGURE A.37. Thing: Main link 2

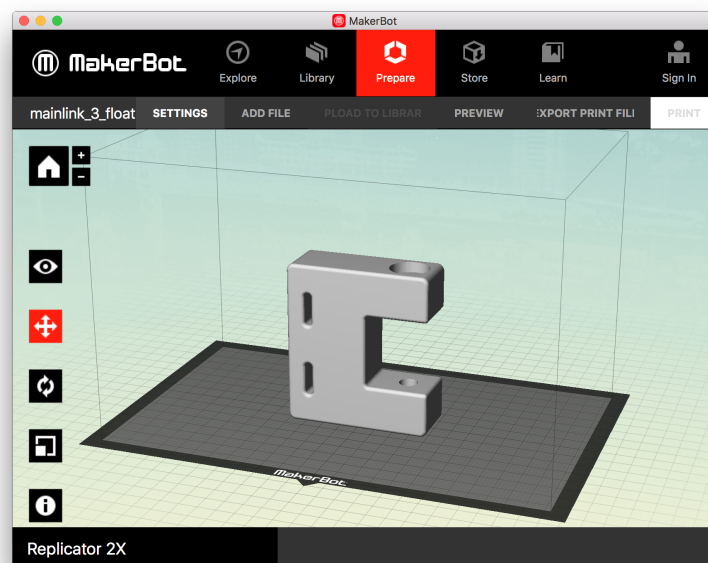


FIGURE A.38. Thing: Main link 2

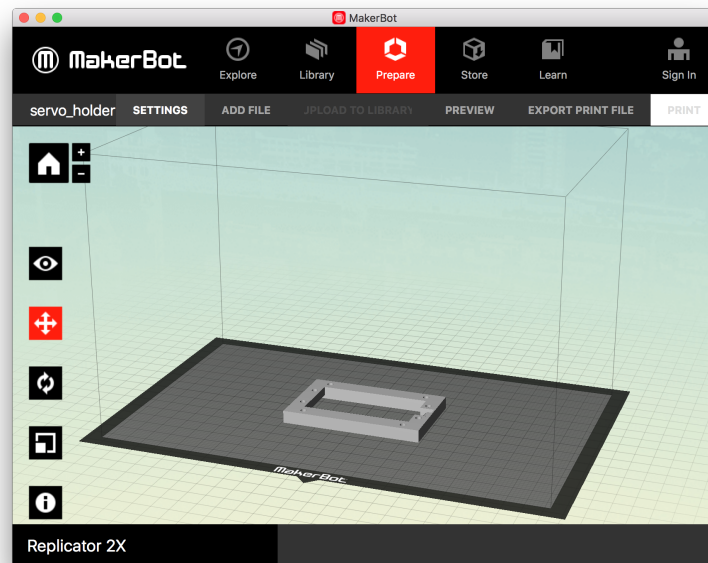


FIGURE A.39. Thing: Servomotor holder

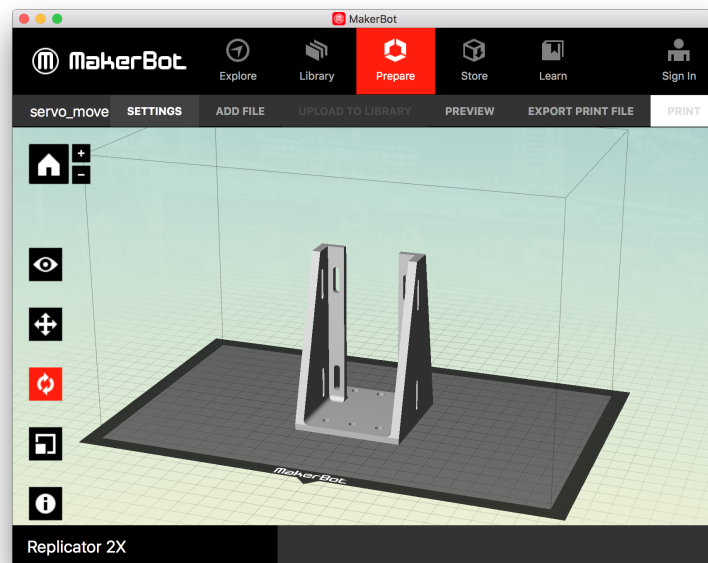


FIGURE A.40. Thing: Servomotor movable holder

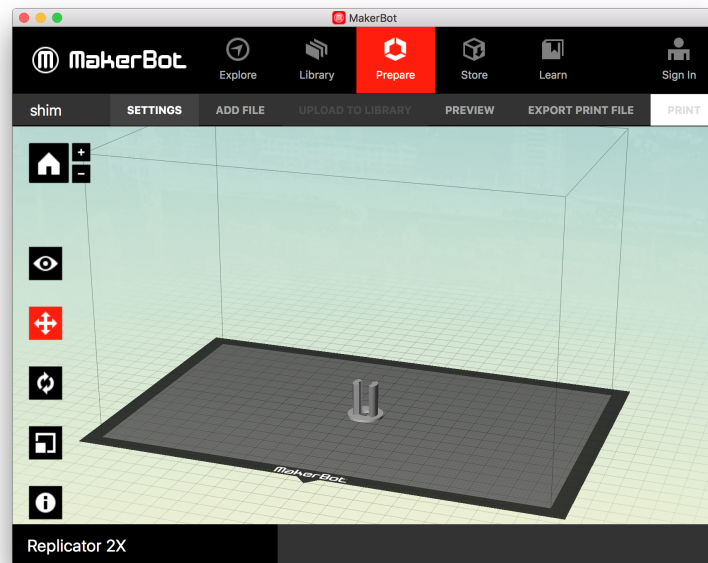


FIGURE A.41. Thing: Bushing

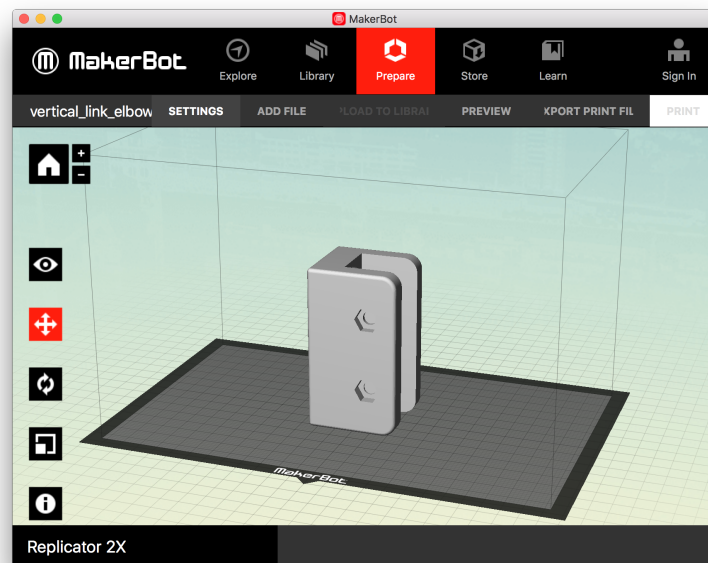


FIGURE A.42. Thing: Vertical link at elbow

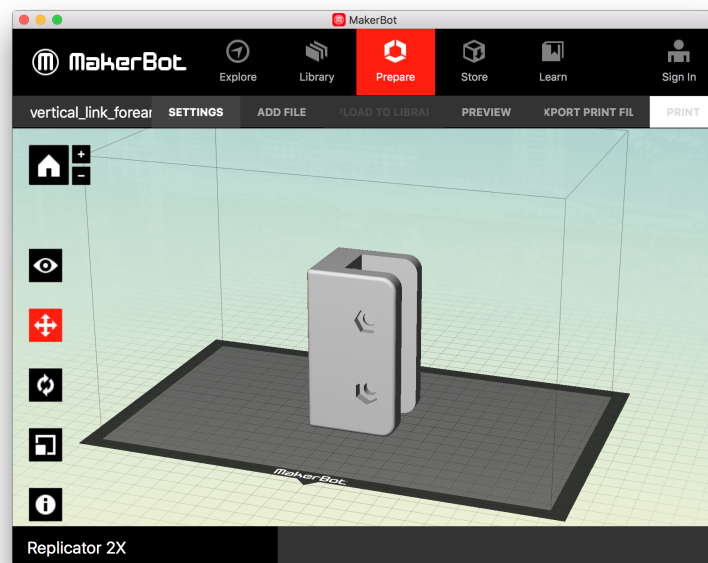


FIGURE A.43. Thing: Vertical link at forearm

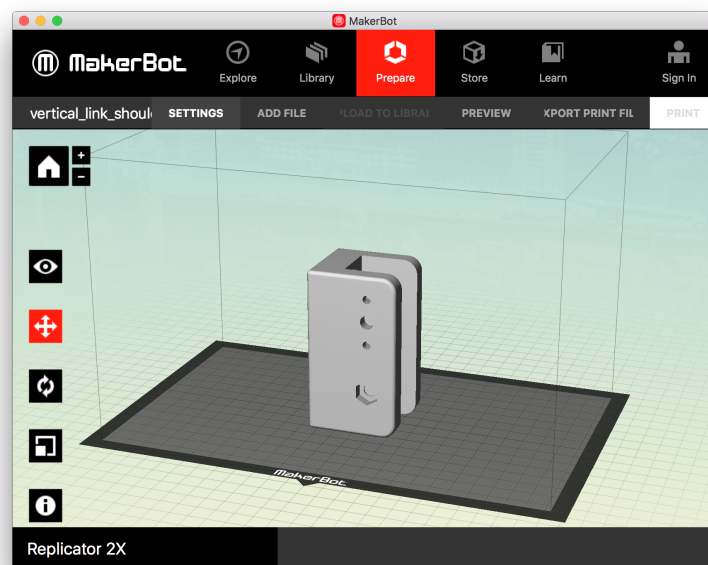


FIGURE A.44. Thing: Vertical link at shoulder

A.9. CEDETI Functional Evaluation Guide

Manual Evaluación Funcional

Introducción:

El presente manual consiste en una guía de aplicación de una escala de evaluación de funcionalidad de extremidades superiores (EESS) válida para enfermedades neuromusculares (ENM) como la Distrofia muscular de Duchenne (DMD). Este instrumento es especialmente útil para evaluar la funcionalidad de niños o adultos que se encuentren en etapas posteriores a la pérdida de la marcha y entrega información objetiva que permite evaluar el efecto de intervenciones terapéuticas así como la progresión en el tiempo de la condición, ayudando a mejorar el manejo adecuado de estos pacientes.

El presente instrumento ha sido desarrollado con el objetivo de que su adquisición sea gratuita y de fácil acceso. Los diferentes estímulos que se necesitan para su correcta aplicación consisten en materiales cotidianos, de bajo costo y de fácil adquisición.

La escala está dividida en la evaluación de cuatro dimensiones: hombro, codo, muñeca y habilidades instrumentales. En el apartado “materiales” de este manual se encuentra una lista con todos los materiales necesarios para la aplicación de la escala y **una descripción detallada con las indicaciones para montar alguno de los estímulos**. Para la evaluación de cada una de estas dimensiones se requiere el manual de aplicación, el protocolo de aplicación y los materiales específicos de cada dimensión. Además de este manual está disponible en (LINK) un vídeo con un instructivo de la aplicación de la escala.

Materiales

- 1 Hoja de papel tamaño carta
- 1 Diagrama de círculos
- 1 Diagrama de laberinto
- 1 Lápiz tipo crayón
- 1 Lámpara de mesa, con interruptor de timbre.
- 1 Vaso de plumavit o plástico de 200cc
- 5 monedas de \$100 o 1 euro
- 1 Camiseta con manga corta
- 1 Peine con mango
- 1 Cuchara de comida
- 1 Cepillo de dientes
- 1 Botella plástica de coca cola vacía de 500 cc
- 1 Recipiente tipo tupper o ziploc de 8 onzas o 225 gr
- Pesas de 200 grs, 500 grs, 700 grs y 1000 grs (2 de c/u)
- Pesos de 50 gr, 100gr, 150 gr, 200 gr
- 6 latas de bebida tipo RedBull
- Pesos de 20 gr, 30 gr, 40 gr (1 de c/u):

Estímulos

En esta sección se describen los distintos elementos que son necesarios para la creación de los materiales que se utilizan en la aplicación de la escala.

- **Confección de Pesos de 200 grs, 500 grs, 700 grs y 1000 grs (2 de c/u):**

Materiales y Herramientas necesarias:

- Neopreno u otro tipo de material similar.
- Correa de poliprepileno o correa de mochila
- Bolsas Plásticas
- Selladora para cerrar las bolsas plásticas. (Hay alguna otra forma de cerrarlas sin que sea necesaria la selladora)
- Granalla u otro material similar.
- Balanza de precisión
- Stickers
- Lápices

Descripción:

1. Cortar un trozo de neopreno de forma rectangular (agregar medidas según peso). Doblarlo con la forma de un sobre y coser por los bordes.
2. Cortar un trozo de la correa de la mochila (agregar medidas según peso), coser a ambos lados del sobre de neopreno. Coser de un extremo a otro del rectángulo.
3. Cortar una bolsa de plástico de las mismas medidas que el sobre. Sellarla los extremos dejando el largo sin sellar para introducir por el la granalla necesaria para cada peso.
4. Agregar la granalla graduando el peso requerido (el peso 200,500,700 y 1000). Utilizar balanza de precisión.
5. Forrar las bolsas plásticas de granalla utilizando el sobre de neopreno previamente elaborado.
6. Por último, utiliza los stickers para etiquetar el peso de cada una de las pesas.

- **Confección de Pesos de 50 gr, 100gr, 150 gr, 200 gr.(1 de c/u):**

Materiales y Herramientas necesarias:

- Bolsas plásticas
- Selladora

- Granalla u otro material para realizar pesos.
- Balanza de precisión.

Descripción:

1. Cortar un trozo de bolsa plástica de las medidas (**agregar medidas dependiendo de peso**) dependiendo de cada peso.
2. Sellarla los extremos dejando el largo sin sellar para introducir por el la granalla necesaria para cada peso.
3. Por último, utiliza los stickers para etiquetar el peso de cada una de las pesas

• **Confección de Pesos de 20 gr, 30 gr, 40 gr (1 de c/u):**

Materiales y Herramientas necesarias:

- 3 frascos de tempera o pintura pequeños.
- Granalla u otro material para realizar pesos.
- Hebillas plásticas tipo asas
- Velcro soft de dos centímetros de ancho y 15 cm de largo
- Stickers
- Balanza de precisión.

Descripción:

1. Rellenar los frascos con la granalla hasta alcanzar el peso requerido. Utilizar la balanza de precisión para medir pesos
2. Cortar los velcros con las medidas indicadas (**añadir medidas**).
3. Pegar tapas al frasco de tal modo que no se puedan abrir.
4. Colocar plástico en tapa para formar un agarre o manilla.
5. Por último, utiliza los stickers para etiquetar el peso de cada una de las pesas

Confección de Pesos de 6 latas de bebidas de 310 cc (añadir los diferentes pesos de las latas**):**

Materiales y Herramientas necesarias:

- Clavo
- Martillo
- Lata de bebida
- Balanza de precisión
- Vela
- Encendedor o fosforo
- Sticker

Descripción:

1. En la parte superior de la lata realizar orificio con un clavo o similar. El mejor lugar para realizar el orificio es el espacio que queda en el centro del abre fácil.
2. Vaciar el contenido de la lata hasta conseguir el peso requerido. Ir pesando en balanza de precisión.
3. Sellar el orificio utilizando para vaciar la lata con cera de vela y aplastar hasta que se selle por completo.
4. Por último, utiliza los stickers para etiquetar el peso de cada una de las pesas

Administración

DIMENSIÓN I: ZONA PROXIMAL HOMBROS

MATERIALES ESPECÍFICOS PARA ESTA DIMENSIÓN:

- Pesas de 200 grs, 500 grs, 700 grs y 1000 grs (2 de c/u)

ÍTEMS DIMENSIÓN I

ITEM 1: Abducción de hombros hasta la altura de los hombros (codos a la altura de los hombros) **

Posición del paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°.

Instrucción o consigna: “Tienes que levantar ambos brazos estirados hacia al lado hasta la altura de tus hombros”.

Indicaciones para el evaluador:

- Se permite realizar imitación del gesto motor.
- En caso que el paciente logre realizar lo solicitado, se procede a entregar los pesos de menor a mayor.
- Siempre preguntarle al paciente si está cansado y darle tiempo para que él mismo descanse e indique cuando está en condiciones nuevamente de partir.
- El paciente no debe realizar compensaciones, principalmente con el raquis.
- Se asignan puntuaciones para cada extremidad.

Puntuación:

0: No logra

1: Capaz sin peso adicional

2: Capaz con peso de 200 gr

3: Capaz con 500 gr

4: Capaz con 700 gr

5: Capaz con 1000 gr

ITEM 2: Abducción de hombros sobre la altura de los hombros (codos a la altura de los ojos)*

Posición del paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°.

Instrucción o consigna: “Tienes que levantar ambos brazos estirados hacia al lado hasta la altura de tus ojos”.

Indicaciones para el evaluador:

- Se permite realizar imitación del gesto motor.
- En caso que el paciente logre realizar lo solicitado, se procede a entregar los pesos de menor a mayor.
- Siempre preguntarle al paciente si está cansado y darle tiempo para que el mismo descansa e indique cuando está en condiciones nuevamente de partir.
- Observar que el paciente no realice compensaciones, principalmente con el raquis.
- Se asignan puntuaciones para cada extremidad.

Puntuación:

0: No logra

1: Capaz sin peso adicional

2: Capaz con peso de 200 gr

3: Capaz con 500 gr

4: Capaz con 700 gr

5: Capaz con 1000 gr

ÍTEM 3: Flexión de hombros hasta la altura de los hombros (codos a la altura de los hombros)

Posición del paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°.

Instrucción o consigna: “Tienes que levantar ambos brazos estirados hacia adelante hasta la altura de tus hombros”.

Indicaciones para el evaluador:

- Se permite realizar imitación del gesto motor.
- En caso que el paciente logre realizar lo solicitado, se procede a entregar los pesos de menor a mayor.
- Siempre preguntarle al paciente si está cansado y darle tiempo para que el mismo descansa e indique cuando está en condiciones nuevamente de partir.
- Observar que el paciente no realice compensaciones, principalmente con el raquis.
- Se asignan puntuaciones para cada extremidad.

Puntuación:

0: No logra

1: Capaz sin peso adicional

2: Capaz con peso de 200 gr

3: Capaz con 500 gr

4: Capaz con 700 gr

5: Capaz con 1000 gr

ÍTEM 4: Flexión de hombros hasta la altura de los hombros (codos a la altura de los hombros)

Posición del paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°.

Instrucción o consigna: “Tienes que levantar ambos brazos estirados hacia adelante hasta la altura de tus ojos”.

Indicaciones para el evaluador:

- Se permite realizar imitación del gesto motor.
- En caso que el paciente logre realizar lo solicitado, se procede a entregar los pesos de menor a mayor.
- Siempre preguntarle al paciente si está cansado y darle tiempo para que el mismo descanse e indique cuando está en condiciones nuevamente de partir.
- Observar que el paciente no realice compensaciones, principalmente con el raquis.
- Se asignan puntuaciones para cada extremidad.

Puntuación:

0: No logra

1: Capaz sin peso adicional

2: Capaz con peso de 200 gr

3: Capaz con 500 gr

4: Capaz con 700 gr

5: Capaz con 1000 gr

DIMENSIÓN II: ZONA MEDIA – CODOS

MATERIALES ESPECÍFICOS PARA ESTA DIMENSIÓN:

- 1 Hoja de papel tamaño carta
- 2 Diagramas de círculos
- 1 Vaso de plumavit o plástico de 200cc
- 6 latas de bebida de diferentes pesos (15 gr, 50 gr, 100 gr, 200 gr y 310gr)
- Pesos de 100 gr, 300 gr y 500 gr

ÍTEMS DIMENSIÓN II

ÍTEM 5: Mano(s) a la boca

Posición del paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos apoyados en mesa, pero no los codos.

Instrucción o consigna: “Toma el vaso tal como tú lo harías y llévalo a la boca”

Indicaciones para el evaluador:

- No se debe permitir realizar el gesto con imitación.
- Colocar el vaso frente al paciente a una distancia en la que le resulte sencillo alcanzar el vaso
- En caso de que el paciente logre realizar lo solicitado, se procede a meter los pesos de menor a mayor dentro del vaso según corresponda para cada ítem.

Puntuación:

0: No logrado

1: Capaz de llevar vaso a la boca usando 2 manos con apoyo de codos.

2: Capaz de llevar 100 g en un vaso a la boca con 2 manos con apoyo de codo

3: Capaz de llevar 100 g en un vaso a la boca con 2 manos sin apoyo de codo

4: Capaz de llevar 300 g en un vaso a la boca con 1 mano con apoyo de codo

5: Capaz de llevar 300 g en un vaso a la boca con 1 mano sin apoyo de codo.

ÍTEM 6: Trasladar peso desde muslos a la mesa o a la altura de hombros con las dos manos.

Posición paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. Las manos deben estar posicionadas sobre los muslos.

Instrucción o consigna *“Toma la pesa que está en tus piernas con ambas manos y llévala hasta la altura de tus hombros y luego dejarla sobre la mesa”*

Indicaciones para el evaluador:

- Los pesos deben de ser levantados con ambas manos.
- Colocar peso de 500 grs en las piernas del paciente.
- En caso de que el paciente no logre realizar lo solicitado, se procede a colocar los pesos de mayor a menor según corresponda.

Puntuación:

0: No logrado

1: Lleva ambas manos a la superficie de la mesa en forma incompleta (solo los dedos o solo 1 mano)

2: Lleva ambas manos completamente a la superficie de la mesa, pero no al mismo tiempo

3: Lleva ambas manos completamente y en forma simultánea a la superficie de la mesa

4: Lleva ambas manos completamente y en forma simultánea a la superficie de la mesa con peso de 200 grs

5: Lleva ambas manos completamente y en forma simultánea a la superficie de la mesa con peso de 500 grs.

ÍTEM 7- Levantar y trasladar latas

Posición del paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. De frente a una mesa o con mesa adaptada.

Instrucción o consigna: *“Toma la lata de la bebida que está en el círculo de afuera y debes llevarla al círculo que está en el centro”*

Indicaciones para el evaluador:

- En caso que el paciente logre realizar lo solicitado, se procede a entregar los pesos de menor a mayor
- No se debe permitir realizar el gesto con imitación.

Puntuación:

0: Levanta lata vacía

1: Levanta 1 lata de 50 grs (desde extremo hacia al centro)

2: Levanta 1 lata de 100 grs (desde extremo hacia al centro)

3: Levanta 1 lata de 150 grs (desde extremo hacia al centro)

4: Levanta 1 lata de 200 grs (desde extremo hacia al centro)

5: Levanta 1 lata de 350grs (desde extremo hacia al centro)

ÍTEM 8- Rasgar Papel

Posición paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos apoyados en mesa, codos pueden o no pueden estarlo. Entregue al paciente una hoja doblada en cuatro partes.

Instrucción o consigna “Intenta romper el papel con tus manos”

Indicaciones para el evaluador:

- Se entrega papel tamaño carta, doblado en 4.
- Si no consigue romper el papel doblado, se procede a desdoblar el papel en dos y posteriormente sin doblar.
- No se permite realizar el gesto con imitación

Puntuación:

- 0: No puede sostener ni rasgar el papel
1: Puede sostener hoja de papel estirada, pero no lo puede rasgar
2: Rasga la hoja de papel sin doblar, pero no completamente 4 cm
3: Rasga la hoja de papel sin doblar completamente >4cm
4: Rasga la hoja de papel luego de doblarla en dos comenzando por el borde doblado >4 cm
5: Rasga la hoja de papel luego de doblarla en cuatro comenzando por el borde doblado > 4cm

ÍTEM 9: Desplazar peso llevarlos desde un circulo a otro.

Posición paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción o consigna: “Toma el peso y llévalo hasta el otro punto ubicado en la hoja”

Indicaciones para el evaluador:

- No se debe permitir realizar el gesto con imitación
- En caso que el paciente logre realizar lo solicitado, se procede a entregar los pesos de menor a mayor.

Puntuación:

- 0: No puede mover el peso.
1: Si puede, levantar y mover 50 gr a ras de mesa
2: Si puede, levantar y mover 100 gr ras de mesa
3: Si puede, levantar y mover 200 gr ras de mesa
4: Si puede, levantar y mover 250 gr ras de mesa
5: Si puede levantar y mover 500 gr. ras de mesa

DIMENSIÓN III: ZONA DISTAL, MUÑECA Y MANO

MATERIALES ESPECÍFICOS PARA ESTA DIMENSIÓN:

- 1 Diagrama de laberinto
- 1 Lámpara con interruptor modificado
- 1 Lápiz
- 5 monedas de 100\$
- Pesos de 20 gr, 30 gr, 40 gr (1 de c/u):

ÍTEMS DIMENSIÓN III

ÍTEM 10.- Trazar trayecto (hoja de papel)

Posición paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción o consigna: “Toma el lápiz y sigue el camino desde el inicio al fin, tratando de no detenerte y no salirte del laberinto”

Indicaciones para el evaluador:

- No se debe permitir realizar el gesto con imitación
- Colocar el lápiz en el centro de la mesa.
- La hoja con el diagrama va en forma horizontal en el centro de la mesa (se puede acomodar el papel).

Puntuación:

0: No logra mantener lápiz en la mano o hacer una marca con el

1: Capaz de mantener lápiz en la mano y de hacer una marca con el

2: Capaz de seguir trayectoria por al menos 8 cm pero no en forma continua y no logra completar el trayecto

3: Capaz de seguir trayectoria por al menos 8 cm en forma continua, pero no logra completar el trayecto

4: Capaz de completar el trayecto pero necesita parar o levantar el lápiz del papel

5: Capaz de tomar el lápiz y de completar el trayecto sin parar ni levantar el lápiz del papel

ÍTEM 11: Encender una luz presionando

Posición paciente: Ubique al paciente sentado en una silla, o en su silla de ruedas, con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos estirados sobre la mesa.

Instrucción o consigna: “*Aprieta el botón para encender la lámpara lo suficiente para mantenerla encendida. Hazlo como tú lo harías y mantén el interruptor pulsado hasta que yo te diga*”.

Indicaciones para el evaluador:

- Colocar la lámpara frente al niño y el interruptor de la lámpara al alcance de la mano del niño.

Puntuación:

- 0: No logrado de encender la luz con dos manos
- 1: Capaz de encender la luz momentáneamente con las dos manos
- 2: Capaz de encender la luz momentáneamente con una mano
- 3: Capaz de encender la luz permanentemente con dos manos. Por 10 segundos
- 4: Capaz de encender la luz permanentemente con una mano

ÍTEM 12: Tomar monedas

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción o consigna: “Toma las monedas de una en una, como yo lo estoy haciendo y mantenlas al interior de tu mano”

Indicaciones para el evaluador:

- Colocar 5 monedas en el centro de la mesa. Las monedas deben de estar colocadas en frente al niño, formando una línea horizontal.
- Esta tarea se hace con imitación. Es decir, mientras se da la instrucción el evaluador debe realizar la tarea.

Puntuación:

- 0: No puede agarrar una moneda
- 1: Puede agarrar una moneda
- 2: Puede agarrar monedas y mantener 2 en una mano
- 3: Puede agarrar monedas y mantener 3 en una mano
- 4: Puede agarrar monedas y mantener 4 en una mano
- 5: Puede agarrar monedas y mantener 5 en una mano

ITEM 13: Levantar con agarre con tres puntos de apoyo (pinza trípode)

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa. Fijar antebrazo al eje del cuerpo, para evitar compensaciones de abducción o flexión de hombro

Instrucción o consigna: "Toma el peso, con tus tres dedos, levántalo y vuelve a dejarlo sobre la mesa." Con imitación.

Indicaciones para el evaluador:

- Colocar peso en el centro de la mesa.
- Con Imitación: El evaluador realiza la tarea mientras da la instrucción.

Puntuación:

- 0: No logrado de lograr agarre con tres puntos de apoyo
1: Capaz de lograr pinza trípode con pulgar pero no puede levantar peso
2: Capaz de lograr agarre con tres puntos de apoyo y de levantar 20 g
3: Capaz de lograr agarre con tres puntos de apoyo y de levantar 30 g
4: Capaz de lograr agarre con tres puntos de apoyo y de levantar 40 g

ITEM 14: Levantar con agarre que incluya pulgar (pinza termino-terminal)

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa. Fijar antebrazo al eje del cuerpo, para evitar compensaciones de abducción o flexión de hombro.

Instrucción o consigna "Toma el peso, con tus dos dedos y levántalo y vuelve a dejarlo sobre la mesa".

Indicaciones para el evaluador:

- Colocar peso en el centro de la mesa.
- Con Imitación: El evaluador realiza la tarea mientras da la instrucción

Puntuación:

- 0: No logrado de lograr pinza con pulgar o dobla última falange de pulgar
1: Capaz de lograr pinza con pulgar pero no puede levantar peso
2: Capaz de lograr pinza con pulgar y levantar 20 g
3: Capaz de lograr pinza con pulgar y levantar 30 g
4: Capaz de lograr agarre con dos puntos de apoyo y de levantar 40 g

DIMENSIÓN IV: INSTRUMENTAL

MATERIALES ESPECÍFICOS PARA ESTA DIMENSIÓN:

- 1 Camiseta con manga corta
- 1 Peine con mango
- 1 Cuchara de comida
- 1 Cepillo de dientes
- 1 Botella plástica vacía de 500 cc
- 1 Recipiente tipo ziploc de 8 onzas o 225 gr
- 1 Lata de bebida de 310 gr

ÍTEMS DIMENSIÓN IV

ÍTEM 15: Ponerse una camiseta* sin mangas.

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción o consigna: “Toma la camiseta* y colócatela, tal como tú lo harías”.

Indicaciones para el evaluador:

- Colocar camiseta* estirada (lista para ponérsela) sobre la mesa, frente al paciente

Puntuación:

0: No logrado

1: Capaz de ubicar la camiseta en superficie

2: Logra pasar cabeza, pero no EESS

3: Logra pasar cabeza, y solo una ES

4: Logra ponerse camiseta con compensaciones

5: Logra ponerse polera sin compensaciones

*En Chile: Camiseta cambiar por Polera.

ÍTEM 16: Llevar lata de bebida a la boca

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción o consigna: “Toma la lata, tal como tú lo harías y llévala a la boca”.

Indicaciones para el evaluador:

- Lata de 350 ml colocada en el centro de la mesa, frente al paciente.
- No se permite imitación.

Puntuación:

0: No logrado

1: Capaz de tomar lata de bebida de la mesa

2: Logra llevarla a la boca con ambas manos con compensación

3: Logra llevarla a la boca con ambas manos sin compensación

4: Logra llevar lata a boca con flexión de codo y hombro, CON compensación

5: Logra llevar lata a boca con flexión de codo y hombro, SIN compensación

ÍTEM 17: Llevar cuchara a la boca

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción y consigna: “Toma la cuchara, tal como tú lo harías y llévala a la boca”

Indicaciones para el evaluador:

- Colocar cuchara sobre la mesa, cerca de la mano preferente.
- No se permite imitación.

Puntuación:

0: No logrado

1: Capaz de tomar cuchara desde la mesa

2: Logra llegar a la boca con la cuchara pero con flexión de cuello y con ayuda de la mano opuesta

3: Logra llegar a la boca con la cuchara pero con flexión de cuello y apoyo de codo

4: Logra llegar a la boca con la cuchara pero con flexión de cuello.

5: Logra llegar a la boca con la cuchara con flexión de codo y hombro. No hay apoyo de codo.

ÍTEM 18.- Peinarse

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas dobladas en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción y consigna: “Toma el peine* tal como tú lo harías y péinate”

Indicaciones para el evaluador:

- Colocar un peine* sobre la mesa enfrente al paciente.
- No se permite imitación.

Puntuación:

0: No logrado

1: Capaz de tomar el peine desde la mesa.

2: El peine llega a la cabeza con ayuda de flexión de cuello y/o con ayuda de mano opuesta.

3: El peine llega a la cabeza con ayuda de flexión de cuello con apoyo de codo.

4: El peine llega a la cabeza con ayuda de flexión de cuello

5: El peine llega a la cabeza con ayuda de flexión de codo y hombro. No hay compensación.

* En Chile decir Peineta

ÍTEM 19.- Lavarse los dientes

Posición paciente: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas doblada en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción y consigna: “Toma el cepillo de dientes tal como tú lo harías e imita como te lavas los dientes. Sin llevar el cepillo al interior de la boca”.

Indicaciones para el evaluador:

- Colocar el cepillo de dientes sobre la mesa frente al paciente y cerca de la mano dominante.
- No se permite imitación.

Puntuación:

0: No logrado

1: Capaz de tomar cepillo desde la mesa

2: Logra llegar a la boca con el cepillo pero con flexión de cuello y/o con reforzamiento de mano opuesta.

3: Logra llegar a la boca con el cepillo a la boca pero con flexión de cuello con apoyo de codo

4: Logra llegar a la boca con el cepillo pero con flexión de cuello

5: Logra llegar a la boca con el cepillo flexionando el codo y hombro. No hay compensación

ITEM 20.- Abrir una botella

Posición inicial: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas doblado en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción y consigna: “Toma la botella con una mano y con la otra ábrela. Saca la tapa”

Indicaciones para el evaluador:

- Colocar botella de bebida vacía de 500 ml, en el centro de la mesa, de frente al paciente.
- Mientras el evaluador da la instrucción debe realizar la tarea de tal forma que se permita la imitación de la acción.

Puntuación:

0: No logrado

1: Posiciona manos e intenta abrir, pero no lo logra

2: Abre parcialmente la botella, pero no logra sacar completamente la tapa

3: Abre completamente la botella pero no logra sacar la tapa.

4: Abre completamente la botella y logra sacar la tapa.

ITEM 21.- Remover la tapa del recipiente.

Posición inicial: Paciente sentado en una silla o en silla de ruedas con adecuado apoyo de pies en superficie, rodillas y caderas doblado en 90°. En frente a mesa o utilizando mesa adaptada, antebrazos y codos apoyados en mesa.

Instrucción y consigna: “Toma el recipiente con una mano y con la otra ábrelo, sacando la tapa”

Indicaciones para el evaluador:

- Colocar en el centro de la mesa y frente al paciente un recipiente de capacidad aproximada 8 onzas o 225 gr con la tapa cerrada.
- Mientras el evaluador da la instrucción debe realizar la tarea de tal forma que se permita la imitación de la acción.

Puntuación:

0: No logrado

1: Posiciona manos e intenta abrir, pero no lo logra

2: Abre parcialmente el recipiente, pero no logra sacar completamente la tapa

3: Abre completamente el recipiente pero no logra sacar la tapa.

4: Abre completamente el recipiente y logra sacar la tapa.



ESCUELA DE PSICOLOGÍA
FACULTAD DE CIENCIAS SOCIALES



FACULTAD DE MEDICINA
PONTIFICIA UNIVERSIDAD
CATÓLICA DE CHILE



CEDETi UC
Centro de Desarrollo de Tecnologías de Inclusión

Nombre Paciente: _____

Apellidos Paciente: _____

RUT: _____

Decha de nacimiento: __/__/__

Lateralidad: _____

Escolaridad: _____

Diagnóstico: _____

Nombre Evaluador o Terapeuta: _____

Fecha Evaluación: __/__/__

Puntuación dimensión proximal hombro: ☐

Puntuación dimensión media codos: ☐

Puntuación dimensión distal muñeca y manos: ☐

Puntuación dimensión: ☐

Puntuación total: ☐

Observaciones: _____

DIMENSIÓN PROXIMAL HOMBROS								
	DESCRIPCION	0	1	2	3	4	5	PUNTOS
DER	Abducción de hombros hasta la altura de los hombros (codos a la altura de los hombros)	No logrado	Capaz sin peso adicional	Capaz con peso de 200 gr	Capaz con 500 gr	Capaz con 700 gr	Capaz con 1000 gr	
IZQ								
DER	Abducción de hombros sobre la altura de los hombros (codos a la altura de los ojos)	No logrado	Capaz sin peso adicional	Capaz con peso de 200 gr	Capaz con 500 gr	Capaz con 700 gr	Capaz con 1000 gr	
IZQ								
DER	Flexión de hombros hasta la altura de los hombros (codos a la altura de los hombros)	No logrado	Capaz sin peso adicional	Capaz con peso de 200 gr	Capaz con 500 gr	Capaz con 700 gr	Capaz con 1000 gr	
IZQ								
DER	Flexión de hombros sobre la altura de los hombros (codos a la altura de los ojos)	No logrado	Capaz sin peso adicional	Capaz con peso de 200 gr	Capaz con 500 gr	Capaz con 700 gr	Capaz con 1000 gr	
IZQ								

DIMENSIÓN MEDIA CODOS							
DESCRIPCION	0	1	2	3	4	5	PUNTOS
Mano(s) a la boca	No logrado	Capaz de llevar vaso a la boca usando 2 manos con apoyo de codos	Capaz de llevar 100 g en un vaso a la boca con 2 manos con apoyo de codo	Capaz de llevar 100 g en un vaso a la boca con 2 manos sin apoyo de codo	Capaz de llevar 300 g en un vaso a la boca con 1 mano con apoyo de codo	Capaz de llevar 300 g en un vaso a la boca con 1 mano sin apoyo de codo	
Trasladar peso desde muslos a la mesa o a la altura de hombros con las dos manos.	No logrado	Lleva ambas manos a la superficie de la mesa en forma incompleta (solo los dedos o solo 1 mano)	Lleva ambas manos completamente a la superficie de la mesa, pero no al mismo tiempo	Lleva ambas manos completamente y en forma simultánea a la superficie de la mesa	Lleva ambas manos completamente y en forma simultánea a la superficie de la mesa con peso de 200 grs en cada muñeca, pero no al mismo tiempo	Lleva ambas manos completamente y en forma simultánea a la superficie de la mesa con peso de 500 grs en cada muñeca, pero no al mismo tiempo	
Levantar y trasladar latas	Levanta lata vacía	Levanta 1 lata de 100 grs (desde extremo hacia al centro)	Levanta 1 lata de 200 grs (desde extremo hacia al centro)	Levanta 1 lata de 250 grs (desde extremo hacia al centro)	Levanta 1 lata de 300 grs (desde extremo hacia al centro)	Levanta 1 lata de 350grs (desde extremo hacia al centro)	
Rasgar papel	No puede sostener ni rasgar el papel	Puede sostener hoja de papel estirada, pero no lo puede rasgar	Rasga la hoja de papel sin doblar, pero no completamente 4 cm	Rasga completamente la hoja de papel sin doblar >4cm	Rasga la hoja de papel luego de doblarla en dos comenzando por el borde doblado >4 cm	Rasga la hoja de papel luego de doblarla en cuatro comenzando por el borde doblado >4cm	
Desplazar peso llevarlos desde un círculo a otro.	No puede mover el peso.	Si puede, levantar y mover o trasladar a ras de mesa 50 gr	Si puede, levantar y mover o trasladar a ras de mesa 100 gr	Si puede, levantar y mover o trasladar a ras de mesa 200 gr	Si puede, levantar y mover o trasladar a ras de mesa 250 gr	Si puede levantar y mover o trasladar a ras de mesa 500 gr.	

DIMENSIÓN DISTAL MUÑECA Y MANO (DEPENDIENDO DE LATERALIDAD)							
DESCRIPCIÓN	0	1	2	3	4	5	PUNTOS
Trazar trayecto (hoja de papel)	No logra mantener lápiz en la mano o hacer una marca	Capaz de mantener lápiz en la mano y de hacer una marca	Capaz de seguir trayectoria por al menos 8 cm **pero no en forma continua y no logra completar el trayecto	Capaz de seguir trayectoria por al menos 8 cm en forma continua, pero no logra completar el trayecto	Capaz de completar el trayecto pero necesita parar o levantar el lápiz del papel	Capaz de tomar el lápiz y de completar el trayecto sin parar ni levantar el lápiz del papel	
Encender una luz presionando	No logra de encender la luz con dos manos	Capaz de encender la luz momentáneamente con las dos manos	Capaz de encender la luz momentáneamente con una mano	Capaz de encender la luz permanentemente con dos manos. Por 10 segundos	Capaz de encender la luz permanentemente con una mano por 10 segundos		
Agarrar 5 monedas De \$100 c/u o 1 euro c/u	No logra agarrar una moneda	Puede agarrar una moneda	Puede agarrar monedas y mantener 2 en una mano	Puede agarrar monedas y mantener 3 en una mano	Puede agarrar monedas y mantener 4 en una mano	Puede agarrar monedas y mantener 5 en una mano	
Levanta con agarre con tres puntos de apoyo (pinza trípode)	No logra agarre con tres puntos de apoyo	Capaz de lograr pinza trípode con pulgar pero no puede levantar peso	Capaz de lograr agarre con tres puntos de apoyo y de levantar 20 g	Capaz de lograr agarre con tres puntos de apoyo y de levantar 30 g	Capaz de lograr agarre con tres puntos de apoyo y de levantar 40 g		
Levantar con agarre que incluya pulgar (pinza terminal)	No logra pinza con pulgar o flexa última falange de pulgar	Capaz de lograr pinza fina con pulgar pero no puede levantar peso	Capaz de lograr pinza con pulgar y levantar 20 g	Capaz de lograr pinza con pulgar y levantar 30 g	Capaz de lograr agarre con dos puntos de apoyo y de levantar 40 g		

DIMENSIÓN INSTRUMENTAL							
DESCRIPCIÓN	0	1	2	3	4	5	PUNTOS
Ponerse una polera sin mangas.	No logrado	capaz de ubicar la polera en superficie	logra pasar cabeza, pero no EESS	logra pasar cabeza, y solo una ES	logra ponerse polera con compensaciones	logra ponerse polera sin compensaciones	
Llevar lata de bebida a la boca lata de 350 ml llena	No logrado	capaz de tomar lata de bebida desde la mesa	logra llevarla a la boca con ambas manos con compensación	logra llevarla a la boca con ambas manos sin compensación	logra llevar lata a boca con flexión de codo y hombro, CON compensación	logra llevar lata a boca con flexión de codo y hombro, SIN compensación	
Llevar cuchara a la boca	No logrado	capaz de tomar cuchara desde la mesa	cuchara logra llegar a boca, pero con flexión de cuello con reforzamiento de la mano opuesta	cuchara logra llegar a boca, pero con flexión de cuello y asistencia de codo	Cuchara logra llegar a boca, pero con flexión de cuello	Cuchara llega a boca con flexión de codo y hombro, sin soporte de codo	
Peinarse	No logrado	Capaz de tomar peineta desde la mesa	Peineta llega a cabeza con flexión de cuello, con reforzamiento de mano opuesta	Peineta llega a cabeza con flexión de cuello, con soporte de codo	Peineta llega a cabeza con flexión de cuello	Peineta llega a cabeza con flexión de codo y hombro, sin compensación	
Lavarse los dientes (gesto motor).	No logrado	capaz de tomar cepillo desde la mesa	cepillo logra llegar a boca pero con flexión de cuello, con reforzamiento de mano opuesta	cepillo logra llegar a boca pero con flexión de cuello, con soporte de codo	cepillo logra llegar a boca pero con flexión de cuello	Cepillo llega a boca con flexión de codo y hombro, sin compensación	
Abrir una botella Botella de gaseosa de 500 cc	No logrado	Posiciona manos e intenta abrir, pero no lo logra	Abre parcialmente la botella, pero no logra sacar completamente la tapa	Abre completamente la botella pero no logra sacar la tapa	Abre completamente la botella y logra sacar la tapa		
Remover la tapa del recipiente. ziploc 225 gr	No logrado	Posiciona manos e intenta abrir, pero no lo logra	Abre parcialmente el recipiente, pero no logra sacar completamente la tapa.	Abre completamente el recipiente pero no logra sacar la tapa	Abre completamente el recipiente y logra sacar la tapa		