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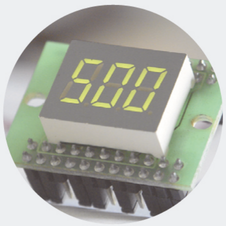

Human-Robotic manipulators electromechanical interface

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Human-Robotic manipulator's electromechanical interface

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Abstract

Limb impairments, particularly among stroke survivors, often become permanent without adequate therapy. Physiotherapy plays a crucial role in rehabilitation, but it can be physically demanding for therapists. Robot-assisted therapy offers more intensive and consistent treatment, but selecting the right equipment is critical for patient safety. In the context of robotic manipulators, the Human-Machine Interface (HMI) plays a crucial role in enabling effective interaction between the human and the robotic system. This project focuses on designing a novel electromechanical interface that connects the patient's upper limb to the UR5 manipulator from Universal Robots, ensuring accurate movement during rehabilitation exercises. To validate this interface across various arm dimensions, its performance was analyzed based on its comfort to the user, task performance and accuracy across individuals with different physical characteristics.

Keywords: Human-Machine Interface (HMI), Stroke, Rehabilitation, Electromechanical, Manipulator.

Resumo

As deficiências nos membros, particularmente entre os sobreviventes de AVC, muitas vezes tornam-se permanentes sem terapia adequada. A fisioterapia desempenha um papel crucial na reabilitação, mas pode ser fisicamente exigente para os terapeutas. A terapia assistida por robôs oferece um tratamento mais intensivo e consistente, mas a seleção do equipamento adequado é fundamental para a segurança do paciente. No contexto dos manipuladores robóticos, uma interface de interação homem-máquina desempenha um papel crucial ao permitir uma interação eficaz entre o ser humano e o sistema robótico. Este projeto foca-se na conceção de uma interface eletromecânica inovadora, que conecta o membro superior do paciente ao manipulador UR5 da Universal Robots, garantindo movimentos precisos durante os exercícios de reabilitação. Para validar esta interface em diferentes dimensões de braço, o seu desempenho foi analisado com base no conforto para o utilizador, no desempenho das tarefas e na precisão em indivíduos com diferentes características físicas.

Palavras-Chave: Interface Homem-Máquina, AVC, Reabilitação, Eletromecânica, Manipulador.

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List of Acronyms

AAN	Assist-As-Needed
ADL	Activities of Daily Living
COBOT	Collaborative Robot
DoF	Degrees of Freedom
EMG	Electromyography
EULRR	End-effector Upper Limb Rehabilitation Robot
FES	Functional Electrical Stimulation
FM	Fugl-Meyer
GH	Glenohumeral
HMI	Human-Machine Interface
IMU	Inertial Measurement Units
INESC TEC	Institute for Systems and Computer Engineering, Technology and Science
MAS	Modified Ashworth Scale
MeCFES	Myoelectrically Controlled Functional Electrical Stimulation
MI	Motricity Index
PAMs	Pneumatic Artificial Muscles
PETG	Polyethylene Terephthalate Glycol
PLC	Programmable Logical Controller
PPAMs	Pleated Pneumatic Artificial Muscles
pROM	Passive Range of Motion
RoM	Range of Motion

ROS	Robot Operating Systems
RT	Robot-assisted Therapy
SEAs	Series Elastic Actuators
sEMG	Surface Electromyography
VSAs	Variable Stiffness Actuators
WMFT	Wolf Motor Function Test

Chapter 1

Introduction

The evolution of technology has been a continuous road since the beginning of the human species. It has marked each era and century with new innovative ideas that keep changing our way of thinking and acting. Areas like medicine and engineering are, today, the fruit of years of studying and development. It is safe to say that thanks to technological advancements, the world has become more automated. Our Activities of Daily Living (ADL) have become more effortless, surrounded by machines that do repetitive and exhaustive work that humans once did in so many areas: cleaning, communication, transportation, etc. It has become a whole new world.

In the context of rehabilitation, it has been proven that repetitive exercises are effective in improving movements in a given area [1]. A few years ago, therapists were the only personnel capable of performing those exercises on patients, therefore taking hours of training into therapists schedules as well as consumption of medical resources [1]. The development of automated systems into these areas of work could potentially make them more affordable, less intensive and even more effective.

As a consequence of this technological growth, the field of robotics has also seen much progress throughout the years. As there are no signs of that slowing down, the best approach for society is to embrace such systems. This means that maintaining a secure human-robot interaction is crucial [2]. One of the examples of this growing phenomenon is the existence of manipulators which can interact alongside humans [3], avoiding collision with their surroundings. To merge this theme into rehabilitation scenarios, the problem becomes more complex: how to ensure the safety of patients during exercises performed by these systems? Therefore, studying what type of movements the manipulators can perform, and its limits, is a way of making these systems into safe environments.

Manipulators are usually divided into two categories: robots with end-effectors and exoskeleton devices [4]. The key difference, between them two, is that exoskeleton devices have multiple contact points along the exercised area. Normally, it is merged with the patient. On the other hand, the end-effector is simpler and, usually [3],[5],[6], it's a one hand contact point, for upper limbs. Its installation point is on the extremity of the manipulator.

1.1 Contextualization

The field of robotics has been growing exponentially. Robots are being used to solve problems in a wide variety of environments, like Medicine, and are becoming more and more useful. It's also a good way of changing into a more secure and efficient environment. There is a huge diversity when it comes to robotic manipulators and their field of expertise, such as in exploration, humanoid robots and industrial robots [7],[8]. In this scenario, developed in Institute for Systems and Computer Engineering, Technology and Science (INESC TEC), it is being studied and implemented a way of rehabilitation through an electromechanical manipulator. Its goal is to help patients to recover member activity and mobility in case of, for example, a stroke.

In rehabilitation, passive movements means that the patient is effortless during the exercise, and active movements means that the patient performs the exercise with minimal help from devices or therapists [9]. There are a few exercises worth mention: bilateral arm training, consisting of doing identical movements at the same time with both arms, either passively or actively; in contrast there's unilateral arm training which is the exercise of only one arm, either actively or passively [10].

These types of systems also might have a strategy where the robot helps the patient finish the exercise, or even challenges him when it receives feedback that the person has good mobility. This is a strategy called Assist-As-Needed (AAN), which means that it uses the minimum amount of manual assistance as possible [11] and has had better results than traditional therapy [12].

The need for these strategies are becoming more and more useful for rehabilitation solutions in paralyzed limbs as, according to Jiahui Fan *et al.* [13], there's an increasing prevalence of strokes between 1990 and 2019. While the number of occurrences continues to rise, strokes remain one of the leading causes of disabilities. At the moment, physical therapy is the best way for people to recover the control of their motor abilities [4].

1.2 Motivation

In the contemporary landscape, the advancements in the field of robotics have become increasingly noticeable, and this master's thesis is no exception to this transformative wave. As the era of technology progresses, this research delves into the integration of robotic arms with physical therapy, aiming to unlock new possibilities for individuals seeking to overcome limitations and chronic pain. This exploration reflects not only the evolution of robotics but also a commitment to improving lives through innovative solutions.

From an engineering standpoint, manipulators play a crucial role in enabling robots to tackle challenges effectively. The integration of manipulators into physical therapy is particularly ingenious, considering that their movements can closely mimic those of human limbs.

Therefore, investigating the range of movements manipulators can execute, along with understanding their limitations, emerges as an important step for transforming these systems into secure environments. This approach underscores how integrating robotics into therapy not only harnesses innovation but also prioritizes the well-being and safety of individuals that are on their path towards recovery.

Beyond the joy of building something, there's a deep sense of satisfaction in using technology to make a positive impact on society. Helping people with severe conditions overcome their disabilities, minimize secondary effects, such as limb impairments, and give back their quality of their life is a rewarding outcome of the entire process. Because, now that it can be possible to help people recover from post-stroke effects, maybe those would come back to their lives and live the rest of them with quality.

In short, this Master's Thesis also serves as a great introduction and a leap of faith to what an aspiring student wishes for his future career as an engineer. To help those in need while also doing what an engineer does best: turning problems into real life solutions with imagination and hard work.

1.3 Problem Definition

In this Master Thesis, an electromechanical manipulator is used in order to help patients obtain, once again, the control of its members. It serves as an alternative to physical rehabilitation and a complement on physical therapy [4]. An example of a situation that might benefit from such systems is its use on victims of a stroke.

Traditional methods, like professionals performing physical therapy directly in contact with their patient [10], are becoming more and more unusable and only result in partial motor ability recovery [14]. This might be due to the existence of more effective ways of doing the same tasks but with more prolonged exercises.

Thus giving more freedom for the user to perform those tasks with a Robot-assisted Therapy (RT) [4].

Nowadays there are still a lot of people who suffer from stroke, and it raises a concern, because it is one of the top diseases that kills or leaves people with disabilities globally [4], [15]. In the United States of America, around 750,000 people suffer a stroke, every year [16]. This not only raises a concern about mortality cases, but also disability cases. It is the third most significant cause of disabilities globally [17], which may cause long-term limitations for the ones that do survive the stroke. So, the central question is how can the integration of electromechanical manipulators in physical therapy assist stroke patients in regaining control of their limbs, especially considering the anticipated rise in stroke cases and the limitations of conventional methods?

It is speculated that until 2030 the number of occurrences are going to keep climbing yearly [16], parallel to the growth of population. Therefore, a rising number of studies and investment into fighting these presumptions should be the current focus. In summary, this Master Thesis contributes as a problem solving study that may restore happiness and comfort for a lot of people.

1.4 Objectives

When it comes to the objectives of this master thesis, there are a number of them that are worth mention.

1. To develop a customized human-robot manipulator electromechanical interface tailored for rehabilitation scenarios.
2. To implement control of the electromechanical interface of the manipulator via an Application Programming Interface (API).
3. To record data related to the functionality and performance of the developed system.
4. To analyze the recorded data to evaluate system effectiveness and user outcomes.
5. To draw conclusions based on the analyzed data results, contributing to the field of rehabilitation technology.

1.5 Plan of Work

To plan this work, a Gantt Chart was created, as shown in Figure 1.1, which presents all information chronologically. Looking at Figure 1.1, the Gantt Chart is structured into three main phases: the beginning, the body, and the end of the work. Each phase corresponds to specific chapters, with the first chapter divided into contextualization, motivation, objectives, problem definition, plan of work, and document organization.

To design the Gantt Chart, the first step was to set the finishing date for the thesis as June 16^{th} and then work backwards to establish the timeline. Consequently, the chart clearly outlines the remaining dates for each section. The introduction and literature review are ongoing tasks, allowing for continual improvements even after the deadline of March 31st.

The second phase, which involves the development of the work and testing, began in July, running concurrently with the work on the initial chapters. Finally, it is anticipated that the written thesis will be finalized by the delivery date of September 22nd.

1.6 Document Organization

To develop a comprehensive plan for this dissertation, the thesis is divided into distinct chapters and sub-chapters.

- Chapter 1 (Introduction): This chapter introduces the thesis theme, outlining various sections that explain the topic, the objectives of the thesis, and constraints related to the main subject.
- Chapter 2 (Theoretical Framework): This chapter provides detailed insights into different types of robots, including actuators and end-effectors, as well as essential concepts pertinent to the research.
- Chapter 3 (State of the Art): In this chapter, existing ideas and technologies are discussed in depth, supported by relevant literature and references.
- Chapter 4 (Interface Design): This chapter presents detailed drawings of the built interface and describes the motor selected for the project.
- Chapter 5 (Testing and Results): Here, the testing procedures and results are documented and analyzed in detail.
- Chapter 6 (Conclusion and Future Work): The final chapter summarizes the discussions held throughout the thesis, addresses challenges encountered during the project, and suggests areas for future research.

Figure 1.1: Gantt Chart for the Master Thesis

Chapter 2

Theoretical Framework

This chapter provides the theoretical framework guiding the design and implementation of a collaborative robotic system for stroke rehabilitation. Collaborative Robot (COBOT)s are integral to this project due to their ability to work safely alongside humans, assisting in therapeutic tasks while maintaining flexibility and adaptability to individual user needs.

Key concepts underpinning this work include Human-Machine Interface (HMI), which facilitate seamless interaction between the robot and patient, ensuring precise and safe movement. The challenge in designing effective rehabilitation robots lies in addressing the wide variety of user characteristics, such as size, weight, and Range of Motion (RoM). Ensuring safety and adaptability requires a deep understanding of human biomechanics and motor control.

In stroke rehabilitation, assessments such as the Fugl-Meyer (FM) and Modified Ashworth Scale (MAS) are crucial for evaluating patient progress and the effectiveness of therapeutic interventions. These assessments offer insight into motor impairments and spasticity levels, providing essential data to inform the design and operation of the robotic system.

An important aspect of this project is the selection of the appropriate motor for the robotic system. The choice of motor directly impacts the adaptability with the robot, particularly in handling patients with varying physical characteristics, and the safety of the patient. To ensure optimal performance, the motor was selected based on its torque and ability to provide controlled movements. This decision was sustained by studying the mechanical requirements necessary for effective rehabilitation exercises.

2.1 COBOTs: From Industry to Therapy

A collaborative robot is primarily designed to work alongside humans, undertaking repetitive tasks and assisting in lifting heavy objects. These robots come in various forms: they can be autonomous systems, teleoperated systems, or a mix of both. The first type, like the name suggests, are systems that can be operated autonomously and, oftentimes, give feedback simultaneously. Teleoperated systems are machines that need a professional individual in order to operate. Although they sound less ambitious or complex, these can be very interesting and quite innovative. The Da Vinci robot is an example of a teleoperated surgical type robot [18].

While commonly associated with industrial environments, where each system has a specific work such as palletizing, assembly and others, these robots can also serve in rehabilitation contexts, particularly when supporting the weight of individuals [19]. In rehabilitation, robots are often viewed as collaborative, bridging the gap between patients and therapists, while facilitating the interaction between them two. Similar to industrial collaborative robots, ensuring the safety of users and individuals with the robot is essential in rehabilitation. This represents a key challenge in the development of these systems. Additionally, the diverse characteristics of users present another significant consideration. Humans vary in size, weight, and physical limitations, posing additional challenges in designing rehabilitation robots that can effectively accommodate a wide range of users [20].

In contrast, non-collaborative robots operate independently without any interaction or cooperation with humans. They are typically deployed to perform tasks autonomously, without considering humans as a potential collision or factor. In industrial settings, these robots are often confined to enclosed spaces to carry out their work. Their primary advantage lies in their speed and efficiency, as they rely solely on their own capabilities without external variables. However, their lack of consideration for human safety makes them unsuitable for environments where humans are present, as they may inadvertently collide with or harm individuals [20].

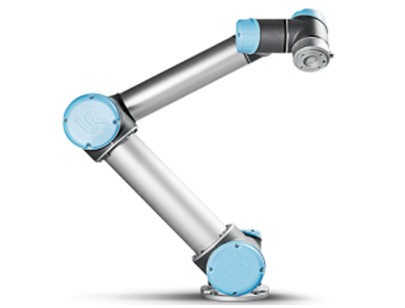
In rehabilitation, particularly for post-stroke patients, assessing a patient's progress is essential for measuring the effectiveness of therapy. Different movement classifications are used to evaluate the improvement in a patient's RoM during therapy. The FM assessment is a widely used global evaluation scale for measuring impairment in stroke patients, alongside other classification systems such as the MAS, which focuses on spasticity and stiffness in the shoulder and elbow. The Passive Range of Motion (pROM) test assesses joint excursion and is correlated with spasticity, while the Motricity Index (MI) evaluates muscle impairments in stroke patients [21]. Finally, the Wolf Motor Function Test (WMFT) is a disability test that measures both the quality and time taken for task performance during rehabilitation [22].

2.2 Manipulators

This section will be more focused in studying commercially available COBOTs. Hence, there are models like the UR3, UR5 (which is represented in Figure 2.1a) and UR10, that are quite efficient when it comes to collaborative work. The models UR3 and UR5 are provided with a safety mechanism that forces the arm to stop when an external force superior than 250 N and 150 N, respectively, is applied (the same as more or less 25 kg of force and 15 kg of force, respectively). This might come in handy when it is introduced into an upper limb rehabilitation [23], [24]. The UR10 is a much more stronger manipulator as it holds a payload of 12.5 kg and weighs about 33 kg. Its reach is also higher than the other two models [25]. In summary, the UR3 and UR5 models are much more versatile, when it comes to their area of specialty. They can be introduced to various situations and adapt to them due to their small design. The UR10 has a design more suited for industrial purposes, due to its mass and height.

In terms of rehabilitation scenarios and manipulators designed specifically for that purpose, the model KUKA LBR Med, Figure 2.1b, is a manipulator designed specifically for medical environments, being the only one with certified license to be used for medical purposes as a rehabilitation robot [32]. It could potentially be used for upper limbs and lower limbs. The manipulator has a very clean design, with its shell made of biocompatible material and stainless steel screws, and it is quite versatile for different kind of useful end-effectors, as described by Takács *et al.* [32]. It is used quite frequently in the robotic community, like Zhang *et al.* [5] did. This robot has two different models, one that supports 7 kg of payload and the other that supports 14 kg and a higher reach. In terms of controller, end-effector adaptor, Degrees of Freedom (DoF) and accuracy they are both quite similar [33]. For further understanding of other characteristics of these manipulator models above mentioned, the Table 2.1 identifies and compares their attributes which reflect into good characteristics for rehabilitation scenarios.

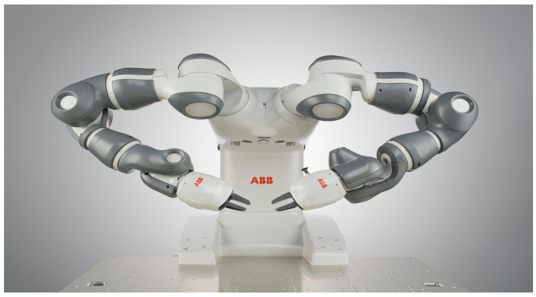
From a broader perspective, several other COBOTs are capable of performing tasks similar to those previously mentioned. The TM5-700, Figure 2.1c, for instance, is a 6 DoF manipulator specifically certified for collaborative work alongside humans. Equipped with an optical camera and image-enhancement light, it excels in recognizing objects and has software compatibility for industrial environments, connecting to networks and Programmable Logical Controller (PLC)s [28].



(a)

(b)

(c)



(d)

(e)

(f)

Figure 2.1: Robotic manipulator models: (a) UR5 model [26]; (b) KUKA LBR Med model [27]; (c) TM5-700 model [28]; (d) YUMI IRB 14000 model [29]; (e) FANUC CRX model [30]; (f) YASKAWA HC10DTP model [31].

The YUMI 14000, in Figure 2.1d, on the other hand, is a dual 7-joint bilateral industrial model renowned for its precision and ability to execute repetitive tasks with utmost accuracy alongside humans. Its versatility extends to assembling various product types simultaneously [29]. This bilateral robot is a combination of two single-arm YuMi IRB 14050 models into a whole system [35].

Meanwhile, the FANUC CRX series, example in Figure 2.1e, comprises robots of

Table 2.1: Specifications of different collaborative robotic models.

Manipulator	Payload (kg)	Operating Temperature (ºC)	DoF	Weight (kg)	Reach (mm)
YASKAWA HC10DTP [31]	10	0 - 40	6	48	1379
UR5 [34]	5	0 - 50	6	20.6	850
TM5-700 [28]	6	0 - 50	6	22.1	700
YUMI IRB 14000 [29]	0.5	5 - 40	7	38	559
FANUC CRX [30]	5 to 30	0 - 45	6	25 to 135	994 to 1889
KUKA LBR Med [33]	7 to 14	5 - 35	7	160	800 to 820

varying sizes and payload capacities designed for collaborative work. These robots prioritize safety, flexibility, and easy installation, offering a range of models tailored to different work requirements, whether low or high-weight tasks [30].

Lastly, the YASKAWA HC10DTP, in Figure 2.1f, is a 6 DoF collaborative robot with an extensive reach (1379 mm). With a high protection rating (IP67), it is suitable for a multitude of applications including handling, assembly, palletizing, and machine tool loading and unloading [31].

Moreover, knowing the payload of the robot is important to define if the system is capable of manipulating human limbs with ease. Normally, these commercial manipulators have 6 to 7 DoF to help their movements on all three dimensional planes and orientations. In terms of the robot operation, their operating temperature underscores normal values that don't allow the robot in neither too cold environments nor too hot. This is justified as these systems are built for collaborative working in closed environments which also have quite stable temperatures.

2.3 Type of Actuators

Although developing a rehabilitation robot seems rather sufficient, they also require actuators on their end-effector, as they are responsible for the movements and interface between the robot and the activity they are performing. There are quite a few that are used in this scenario, some of which are mentioned by Maciejasz *et al.* [12], and some on [36], [37], such as: electric actuators, pneumatic actuators, Pneumatic Artificial Muscles (PAMs), Series Elastic Actuators (SEAs), hydraulic actuators and Variable Stiffness Actuators (VSAs). Each have its advantages and disadvantages that are further specified in Table 2.2, so choosing which one is the best depends essentially on the weight, the location of the actuator, its power and what type of exercise the patient does [12].

Table 2.2: Advantages and disadvantages of different actuators, information adapted from [12],[36],[38].

	Advantages	Disadvantages
Electric actuators	- High power - Versatility	- Too heavy - Impedance too high
Pneumatic actuators	- Lighter weight - High power to weight ratio - Lower impedance than the electric actuators - Can produce elastic behaviour	- Normally these systems are stationary - Its service area is limited - The need for two pneumatic muscles for each joint - Hysteresis - Needs pressurized air - Slow dynamics
PAMs	- Light weight - Low cost - High specific force - High specific power - Backdriveability	- Slow dynamic response - High hysteresis - Non-linear force contraction characteristics - Complex mechanical design and control
SEAs	- Decreased inertia - More stable due to a less user interface impedance - More secure environment - Energy efficiency	- Lower bandwidth - Degree of compliance is fixed
Hydraulic actuators	- High payloads - More precise - Faster positionment compared to SEAs - Brakes with high performance	- Heavy - High impedance - Fluid leakage - Difficult to provide fluid - Usually requires noisy systems [12]
VSAs	- Provides joint stiffness profiles similar to humans - Adapts to their environment - Less energy consumption - Stiffness can be changed manually	- Some have springs, which means they present hysteresis - Some have cables which means more friction - Needs extra mechanisms or motors, which means more weight

Electrical actuators are the most common ones, due to their good adaptability in many situations [12]. Pneumatic Actuators are also very common and have a lot of benefits, like lighter weight than the electric ones, and can produce elastic behaviour. Despite those, these actuators need pressurized air in order to function, have hysteresis and it needs two pneumatic muscles for each joint [12]. PAMs, like the pneumatic ones, are light weight, but become superior due to their backdriveability, which means that the patient has some freedom in exercising their muscles [38]. However, a certain type of PAMs, Pleated Pneumatic Artificial Muscles (PPAMs), managed to reduce their hysteresis [39], [40].

SEAs and VSAs are relatively similar, except that the last one gives more autonomy for the patient to manipulate its stiffness manually [36]. Hydraulic actuators are not so common, but can be very precise and have high performance brakes. On the other hand, the lack of use of those is justified, since they're very noisy and have the risk of leaking fluids [12]. Despite this, Arno Stienen *et al.* [41] managed to develop an hydraulic actuator installed in an exoskeleton to perform rehabilitation for an upper limb.

2.4 End-Effectors

Several commercial brands specialize in developing these systems and ensuring compatibility with various types of manipulators. For instance, Robotiq and Schunk are two well-known brands that provide products compatible with companies such as Universal Robots, Omron, Yaskawa, Fanuc, Techman Robot, and many others. Therefore, determining the optimal design for the proposed solution is essential.

Despite the extensive array of grippers offered by sellers, common descriptors can be employed to categorize them based on their operational mechanisms and designs. Grippers are typically classified as anthropomimetic or non-anthropomimetic with further distinctions including biomimetic and non-biomimetic on the way their movements are done. These grippers can be grouped into two main categories: fully actuated or underactuated grippers, where they either actuate and control its DoF directly with a motor, or some DoF activate passively, respectively [42]. Anthropomimetic means that the system, in this case the end-effector, mimics the movements of a human and it also tries to replicate the dexterity of human parts. Not to confuse with anthropomorphic, where the systems have a design similar to humans. Similarly, biomimetic means that the gripper mimics movements from bio-mechanical structures, excluding anthropomimetic movements [42].

The end-effectors used for the majority of collaborative work are normally the simple pinch like grippers. In Figure 2.2 there are two examples of those systems [43], [44], where they are mostly used in collaborative industrial environment. These end-effectors are very versatile as they can be integrated into different situations such as palletizing, assembly, pick & place, quality testing, etc [43].

(a)

(b)

Figure 2.2: Normal industrial grippers with pinch-like movement (Non-anthropomimetic and non-biomimetic) (a) Robotiq's 2F-85 Gripper [43]; (b) Schunk's Co-act EGP-C gripper [44].

In spite of that, there are other types of end-effectors developed by brands specifically for collaborative work. For instance, solutions such as in the Figure 2.3a, which represent a Robotiq product, demonstrate that an anthropomimetic design could increase the grasp technique and be much more stable than other examples [45]. Similarly, when in the case of solid surfaces for pick and place types of work, the Figure 2.3b represents a vaccum gripper, also from Robotiq, which excells in doing the job as it holds on tight on the object and can be costumizable as the user sees fit [46].

(a) (b)

Figure 2.3: Anthropomimetic plus a non-biomimetic and non anthropomimetic end-effectors (a) A three finger gripper (anthropomimetic) [45]. (b) A vaccum gripper (non-biomimetic and non-anthropomimetic). [47].

In the case of rehabilitation robotics, the end-effectors chosen by brands are limited and normally are always the same type. They are provided with a cylindrical shaped piece with the objective of the patient to hold it. Usually, the solution only supports unilateral movement and, sometimes, they try to immobilize the arm in velcro straps to the manipulator for better support. To further explore these kind of end-effectors, the InMotion Robot models, Figure 2.4, which later were bought by BIONIK are a great example. BIONIK labs now uses the InMotion robot to study, develop and commercialize these systems as well as using them in post stroke patients. Similarly, AKINESIS has an identical system, an upper limb rehabilitation robot called the REAplan [48]. Its end-effector is also cylindrical shaped and with the same purposes as the InMotion models. Alternatively, they have a glove available in different sizes for patients with grasping weaknesses that lack the ability to hold the cylindrical shaped end-effector [48].

2.5 Exoskeletons

The problem with end-effector solutions is that it only supports single contact points, which in rehabilitation scenarios can be difficult as it lacks stability and is limited in movements of the patients' arm. Sometimes, like in the InMotion Robot and the

Figure 2.4: InMotion Robot from Bioniks Laboratories [36], [49].

REAplan, there are velcro straps that solve the lack of stability, but even in those cases there isn't much movement in the elbow and shoulder joints.

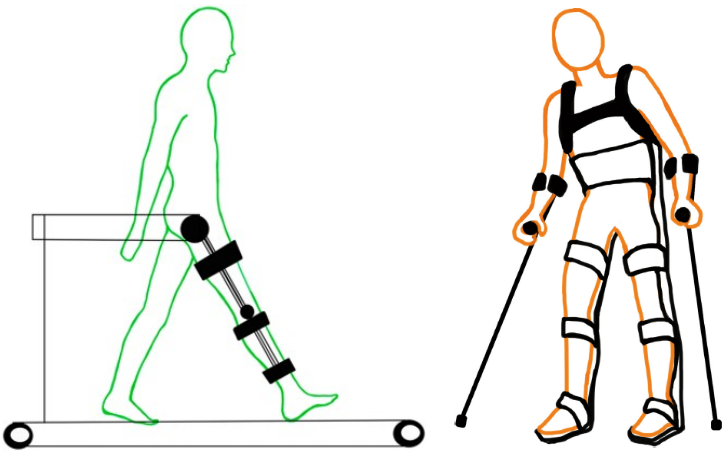
In terms of collaborative work, exoskeleton devices can help humans in performing their work with higher payloads, more precision and higher stability. For instance, the model from Skelex [50] is a collaborative exoskeleton that helps workers in prolonged overhead work which, in normal circumstances, may cause severe injuries over time. This system tights on the shoulders and back of the user, thus giving a sensation of security and comfort.

In order to solve stability issues and lack of joint actuation, exoskeletons are a great substitute as they exercise more closely to patients' joints and have no problem with arm stability. There are a lot of cases of these kind of exoskeletons, however they can be quite expensive and heavy when linked to electric drive exoskeletons, except when using pneumatic exoskeletons as they have a higher force-weight ratio [16].

Exoskeleton robots, like the end-effector ones, can be divided into unilateral and bilateral robots, which means they either exercise one limb at a time or both limbs at the same time [51]. The MyoPro Motion-G, Figure 2.5, is a great example of an unilateral commercially available exoskeleton device. It is designed to help the wearer restore paralyzed or weakened upper limbs. It also helps patients to perform ADL while encouraging muscle regrowth, reeducation and increasing their RoM. It uses technology that senses the patient brain information and instructions by reading myoelectric signals from the surface of the skin, which then rewards the user with arm movements as they intended [52]. In terms of its end-effector, it is designed so the touch and grab feel natural for the person. The design was made with post-stroke patients in mind. It has a hand strap to support the wrist and two additional supports for the hand, one for the thumb and another for the index and middle fingers.

Figure 2.5: MyoPro Motion-G device [52].

In the case of lower limbs, there are static robots and overground robots, Figure 2.6. The first means that the space for the patient is confined and the exercise is made, for example, in body weight supports and treadmills [51]. While the second one is a robot made for the patient to exercise freely in the world, commonly it is a bilateral robot [51].



(a) (b)

Figure 2.6: Different types of exoskeletons. (a) Static Exoskeleton for lower limb rehabilitation [51]. (b) Overground exoskeleton for lower limb rehabilitation [51].

On the other hand, exoskeletons also allow a more direct and practical help. They can be used as an additional instrument to help people in their ADL. This same description is depicted in a testimonial from a post-stroke patient that used the MyoPro Motion-G device from Myomo [53].

2.6 Motor Study

The selection of the most suitable motor requires considering several variables. Notably, the UR5 manipulator has a payload capacity of only 5 kg, which is a significant constraint of the system. Silva *et al.*, if the maximum mass specification for an individual is set to 155 kg (approximately 340 lb), the designed device can accommodate 98.8% of the American population[54]. Although this may sound the best generalized scenario, based on this work, the forearm of an individual of this weight is estimated to weigh approximately 2.5 kg, and the hand 0.9 kg, while the arm, which they only classify it as such weighs 4.3 kg. Alternatively, Lin *et al.* specified that the forearm plus the upper arm weighed in average a total of 4.2 kg [55].

Additionally, a research conducted by Zwerus *et al.* on elbow movements and their limits found that the average flexion of an elbow is around 146º. Their study, which included 352 participants comprising 47.2% males and 52.8% females, also examined elbow extension, supination, and pronation [56]. Based on these facts, a human forearm plus hand weighs about 3 kg, which is crucial information for the choice of the motor.

$$T = F * d \tag{2.1}$$

- T = Torque;
- F = Force applied;
- d = distance to the force point;

To find the correct torque for the motor, the equation 2.1 must be acknowledged, and as such, the length of the forearm and its weight must be acknowledged. For this system the force applied by the person will consist of only the weight of the forearm plus the hand, since the motor will only be actuating on the elbow, and the length will consist of the length from the actuation point, to the extremity of the hand. Based on the papers of Perry *et al.*, an average forearm plus hand has about 0.35 m (350 mm) and around 3 kg, which translates into a force of 30 kg.f (30 N).

In order to choose motors based on their torque, first the difference between the various types of torque must be fully understood. There are different types of torque, the stall torque and continuous torque. The first one is measured when the motor is idle and supporting all the weight. The continuous torque is the torque necessary when performing the movement. Because of the UR5's constraint of 5 kg, it limits this system. A person's total arm weighs around 4 kg, which means that it leaves almost less than 1 kg for the choice of this motor, [54], [55].

For this project, only a limited amount of motors were considered as good candidates. For instance, hydraulic motors were immediately discarded due to their common robustness and heavy weight. Consequently, only servo motors, brushless DC motors, brushed DC motors and stepper motors were analyzed. Additionally, because the system doesn't require significant power, AC motors were also not considered as a viable option, as motors of such type are more efficient in high power environments.

2.6.1 Servo Motors

There is not an actual type of motor called servo motor. The term servo simply means that the motor operates within a closed-loop control system, which uses the feedback from, for example, an encoder. Then those encoder values are used to compare the motor's actual position, velocity, or torque. This definition does not specify the motor's basic construction or operation, allowing for a variety of motor types to be used in servo applications [57].

Both AC and DC motors can work as servo motors. Synchronous AC motors, also known as permanent magnet AC (PMAC) or brushless AC (BLAC) motors, are frequently used in servo systems due to their high torque and excellent performance in dynamic applications. These motors are particularly well-suited for applications requiring precise and rapid responses. Asynchronous or induction motors are often used with variable frequency drives to achieve speed control. However, the lack of feedback mechanisms limits their effectiveness in applications requiring high precision and dynamic response, meaning they are not true servo motors.

Brushed motors are less common in servo applications due to the wear and associated maintenance. The physical contact in brushed motors leads to higher maintenance requirements and reduced longevity, making them less desirable for high-precision applications. Brushless DC motors, on the other hand, are particularly well-suited for servo applications due to their high efficiency and reliability. BLDC motors, like synchronous AC motors, use permanent magnets on the rotor and run at synchronous speed, which makes them somewhat equal and fall under the same category of permanent magnet synchronous motors [58].

2.6.2 Brushless DC Motors and Brushed DC Motors

The main difference between a brushless DC motor and a brushed DC motor is, as the name suggests, the existence of "brushes", where metallic structures make, mechanically, rotate the motor. As opposed to this, brushless DC motors don't have such mechanical parts, instead they rotate the motor electronically.

Several factors favour the choice of BLDC motors over other types: they require less maintenance, generate less friction, produce less heat, and are more energy efficient. These characteristics make them particularly suitable for systems where the motor needs to be reliable and have a long lifespan.

Moreover, BLDC servo motors provide excellent performance in terms of speed and position control. The existence of a more electronic setup rather than a mechanical one, allows for precise control over the motor's operation, which is essential in applications requiring high accuracy. The integrated feedback mechanisms ensure that the motor's position and speed are constantly monitored and adjusted, maintaining stable and accurate performance.

These advantages of BLDC motors, combined with their high efficiency and reliability, make them optimal choices for a HMI application. By integrating a BLDC motor into the human-robotic manipulator system, the design ensures precise, reliable, and efficient control of arm movements, thereby enhancing the overall functionality and performance of the system.

2.6.3 Stepper Motors

Stepper motors like the name suggests, are motors that work based on steps. Unlike the other types of motors that rotate continuously, this type of motor rotates in small angular steps at a time. The advantage of this application is that it can be set to any given step angle and step position without encoders or other sort of sensors. Its velocity can also be changed which can contribute in creating a continuous rotation. They are usually small, but these motors could also vary in size and torque. Despite these motors achieving a high torque based on their size, it might not be sufficient to HMI applications, which require the movement of human limbs, that may vary in weight.

2.6.4 Motor Research

The research initially focused on identifying a suitable servo motor that could both record its rotation and measure the degree of rotation. During the market analysis, it became clear that servo motors offering the necessary torque for the project tend to be expensive. In the Digikey and Mouser websites, which sell a variety of electronic components, including servo motors, a motor capable of withstanding a torque of around 10 to 20 N.m is already considered a big motor for this project. For instance, a servo motor developed by the Crouzet company (model number 80289713), which was found on the Digikey website, can reach up to 4.3 kg, which isn't viable to this system. Alternatively, other servo motors were found, but they lack the torque necessary for the system' requirements.

To overcome the torque limitations, gears and planetary gear systems were considered as potential solutions to boost torque while maintaining the desired speed [59]. This approach offered the possibility of using smaller, lighter motors while achieving the necessary performance. However, balancing high torque efficiency with lightweight designs proved to be challenging. For instance, the geared DC servos, models *HG16-030-AB-00* and *HG37-010-AA-00*, though capable of using a 1/240 gear ratio, could only reach a torque of 0.075 N.m with a 1/10 gear ratio far below the required threshold.

Table 2.3 lists several brushless DC motors considered as an alternative solution. As it can be interpreted from the table, high torque usually means that the weight is also higher. From all the alternatives of the DC motors, the models L54-30-S500-R and the YM070-210-R099-RH seem to be the most viable options, as they can reach rather high torques, while weighing less than 1kg which checks on the objectives for the choice of the motor.

Table 2.3: List of motor's studied.

Model reference name	Manufacturer	Type	Weight (g)	Dimensions (mm)	Torque (N.m)
HG16-030-AB-00	NIDEC Components	Geared DC Servo	27	pi x 64 x 16	0.075
HG37-010-AA-00	NIDEC Components	Geared DC Servo	155	pi x 334.89 x 38.5	0.027
L54-30-S500-R	ROBOTIS	BLDC	591	54 x 108 x 54	5.4
YM070-210-R099-RH	ROBOTIS	Frameless BLDC	790	pi x 1225 x 71.1	14.6
YM080-230-R099-RH	ROBOTIS	Frameless BLDC	1200	pi x 1600 x 78.1	26.0
VG.ECI6340BK1.EC75.2.33	ebm-papst Inc.	Frameless BLDC	1350	pi x 56.25 x 30	22.31
VG.ECI6340BK1.P63.2.30	ebm-papst Inc.	BLDC	1350	pi x 56.25 x 39	20.1
80289713	Crouzet	Servo Motor	4300	pi x 90.25 x 49	27.16

2.7 Summary

In summary, to develop a rehabilitation robot, not only a study around the control, safety and type of robot to be implemented is necessary, but also actuators and characteristics such as the temperature and humidity of the place. It can be concluded that exoskeleton types of robot can be quite effective, maybe surpassing the end-effector ones. However, they can be quite expensive and some even more heavy.

As a side note, when creating a system for rehabilitation, certain aspects need to be looked over. Firstly, the design, since it can follow a more anthropomorphic approach or a non-anthropomorphic [60]. The anthropomorphic would be more suitable for human patients, but would require more setup time. On the opposite, the non-anthropomorphic would be a more straightforward and quicker preparation. Secondly, the actuators, because they can give a more centralized exercise on muscles and improve the results [61], [21]. Finally, the classification of the exercises which help analyse and compare the results between experimental groups and control groups.

Chapter 3

Literature Review

This chapter dives into the literature available around COBOTs and exoskeleton devices within rehabilitation environments, explaining the various systems and their potential modes of actuation. It also explains how an interaction between humans and robots is possible, and what normally is used in literature available. Through this review, a deeper understanding of the capabilities and limitations of COBOTs in rehabilitation environments is sought.

The traditional physical therapy has the advantage of being more focused to each joint and member whenever necessary, as the therapist is more focused on the area of effect. However, in order to obtain great results and improvements on post-stroke patients, the treatment must be followed with high-intensive and repetitive tasks [62]. Therefore, solutions based on robotic systems with an end-effector or just an exoskeleton, followed with an AAN concept, could increase the duration and intensity of each training, and as such getting better results with them [62]. In the case of an exoskeleton rehabilitation robot it could also provide direct assistance for each joint [5]. Although results around these solutions find modest reduction on limb impairments, they also find little functional improvement compared to conventional therapy [62], thus more work around rehabilitation robotic systems must be made to address the right conclusions.

3.1 Human-Robot Interface

There are various examples of human-robot interaction in rehabilitation, and the key to find the ones suited for this work is searching for robots that have adaptability for various types of end-effectors and, if possible, with AAN concept. AAN in a rehabilitation scenario refers to the robot assisting the movements of the patient only when necessary, and with the minimal manual assistance as possible. Emken *et al.* uses this concept as an optimization problem, where they studied on how to perfect this type of assistance in rehabilitation [11]. They also used a controller that automatically calculates the kinematic equations and the forces necessary for the patient's movements.

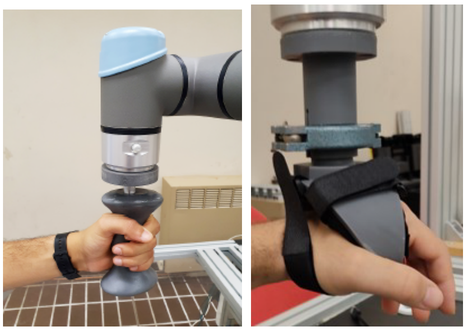
The challenge associated with humans and robots working together lies in the potential risk of subjects getting injured. This arises from the inherent limitation of robotic systems, as they often struggle to fully understand human behavior and the subtle dynamics of interaction with humans, leading to instances where they operate at potentially hazardous speeds and high inertia [20].

In the context of rehabilitation scenarios, there are two primary forms of interaction between humans and robots: interaction through a device with multiple contact points, such as an exoskeleton, and interaction through a single contact point, typically involving a manipulator.

When employing an exoskeleton, the interaction is relatively straightforward, focusing on ensuring correct alignment between human limbs and the device, maintaining safe force interaction, and limiting the workspace. In contrast, when relying solely on a single contact point, the dynamics change. This typically involves a single manipulator; however, it could also include a bilateral robot with two manipulators, although this is less common.

To further explore this interface, the Figure 3.1a and Figure 3.1b are a good example. The first one is a practical handle with a design that favours all types of patients. Essentially, this handle could be used in favour of the exercise if used passively or actively-assisted, in earlier rehabilitation stages [63]. On the other hand, the second prototype gives more stability to the user. The straps and ring shaped handle give a more natural grip. For these reasons, this end-effector is well suited for exercises where the person actively moves the robot. It also encourages the arm movement, rather than having pressure on the wrist due to having the fist closed [63]. However, for post-stroke patients with potential limitations in their hand RoM, this method poses challenges, as they might struggle to grasp the cylinder comfortably.

Alternatively, a more advantageous solution could involve the manipulator securing the patient's pulse, forearm, or even the leg. In this scenario, there is minimal risk for the patients to harm themselves while attempting to grasp an object or even during the exercise.



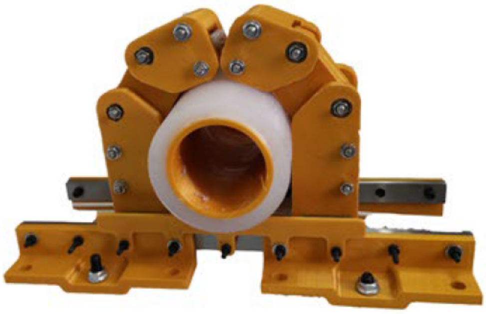
(a) (b)

Figure 3.1: Examples of end-effectors for active and passive movements by the patient. (a) Practical end-effector [63]. (b) Prototype done by [63] that suits patients for more active kind of movements.

Xu *et al.* explain that the human hand is very dexterous and can carry out almost any work or object safely [64]. Therefore, using an anthropomorphic inspired design for the end-effector is a really smart solution. Of course the human hand has a lot of joints and muscles, making it almost impossible to replicate. Nevertheless, the simple strategy of grasping objects with a human like gripper is the key idea that Xu *et al.* [64] wanted to pass through. They even developed a gripper inspired on human hands, Figure 3.2a, where the objective was to grab human limbs and manipulate them safely. The gripper and its links grab the human wrist safely and with no risk of slipping. The only problem they encountered was that it is a preliminary prototype based on a static structure. Although the experiments show positive scenarios when grasping non-rigid objects, it still needs to ensure a safe environment between people and the robotic device [64].

Similarly, the DARR, Figure 3.2b, is a robot with two collaborative manipulators that uses this kind of technique. Each manipulator has a gripper with velcro connectors to support the arm, and one of them holds the upper arm while the other the lower arm of the user. Each robotic arm has six DoF, allowing the system to assist the person's upper limb move in three dimensions and orient their hand as needed. The objective of the DARR is to perform rehabilitation on post-stroke patients [65].

Hence, an approach like that of the ANYexo 2.0 appears to be a more reliable option, as it isn't a static cylindrical shaped object left for the patient to hold. Unlike its predecessor, the ANYexo 1.0, which lacks wrist and hand DoF, the ANYexo 2.0 incorporates a three DoF end-effector, as justified by Zimmerman *et al.* [66]. This enables full RoM for the wrist and hand. The hand attachment mechanism of the ANYexo 2.0 consists of a plate that makes contact with the metacarpals on the dorsal side, along with a 25 mm wide textile strap with velcro. This velcro strap secures the hand to the plate while allowing for object grasping [66]. For a better understanding of this design, the Figure 3.3b highlights the wrist and hand interface,



(a)

(b)

Figure 3.2: (a) Gripper built to rehabilitate or nurse human limbs by grasping them [64]. (b) DARR COBOT [65].

where it's possible to see that it uses a handful of mechanisms to help in ensuring a more dexterous movement. This interface needs two Dynadrives, which are the two cylindrical drives in each side of the figure, to help the wrist and hand actuation. In total, those two drives weigh about 1.6 kg. Zimmerman *et al.* demonstrated various hand positions, movements and outcomes in their work.

In addition to the velcro straps used by Zimmerman *et al.* in their wrist and hand interface, the MIT-Manus, which later became the InMotion robots from BIONIK [49], also uses velcro to stabilize the arm, as depicted in Figure 3.3a. These straps are also followed by a comfortable structure for resting the arm [21]. This whole system helps in elbow, shoulder and arm rehabilitation. This kind of method based on enveloping the arm of the patient for better comfort and stability almost mimics exoskeleton systems, but with no actuation.

(a)

(b)

Figure 3.3: (a) MIT-Manus/InMotion wrist and hand interface [49]. (b) ANYexo 2.0 wrist and hand interface [66].

Exoskeleton devices are also a way of connecting human limbs to robotic systems in order to practice robot rehabilitation. Solutions have been made in this domain and numerous devices have been developed to evolve these kind of systems [66], [67], [68], [69], [70].

Despite the various systems referenced, another viable solution for a human-robot interface involves 3D-printed designs where custom parts are tailored to be compatible with both the user and the robot. Liu *et al.* developed a 3D-printed structure to support a servo motor, presented in Figure 3.4. Building upon their work, a structure for the upper arm and another for the forearm were created, along with a mechanism to secure the motor. Straps were used to attach the user's arm to the 3D-printed structure [71].

Figure 3.4: Structure based in 3D printing for an exoskeleton actuated system [71].

In addition to these components, the authors incorporated a MYO armband, which is a bracelet that collects Surface Electromyography (sEMG) signals from the user. These signals are used to determine the user's intended motor movements, allowing for intuitive control of the motorized actuation.

The objective of this work was to create a low-cost platform for human arm actuation at the elbow level. Although the motor rested on a table, requiring the user to sit in a chair, this approach still demonstrates that 3D-printed designs are a viable alternative for creating interfaces between robots and humans. The feasibility and effectiveness of such designs validate their potential as a cost-effective and customizable solution in human-robot interaction.

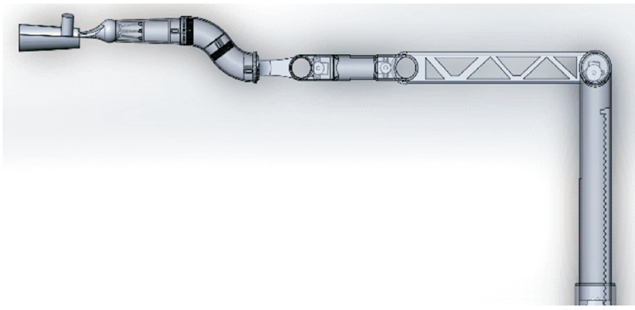
3.2 End-Effectors

While manipulators constitute a crucial element in end-effector based robots, the actuation and possession of an end-effector are equally vital components of these robotic systems. These end-effectors can assume various shapes, each with specific outcomes, but the design and construction of those are more common for upper limbs in robotics. As an example, Hao Ren *et al.* developed an algorithm optimization for a wrist rehabilitation robot [72]. Although a wrist mobility end-effector would be a great idea for rehabilitation scenarios, since it can also exercise certain aspects for the patient's hand, the focus here is to have an end-effector that is compatible with collaborative robots.

Starting from the most simple ones, the patient reaches for the end-effector and grabs a holder, shaped like in Figure 3.1a. In order to help the patient to be more stable and comfortable, having an additional platform to rest the arm could also be a solution. This was the work done by Li *et al.*, where a three DoF robot proceeds to rehabilitate a single upper limb with an active end-effector, controlled by an electric valve that uses a pneumatic system to expand the end-effector or contract it, Figure 3.5a [73]. This system controls the limb movement in the vertical plane. The purpose of this test was creating a simple and economic end-effector for rehabilitation.

Similarly, Ponomarenko *et al.* also developed the same kind of holder and platform, but with a different approach on the end-effector [74]. The robot developed was a bilateral system with five DoF on each robotic arm, Figure 3.5b. Its end-effector is made of aluminum and its actuation is based on elastic springs which hold a rotational ball. It also uses electromagnetic actuators for the joint powering. This kind of devices show that an economic solution with high range of workspace is possible. However, the systems in Figure 3.5 show a lack of sense in, for example, post-stroke patient's disabilities.

(a)



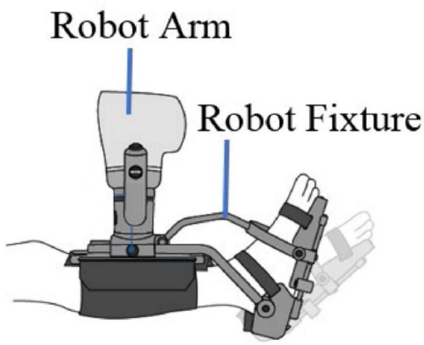
(b)

Figure 3.5: (a) End-effector used that controls vertical movement [73]. (b) Bilateral robot with electromagnetic actuators and a ball joint controlled by springs on the end-effector [74].

Another solution might be related to grasping technique focused end-effectors. Hernandez *et al.* conducted a systematic review focusing on diverse gripper designs [75]. Their study delved into various gripping modes, exploring how end-effectors can be customized for optimal object grasping. The grippers were classified based on factors such as DoF, actuation systems, design approaches and the shape employed for grasping objects. The review also provided insights into the advantages and disadvantages associated with each gripper type. Their conclusion highlighted a challenge in accurately evaluating the force applied to objects, leading engineers to prefer a more deformable gripper approach. Passive-compliant mechanisms become a preferred choice, offering the advantage of exerting a moderate output force, suitable for handling objects with moderate weights, especially when constructed with rigid links. This mechanism strikes a balance between flexibility and strength, due to the fact that rigid links can support substantial weights while adapting to the shapes of various objects. Consequently, it is ideal for applications in environments that are uncontrolled or unpredictable [75].

Taking the Hernandez *et al.* study as reference to know which gripper allows a more controlled and secure grasping technique, then it is safe to say that an anthropomorphic or biomorphic design are superior to the basic grippers [75]. It is quite visible that the Figure 2.3a shows an end-effector with great versatility and flexibility for picking up objects. The human like fingers allow the gripper to pick safely irregular shaped objects quite easily due to their possible ten contact points with objects (three on each of the phalanges and one on the palm) [76]. However, a system like so would reach higher levels of complexity.

In contrast, a more stable and limb disability focused solution would be the end-effectors used in the ROBERT system. According to Petersen *et al.*, the end-effector used for lower limb rehabilitation enables the leg press and the dorsiflexion exercises [14], and is provided with electrical actuators, Figure 3.6a. It could also be handled by a therapist to set the trajectories desired for when it actuates autonomously and change the exercises it makes [77].



(a)

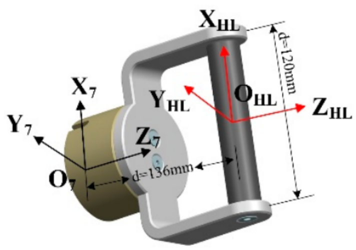
(b)

Figure 3.6: (a) ROBERT lower limb end-effector [14]. (b) ROBERT upper limb end-effector [77].

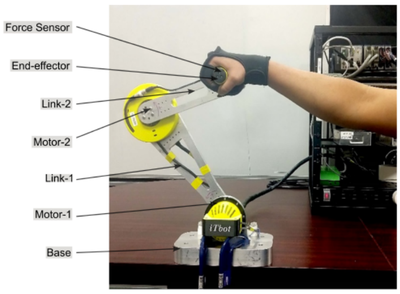
Petersen *et al.* developed a system where they added Functional Electrical Stimulation (FES) technique to this lower limb end-effector. The FES technique is used to stimulate the member with an electrical charge, it allows patients to exercise muscles and it can be used alongside physical therapy [12]. Sometimes this actuator is followed by an Electromyography (EMG) sensor that monitors the electrical impulses from the area it is associated [78]. It encourages muscle bulk and strength, but may cause muscle contractions and can be painful. Alternatively, the ROBERT also has an upper extremity end-effector and there are testimonials of it being quite effective, Figure 3.6b. It shares the same active and passive types of exercise, but now on the arm and shoulder movement [77].

3.3 End-Effector Based Robots

An EULRR normally means the robot in question is provided with an end-effector specifically to help in upper limb physical therapy. There are various case studies, papers and theses that use this terminology when the manipulator used has an end-effector, which the patient holds with one hand. Based on this principle, Liu *et al.* developed a robot with 5 DoF where the controller, computer, power unit and manipulator are all merged together [6]. The end-effector used on that work had only one contact point, which gives great versatility into manipulators due to its simplicity.



(a)



(b)

Figure 3.7: Different works done around similar kind of end-effectors: (a) End-effector for an upper limb rehabilitation robot [5]. (b) Robot followed by its characteristics [17].

Furthermore, Zhang *et al.* and Khan *et al.*, used a similar gripper for one hand only, like in Figure 3.7a and Figure 3.7b [5], [17]. The main difference resides in the way it is exercised. Zhang's end-effector is used into a more robust manipulator than the Khan one, and the person exercising is sat in a chair facing away from the manipulator. The Khan's manipulator, the iTbot, must be exercised facing towards it and hold the hand horizontally. This robotic device has a fixed base and the whole movement is limited to the reach of its manipulator. It has a maximum horizontal reach of 0.55m and a maximum vertical reach of +0.1 to +0.55m. It's made of two links and two motors, one for the control of each link. This case of study developed this two DoF robot that helps the user in restoring upper limb movement, in the early stages of therapy. Its creation has in mind the possible reach of a human and the limits of the limbs. The design of the robot is explained in Figure 3.7. The control of the robot was made by first setting the workspaces of the human and then calculating the kinematics and dynamics of the manipulator. Also the Zhang's manipulator is more ambitious as it provides a more controlled environment as well as a more capable robot.

To fully understand how an end-effector can be effective in upper limb rehabilitation and its disadvantages, Zhang *et al.* have conducted a study followed by the creation of an EULRR and a controller based on AAN [5]. Its use resembles the work done by Liu *et al.*, where the manipulator is followed with a whole setup (power unit, screen, camera) for the robot [6]. Basically, as depicted in the Figure 3.8, the body of the robot has a chair for the patient to sit, and its dimensions are capable of fitting the majority of sizes, male and female. The patient then holds an end-effector, with the format depicted in Figure 3.7a, and starts the exercise. This was done based on the principle that the patient already had some autonomy on some easy movements and only needed to be helped by benefiting on the active movement of the manipulator. This was achieved due to the creation of a virtual channel in order to design and allow the existence of a virtual workspace [5]. A virtual workspace, in this case, is a simulated space where an area of effect is set throughout the exercises the manipulator performs [23]. This channel limited the zones of exercising and the amount of force the manipulator did. Because of this, the rest of the exercises were left for the person to do them, with no robotic help, in order to encourage effort and muscle growth.

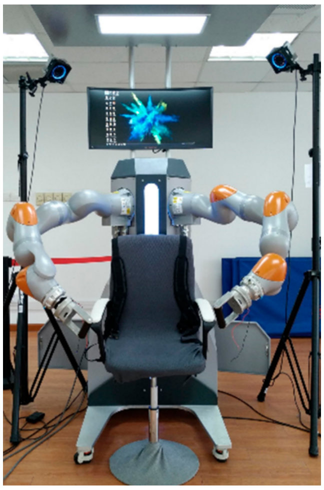


Figure 3.8: End-effector upper limb rehabilitation robot [5].

Zhang *et al.* findings highlight the effectiveness of employing a virtual channel and an AAN strategy to facilitate a more controlled trajectory [5]. The study delineated results across three distinct tasks. The initial task allowed patients full autonomy in manipulating the robotic arm, representing an uncontrolled movement. The second task involved the arm intervening when subjects deviated from the prescribed exercise trajectory. The final task incorporated a virtual workspace, where the arm would only intervene if the patient deviated from the designated space.

Notably, the second task exhibited superior control outcomes, with the manipulator being called upon more frequently compared to the third task. While the third task may seem less successful in terms of direct arm control, the implications for rehabilitation are promising. The results suggest that, from a rehabilitation standpoint, the approach of selectively intervening when deviations occur holds huge potential.

In summary, the first task doesn't appear to be compatible for therapy as it involves only natural patient's movements. The second task, on the other hand, emerges as an ideal fit for early rehabilitation stages, catering to individuals with limited autonomy in arm movements, thereby needing more assistance. The final task represents a consistent therapeutic approach, allowing patients the freedom to exercise their limbs while correcting errors with a more lenient space threshold.

This technique of creating virtual channels or virtual workspaces isn't unknown. Kyrkjebo *et al.* also used a virtual workspace for the UR5 model from Universal Robots, in order to limit the field of work of the arm and the force applied into the patient, to avoid injuries [23]. This work also limited the force and torque of this very robot to an emergency shutdown, when a certain value is exceeded (value set by the user). Because of this, it is possible to draw the field of work of the arm into whatever the user desires. In this case, the field of work was set into cylindrical shapes, in order to avoid injuries and singularities. Other strategy adopted was setting up three kind of controls [23]. These controls are divided into either giving liberty to the patient to use the arm and helping him to complete the exercise, or resisting the limb of the user for a more challenging training. It is also provided with a mode where it challenges the patient into either resisting or doing certain exercises, with random orientations and intensities [23].

The UR5 robot from Universal Robots, because of its versatility and low weight, is a great candidate to be used in collaborative work alongside humans, but with extreme care, as it isn't medically certificated the KUKA LBR. Due to its promising characteristics, Chiriatti *et al.* developed a study around upper limb robotic systems and ended up using the UR5 model to further extend their work [63]. Different techniques and devices were produced in order to test strength and mobility between certain groups of people, they are presented in Figure 3.1. The goal was to improve available systems with new ideas and explore its results. In this study, Chiriatti also made pilot studies with groups of people documenting the results around this robotic device and prototypes developed. The participants, in general, accepted the system well, showing a high level of satisfaction. They only had difficulty on performing the exercises on the first model, Figure 3.1a. The study managed to obtain somewhat good results with differences between the experimental group and the control group. However, the results are also conflicting, as the differences between the two groups aren't too significant. This could also be explained by the low heterogeneity of the groups and for the first model, Figure 3.1a, the patients had a hard time using it, as it didn't hold the wrist like the second did, Figure 3.1b.

In terms of rehabilitation, the most important part is restoring the RoM and strength into the patient. Moreover, passive arm movements are key in that area, in order to keep limb joints healthy as well as muscles, and are essential in the early stages of the therapy [15]. Nowadays, when talking about RT, usually means that the robot is provided with active only, passive only or active and passive movements, like in the case of the work done by Khan *et al.* [17].

Despite its age, The MIT-Manus, stands as an unique end effector based robot that revolutionized the integration of RT into the rehabilitation of limb impairments following strokes. There's even a case study which analyses further its impact, involving the testing of the system on 130 patients. The findings from this investigation, as reported by Sale *et al.* affirm the positive influence of RT on improving upper limb mobility in individuals recovering from ischemic mono-hemispheric strokes [21]. The study also suggests that after a certain number of sessions, an intensive RT may significantly reduce motor impairment in upper limbs [21]. Although these results seem positive, due to its design, the robot didn't verify if bilateral training could also obtain such results, as the only option for the robot is the unilateral training due to its design.

Additionally, ROBERT is a rehabilitation robot based on the KUKA LBR Med manipulator. It provides treatment for patient's lower limbs and its body is like in Figure 3.9a. Moreover, the Yaskawa company also has a model, the LR2 - Leg Rehabilitation Robot, Figure 3.9b, quite similar to the ROBERT [79]. It can provide therapy effectively and smoothly, with the purpose to replace and imitate the movements of a professional therapist. It is also provided with sensors to help guiding the robot to perform its tasks.

(a) (b)

Figure 3.9: Robotic models used in rehabilitation environments (a) ROBERT system [32]. (b) LR2 from YASKAWA [79].

This particular robot can actuate actively or passively, encouraging the patient to perform the exercise as well as helping him whenever he needs [32]. It comes as a great way to evolve the conventional therapy into a less time consuming and patient focused. Combining ROBERT with surface EMGs and FES technique, could potentially stimulate paralyzed and weakened muscles, thus becoming more muscle efficient. This was the topic of the work done by Petersen *et al.* where they used patients and alternated the position of their lower limb between 90º and almost 0º, in a bed inclined in about 30º [14]. The FES were installed in each muscle (*Rectus Femoris* and *Tibialis Anterior*) as well as the surface EMG electrodes, and released a stimulus every 4 to 6 seconds of exercise. This would repeat until 10 repetitions had been reached and a 10 min break was followed. They found that 97% of the subjects managed to complete the exercises as intended. they believe that an insufficient stimulation was the reason why the other 3%, represented by two participants only, couldn't finish the program. The exercises this system performs are restricted to lower limbs, but knowing that the manipulator Kuka LBR Med has great adaptability, then it might be possible that further studies could go beyond and develop a system for upper limbs.

Another research by Leerksov *et al.* [78] studied the same outcome of a hybrid system between ROBERT and FES actuators, in order to understand if improvements on lower limb capabilities were possible. The investigation analyzed variations in velocity and force at the start of the exercise and at the end. Interestingly, while certain patients exhibited potentiation, characterized by an increase in synaptic strength and plasticity as defined by Verslegers *et al.*, others failed to demonstrate any discernible improvement [80]. Rather some experienced fatigue from the whole exercise, leading to a decline in the exerted velocity and interaction force. This conflicted outcome originated confusion and ambiguity during the data discussion, which made the authors unable to take a stand if robotic-FES exercises actually improve or not RoM on patients. The complexity of the responses observed highlights the need for further exploration and nuanced analysis to elucidate the conditions under which such hybrid systems may or may not be effective in promoting rehabilitation.

Rikhof *et al.* also did a similar investigation where ROBERT was used for lower limb rehabilitation [81]. In this case study EMGs and FES actuators were used parallel to the movement of the robot. Three stroke patients were enrolled for this test and two of them showed severe limitations in terms of motor functions, when looking at the FM scoring. The results were quite promising and interesting, because it validated that it is possible to boost limb recovery combining those actuators with robotic systems [81].

Furthermore, a pilot study conducted by Perini *et al.* wanted to go beyond [61]. The aim was to assess the viability of Myoelectrically Controlled Functional Electrical Stimulation (MeCFES) as a potentially more feasible and effective solution. To validate their findings, the study enlisted post-stroke patients and a control group. Firstly, the patients were subjected to a MeCFES alongside a task oriented reaching session. Subsequently, a session featuring a planar robotic system was introduced. This one, on the other hand, showed promising results and actually got better results with the experimental group than the control group, validating the initial premise. The success of the experimental group underscores the potential effectiveness of MeCFES in enhancing rehabilitation outcomes. However, due to the small size of the group used and low heterogeneity, the conclusions can't be generalized.

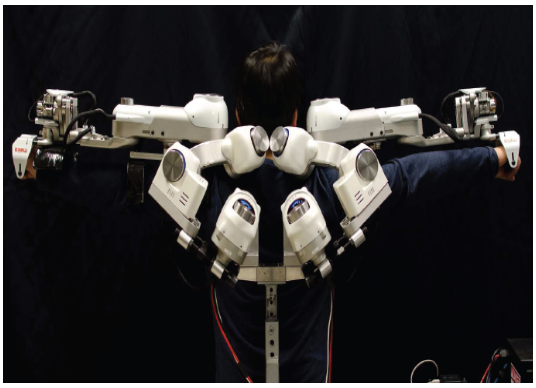
3.4 Exoskeleton Based Robots

Despite end-effector based robots having great effectiveness, exoskeleton robots could also obtain promising results and provide single-joint robotic assistance for patients. Some also have an end-effector for better stability to the patient's limbs. They are quite effective in the case where the patient has the necessity of working all DoF of his arm, without creating any limb impairments [69]. For even better results with these systems, coordinating the whole arm movement with the shoulder should also be acknowledged. This type of coordination was studied by Kim and Deshpande [82].

The ANYexo model, Figure 3.10a, and the Harmony SHR, Figure 3.10b, are exoskeleton robots that combine end-effectors with exoskeletons, leveraging the advantages of both technologies. Like these examples, there are others, like the ARMin series in Figure 3.10c, ALEx in Figure 3.10d, EXO-UL77 in Figure 3.10e and, at last, ABLE exoskeleton in Figure 3.10g. For a more extended source that has more of these types of systems, Frisoli *et al.* in their book explain types of upper limb exoskeletons and how they can be introduced in robotic rehabilitation [83].

Before diving into the aspects and characteristics of the ANYexo and Harmony SHR systems, when talking about exoskeletons that reach around the arm and shoulder joints, the limits of the elbow joint and the Glenohumeral (GH) joint need to be acknowledged. The GH joint, for instance, is a joint situated in the shoulder and it is responsible for the rotation and mobility of the shoulder [91]. The ANYexo is a robot suited to help people with ADL, but can also be used as a rehabilitation robot. The main objective of Zimmermann *et al.* with this robot was to validate algorithms and hardware, such as certain actuators, to use in patients with neural impairments [69]. The ANYexo uses SEAs and electrical actuators for a lightweight approach and a less stiff design. It's a 6 DoF exoskeleton with a Linux operating system as a control PC [69]. Unfortunately, the robot is only made for the right arm, so any left arm rehabilitation is out of the picture. It also comes with 8 Inertial Measurement Units (IMU), 6 joint torque sensors, 6 joint position sensors, 2 force-torque sensors and two D435 Intel Real Sense cameras [69], [84]. Although this robot aligns well

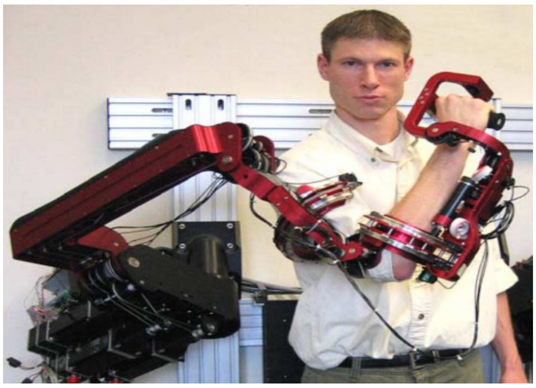
(a)



(b)

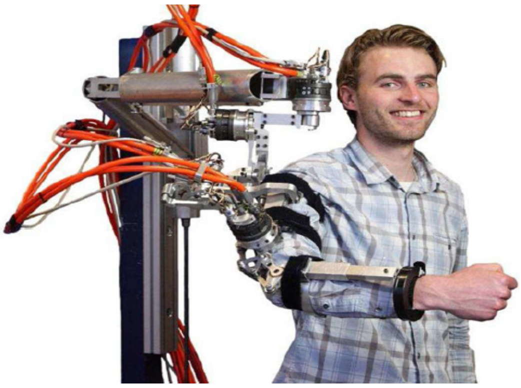
(c)

(d)



(e)

(f)



(g)

Figure 3.10: Different exoskeleton models. (a) ANYexo [84]. (b) Harmony SHR [85]. (c) ARMin III [86]. (d) ALEX [87]. (e) EXO-UL77 [88]. (f) ABLE [89]. (g) LIMPACTA [90]

with human joints, its placement needs to be done manually, whereas the LIMPACT model done by Otten *et al.* self-aligns with the shoulder and elbow joints [90]. This robot, like the other, is also a rehabilitation robot, but with a hydraulic motor.

Nowadays, there is an improved version of the ANYexo, the ANYexo 2.0 [66]. The ANYexo 2.0, Figure 3.11, compared to its predecessor is better prepared for helping in ADL and performing movements smoothly, due to its additional actuators and joint freedom. In total the robot has nine DoF: sternoclavicular protraction or retraction, sternoclavicular elevation or depression, glenohumeral plane of elevation or glenohumeral elevation, glenohumeral axial rotation, elbow flexion or extension, forearm pronation or supination, wrist flexion or extension, and wrist ulnar or radial bend [66]. The ANYexo 2.0 uses three types of actuators, two ANYdrive with different sizes, the 1.4 kg and 1.1 kg versions, and a Dynadrive of up to 0.8 kg [66].

Figure 3.11: ANYexo 2.0 [66].

The Harmoy SHR is a 6 DoF exoskeleton, bi-manual robot, which means that it has two robotic arms for a more natural mobility to the patients [82]. The problem of having this bi-manual system is that it limits the RoM of patient's arms, to the point where it's not possible to extend them backwards like in ANYexo [69]. It's possible to acknowledge that information from the Figure 3.10b. The authors would rather focus on a natural shoulder mobility and passive exercises by the robot. That wouldn't be possible without a joint-space impedance controller where it calculates the torque necessary for the shoulder rotation, so it doesn't harm patients with severe and painful impairments [82]. Its control is done by kinematic and dynamic equations with a baseline control. This baseline control is a model developed by the authors to merge the robot dynamics with weight and frictional force compensations. They explained that its purpose was for the robot to seem weightless and keep the patient's arm movements more natural. They also included assistive and resistive forces [82].

It's also important to state that the robot doesn't have a strict payload, since the system can be defined into whatever arm weight the patient has or desires. This not only gives more freedom for the patient, but also compensation and better movement precision [85]. The mobility of the GH joint on the Harmony robot is done essentially by the rotation of a ball inside a socket, called ball-and-socket joint mechanism in exoskeletons [82]. The ball-and-socket of this exoskeleton is constituted of three revolute joints to further extend the RoM of the robotic shoulder. The shoulder size and arm size is all adjustable so it is possible to turn the system compatible with every type of person.

To validate this system into rehabilitation scenarios, Ogden *et al.* performed therapeutic exercises with a chronic stroke patient [92]. What they concluded was that the Harmony SHR allowed the subject to explore scapula-focused exercises with a large workspace. The patient was a fifty eight year old male and the status of his GH, muscle status and shoulder motion was monitored throughout twenty two sessions. Similarly, Oliveira *et al.* used the Harmony SHR to perform on post stroke patients and also validated and recommend the system as safe and comfortable for upper limb interventions [68]. In this case, they subjected five stroke survivors to 1130 motions over seven hours of therapy each. In this last case of study, they obtained very positive results and indeed verified that it is possible to reach or even surpass the results from conventional therapy. Another milestone they obtained was that the Harmony SHR is very human friendly and comfortable for rehabilitation therapy, as it satisfied the patients RoM, even though the limits of its design.

Burns *et al.* also developed the HERCULES, an exoskeleton type of robot like the previous ones [16]. It is a three DoF pneumatic upper limb exoskeleton for stroke rehabilitation. Its design is limited and restricted to the basic function of rehabilitation, it is not suited for other scenarios. The pneumatic cylinders actuate on different muscles of the patient, the biceps, triceps and trapezius. In spite of its limits, it could potentially be improved into having different types of actuators and improve its system.

Likewise, the ARMin is an exoskeleton device compatible with human characteristics. There are several versions, the latest being the ARMin V developed by the Sensory-Motor Systems Lab at the ETH Zurich. The models are distinct from one another. For instance, the ARMin I has four DoF and actuates the shoulder in three dimensions, while flexing or extending the elbow [93]. It is an exoskeleton with 4 DoF, electrical actuators, 2 kg of payload, 6.5 kg of weight, a stiffness no less than 714 N/m and an end-effector [86]. It can also do passive and active exercises in an AAN strategy [93]. The ARMin II added two more DoF, being six DoF altogether, and an optimal shoulder actuation [86]. It also focused on the hand movements, wrist and forearm, its rotation, extension and flexion [86]. The ARMin III, Figure 3.10c, was prepared to be more robust, more reliable, with less stiffness, higher payload, and better equipped to obtain better results in clinical trials [86]. The ARMin IV and ARMin V are seven DoF exoskeletons with contact points all over the arm, capable of horizontal shoulder abduction or adduction, shoulder elevation, internal or external shoulder rotation, elbow flexion or extension, forearm pronation or supination, wrist flexion or extension and hand opening or closing [94]. Relatively to the ARMin I and ARMin II, they're very popular when it comes to using them as clinical trials on stroke patients. Klamroth *et al.* and Nef *et al.* each made a clinical trial on patients and registered the results [22], [67]. In terms of evaluation to compare data on control groups and experimental groups, before and after the sessions, they based it on the FM test. However, there weren't really improvements registered. In the Klamroth *et al.* study, they couldn't conclude if RT was indeed better than conventional therapy when using the ARMin II. Table 3.1 has further details and compares the models ARMin I and III with the Harmony SHR model. To further understand clinical trials explained in this chapter, Table 3.2 was made to group the most important ones for a better perspective and to serve as comparison between them.

Table 3.1: Different types of exoskeleton models and their characteristics.

	Harmony SHR [85]	ARMIN I [67]	ARMIN III [86]	ANYexo [84]	ANYexo 2.0 [66]
Payload	*	2 kg	4.6 kg	*	*
DOF	7	4	7	6	9
Weight	31.8 kg	6.5 kg	18.75 kg	*	*

Note: The * symbol means that the author didn't specify that characteristic.

Table 3.2: A comparison between different trials with different robots for a better understanding of each system .

Case of Study	Robotic Model	Type of Robot	Actuators used	Classification	Results	Limitations
Nef *et al.* [67] (2010)	ARMin I	Exoskeleton	Electrical actuators	FM tests	Registered results and positive improvement	Patients didn't improve in all parameters and dubius information
Klamroth *et al.* [22] (2014)	ARMin II	Exoskeleton	Electrical actuators	FM and WMFT	Successful results, improvement on patients	Couldn't conclude if RT is better than conventional therapy
Sale *et al.* [21] (2014)	MIT-MANUS/ /IM2	End-Effector based	Electrical actuators	FM, pROM, MAS, MI tests	Successful results, improvement on patients	Unilateral training as the only option
Oliveira *et al.* [68] (2019)	Harmony SHR	Exoskeleton	SEA, Electrical actuators	FM tests	Very good results	RoM satisfies and is compatible to patients RoM. However, it is limited due to the robots' design
Perini *et al.* [61] (2021)	Parallel Robot	End-Effector based	EMG, FES, MeCFES	FM tests	Validates that MeCFES can provide relevant results	Small sizes and comparisons, needs more heterogeneity of the group, can't be generalized
Rikhof *et al.* [81] (2022)	ROBERT	End-Effector based	EMG, FES, Electrical actuators	FM tests	Interesting results, promising study	Could benefit if the group tested was bigger and with more heterogeneity
Chiriatti [63] (2023)	UR5	End-Effector based	Electrical actuators	FM, MAS tests	Slight differences, and concrete results	The results are somewhat conflicting, difficulties in the equipment used, needs more heterogeneity of the group used

3.5 Limitations

When developing effective rehabilitation solutions for upper limb impairments, several limitations persist despite advancements in technology. This section highlights the key limitations encountered in the literature regarding current upper limb rehabilitation robotic systems and techniques.

1. Restricted Range of Motion: Parallel robots, such as the MIT-MANUS and the InMotion robot series, primarily actuate in two dimensions. This limitation prevents them from providing a natural RoM that closely mimics human movement [73]. As a result, these systems need to be replaced with options that allow for three-dimensional motion to effectively train patients.

2. Inability to Simultaneously Actuate All Joints: EULRR systems, often based on manipulators, face constraints in actuating all arm joints simultaneously, unlike exoskeleton devices. This limitation leads to restricted movement capabilities for users.

3. Cylindrical End-Effectors: Many manipulator-focused EULRR solutions feature cylindrical end-effectors, which can pose challenges for post-stroke patients. Such designs may hinder patients' abilities to open, close, and grasp objects, potentially causing discomfort and pain.

4. Complexity and Cost of Exoskeleton Devices: While exoskeleton devices provide adaptability and comfort due to their stability on the human arm, they come with complexities, added weight, and higher costs to achieve the desired stability and RoM. As a countermeasure, Demofonti *et al.* propose cost-saving strategies such as utilizing more affordable materials, investing in local resources, or reducing the DoF of the device [95]. Moreover, having local 3D printers could further mitigate the expenses associated with developing these systems.

5. Inconclusive Findings in Literature: A significant portion of the literature on post-stroke rehabilitation presents inconclusive findings. Conflicting results are common, with some studies reporting positive outcomes while others yield less favorable results. This variability highlights the complexity of post-stroke rehabilitation and emphasizes the need for further research to identify the most effective approaches for enhancing patient outcomes.

3.6 Summary

This chapter provides an overview of various rehabilitation systems and their potential contributions in enhancing physical therapy. It examines different types of actuation methods employed in human-robot interactions to establish a secure and collaborative environment. The analysis considers both commercial models and research conducted by the scientific community. While the selected studies are chosen to be as recent as possible, it is important to note that other studies and models exist in the field of rehabilitation. This thesis focuses on a wide selection, prioritizing the most recent and most recognized ones. It also serves as an introduction for the next chapter that implements these ideas into a more general idea, focusing on one solution.

Chapter 4

Interface Model Engineering

The primary aim of this work is to facilitate the rehabilitation of upper extremities, which may prove particularly beneficial for individuals recovering from cerebrovascular accidents. This chapter delineates the creation of an electromechanical interface, which integrates with a robotic manipulator, employing the UR5 robotic arm for this purpose. To achieve this integration, a structure was designed and produced using 3D printing technology, ensuring a comfortable connection of the manipulator with the human arm. The design and development of all components was conducted using the SolidWorks software. While alternative software platforms such as Fusion 360 and Autodesk were evaluated, SolidWorks was ultimately chosen, due to the team's familiarity with its features and capabilities.

In the development of this project, numerous components were meticulously engineered, with a particular emphasis on a mechanism to secure the human arm in a comfortable position. The initial point of contact was strategically selected to be on the upper arm, and, utilizing a controllable motor, the forearm was securely and comfortably fixed to that hardware. Leveraging the rotational capabilities of the motor, a structural model was conceived and designed, within the software framework, to stabilize the motor to the upper arm model, while another model was designed to be screwed to the tool flange of the motor and fix a person's arm to it. Furthermore, a flange was crafted to facilitate a seamless integration between the overall interface structure and the UR5's tool flange.

The selection of the UR5 manipulator was made based on its suitability and immediate availability at INESC TEC, the institution where this thesis research was undertaken. Accordingly, the dimensions and mass of the designed structure were tailored to align with the unique specifications of the UR5 robotic system.

4.1 System Architecture

This section details the system architecture of the human-robotic interface, emphasizing the integration and functionality of its components. The system is designed to facilitate precise and controlled assistance to the user's arm movements through a combination of 3D-printed structures, robotic manipulation, and motorized actuation. Figure 4.1 illustrates the comprehensive setup required for the system to function effectively. By incorporating these elements, the system is able to ensure a high degree of accuracy and reliability in operation.

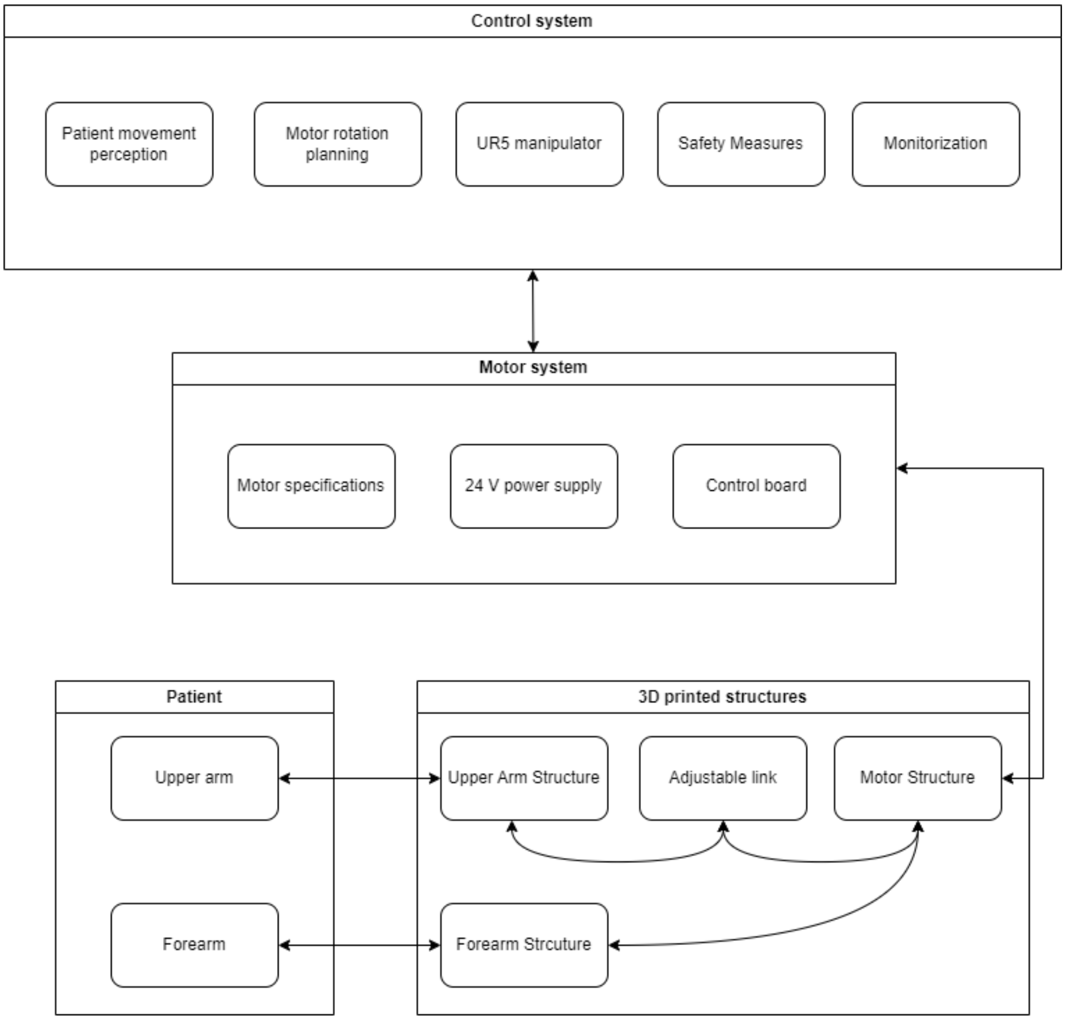


Figure 4.1: Block diagram of the system architecture

The primary component of the system is the UR5 robot manipulator from Universal Robots, chosen for its capability of interacting with humans and its compact size relative to its other similar models, such as the UR10 and UR30. The system architecture depicts the secure attachment of the user's arm, the connection to the UR5 manipulator, and the necessary control mechanisms for accurate operation and data recording.

A key aspect of the system is the use of custom 3D-printed structures designed to securely hold the user's upper arm and forearm while facilitating the required range of motion. The motor responsible for elbow actuation is integrated, ensuring seamless interaction between the upper arm and forearm components. The inclusion of a control device, power supply, and real-time monitoring system further enhances the system's performance and reliability.

This comprehensive setup ensures the system operates effectively, offering precise and controlled assistance to the user's arm movements through the integration of 3D-printed components, robotic manipulation, and motorized actuation. The following subsections will delve into the specific components and their roles within the system, illustrating how their integration results in a robust and efficient human-robotic interface.

4.2 Tool Flange

Before drawing any structure to connect the UR5 to the patient, the tool flange of the robot must be acknowledged. For that matter, Universal Robots has the UR5's datasheet publicly available [34]. This datasheet has all the dimensions about the manipulator's structure overall, and many other specifications, such as its weight and features.

For a better understanding, the tool flange of the UR5's manipulator is illustrated in Figure 4.2; its characteristics are measured in millimeters, and are as followed:

- A cylinder body shaped like object with 63 mm diameter by 41,7 mm height.
- Four holes for fixing objects, evenly spaced, 90º between each of them, starting at 45º from the top, around a 50 mm diameter circle.
- Each hole is cylinder shaped and adjusted for M6 screws.
- A Lumberg RKMW 8-354 connector for communication with specific end-effectors or tools, such as the Robotiq branded ones, like in Figure 2.2a.

As a result, a flange was designed to ensure an interface between the UR5's tool flange and the overall structure, connected to the patient, once developed. For that matter, a cylinder shaped object was drawn to connect the two of them. This cylinder has identical dimensions as the UR5's tool flange, where the diameter of the cylinder is 63 mm and the height 10 mm. Essentially, one of the sides of the cylinder,

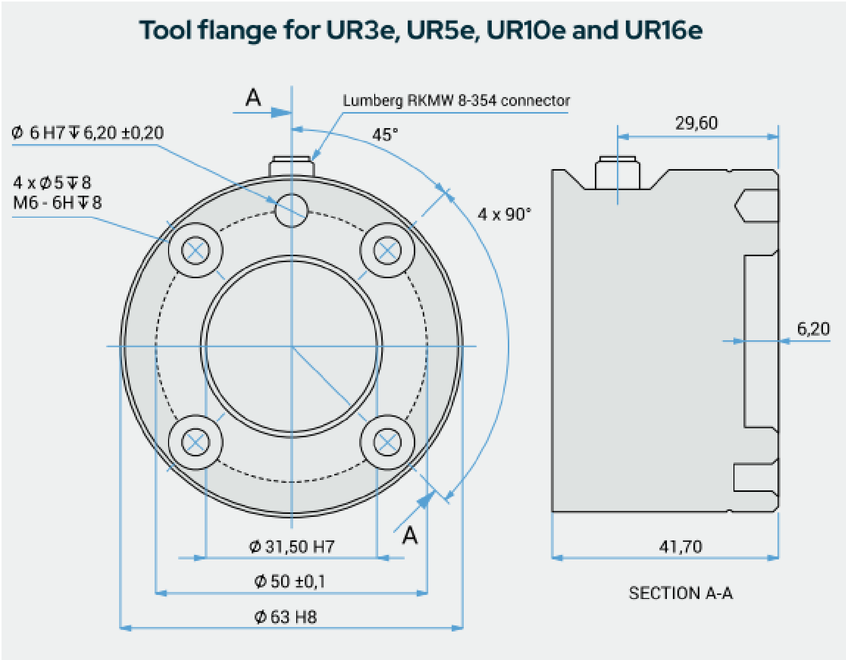
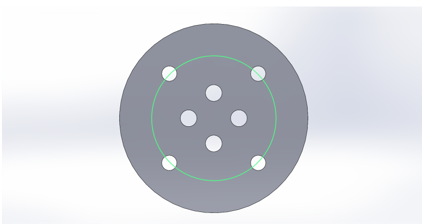
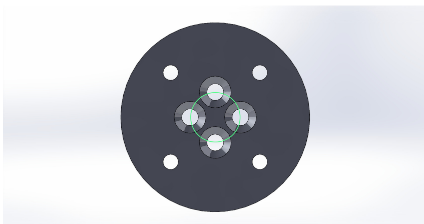


Figure 4.2: Dimensions of the UR5's tool flange [34].

the one in Figure 4.3a, connects to the tool flange of the UR5, while the other side, Figure 4.3b, connects to the structure. Therefore, 4 M6 screw holes evenly spaced are drawn around a circle of 50 mm of radius, as depicted by the green circle in Figure 4.3a. Alternatively, 4 other holes of the same type are also drawn in the middle of that cylinder where they were rotated 45º compared to the previous ones, and evenly spaced around a circle with 20 mm of diameter, as illustrated by the circle in Figure 4.3b. As a result, this designed flange has the advantage of being flexible to any interface. This means that in the case another interface is to be fixed to the UR5 robot, this flange will be the intermediate between the robot system and that interface.



(a)



(b)

Figure 4.3: Designed 3D models for the flange, between the UR5 robot and the structure. (a) Front view of the flange. (b) Back view of the flange.

4.3 Motor Behavioral Analysis

Additionally to the flange, a real motor for the elbow actuation was also chosen. In order for this to work, the right motor had to be found. To select the best choice for controlling elbow movements, various types of motors were studied to determine a good solution and to gain an understanding of how different motors function. Table 2.3 of the literature review identifies all the motors studied and considered relevant for the choice.

The selection took in consideration the availability, weight and torque. The one chosen for this project was the L54-30-S500-R from ROBOTIS, a motor with 591 g which is compatible with the objective weight. Its torque is also compatible with the objective torque. Other specifications of this motor are presented in the Table 4.1. As it is possible to interpret from the table, the motor consumes 30 W of power and needs an input voltage of 24 V. This means that it also needs a power supply capable of an output of at least 24 V, which would be added as a requirement when assembling the system and testing it out.

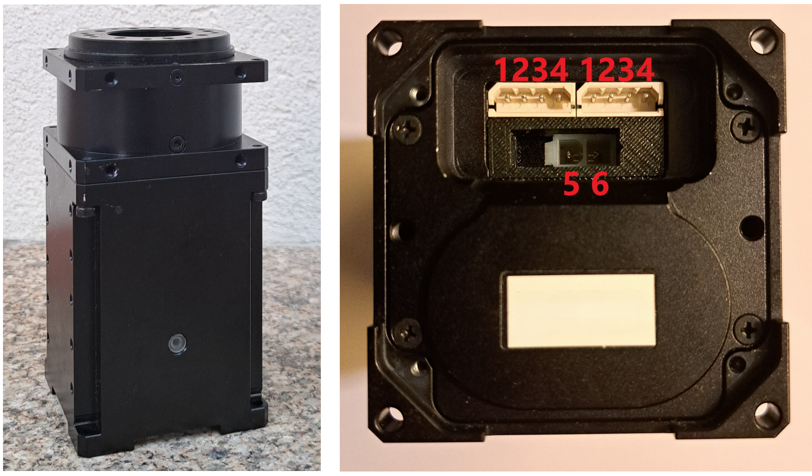
Table 4.1: L54 30 S500 R motor Specifications

Motor	BLDC
Weight	591 g
Dimensions	54 x 108 x 54 [mm]
Continuous Torque	5.4 N.m
Output	30 W
Protocol Type	RS485 Asynchronous Serial Communication

The L54-30-S500-R model, as depicted in Figure 4.4a, is a rectangular shaped motor with dimensions as presented in Figure A.1. The tool flange of the motor has eight M3 screw holes around a 36 mm diameter to fix to any other surface safely. The sides of its body also have the same type of screw holes for the possibility to screw them against other structure for a more stable support. The communication and power supply connect to the reqar end of the motor. For communication, it uses the RS485 Asynchronous Serial Communication protocol. Looking into the Figure 4.4b it is possible to see that the communication is done by the numeric ports presented in red as 1, 2, 3 and 4, while the power input by the numeric ports 5 and 6. Their meaning is as followed:

1. Ground (GND)
2. 24 V Digital Operating Voltage (VDD)
3. Data (D+)
4. Data (D-)

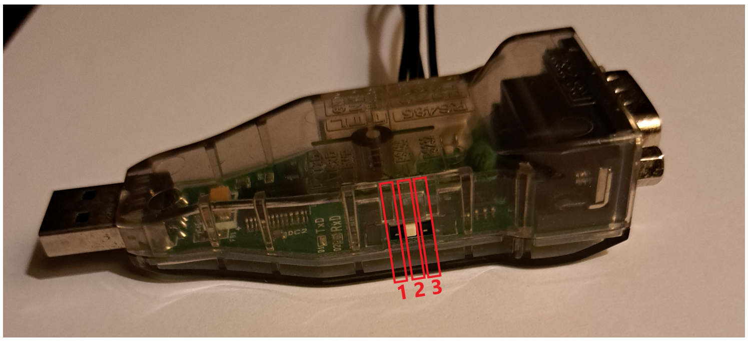
5. Ground/GND (power supply)
6. 24 V Digital Operating Voltage/VDD (power supply)



(a) (b)

Figure 4.4: L54-30-S500-R model. (a) L54-30-S500-R model of the PRO Series from Dynamixel chosen for this project. (b) Rear end of the model.

In order to control the motor, an external device must be present. The USB2 Dynamixel device is a controller that can use communication modes such as TTL, RS485 and RS232. The L54-30-S500-R uses the protocol RS485. In the switch present in the Figure 4.5a the protocol RS485 can be set up when switching to the second (middle) state as illustrated.



(a)

Figure 4.5: USB2 Dynamixel, the communication device for the L54-30-S500-R motor. Switch device that changes between 1 (TTL), 2 (RS485) and 3 (RS232).

This whole system needs to be supplied with energy. More specifically, the motor needs 24 V of input voltage. Therefore, a power supply was configured to feed this sytem. This power supply connects to a normal home AC power socket with 200-240 V. The voltage output is transformed into 24 V DC and the current 2.1 A. The

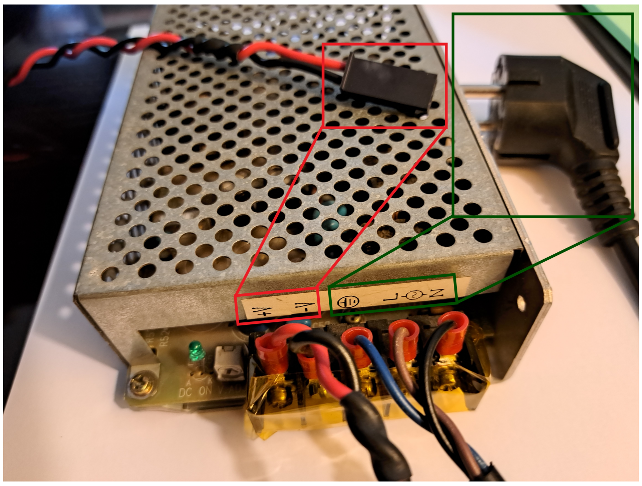


Figure 4.6: 24 V DC Power Supply.

representation of that power supply is in the Figure 4.6, where in red is illustrated the connection to the motor, and in green the connection to the power socket.

For a more detailed information of the L54-30-S500-R, Figure 4.7 compares the efficiency, with the speed in rpm and current in Ampere, in function of the torque. With all these variables it is possible to conclude that the motor has more efficiency between 7.5 N.m and 10 N.m, but requires around 2 A of current. At around 15 N.m to 17 N.m its efficiency is at around 30%, but its current tripled as compared to the no load state. Although its continuous torque is 5.4 N.m, based on the Figure 4.7, the motor is capable to withstand the torque of 10.5 N.m necessary for the system, and close to its top efficiency.

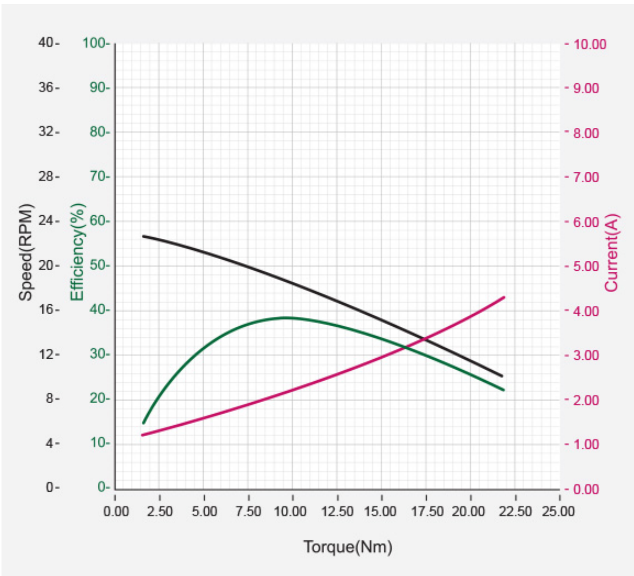


Figure 4.7: Speed, efficiency and Current variation as function of the torque of L54-30-S500-R motor [96].

4.4 Interface Conceptualization

Following the design of the flange to link the UR5 tool flange and the user interface, the next step involved designing the structure that would securely hold the user's arm. To achieve this, several variables needed to be considered, such as the weight, length, and circumference of the patient's arm. Due to the significant variability in arm sizes, a generalized approach was deemed the most practical.

Several studies in the literature provide detailed measurements of arm and forearm dimensions. For instance, Perry *et al.* conducted a study involving diverse subjects to observe forearm types and dimensions [97]. Subjects were categorized by body mass index, and their forearm circumferences plus arm lengths were measured. The study included six subjects from the United States of America, resulting in an average forearm circumference of 277.17 mm when not flexed, 281.17 mm when flexed, and a length of 244.83 mm [97]. Similarly, Linnenberg *et al.* also studied the design of human-machine interfaces for exoskeletons on three male subjects. Each of the three subjects, as described by the author, fall in three categories, one was considered slim, other normal and the last extra strong. The categorization was based on the chest girth. The authors found the average upper arm circumference to be 345 mm, with an average length of 330 mm [98].

To accommodate a range of arm sizes and ensure comfort, initial models were designed with curved geometries, such as cylinders and circles, as these shapes better fit the human arm, which is more ellipsoid than cuboid. Figure 4.8 illustrates these initial models of the upper arm. One such model, shown in Figure 4.8a, measures 120 mm x 120 mm with a certain accentuated curvature. These dimensions, based on the findings of Linnenberg *et al.*, provide sufficient room for modifications given the average upper arm length of 330 mm. This model serves as the foundation for further development.

Integrating the curved model with the previously designed flange was the next step. To safely and accurately attach this part, a cylinder followed by a cuboid was added to the top of the previous model. As illustrated in Figure 4.8a, this cuboid, linked with the flange, has a width of 50 mm and a height of 10 mm. The cylinder, with a diameter of 31.50 mm, matching the middle circle of the UR5's tool flange, was designed to accommodate the screws from the flange, standing above the cuboid. The initial height of the cylinder was 30 mm, but this varied throughout the design process. The underside of the cuboid was designed to attach both the flange and the manipulator's tool flange, screwed from bottom to top, as shown in Figure 4.8b. The screw holes were made compatible with M6 screws, in line with the UR5's specifications.

Ensuring the curvature of the model was the most compatible with human arms was a crucial part of the project. At first, it was thought that a lower curvature

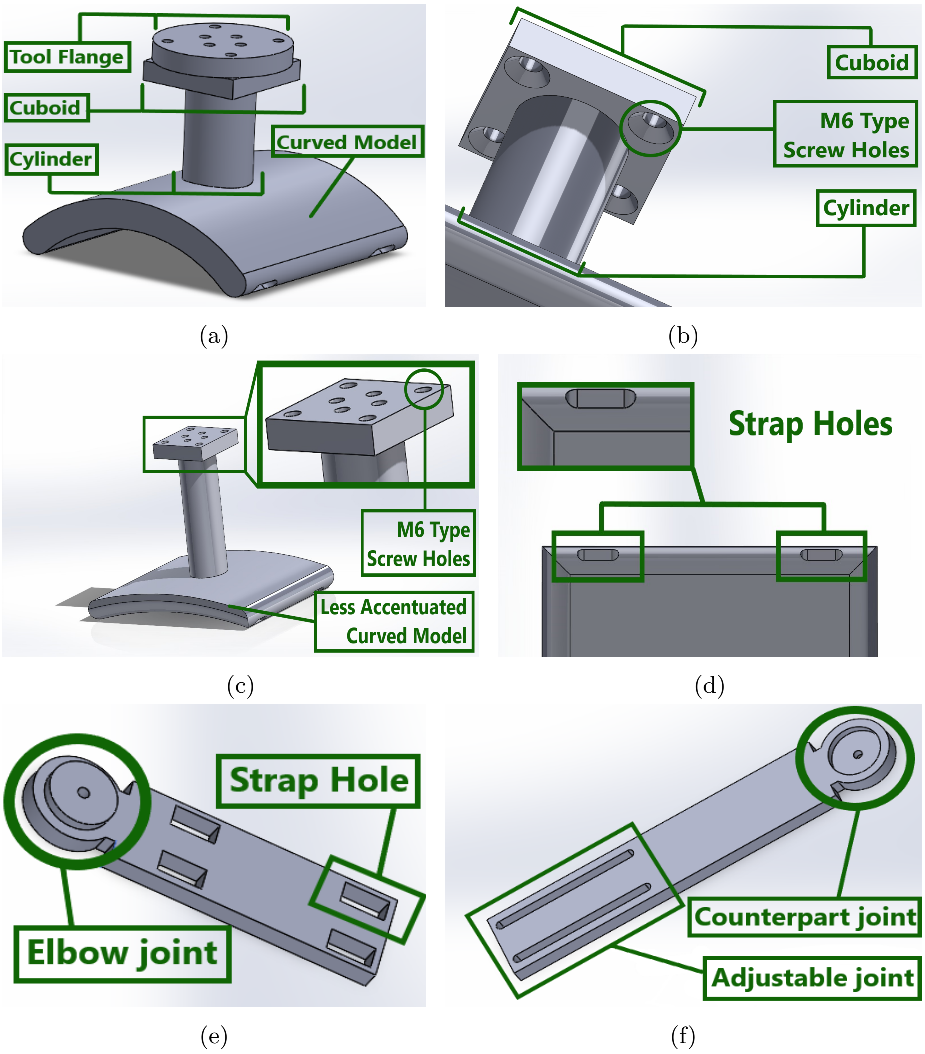


Figure 4.8: Experimental 3D designed models for the structure that links both the patient's arm and the UR5 manipulator. (a) Distant view of the first upper arm model with the flange attached, plus a cylinder and a cuboid to link them both. (b) Closed view of the cylinder and the cuboid. (c) Point of view under the structure, with emphasis on the strap holes. (d) Cylinder and cuboid added to new curved model. (e) Experimental and first model drawn for the forearm. (f) First model designed to link both the forearm structure and the upper arm structure.

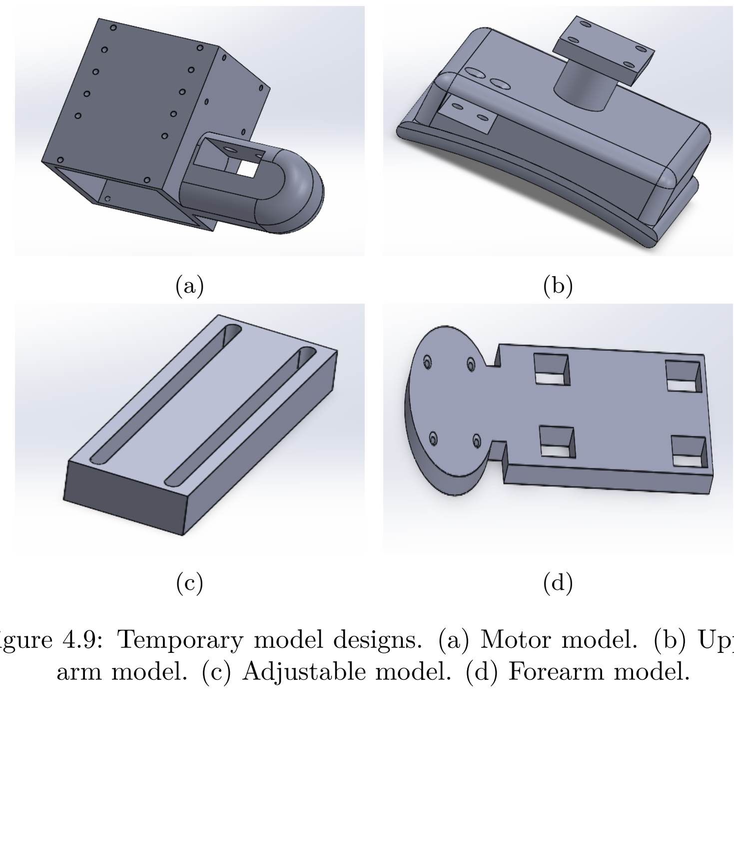
could achieve a more ergonomic and generic design for most arms. Therefore, a lower curvature was drawn to understand and better visualize the results, Figure 4.8c represents that model. Additionally, four holes, each 15 mm wide and 5 mm thick, were created, two on each underside, for straps or belts to pass through and securely fix the subject's upper arm. Figure 4.8d depicts the underside of the structure where these holes are located.

Contrary to the approach taken on the upper arm, the forearm model started out as a planar model. The inspiration came from the paper done by Liu *et al.*, where they sought to create a lightweight model for an exoskeleton [71]. It made sense as the model for the forearm would only serve as a holder. In Figure 4.8e it is possible to observe the first forearm model drawn. The circular part at the far extremity was also a preliminary design which would serve as a simple passive joint, in order to link both the upper arm model and the lower arm model. The four rectangular holes present were made so two straps could pass through them and fix the model to the forearm. Figure 4.8f is the next model that should be responsible of linking the motor and forearm part with the upper arm. It was an adaptive model which can be set accordingly to the user's arm size. One of the extremities of this later model is a counterpart of the extremity referred in the forearm model, shown in Figure 4.8e. Its initial purpose was to serve as a placeholder of where the motor should be. Later on, a motor was chosen to actuate on the elbow level, which means that this forearm model would have to adapt to it, more specifically the part of the joint.

4.5 Model Refinement

4.5.1 First version

After the first conceptualization of the interface part models, the next step was to design a 3D model to fix and stabilize the motor to the structure. Figure 4.9a represents the model designed. First a hollow cubic structure with M3 screw holes was drawn to stabilize the motor. Afterwards, a second part was drawn to fix the adaptable model, depicted in Figure 4.8f, to this one, with the help of M6 screw holes (right section of the Figure 4.9a).



(a) (b) (c) (d)

Figure 4.9: Temporary model designs. (a) Motor model. (b) Upper arm model. (c) Adjustable model. (d) Forearm model.

Following the building of the human robotic interface, the 3D models now need to be compatible to the motor chosen. Starting from the upper arm, the model was changed quite a bit compared to the previous version, shown in Figure 4.8a. In order to fix the adaptable model to this new upper arm part, a hole of the same size of the adaptable piece was carved at the top, as in Figure 4.9b. This rectangular hole designed into the model was measured to fit the part shown in Figure 4.9c and align the motor model to the center of the patient's arm, more specifically to the elbow. For securing the adaptable model depicted on Figure 4.9c, two M6 screw holes were added. In order to avoid injuries, the edges and vertices were replaced by fillets (round edges).

Because the adaptable model's purpose changed, shown in Figure 4.8f, as it is not going to be fixed to the motor itself, its shape was also modified to be more desirable one. Figure 4.9c has that updated illustration of the model, where it is supposedly possible to adjust the position to the user preferences. The hollowed sections were drawn to be compatible to the screw holes from both the upper arm and the motor models (M6 screws).

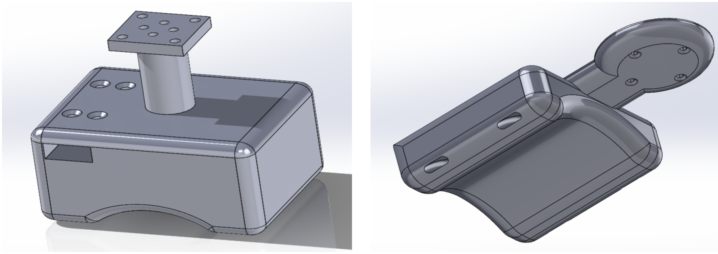
Finally, the last model to change, due to the motor modifications, was the forearm part. The changes were based on adjusting the circular part on the extremity, to be possible to fix the rotation part from the motor, as it can be seen in Figure 4.9d. Four M3 screw holes were drawn around a 36 mm circumference, which is compatible to the version of the motor.

Although the system itself seemed to be complete, as it had all the necessary models, some very important factors were missing. First of all, between the forearm and the upper arm, the system couldn't rotate in the perpendicular axis to it. This was a concern because it meant it might not be able to fix itself onto irregular shaped arms overall. Also, the forearm model still seemed to have sharp edges which might hurt the person using the interface. The upper arm model, illustrated in Figure 4.9b, had an exaggerated curvature, which needed to be adjusted with dimensions that fell under the average category. Therefore, other changes were also made to the models with the intent of fixing these problems.

4.5.2 Second version

As the first step, the forearm model was redesigned to resemble the upper arm model, in the sense that it uses the same kind of curvature and the same kind of holes for straps. This not only would make the model sturdier, but also with dimensions compatible with an average looking human forearm would turn it more ergonomic. Afterwards, for a more uniform approach on the upper arm model, the part that makes the curvature was removed, and instead the curvature was measured and drawn on the model itself. To perfectly align the adjustable model to the motor model, the upper arm model had to be changed accordingly. Furthermore, two other

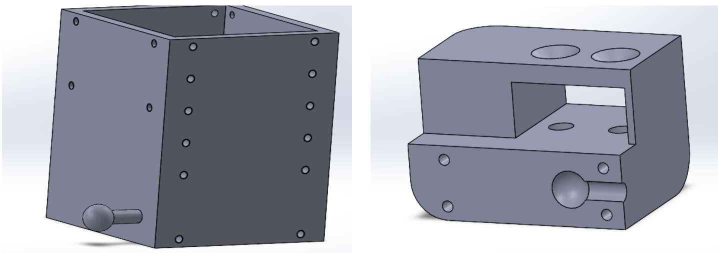
M6 screw holes were also carved on the other side of the upper part of the upper arm model. These changes result in the models illustrated in Figure 4.10.



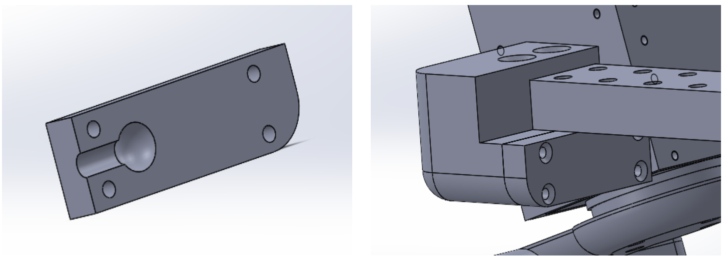
(a) (b)

Figure 4.10: Models for the upper arm and for the forearm. (a) Preliminary upper arm model. (b) Final forearm model.

To tackle the issue of the rotation in the perpendicular axis of the forearm and the arm, a spherical joint was created on the side of the motor model, as shown in Figure 4.11a. This spherical joint is to replace the previous section next to the motor model, which had 5 mm of radius. In terms of the adjustable model, this one would stay the same, but this time a new model part, shown in Figure 4.11b, was created to fix this adjustable model, and be prepared to help the rotation of the sphere. This new part also had the same format as the previous one, where M6 type screw holes fix the adjustable model. To make this system functional, a counterpart was added to lock the sphere in place, as illustrated in Figure 4.11c. To understand how this whole system would look like Figure 4.11d illustrates all the parts mounted.



(a) (b)



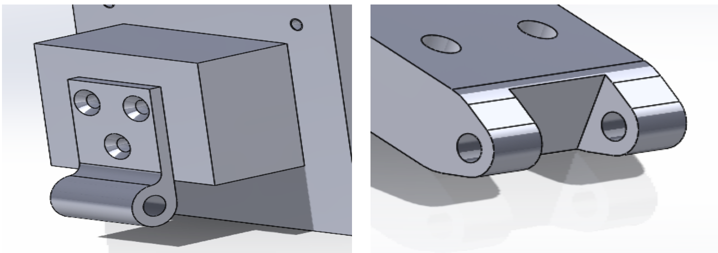
(c) (d)

Figure 4.11: Provisional joint design for rotation in the perpendicular axis to the rotation of the motor. (a) Motor model with spherical joint. (b) Joint between the adjustable model and the motor model. (c) Joint counterpart. (d) Mounted joint representation.

Although the idea, at first glance, could work, there are some problems with this sphere. More specifically, the size of the sphere might become an issue, as the tensile strength of the model may not support the weight and could eventually break.

4.5.3 Last version

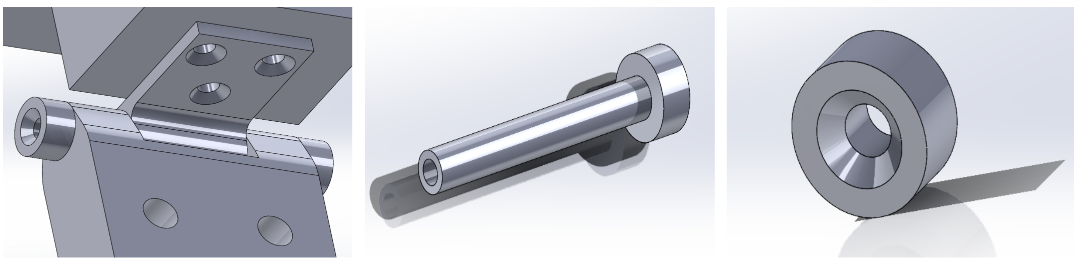
Therefore, a different idea was instead put in work. A hinge joint was employed where a part, in the form of a screw, controls the rotation on the motor model. In order for this to work, the motor model and adjustable model had to be once again changed. For the motor model, a cuboid plus a hinge design was added to the side as shown in the Figure 4.12a.



(a) (b)

Figure 4.12: Changes to allow hinge movement on the motor and adjustable models. (a) Motor model. (b) Adjustable model.

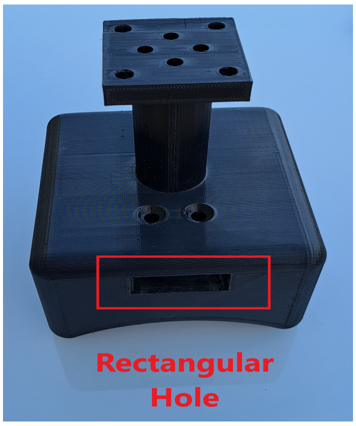
Also a section for the hinge part was added at the extremity of that cuboid. For the adjustable model, a circular section to allow the entrance of a hinge joint was added at one of the extremities, as illustrated in the Figure 4.12b. The hinge assembly is represented in Figure 4.13a. To allow the connection between the models illustrated in Figures 4.12a and 4.12b, a custom made screw was also printed, where a hole is presented to allow the entrance of a M3 screw, as shown in Figure 4.13b. To fix the screw to the whole assembly, the model in Figure 4.13c is the other extremity of that screw, except that this one is separated and is screwed after the mounting of the whole hinge joint.



(a) (b) (c)

Figure 4.13: Finished motor and upper arm model joint. (a) Hinge joint representation. (b) Hinge screw. (c) Hinge screw counterpart.

There was no reason for the adjustable part to be linked and fixed to the side of the upper arm model. Therefore, a rectangular hole in the middle was chosen as an, marked in red in the Figure 4.14a. This was made so the system could be used on the right and on the left arm of the subject, without any removal or additional of a model or part. The curve of the upper arm model was extended to incorporate both extremities of the said model. The model would now be a 120 x 120 mm 3D part with an arc length of about 133 mm from one extremity to the other. The final and printed upper arm model is presented in Figure 4.14a. For the adjustable link made to attach the motor model to the upper arm model, the final and printed design is illustrated in Figure 4.14b



(a)

(b)

Figure 4.14: Printed upper arm and adjustable part models. (a) Upper arm model. (b) Adjustable model.

The chosen motor, which has multiple M3 screw holes for mounting purposes and responsible for the system's actuation, acts as an intermediary between the upper arm structure and the forearm structure, which is also 3D-printed. To activate the motor a control device is required to manage the data exchange with the motor, and a 24 V power supply provides the necessary energy for its operation. Finally, a control system is necessary to monitor and record all motor data and information in real-time.

The other 3D models printed are present in Figure 4.15. In Figure 4.15a is the flange, Figure 4.15b the motor model and, lastly, in Figure 4.15c the forearm model with the straps already set up. When trying to assemble all the 3D parts, the hinge screw, illustrated in Figure 4.13b, broke. This happened due to its diameter being exactly the same as the hole (5 mm). Instead, a 4 mm diameter and 60 mm length screw, followed with its respective screw nut were used. Those materials are depicted in Figure 4.15d.

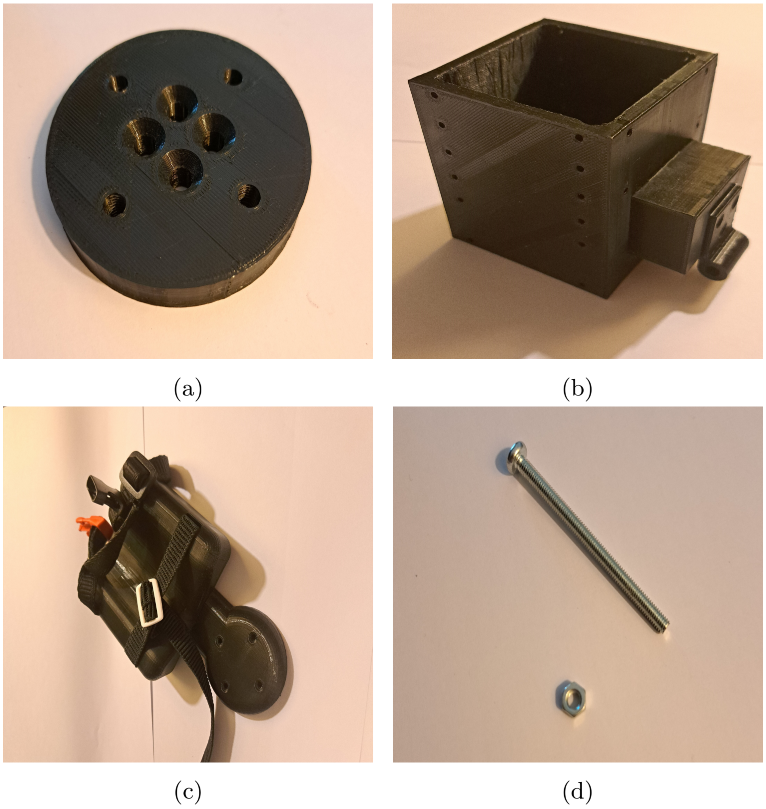


Figure 4.15: Final models. (a) Flange model. (b) Motor model. (c) Forearm model. (d) Screw and screw nut, hinge screw substitute.

To understand how the design should look like in the end, Figure 4.16 refers to the different parts that suffered changes throughout the whole process until reaching this final result. This illustration is the assembly of all the models built, which was then compared to a real life sized dummy's arm.

1. Upper arm part;
2. Designed flange;
3. Adjustable part;
4. Motor chosen;
5. Motor support model part;
6. Forearm part

For additional information about the parts dimensions, Appendix B has all the documentation necessary for each model designed.

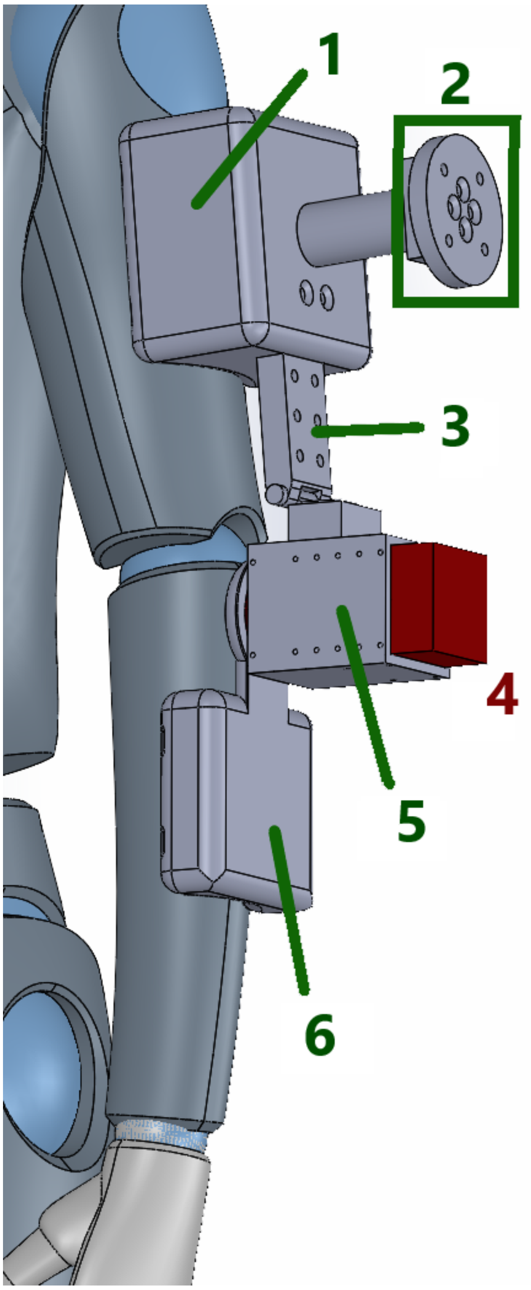


Figure 4.16: Illustration of the whole interface, next to a dummy human model. (1) Upper Arm model. (2) Flange. (3) Adjustable model. (4) Motor. (5) Motor model. (6) Forearm model.

4.6 Summary

In this chapter, the development of 3D models for the robotic interface components is discussed in detail, with a focus on designing key parts to ensure proper adaptability for upper limb rehabilitation. The models include components for the upper arm, forearm, motor, and an adjustable part that connects the motor to the upper arm segment. Additionally, a hinge joint was designed to secure the adjustable part to the motor, allowing for smooth movement and flexibility. Each component was modeled to meet the requirements for safe and comfortable rehabilitation exercises.

The motor selection process is also detailed, explaining the motor's characteristics that make it suitable for this project. The chosen motor was selected based on its torque, size, and weight, providing the necessary control for rehabilitation while maintaining a lightweight structure.

Chapter 5

Interface and Motor Control Simulation

This chapter delves into the development and implementation of an interface, made of 3D models and a motor system, connecting the UR5 robotic manipulator to a patient's arm. At the core of this interface lies the Robot Operating Systems (ROS) framework, which acts as a middleware that coordinates the flow of information between the manipulator and the motor system. Through ROS, commands are transmitted to control the movements of the UR5 and the motor, while simultaneously receiving real-time feedback from both. This continuous exchange of data allows the system to maintain a high level of precision, crucial in sensitive applications involving human subjects.

The motor plays a pivotal role in executing movements dictated by an operator, with the need to be pre-trained before inserting on a person's arm. ROS ensures that the motor's movements are synchronized with the UR5 manipulator, allowing for accurate and smooth operations, whether in rehabilitation scenarios or robot therapy.

This chapter will explore the communication protocols, software integration, and control mechanisms that govern the behavior of the system. Diagrams and images are provided to illustrate the key components, control flow, and interactions between ROS, the motor, and the UR5 manipulator.

The UR5 manipulator is controlled via a ROS based communication setup, where specific ROS topics and nodes handle the transmission of control commands and feedback signals. These topics serve as channels through which the control computer communicates with the UR5, sending position, velocity, and effort commands while receiving feedback data, such as joint angles and force readings. This bidirectional communication ensures that the manipulator can respond dynamically to external stimulation and execute precise movements based on predefined or user-defined commands.

On the motor side, the control system utilizes an RS485 protocol to communicate with the motor and the control computer. ROS topics handle the flow of certain motor control commands, such as, torque, speed, or position, and receive feedback on motor performance and status.

5.1 Interface

The interface consists of 3D printed models and a motor, using Polyethylene Terephthalate Glycol (PETG) as the printing material. It was specifically designed for use on upper limbs and is not recommended for lower limbs. To adapt it for lower limb, the models would need redesigning to account for the different proportions in length and circumference. Additionally, all trials in this project were conducted on upper limbs.

The adjustable component of the interface ensures proper alignment along the arm, accommodating different arm shapes. This allows the structure to stay aligned with the subject's elbow, which is crucial to prevent discomfort and reduce stress on both the motor and the subject's arm. However, due to the lack of gap between each part, this part felt hard to adjust between each arm encountered. In contrast, the curves selected for the upper arm and forearm parts, based on subject feedback, were reported to be comfortable.

Furthermore, two straps were used on the upper arm and two on the forearm, combining elastic and regular straps. Elastic straps were chosen to improve comfort and provide better resistance, as the regular straps were smooth and offered limited grip. However, the elasticity of the elastic straps made securing them to the arm challenging. Regular straps were used to ensure a secure and comfortable fit for each arm section. While this setup successfully secured the interface to the subjects, most reported that the straps felt less stable than desired.

The hinge joint performed well across the different arm types tested. Since each subject had varying forearm circumferences, the hinge joint was a valuable feature, especially when a subject's forearm was significantly elevated. Without this rotation, the interface would have been less flexible and more fragile, based on visual feedback.

5.2 Pseudo-code and integration with ROS

This section provides an explanation of the integration with ROS for motor control. For that matter, pseudocode was utilized to distinguish the two pieces of code, responsible to achieve full motor operation. The overall system is designed to communicate and control the motor, while also monitoring and marking its performance data.

The first program, described by the Algorithm 1, directly interfaces with the motor using ROS, allowing communication via predefined ROS topics and services. This allows the user to send commands to the motor to adjust its rotation, and read data, such as electric current and angle rotation, from it. It is responsible for establishing the connection and enabling the control of motor behavior. This program communicates with the motor via the RS485 protocol. In order to send and receive the right data, there are certain address values, each responsible to their unique information. To understand the meaning of the address values, Table 5.1 has a description for the used ones in this project. The rest of the address values are explained in the specification page of the motor [96].

Table 5.1: Address values and their different meanings of the L54 30 S500 R motor.

Address	Size (Byte)	Data Name
562	1	Torque Enable
569	4	Goal Position
600	4	Goal Velocity
611	4	Present Position
615	4	Present Velocity
621	2	Present Current

Although the table has all the address values and what their meaning is, in order for the code to work, the protocol version, ID, baud rate and port number must also be acknowledged. Only when all this information is well accounted for, the motor is ready to receive instructions.

As a side note, topics for the electric current, motor velocity and motor angles need to be created. This is to ensure all the information has its personal type of message (int, float, char...). These topics were also created, so the two nodes, plus

Algorithm 1 Algorithm that controls motor movements

```
Require: S: Emergency stop button
  NI: Number of iterations
Ensure: NI > 0
  NI ← 5
  for each NI do
      if S is True then Break;
      end if
      Rotate motor to desired position;
      while rotation is running do
          if S is True then
              Break;
          end if
          Publish present position to topic;
          Publish present current to topic;
          if motor reaches desired position then
              Break;
          end if
      end while
      Rotate motor to original position;
      while rotation is running do
          if S is True then
              Break;
          end if
          Publish present position to topic;
          Publish present current to topic;
          if motor reaches original position then
              Break;
          end if
      end while
  end for
```

the UR5, could communicate between them through ROS without each of them needing to connect to the same port.

The process begins by launching the UR5's control system. This is done by starting its launch file, which establishes communication between the robotic manipulator and the control computer. At this point, the system is ready to send commands to the UR5 and receive feedback, such as joint positions and forces.

Next, Algorithm 1 is executed. This algorithm initiates communication with the motor by setting up the necessary parameters, such as the protocol version, motor ID, and baud rate. This step allows the system to control the motor's movements and receive feedback data, such as electric current and angle position.

Therefore, Algorithm 1 defines the number of repetitions for the motor. This means that after the program receives a desired angle position, the variable NI will control how many times the motor repeats the same angle rotation. Afterwards,

Algorithm 2 Algorithm that chooses which arm to exercise, sends the desired angle positions and creates graphics of the data received.

Require: A: Current Values
  P: Rotation angle values
  S: Time in seconds
  T: Torque values
  q: Exit button
  arm: "Left" or "Right"
Ensure: $T \leftarrow 0$
  while True **do**
    Choosing which arm side is going to be exercised;
    if arm is "Left" **then**
      P values are positive
      Check if angle inputs are within the right limits;
    else if arm is "Right" **then**
      P values are negative
      Check if angle inputs are within the right limits;
    else
      Input is wrong
      Break
    end if
    Publish angle values to the right topic
  end while
  $T \leftarrow \frac{(A \times 2.048)}{33.000}$
  Plot T, and the average T as a function of S;
  Plot P as a function of S;

there are two while loops, each one for each travelling movement (either from 0º to desired angle, or from desired angle to 0º), that publish to the respective topic the electric current and current angle position of the motor.

Once communication is established, Algorithm 2 is started. This algorithm allows the user to specify desired motor positions and simultaneously processes the motor's feedback. The data collected during motor operation, such as electric current and angular position, is processed and used to create performance graphs for further analysis.

After data collection, it calculates the torque through an equation given by the manufacturer, which is present in the motor's specifications page [96]. In the end, the algorithm marks the calculated motor's torque and angular position over time, helping the visualization of its performance and ensuring validation and accuracy in the next steps, which are the tests.

By leveraging ROS topics and services, the integration between these two algorithms provides a robust framework where real-time motor control is combined with performance analysis. This ensures precise position control and detailed feedback, which is crucial for applications where motor dynamics need to be closely observed and adjusted.

In addition to position control, the motor's velocity is managed separately. The motor speed must be set before starting the rotation exercises. This is done through a dedicated command, ensuring the motor knows at what speed to rotate. After each set of iterations, the velocity can be adjusted as needed, by sending new commands to modify the speed before starting the next round of movements.

Several safety measures were incorporated into the system to ensure secure and controlled motor operation, including motor rotation angle limitations and an emergency stop button. These limitations were implemented to prevent the motor from rotating beyond safe ranges, depending on the arm being used. For the left arm, the motor is restricted from rotating into negative angles, while for the right arm, it cannot rotate into positive angles, because the 0º angle of the motor corresponds to the person's arm being straight. Additionally, a maximum rotation limit was imposed to prevent the motor from exceeding a certain angle. This limit was set at 100º for the trials, with a 90º rotation being tested repeatedly. If a user attempts to input an angle greater than 100º for the left arm or less than -100º for the right arm, Algorithm 2 will reject the input and display an error message prompting the user to enter a value within the acceptable range. These limits can be adjusted depending on the patient's needs and comfort level.

An emergency stop mechanism was also integrated to ensure that the motor can be stopped immediately, regardless of its state. The button was programmed to halt the motor's rotation whether it is moving or idle. For ease of use, the emergency button is currently set as the 's' key on the keyboard. It was implemented both inside and outside the loop function in Algorithm 1, allowing the system to be interrupted at any point during operation. The flexibility of the stop function ensures patient safety by providing an instant way to stop motor movement if needed. To understand the relation between all this information previously detailed, Figure 5.1 depicts the automatically generated rqt_graph.

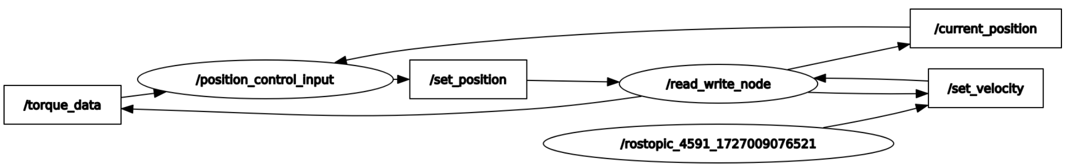


Figure 5.1: Automatically generated graph of all the topics and communication between the electromechanical interface and the computer.

5.3 Motor and Elbow Rotation

In this section, an in-depth analysis of the motor's performance in controlling elbow rotation, across four different test subjects, will be conducted. By examining the physical characteristics of each subject, such as height, weight, upper arm circumference, forearm circumference, and age, the aim is to explore how individual differences impact the motor's dynamic movements.

For each test, the electromechanical interface was used to execute controlled elbow rotations at varying angles, with torque values measured and recorded. These tests provide insights into the torque required for different angles of rotation. The inclusion of graphical representations of both the rotation angles and the corresponding torque values, offer a visual understanding of the motor's performance under various conditions.

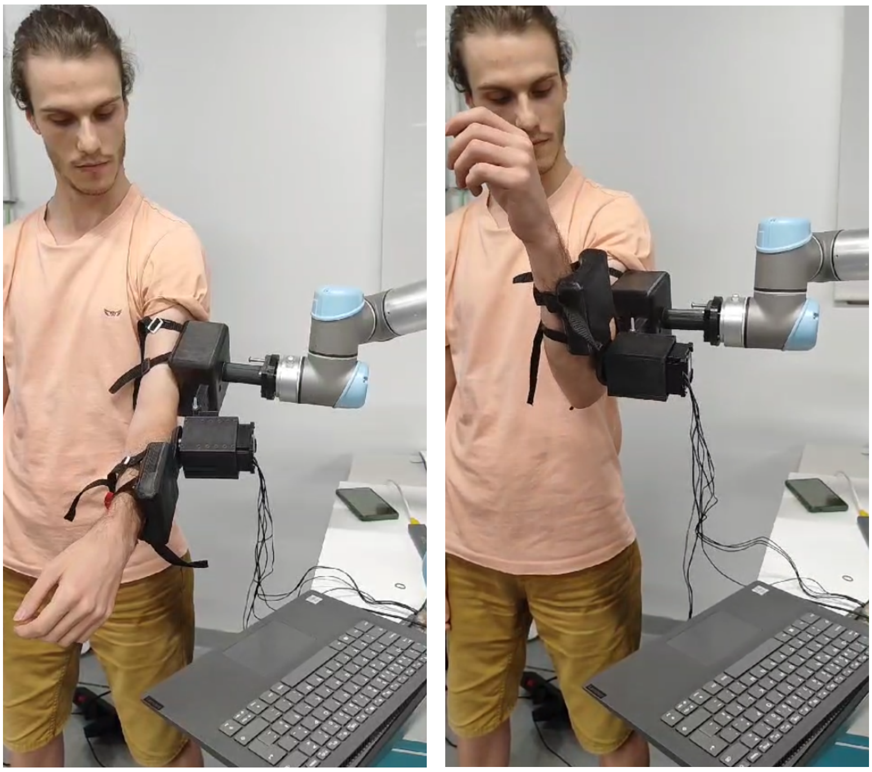
Through this approach, the interface's behavior is understood across a range of physical characteristics, allowing for tuning and performance in real-world applications. This data-driven analysis helps in understanding the motor's control system for different users, contributing to the reliability and precision of elbow joint movements.

Afterwards, the interface was inserted on the arm, and fixed comfortably, like in Figure 5.2. For this simple demonstration, the interface motor was rotated between 0º and 90º, which corresponds to the straight arm state and 90º elbow rotated state. This test was made on subject 1 to understand UR5's movement and perception, alongside the motor's rotation on the arm, thus having the upper arm plus the forearm exercised.

The tests were conducted with subjects in a relaxed, seated position. Both the left and right arms were tested to observe motor performance in both directions of rotation. Due to the models being symmetrical, they ensure ease of use and consistency in testing, regardless of which arm is being evaluated. Table 5.2 has all the measures of each subject tested. It is also worth noting, that these tests were performed with not UR5 support, meaning that the interface was more likely to slip and not properly fit.

For each subject, the motor rotates 90 degrees 5 times in each arm, then the torque and angle position of the motor, throughout the whole process, were recorded. Figures 5.3a and 5.3b illustrate the variation of the angle position of the motor throughout the whole 5 repetitions. These curves, since the test was made the same on every subject, are also identical to everyone. The torque recorded on each subject is depicted in Figures 5.4 and 5.5. Figure 5.4 illustrates the torque variation in each of the three subjects for the left arm, while Figure 5.5 shows the torque variation in each of the three subjects for the right arm.

Looking at all the tests made, it is possible to notice some significant differences, as well as some similarities. Looking at the results from subject 2 and subject 3, depicted in Figures 5.4b, 5.4c, 5.5b, 5.5c, the raw torque fluctuates dramatically, while the fluctuations in torque of the subject 1, shown in Figure 5.4a and Figure 5.5a, are less extreme. This difference becomes even more clear when looking at the



(a) (b)

Figure 5.2: Interface model. (a) Interface with elbow completely straight. (b) Interface with elbow rotated 90º.

smoothed torque, where the peaks and valleys are much more visible. This suggests that the arms of subject 2 and subject 3 offer more resistance and the motor requires more effort to achieve the same movement.

These results could also be due to factors like arm circumference, or overall muscle stiffness. The more stable torque curve in the first subject may also suggest they had more relaxed or controlled movements during the test, while the second subject likely experienced more resistance, requiring higher torque to achieve similar movements. These findings will be useful in understanding how the motor performs under different conditions and can help optimize control based on subject characteristics.

After the trials, several key observations were recorded. There was a rather misalignment between the forearm of the subjects and the interface, and that misalignment was higher for bigger arms. The improper alignment resulted in increased pressure on the forearm part of the interface, which ultimately caused subject 3 to report discomfort due to the added stress. Due to similar lengths between subject 1 and subject 3, subject 3 has a much different circumference compared to subject 1, which may have resulted in that discomfort. This could also explain why in the torque graphics, the torque variation has a spike on each end of rotation, where the tension between the arm, the straps and the forearm part is higher on the arm being

Table 5.2: Test subject's characteristics.

	Subject 1	Subject 2	Subject 3
Age (years)	23	79	24
Height (cm)	185	169	183
Weight (kg)	65	88.5	70
Left Upper Arm Width (cm)	8.59	9.07	9.7
Right Upper Arm Width (cm)	8.59	9.07	9.7
Left Forearm Width (cm)	7.80	8.44	8.44
Right Forearm Width (cm)	7.80	8.44	8.44
Left Upper Arm Length (cm)	35	34	36
Right Upper Arm Length (cm)	35	34	36
Left Forearm Length (cm)	28	27	28
Right Forearm Length (cm)	28	27	28

90º than in 0º. In the 90º angle position is where subject 3 felt the interface being uncomfortable.

To further investigate the error observed in subject 3, Figure 5.6 shows subject 1 demonstrating the same misalignment. Table 5.3 summarizes the average errors between the right and left arms at different angles, with variations ranging from 15º to 22º. This discrepancy may be due to the performance of the straps, the weight of the interface, and the design of the forearm model. The errors were calculated using a measuring tape and then determining the angle between the interface forearm and subject 1's forearm. The measuring tape has an error margin of approximately 0.5 cm, leading to a maximum standard deviation of around 5 degrees.

Table 5.3: Errors between the motor angle and subject 1 elbow angle.

Motor Angle	Average angle error
0º	+/- 0º
45º	15.375º
90º	16.451º
120º	21.822º

This observation highlights the importance of ensuring the proper fit of the interface for each subject, as misalignment can lead to unnecessary strain and discomfort. Future tests would need to address this issue by improving the designs of the interface parts, and ensure that the motor aligns correctly with the elbow for each individual.

Additionally, subject 2 reported that the system was comfortable and caused no discomfort during the trials. However, subject 2 did experience an issue with the upper arm portion of the interface. Due to its weight, the interface had a tendency to slip or fall from the arm. Despite the absence of discomfort, it was likely that the straps securing the interface were not tight enough, causing this instability. It is also worth noting, that the interface was not linked to the UR5.

This suggests that an improvement could be made by designing better straps or adjusting the current ones to provide a more secure and snug fit. By ensuring that the straps are properly tightened to the user's arm, the system could prevent any slipping during use, further enhancing the overall performance and comfort of the interface.

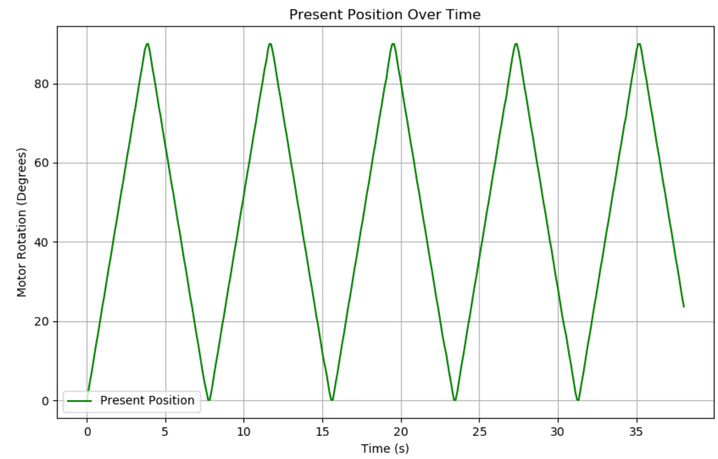
5.4 Summary

In this chapter it was presented an analysis of motor performance during elbow rotation tests conducted on different subjects. The tests were designed to evaluate motor dynamics, torque requirements, and movement smoothness in both the left and right arms. Each subject was tested in a relaxed, seated state to ensure consistency in data collection. Various physical characteristics were gathered for each subject, such as height, weight, upper arm circumference, forearm circumference, and age, providing a comprehensive understanding of the influence of body attributes on motor behavior.

Key findings from the torque graphs show significant variations in torque magnitude, fluctuation patterns, and smoothness between different subjects. One subject demonstrated higher torque demands and more fluctuating torque values, indicating greater resistance or variability in their elbow movement. In contrast, other subject exhibited smoother and more consistent movements, requiring less torque overall. These differences likely stem from variations in body structure, muscle mass, and flexibility.

Additionally, the symmetrical design of the interface proved to be practical, allowing for easy setup on both arms without compromising accuracy or performance. Graphical representations of torque over time provided visual insights into motor response during the tests, with raw and smoothed torque curves highlighting the motor's ability to adjust to each subject's unique movement patterns.

Overall, the results emphasize the importance of understanding individual physical characteristics when optimizing motor control systems for elbow movements. This analysis paves the way for further refinements in motor design and control strategies, ensuring that the motor can effectively adapt to different users' needs while maintaining precision and reliability.



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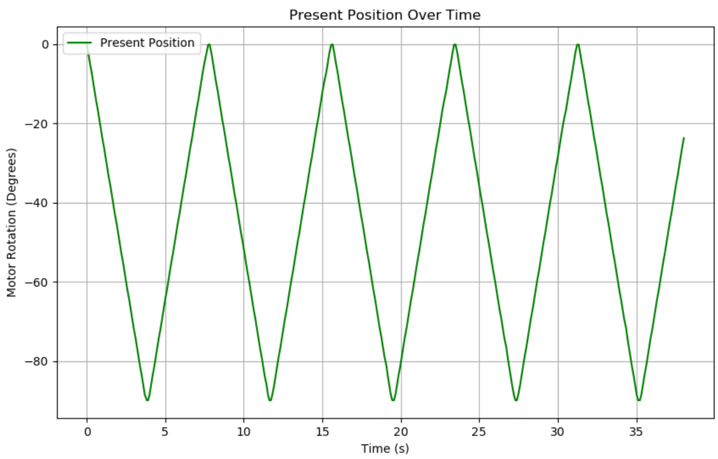
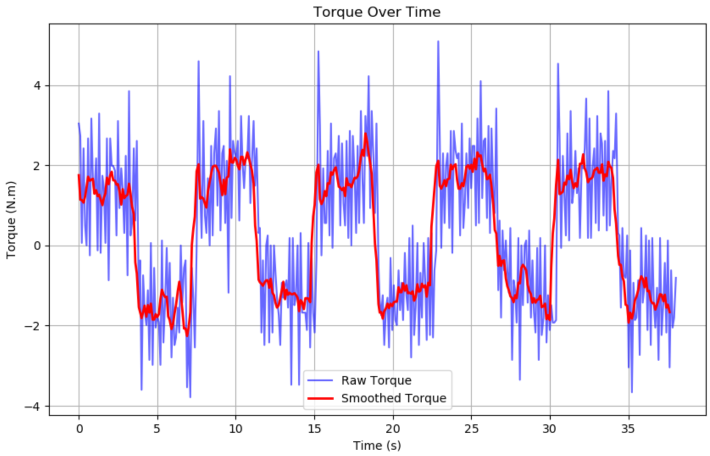


(b)

Figure 5.3: Position results for left arm and right arm on every subject. (a) Position variation on the left arm. (b) Position variation on the right arm.



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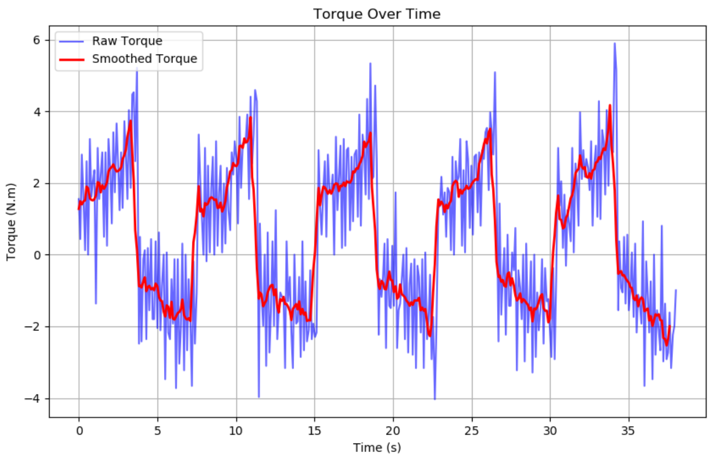

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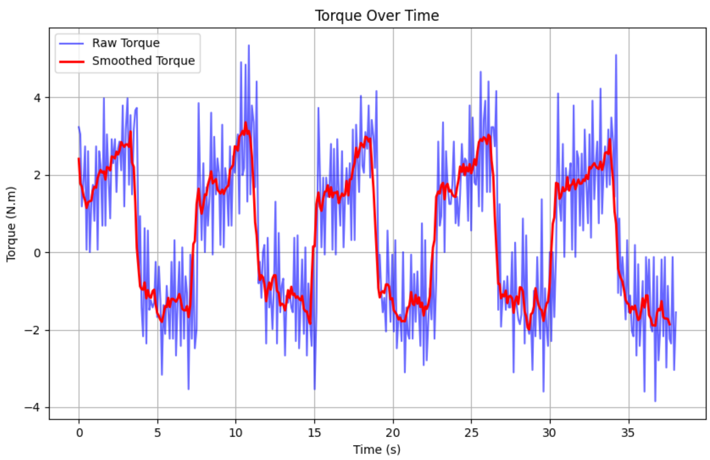
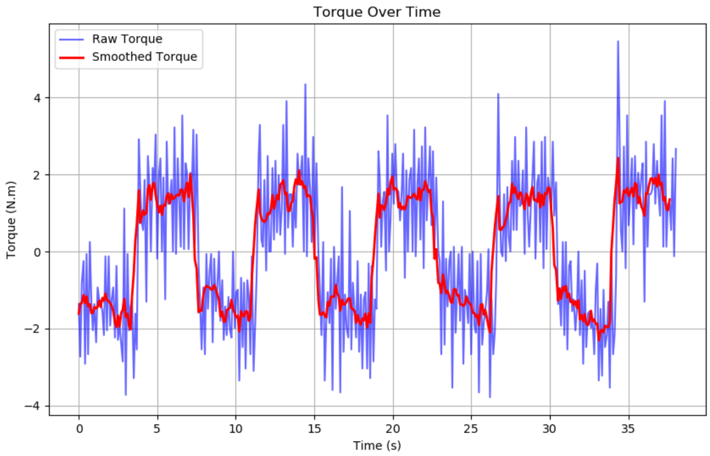


(c)

Figure 5.4: Test results across three subjects for the left arm. (a) Torque variation on left arm from subject 1. (b) Torque variation on left arm from subject 2. (c) Torque variation on left arm from subject 3.



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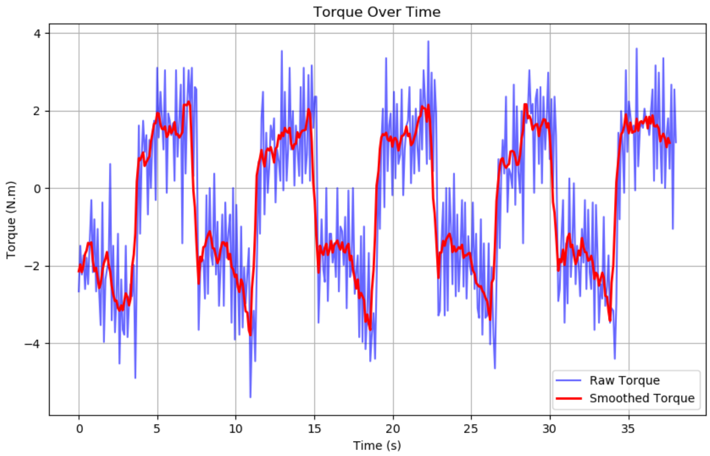

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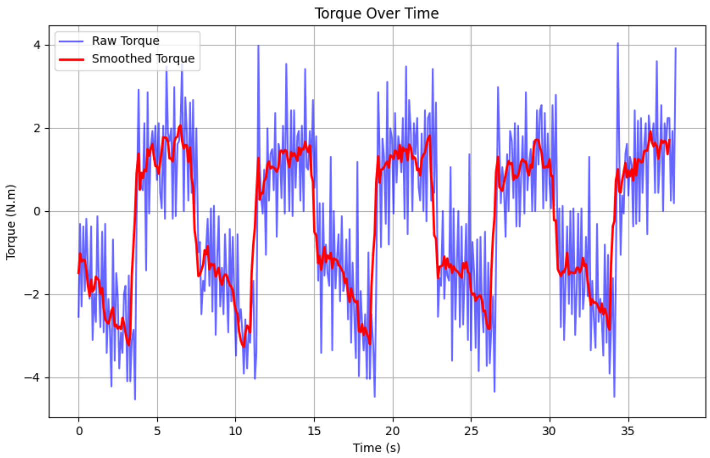


(c)

Figure 5.5: Test results across the three subjects for the right arm. (a) Torque variation on right arm from subject 1. (b) Torque variation on right arm from subject 2. (c) Torque variation on right arm from subject 3.

(a)

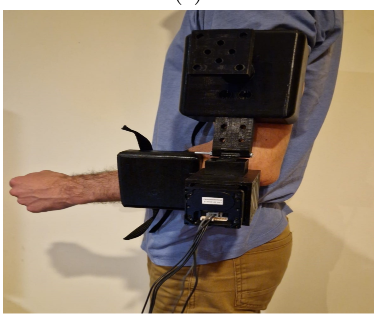
(b)

(c)

(d)

(e)

(f)



(g)

(h)

Figure 5.6: Different interface positions on the right arm. Different interface positions on the left arm.

Chapter 6

Conclusion

This project aimed to create an interface connecting a person's arm to a manipulator, specifically the UR5 from Universal Robots, to be used in a rehabilitation setting for patients who have lost limb mobility. One of the prerequisites was to create an electromechanical interface. To achieve this, the interface was integrated with an electric motor responsible for rotating the patient's elbow. The interface was divided into three parts. The upper arm model which connected the UR5 tool flange to the patient's upper arm. The actuation part which linked the motor to both the forearm and the upper arm models. The forearm model which connected the motor model to the patient's forearm.

The manipulator is compatible with ROS, the middleware used to communicate. Additionally, the Dynamixel actuators required the Dynamixel SDK software, which provides control functions through packet communication. The device that links the computer to the motor via an RS485 communication protocol was also essential. Using the same middleware (ROS) for communication between the UR5, the motor, and the computer is advantageous because it ensures seamless integration and coordination, simplifying the development and maintenance of the system.

To test the system, subjects with varying characteristics were evaluated. The torque of the motor and the angle of rotation were analyzed for both the right and left arms of each subject. The results highlighted differences in resistance between arms, but the motor performed well across all subjects. Because the system is intended for use in a rehabilitation environment with people, safety mechanisms were added to prevent motor rotation in the negative and positive directions when fixed to the left arm and right arm, respectively. Additionally, a stop button (the 's' key on the keyboard) was set up to immediately halt the rotation of the motor whenever used. This is crucial in rehabilitation scenarios to ensure the safety of patients, allowing for quick intervention if any discomfort or unexpected movement occurs.

Overall, this project successfully addressed the challenge of creating an electromechanical interface to assist patients in regaining limb mobility, especially in the context of rehabilitation. By integrating a motor-driven solution with precise control over elbow rotation, this system offers an alternative to traditional rehabilitation methods, potentially improving outcomes for patients with reduced mobility. The use of ROS middleware also ensures that the system can be easily adapted and scaled for different rehabilitation scenarios, providing a flexible and safe environment for patient recovery.

6.1 Future Work

One of the main limitations of the current system is that the motor does not have a passive mode, meaning there is no way to stop the motor from actuating and allow the user to move their arm freely. This limitation prevents the execution of resistive exercises, where patients would exercise independently. Incorporating a motor with a passive mode would significantly improve the system's versatility and allow for a broader range of rehabilitation exercises.

Furthermore, the 3D models were printed with no allowance for dimensional errors, resulting in precise but potentially problematic dimensions due to the inherent inaccuracies of 3D printers. Introducing a gap of 2 to 4 mm between parts during the design phase could address this issue, making assembly easier and more reliable.

Another limitation is the weight of the upper arm model. Once printed, it was found to be dense and heavy, which could reduce the comfort and usability for patients. Redesigning the model to include holes or other weight-reducing features would make the interface lighter and more comfortable for the patient, thereby enhancing the overall effectiveness of the rehabilitation system.

In addition to these hardware improvements, further development in the software and control systems could enhance the system's performance. For example, integrating more advanced safety protocols and refining the motor control algorithms would allow for smoother operation and better real-time adjustments based on the patient's movements. Testing the system on a wider range of subjects with different rehabilitation needs could provide valuable data to refine both the hardware and software, ensuring the system can adapt to various rehabilitation scenarios. Incorporating machine learning techniques could also be explored to create adaptive exercises based on patient progress.

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Appendix A

L54-30-S500-R Dimensions

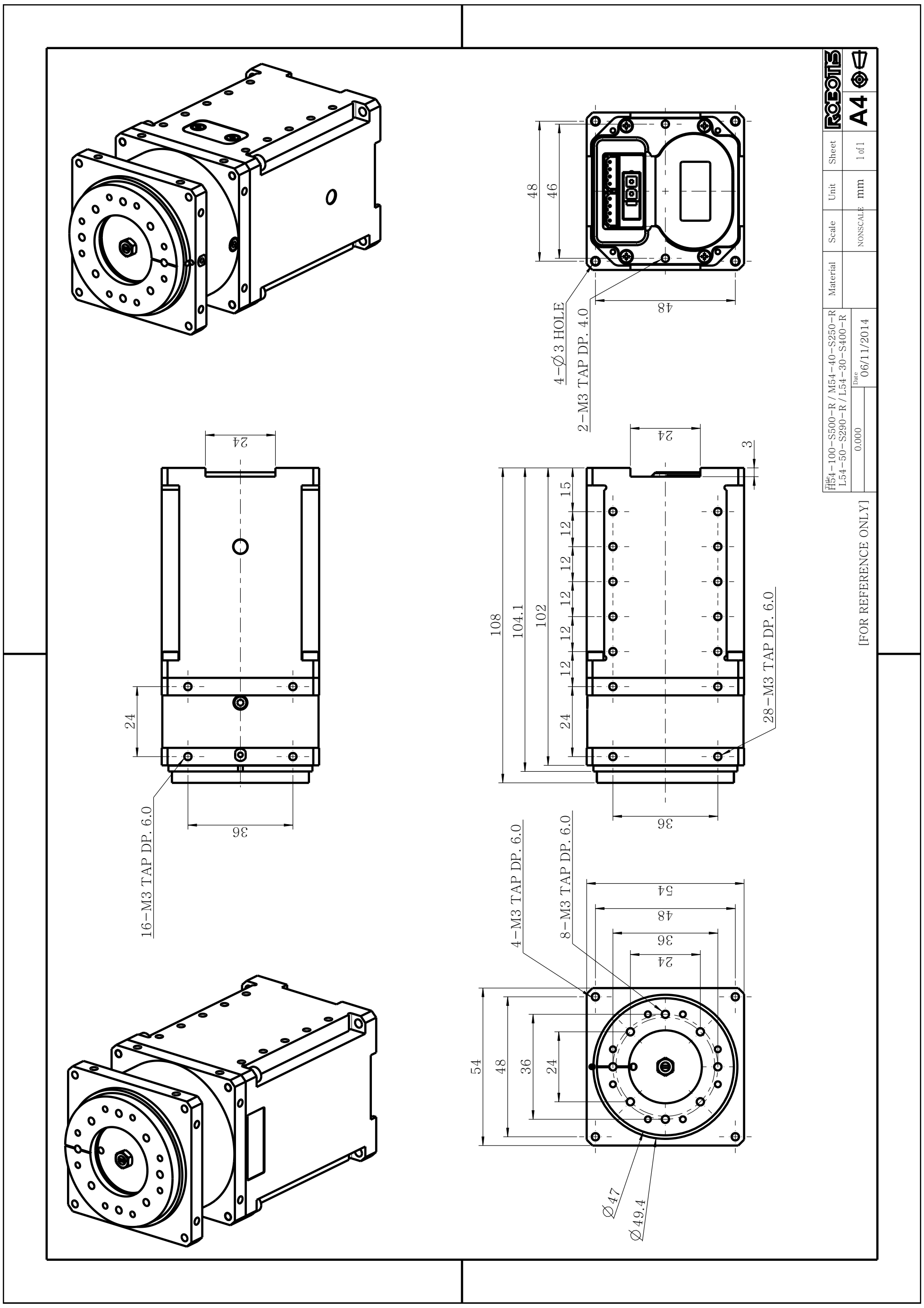

Figure A.1: Dimensions of the L54-30-S500-R motor model [96].

Appendix B

Model Dimensions

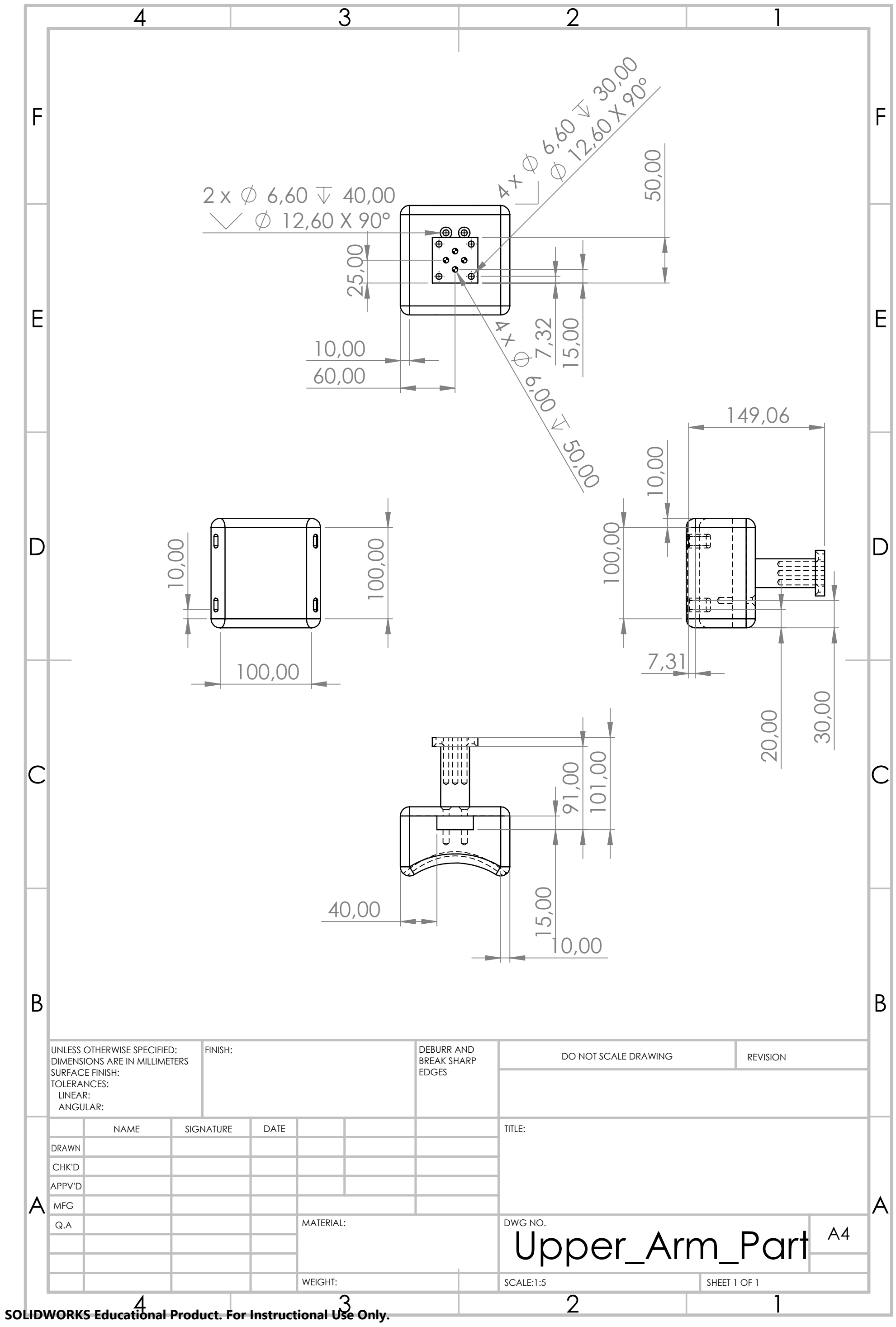

Figure B.1: Upper arm part model.

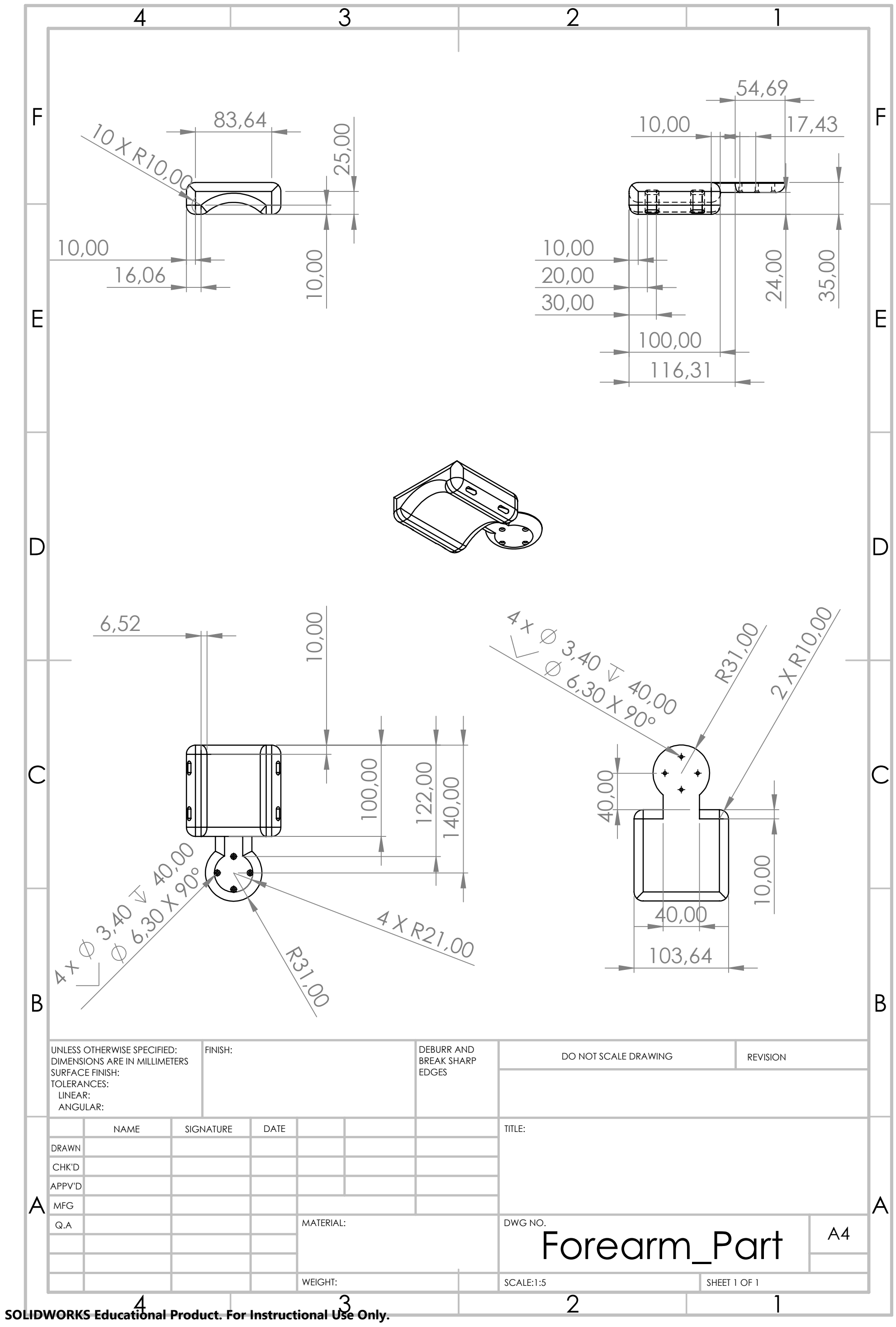

Figure B.2: Forearm part model.

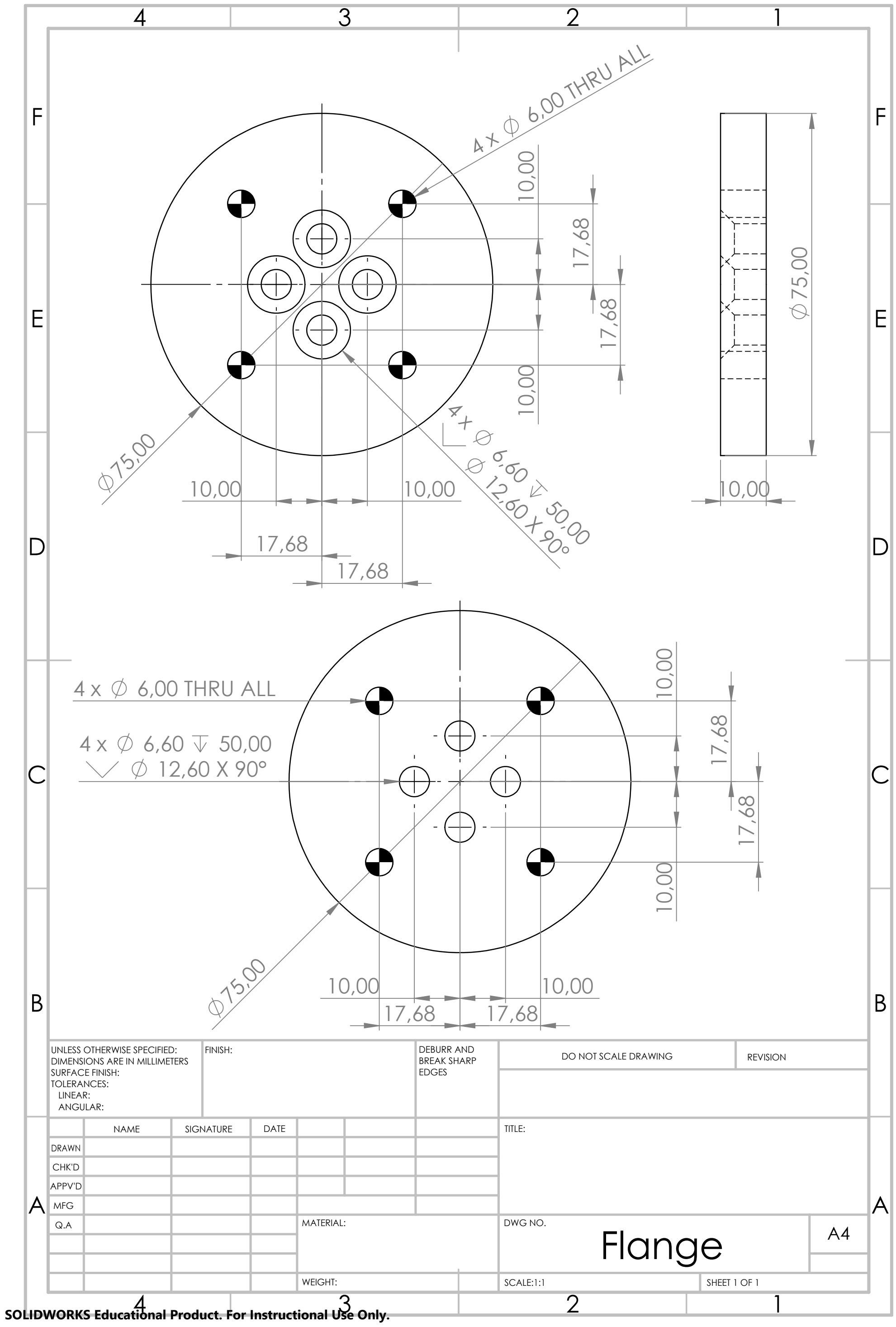

Figure B.3: Flange part model.

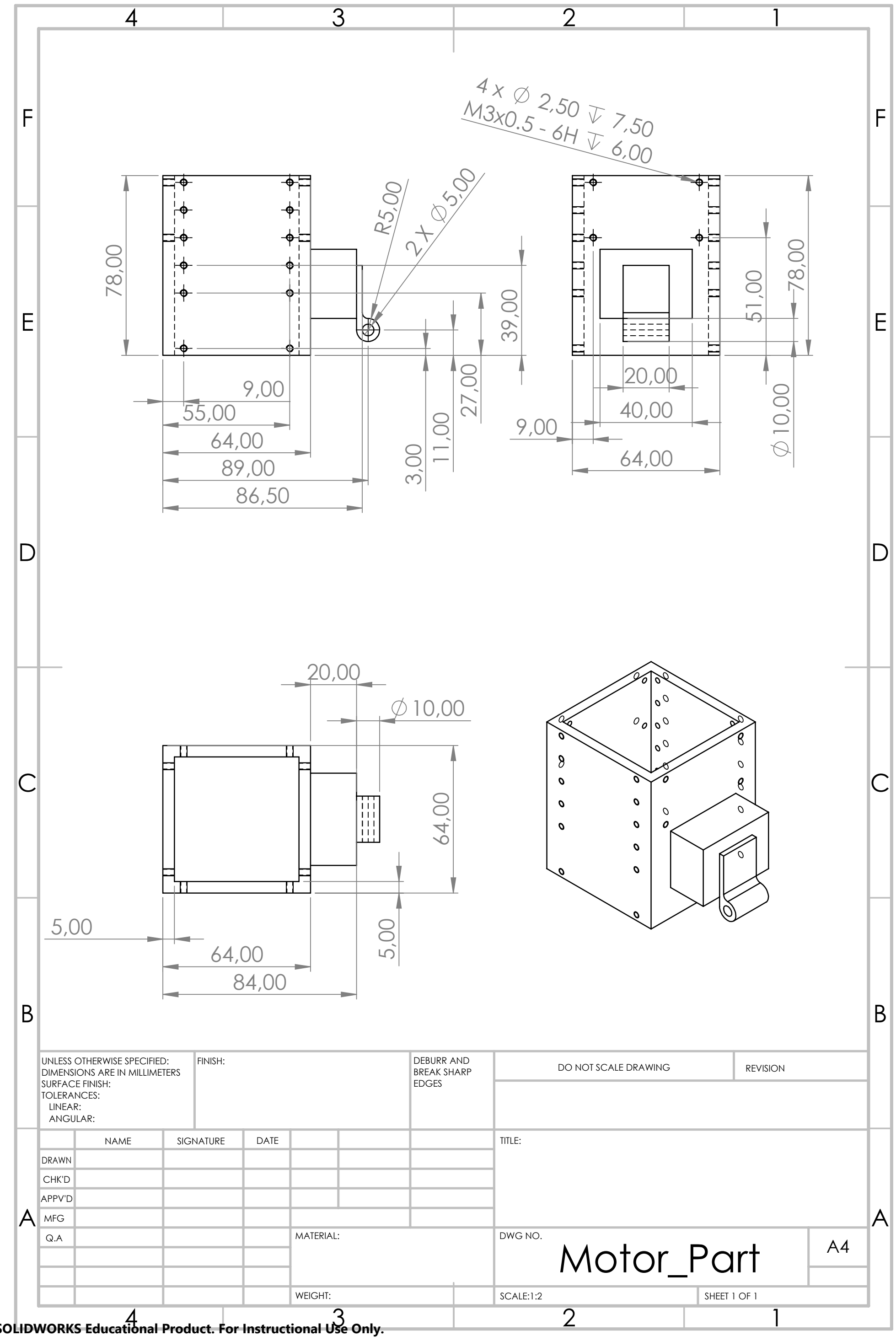

Figure B.4: Motor part model.

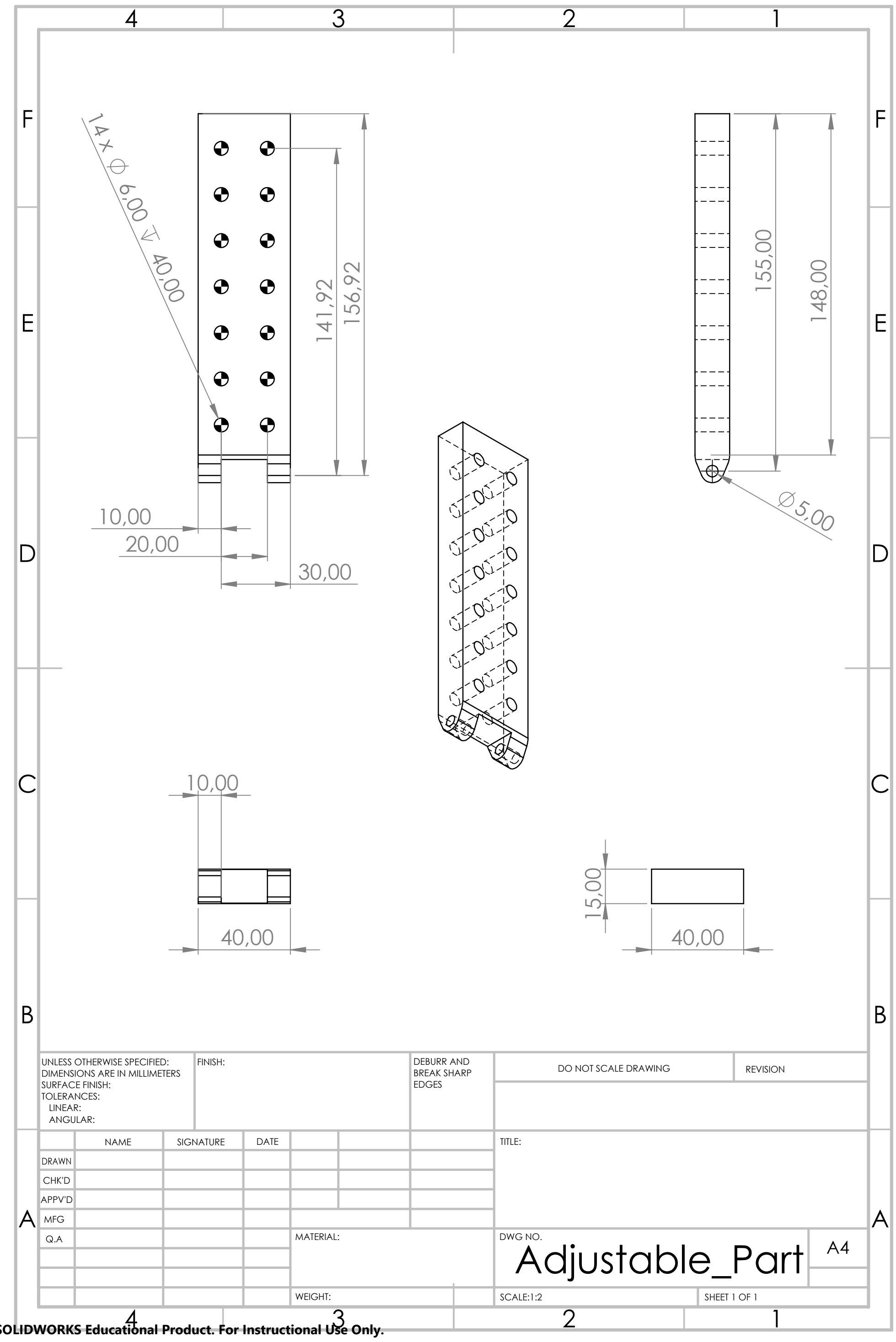

Figure B.5: Adjustable part model.