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Conceptualization of an open-source exoskeleton

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Resumo

Mesmo para o ser humano mais forte, manter uma posição elevada do braço durante um período prolongado representa um desafio significativo, uma vez que a fadiga se acumula inevitavelmente ao longo do tempo. O esforço físico é ainda mais intensificado quando o indivíduo está envolvido em tarefas repetitivas, particularmente as que envolvem a utilização de ferramentas ou equipamento pesado. Estas atividades aumentam a probabilidade de desenvolver fadiga muscular ou lesões devido ao uso excessivo ou a uma postura inadequada. Com o tempo, isto pode resultar no desenvolvimento de doenças crónicas, que podem prejudicar a capacidade do indivíduo para executar tarefas de forma eficaz e potencialmente levar a uma incapacidade física a longo prazo.

Os exoesqueletos desempenham um papel transformador, reduzindo a carga sentida nos músculos e fornecendo apoio mecânico, atenuando o risco de lesões e aliviando a carga física associada a atividades extenuantes. Para além da prevenção de lesões, estes dispositivos também prometem facilitar a reabilitação de indivíduos que tenham sofrido lesões músculo-esqueléticas.

Este documento apresenta o estudo do estado de arte e o desenvolvimento de um exoesqueleto para o membro superior, bem como uma análise teórica de possíveis dimensionamentos de exoesqueletos para várias cargas, com o intuito de ajudar no desenvolvimento de um exoesqueleto para trabalhos pesados como os da agricultura.

Abstract

Even for the strongest human being, maintaining an elevated arm position for an extended duration represents a significant challenge, as fatigue inevitably accumulates over time. The physical strain is further intensified when the individual engages in repetitive tasks, particularly those involving the use of heavy tools or equipment. Such activities increase the probability of developing muscle fatigue or injuries due to overuse or improper posture. Over time, this can result in the development of chronic conditions, which may impair the individual's ability to perform tasks effectively and potentially lead to long-term physical impairment.

Exoskeletons play a transformative role by reducing the perceived load on the muscles and providing mechanical support, mitigating the risk of injuries, and alleviating the physical burden associated with strenuous activities. In addition to injury prevention, these devices also promise to facilitate the rehabilitation of individuals who have sustained musculoskeletal injuries.

This document presents a state-of-the-art study and the development of an exoskeleton for the upper-limb, as well as a theoretical analysis of possible exoskeleton designs for various loads, with the aim of assisting the development of an exoskeleton for heavy work such as that performed in agriculture.

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework to achieve a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice [1].

The specific Sustainable Development Goals mentioned have the following names:

SDG 3 Ensure healthy lives and promote well-being for all at all ages

SDG 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

The work developed in this dissertation contributes to these goals due to the exoskeleton's ability to assist in labor, helping to prevent injuries and facilitating tasks that would otherwise be considered heavy. This study also contributes to the development of a new exoskeleton.

The following table details the specific SDG targets addressed, the nature of the contribution, and the performance indicators that help assess the effectiveness and potential impact of the proposed system

SDG	Target	Contribution	Performance Indicators and Metrics
3	3.4	The exoskeleton aims to reduce the physical strain and risk of musculoskeletal disorders in agricultural workers.	Reduction in reported fatigue or injury risk during task performance
8	8.5	Facilitates access to physically demanding jobs through wearable assistive devices, promoting inclusive labor.	Number of tasks performed with reduced physical burden; perceived comfort levels
	8.8	Improves safety and ergonomics in physically intensive agricultural tasks.	Evidence of reduced biomechanical load or improved task performance with assistance
9	9.5	Contributes to R&D through the design, prototyping, and analyze of an exoskeleton.	Development of functional prototype; publication and accessibility of technical documentation
	9.b	Encourages adoption of innovative robotic technologies in traditional labor sectors.	Integration of advanced control and actuation concepts in wearable systems for field use

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“Impossible is a word to be found only in the dictionary of fools.”

Napoleon Bonaparte

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List of Abbreviations and Acronyms

3D three Dimensional. xvi, xvii, 15, 35, 63, 68, 69, 75

ABS Acrylonitrile Butadiene Styrene. 25, 68

ADC Analog to Digital Converter. 48, 105

BLDC BrushLess Direct Current. 10, 12–14, 19, 28, 37, 38, 41, 45

CAD Computer-Aided Design. xv, 27

CAN Controller Area Network. 47–50

CNC Computer Numerical Control. 82

DC Direct Current. 10, 11, 20, 37

DoF Degrees of Freedom. xv–xix, 2, 7, 8, 12–34, 53, 55–57, 61, 67, 68, 78–81, 83, 87, 88, 92–96, 105, 107, 108

DPL Double-Parallelogram Linkage. 19

EEPROM Electrically Erasable Programmable Read-Only Memory. 48

EMG ElectroMyoGram. 15, 16, 18, 22–24, 30

F/T Force/Torque. 20, 46

HMI Human Machine Interaction. 5, 11, 105, 108

HTD High Torque Drive. 82

I2C Inter-Integrated Circuit. 48

IMU Inertial Measurement Unit. 13, 30

PCB Printed Circuit Board. 49

PD Proportional-Derivative. 17

PETG Polyethylene Terephthalate Glycol. 68, 77

PI Proportional-Integral. 20, 50, 64, 65, 99, 105, 106

PID Proportional–Integral–Derivative. 13, 15

PLA Poly-Lactic Acid. 23, 68

RAM Random Access Memory. 48

ROM Range Of Motion. xix, 3, 8, 9, 53, 59, 97, 98

SEA Series Elastic Actuators. 11, 25, 27

sEMG surface ElectroMyoGram. xv, 14, 16–18, 34, 35

SMA Shape Memory Alloy. 30

SPI Serial Peripheral Interface. 48

TPU Thermoplastic Polyurethane. 68, 77

UART Universal Asynchronous Receiver-Transmitter. 48

Chapter 1

Introduction

1.1 Context

Agricultural work is characterized by physically demanding and repetitive activities, such as lifting heavy crates, hoeing, or prolonged tool use. These tasks frequently lead to muscular strain, fatigue, and long-term musculoskeletal disorders in workers [2]. In parallel, the ongoing decline in the availability of agricultural labor [3] has placed even greater physical demands on the remaining workforce, further exacerbating the risk of injury and overexertion [4].

While tools such as electric shears can reduce the effort required for specific actions, like pruning, they are limited in scope and do not address the broader range of tasks found in agricultural settings. In contrast, wearable robotic devices such as exoskeletons offer a more versatile solution. By actively supporting joint movement, exoskeletons can assist users in performing heavy or repetitive motions more efficiently, reducing physical strain, improving productivity, and lowering the risk of injury [5].

1.2 Motivation

This dissertation stems from a personal initiative aimed at developing practical solutions to enhance physical working conditions in traditionally demanding sectors, such as agriculture. It seeks to address not only the theoretical concepts but also the practical challenges involved in designing, constructing, and controlling a wearable robotic device. From the outset, exoskeletons have been recognized as a technology with considerable untapped potential in this context.

This project was developed within the scope of INESC TEC's TRIBE Lab, whose research focuses on the application of technology to the agricultural sector. This connection allowed the work to be geared towards real challenges identified in the field, reinforcing the relevance of the exoskeleton as a solution to mitigate the physical effort associated with agricultural tasks. The choice of this sector as a case study is justified by the high physical demands related to repetitive and prolonged tasks, as well as the growing labor shortage, which makes these solutions even more relevant.

To deepen practical knowledge in this area, a simple exoskeleton was developed. Although the device has only been tested in a laboratory environment and is not yet capable of field operation, the prototype served as a fundamental proof of concept for understanding the technical and practical challenges of the technology.

1.3 Objectives

The main objective of this work is to perform a state-of-the-art review of exoskeletons, to develop a robotic exoskeleton with four Degrees of Freedom (DoF) combining active and passive joints, and to investigate various combinations for different payloads to complement the prototype results.

This project aims to deepen practical and theoretical knowledge about the design, construction, and control of wearable robotic devices, as well as contribute to the advancement of solutions with real application potential.

1.4 Contributions

One article was derived from the contributions of this work, more specifically, a review on upper-limb exoskeletons:

- A. Pires, F. N. dos Santos, and V. Tinoco, “Review on upper-limb exoskeletons,” *Machines*, vol. 13, no. 8, 2025, ISSN: 2075-1702. DOI: [10.3390/machines13080642](https://doi.org/10.3390/machines13080642). [Online]. Available: <https://www.mdpi.com/2075-1702/13/8/642> [6]

1.5 Document structure

The document begins with a theoretical study and analysis, followed by the construction, validation, and evaluation of the prototype developed in this dissertation. Chapter 2 reviews the state-of-the-art of existing exoskeletons, examining various types and functions. This analysis identifies different approaches to architecture, control strategies, and component selection. Building on this study, Chapter 3 addresses the selection of motors, sensors, and structural elements, considering factors such as torque, technical feasibility, and cost.

Following the theoretical analysis, Chapter 4 presents the development and construction of a validation prototype aimed at testing the control concept and obtaining feedback on its feasibility and potential limitations. Based on the insights gained in this phase, the development and construction of the main exoskeleton prototype are described. Additionally, Chapter 4 presents a theoretical dimensioning study of various configurations for the shoulder and elbow joints, considering different payloads. This study provides a foundation for the future development of a more robust exoskeleton adapted to demanding contexts and evaluates the feasibility of such construction.

Chapter 5 reports the testing of the control system implemented in the final prototype, with particular attention to the exoskeleton's behavior and the evaluation of its Range Of Motion (ROM) in comparison to human movement. Challenges encountered during development and potential adjustments to address them are also discussed.

Finally, Chapter 6 summarizes the dissertation's conclusions and outlines directions for future work.

Chapter 2

State-of-the-art

In Section 1.1, the problem under study was presented, emphasizing its relevance and associated challenges. Although exoskeletons specifically designed for agriculture are limited, these devices are highly versatile and can be adapted to various applications, provided they satisfy the necessary biomechanical and ergonomic requirements.

Consequently, this review is not limited to agricultural exoskeletons; rather, it focuses on identifying and categorizing existing upper-limb exoskeletons, both assistive and rehabilitative, that provide valuable insights into Human Machine Interaction (HMI) strategies, actuation methods, control systems, sensor integration, and mechanical configurations. By extracting and comparing these key specifications, this chapter aims to establish a solid technical foundation for the development of an upper-limb exoskeleton prototype.

2.1 Methodology

This section describes the research methodology, including the databases used and the search strategies implemented to gather relevant information, focusing on the development of upper-limb exoskeletons. Trends in the field are also highlighted to support the study's objectives.

The information used to develop this section was obtained from the following databases: Sage-Journals, Frontiers, Springer Link, ASME, IEEE Xplore, and ScienceDirect.

Searching the Scopus database using the keywords exoskeleton, upper-limb exoskeleton (upper and limb and exoskeleton), and lower-limb exoskeleton (lower and limb and exoskeleton) returns the number of documents published over 10 years. Figure 2.1 shows that there has been an increase in interest in exoskeleton research. Furthermore, it can also be seen in Figure 2.2 that the research interest in lower-limb exoskeletons is greater than in upper-limb exoskeletons.

Although the searched documents are related to exoskeleton control, only a few focus on the development of the exoskeleton, which is the focus of this work.

To refine the search results, the keyword “development” was added, which reduced the number of documents; however, their number has continued to grow steadily over the years, as illustrated in Figure 2.3.

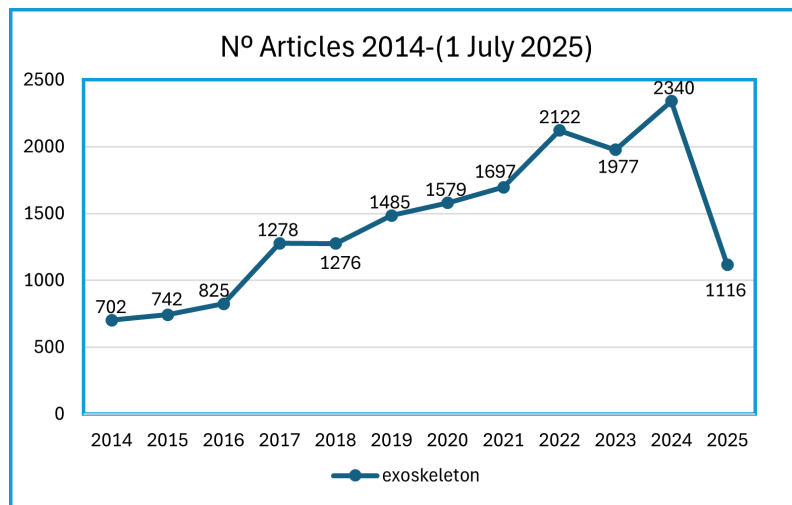


Figure 2.1: Number of articles on exoskeletons written between the years 2014–2025.

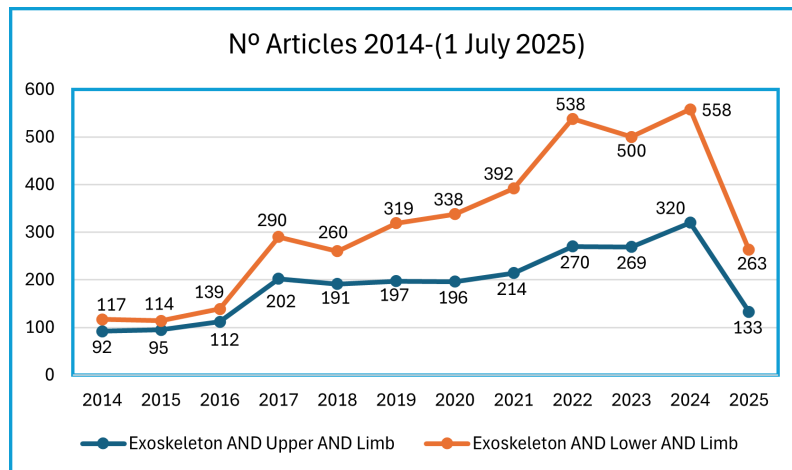


Figure 2.2: Upper- and lower-limb exoskeletons articles written between the years 2014–2025.

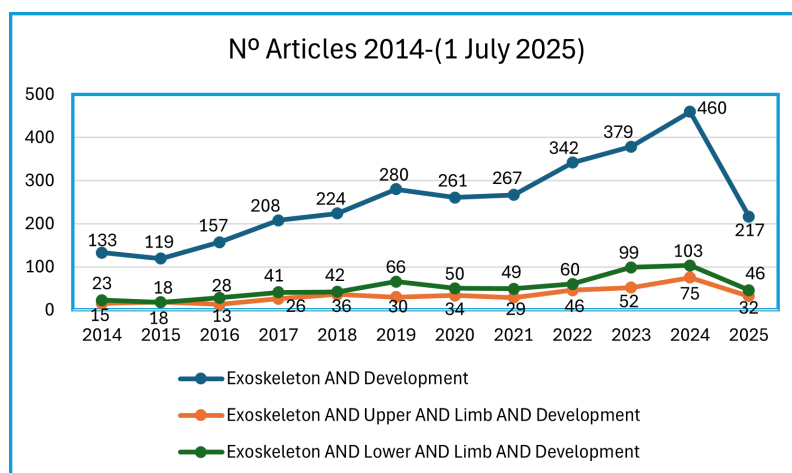


Figure 2.3: Articles about the development of exoskeletons written between the years 2014–2025.

As previously stated, the objective of this review is to establish a foundation for the development of an exoskeleton aimed at agricultural applications. Although the figures show that many papers have been published on upper-limb exoskeletons, only those that meet certain criteria were included. Specifically, papers were excluded if they focused only on control strategies without providing any technical information about the exoskeleton itself; if they described only a single prototype still in simulation stages; or if, despite describing a developed system, they lacked sufficient detail about the components used. These exclusion criteria significantly reduce the number of documents that could be considered relevant for this review. In the following section, some of the exoskeletons that were not excluded by these criteria are selected and analyzed.

2.2 Preliminary information

This section provides preliminary information on wearable robotic exoskeletons and an overview of human upper-limb anatomy.

2.2.1 Wearable robotic exoskeleton

Wearable robotic exoskeletons are mechanical devices that are attached to the operator and follow their movements [7]. They can amplify the operator's strength or help with movement, depending on the type of exoskeleton. These can be defined by two main criteria: the types of actuation and the main purposes. To simplify the terminology, the term exoskeleton will be used throughout this work.

The two principal types of actuation in exoskeletons are: passive actuation (*i*) and active actuation (*ii*). Passive actuation (*i*) refers to actuation that does not require external energy to produce force, but uses a mechanical system, such as a spring system. Active actuation (*ii*) exoskeletons use electric, pneumatic, or hydraulic actuators to assist movement and, unlike passive actuation exoskeletons, depending on the DoF, can assist in various directions, but are also dependent on an external energy source [8].

Although exoskeletons have various purposes, the most notable are: Assistance (*i*) and Rehabilitation (*ii*). When the functionality is Assistance (*i*), exoskeletons are designed to reduce the person's fatigue when performing repetitive tasks or increase their ability to lift heavy loads, increasing production at an industrial level and reducing the user's muscle injuries. In the case of medical rehabilitation (*ii*), they are designed to help disabled patients suffering from post-stroke paralysis, amyotrophic lateral sclerosis, or other physical or cognitive disabilities. In addition, these devices are used to provide therapy consistently over a longer period, regardless of the level of fatigue and training capacity of the physiotherapists. Often, these exoskeletons are static, attached to wall brackets or other structures, and are usually designed for specific parts of the body, such as the hand [8].

The analyzed articles show that the exoskeletons can also be classified by their construction. They can have a rigid construction or a soft construction. What distinguishes the examples in this document is whether the joints are solid, such as the use of motors directly, or whether they are

soft, such as cables or pneumatic bellows. The advantage of using soft structures is that the joints do not need to be perfectly aligned, as the system adapts to the body. However, the disadvantage of these systems compared to rigid ones is that the loads fall on the operator's joints and not on the joints of the exoskeleton.

2.2.2 Human upper-limb

Manual labor tends to put more pressure on the upper-limb, especially the shoulder, since the lower limbs are inherently stronger and better suited to bearing weight. Given this, the exoskeleton would be more effective in reducing muscle injuries if it were designed to support the upper-limb. As this review focuses on upper-limb exoskeletons targeting the shoulder, elbow, and/or forearm, it is essential to understand the anatomical and kinematic characteristics of these segments. Therefore, this section covers the main joints, their types of movement, and the DoF relevant to these regions. Wrist and hand movements are not included, as devices supporting those areas fall outside the scope of this analysis.

At a skeletal level, the upper-limb is made up of various bony elements, organized as follows: The shoulder is made up of the clavicle, the scapula, and the humerus. It is with the latter that the connection to the elbow is made. This bone complex also joins the radius and ulna, the bones of the forearm [8].

In the shoulder, there are four joints: the glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic joints. In the elbow, there is a synovial-type joint made up of two distinct joints, one between the humerus and ulna (humeroulnar joint) and the other between the humerus and radius (humeroradial joint). This can be seen in Figure 2.4B.

The primary movements of the shoulder complex are abduction and adduction, internal and external rotation, and shoulder flexion and extension. Many of the exoskeletons developed only consider the glenohumeral joint to model the shoulder mechanism, producing a 3-DoF joint. The glenohumeral joint is commonly referred to as a ball-and-socket joint, formed between the humeral head joint and the glenoid cavity. However, the glenohumeral joint has an instantaneous center of rotation that changes with the movement of the human upper-limbs [9].

The elbow joint is 1-DoF, with the primary movements being flexion and extension [8]. Similarly, the forearm also has 1-DoF, with its primary movement being pronation and supination.

To support the biomechanical overview of the upper-limb, Table 2.1 presents the main joint movements, their average ROM, and the primary muscles involved. ROM refers to the maximum angular movement that a joint can perform, measured in degrees, and is essential for understanding joint capabilities in exoskeleton design [10]–[12]

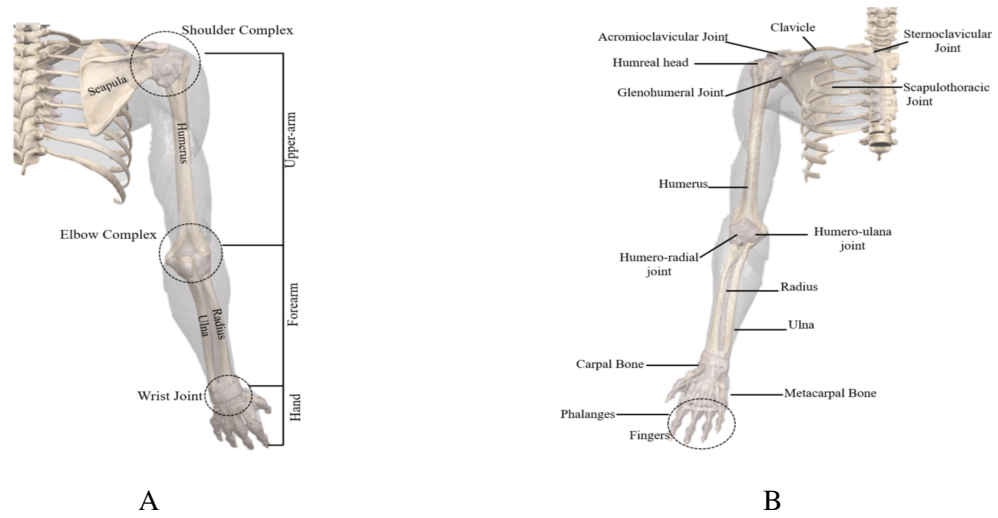


Figure 2.4: Human upper-limb [8].

Table 2.1: Shoulder, elbow, and forearm movements with ROM and muscles involved.

Joint	Movement	ROM (°)	Muscles Used
Shoulder	Abduction	180	Supraspinatus, deltoid
Shoulder	Adduction	50	Coracobrachialis, pectoralis major, latissimus dorsi, teres major
Shoulder	Flexion	180	Pectoralis major, deltoid, coracobrachialis, long head of biceps brachii
Shoulder	Extension	60	Latissimus dorsi, teres major, pectoralis major, deltoid, long head of triceps brachii
Shoulder	Internal Rotation	90	Subscapularis, teres major, latissimus dorsi, pectoralis major, deltoid
Shoulder	External Rotation	90	Teres minor, infraspinatus, deltoid
Elbow	Flexion	140	Biceps brachii, brachialis, brachioradialis
Elbow	Extension	0	Triceps brachii, anconeus
Forearm	Pronation	80	Pronator teres, pronator quadratus
Forearm	Supination	80	Supinator, biceps brachii

2.2.3 Actuators

To facilitate comprehension of the following section, the actuators employed by various authors are discussed.

Cable-driven

Cable-driven actuators use flexible cables to transmit force and motion, allowing for lightweight and compact designs. These actuators are commonly used in robotic and biomechanical applications due to their ability to operate remotely and reduce the weight of moving parts. However,

challenges such as cable tension control and potential stretching must be addressed to ensure precision and reliability. Advanced tensioning mechanisms and feedback systems are often implemented to enhance performance [13]. The Figure 2.5 shows a cable system for operating an exoskeleton.

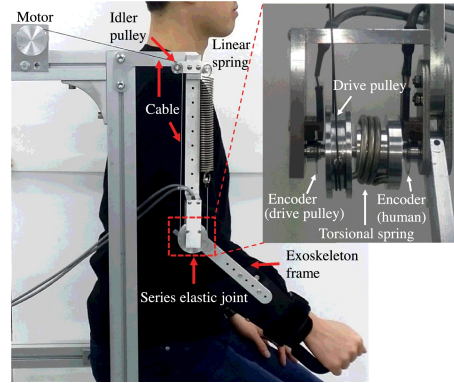


Figure 2.5: Cable system example [14]

Pneumatic

Pneumatic actuators use compressed air to generate motion, making them a popular choice in industrial automation and robotic applications. They offer high power-to-weight ratios and fast response times, making them suitable for tasks requiring rapid actuation. However, their performance depends on air pressure regulation and the efficiency of the pneumatic system. While they are generally durable and cost-effective, precise control can be challenging compared to electric or hydraulic alternatives [15]. The Figure 2.6 shows a pneumatic actuator working principle.

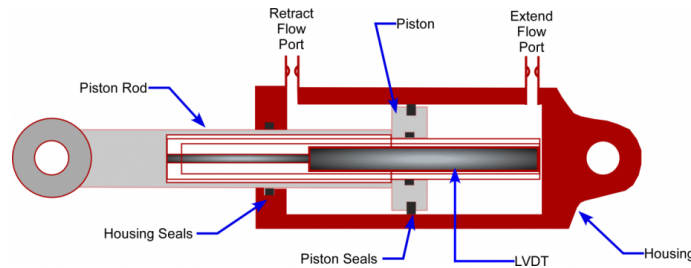


Figure 2.6: Pneumatic actuator example [16]

Direct drive

Direct drive operation means that the system uses a Direct Current (DC) motors directly on the exoskeleton joint. DC motors can be defined as brushed (i) or brushless (ii), which defines the type of system they use. Brushed DC motors (i) rely on mechanical brushes and a commutator to switch the current direction, making them simpler in design but prone to wear over time. In contrast, BrushLess Direct Current (BLDC)(ii) motors use electronic commutation, offering higher efficiency, reduced maintenance, and improved longevity. Due to these differences, the choice

between brushed and brushless motors depends on factors such as cost, durability, and application requirements [17]. The Figure 2.7 shows a direct drive system using a DC motors for operating an exoskeleton.

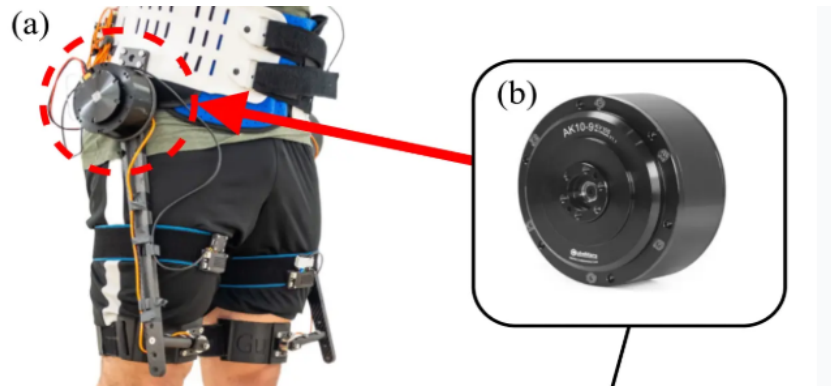


Figure 2.7: Direct drive system actuator example [18]

Linear SEA

Series Elastic Actuators (SEA) Actuators incorporate an elastic element in series with the actuator to improve force control and shock absorption. This design enhances safety in HMIs by reducing abrupt force transmission and allowing for more compliant movements. SEAs are commonly used in applications requiring precise force modulation, such as exoskeletons and robotic prosthetics. However, their performance depends on the stiffness of the elastic element and the control algorithms used to regulate force and motion [19]. The Figure 2.8 shows a Linear SEA actuator for operating an exoskeleton.

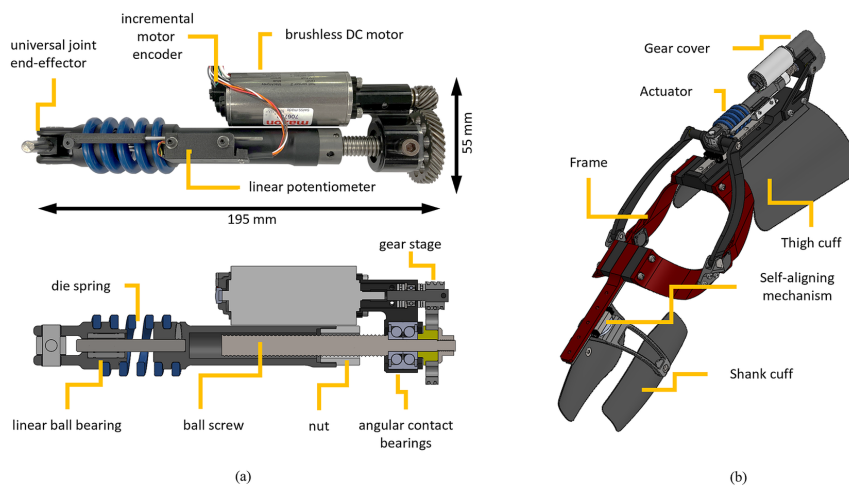


Figure 2.8: Linear SEA actuator example [19]

2.3 Upper-limb exoskeletons

This section aims to review existing exoskeletons in order to understand existing designs as well as the ways in which inputs are read and the types of actuators used. The reviewed exoskeletons are covered in chronological order from the most recent to the oldest and are separated into two categories, assistive and rehabilitation. For each example analyzed, a table summarizes the DoF, the associated joint (shoulder, elbow, or forearm), and the corresponding designated movements. To simplify the analysis, only one side of the body is considered, which means that in exoskeletons designed for both upper-limbs, only the DoFs for one limb are counted in the table. This approach ensures consistency and avoids over-representation of bilateral systems.

2.3.1 Assistive exoskeleton

This section will analyze exoskeletons with an assistive function.

Cable-driven exoskeleton

In 2024, Lim and Sharifi [20] proposed a Cable-driven exoskeleton to assist or rehabilitate users who suffer from spinal cord injuries. These injuries cause difficulties at the motor and sensory level and usually escalate to long-term disability. The exoskeleton reached a total weight of 7 kg and had three DoF, using a BLDC motor and a cable system to transmit the motor's power to the joints. The motors used were AK80-64s [21] which produce around 48 Nm nominal torque and 120 Nm peak torque. However, only 33 Nm peak torque was obtained at the shoulder joint and 18 Nm of torque at the elbow joint. The motors were placed in a carbon fiber box and connected to the joints via the cable system, which is then attached to the user's back, Figure 2.9.

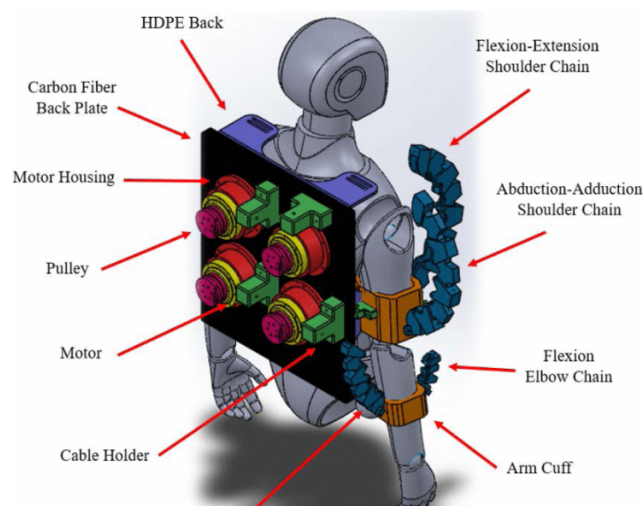


Figure 2.9: Cable-driven exoskeleton [20].

The project did not use sensors to detect the operator's movement; a sine wave was introduced to generate movement. To control the motors, tests were carried out at a reduced speed,

and a Proportional–Integral–Derivative (PID) tuning was performed, obtaining the proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) that allowed for more efficient control of the motors—always considering the limits of human movement—and using Velcro straps to attach the exoskeleton to the user. After carrying out the tests, the authors were able to conclude that the components could withstand the torque applied by the cable system without causing excessive deformation. These experimental tests also validated the intended movement of the exoskeleton, abduction/adduction of the shoulder, flexion/extension of the shoulder, and flexion/extension of the elbow. The authors have thus validated the concept of the exoskeleton, which is lightweight, powered by a cable system and respects human movements.

The corresponding DoFs and primary movements for this system are summarized in Table 2.2.

Table 2.2: Cable-Driven Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	2	Flexion/Extension, Abduction/Adduction
Elbow	1	Flexion/Extension

Pick and place upper-limb exoskeleton

In the same year, Wang *et al.* [22] developed and tested a pick-and-place upper-limb exoskeleton with the main function of pick-and-place, as seen in Figure 2.10. To counteract upper-limb injuries and fatigue caused by heavy lifting operations, the authors used the T-MOTOR AK80-6 BLDC motor [23], which produces 12 Nm of peak torque and is powered by a 24 V lithium battery. The power was transmitted via a system of cables, resulting in a weight of just 4 kg, so that the user does not have to exert a considerable amount of effort to wear the device. The exoskeleton was controlled using a fuzzy PID controller to obtain a smooth response of the cable tension that the exoskeleton needed to produce. The authors also used Inertial Measurement Unit (IMU) sensors to read the angular movement of the joints and use it as control feedback.

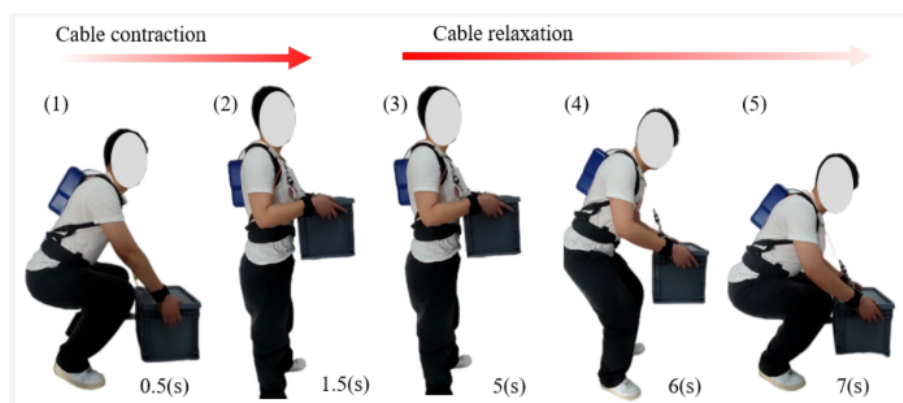


Figure 2.10: Exoskeleton in movement [22].

The human shoulder has a total of 7-DoF, which means that rigid exoskeletons with fewer DoF can cause injuries, which is why the authors preferred to use flexible materials when developing their exoskeleton, resulting in the prototype shown in Figure 2.11.



Figure 2.11: Exoskeleton worn by the operator [22].

The authors carried out two experimental evaluations, first testing the range of movement of the exoskeleton, concluding that it has a low level of interference, with a reduction in shoulder range from 89.6° to 83.2° . They then carried out tests to understand the assistive effect of the exoskeleton, verifying that it is generating support for the user. The authors chose to read surface ElectroMyoGram (sEMG) signals when lifting loads of 5 kg, 10 kg, and 15 kg to make a comparison with and without the exoskeleton. The conclusions were that they significantly reduced muscle activity, and thus were able to demonstrate the support provided by the device and confirm its efficiency in providing physical support and reducing muscle strain during repetitive tasks.

The corresponding DoFs and primary movements for this system are summarized in Table 2.3.

Table 2.3: Pick-and-Place Upper-Limb Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	1	Flexion/Extension (to a certain degree)
Elbow	1	Flexion/Extension

Cable-driven upper-limb exosuit

In 2024, Guo *et al.* [24] proposed an exosuit for the upper-limb to increase human capacity, namely in rock climbing, rope climbing, and carrying boxes. To this end, they developed a soft exoskeleton made with non-stretchable nylon fabric and powered by a system of two cable-driven actuators. The authors also used a system of pressure-measuring gloves to detect when the hand closes and opens, using this to control the system. Excluding the weight of the batteries, the exosuit weighed approximately 3.2 kg. They calculated that the system, using two T-MOTOR AK80-6 BLDC motor [23], could produce a maximum of 340 N, which would be equivalent to lifting 34 kg. Although the authors do not state the exoskeleton's Degrees of Freedom, it is similar to the 2-DoF

exoskeleton previously discussed in Section 2.3.1. Each motor comprises a PID controller with feedback being generated by the pressure-measuring gloves. To validate their solution, the authors used ElectroMyoGram (EMG) signals during barbell lifts and the lifting of a 10 kg box by five healthy people. After several tests, a reduction in the amplitude of the EMG signals was observed, comparing the signals with and without the exoskeleton. In the future, they intend to improve the mechanical system of the exoskeleton and carry out tests in a climbing environment.

The corresponding DoFs and primary movements for this system are summarized in Table 2.4.

Table 2.4: Cable-Driven Upper-Limb Exosuit DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	1	Flexion/Extension (to a certain degree)
Elbow	1	Flexion/Extension

Assistive Exoskeleton with Soft Pneumatic Actuators

In 2023, George *et al.* [25] had the objective of developing a lightweight exoskeleton with soft pneumatic actuators. Their motivation was muscle weakness caused by diseases such as stroke or trauma, which is typically treated using physiotherapy and assistive tools. However, many devices lack customization and affordability. For that, they built the exoskeleton using materials such as plastic using three Dimensional (3D)-printing, to be soft actuated, and to have a high number of DoF, which, in this case, was seven. With this system, the exoskeleton was able to obtain a peak torque of 4.46 Nm and a weight of 1.8 kg, of which 572 g was solely from plastic.

The exoskeleton acts actively on the elbow, shoulder, forearm rotation, and shoulder rotation. It acts passively with an anti-gravity system using elastics so that the user does not feel the weight of the exoskeleton as much. The presented exoskeleton is shown in Figure 2.12.

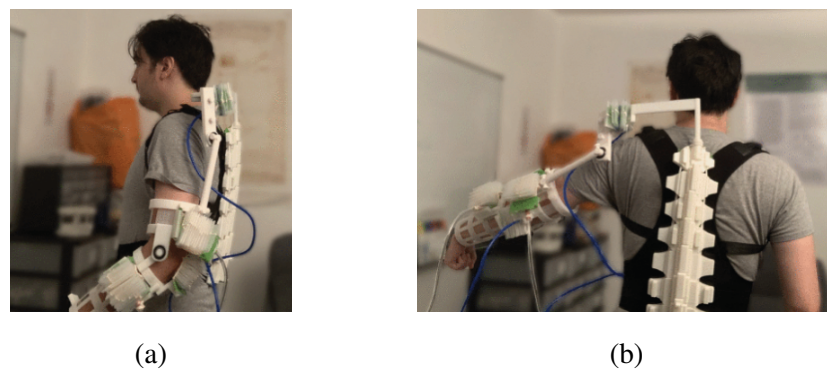


Figure 2.12: Soft Exoskeleton from the side (a) and rear (b) [25].

An electronic goniometer was used to measure the angular position of each joint. Proportional control was used to compare the sensor readings with the target values. As the exoskeleton is pneumatic, if there was a discrepancy between the target angle and the sensor reading, the actuation power would be altered to correct the discrepancy.

The authors carried out tests on the exoskeleton to assess the performance of the actuators in different scenarios. Initially, the measurement of the actuator angle showed that, when isolated, the actuators showed unpredictable variation. However, when integrated into the exoskeleton joints, the addition of inertia provided smoother and more controlled movements. Torque measurements indicated that the actuators generated consistent torques as the joint angle increased, with values ranging from 4.46 Nm to 1.94 Nm as the angle increased. In addition, tests with participants confirmed the effectiveness of the exoskeleton in assisting movement, allowing users to hit targets in a three-dimensional space with controlled times, demonstrating the system's ability to optimize joint movement and improve the efficiency of assistive support during dynamic tasks.

The authors have succeeded in obtaining a light and simple exoskeleton and, in the future, intend to use EMG signals to actuate the exoskeleton.

The corresponding DoFs and primary movements for this system are summarized in Table 2.5.

Table 2.5: Assistive Exoskeleton with Soft Pneumatic Actuators DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	3	Flexion/Extension, Abduction/Adduction, Internal/External Rotation
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

6-DoF dual-arm exoskeleton

In 2020, Hao *et al.* [26] designed a safe human–robot interactive control for the 6-DoF exoskeleton shown in Figure 2.13, with the objective of reducing the risk of muscle pain, fatigue, and musculoskeletal disorders in workers during manual lifting tasks, which involve repetitive movements of lifting, holding, and stacking heavy objects. The exoskeleton has a three-level hierarchical control system, where the high level reads the sEMG signals to detect the user's movement, the middle level uses a Hammerstein adaptive virtual mechanical impedance controller to reduce overshoot and maintain a comfortable torque level for the user, and finally, the low level comprises the motor controllers.

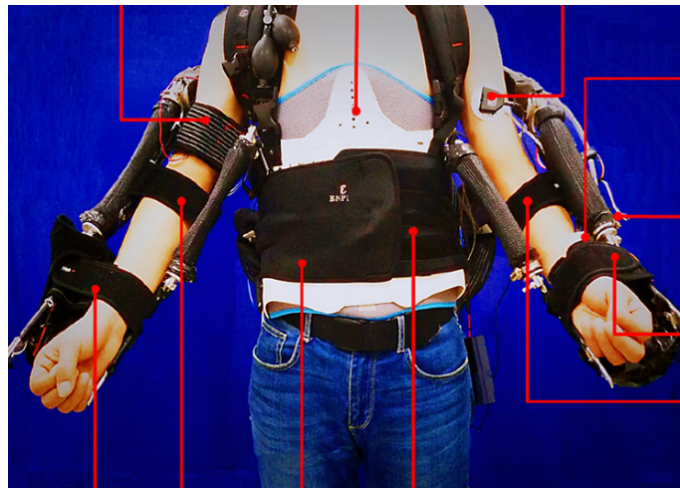


Figure 2.13: 6-DoF exoskeleton [26].

In addition to the sEMG sensors, a pneumatic soft sensor was used to measure the force exerted by the exoskeleton, and a heartbeat reader was used to measure the user's effort. When fully assembled, the exoskeleton had a mass of 5.6 kg and produced at least 30 N m.

The corresponding DoFs and primary movements for this system are summarized in Table 2.6.

Table 2.6: Dual-Arm Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	2	Flexion/Extension, Abduction/Adduction
Elbow	1	Flexion/Extension

Assist upper-limb exoskeleton for manual handling task

In that same year, Yan *et al.* [27] developed a 2-DoF exoskeleton to help industrial workers, who engaged in repetitive handling tasks, and patients with injuries in their upper-limb due to accidents, spinal cord injuries strokes. The exoskeleton seen in Figure 2.14 was moved by cables and actuated by electric motors. The authors were able to achieve an exoskeleton that weighed approximately 2 kg and used an adaptive Proportional-Derivative (PD) controller to control the exoskeleton.

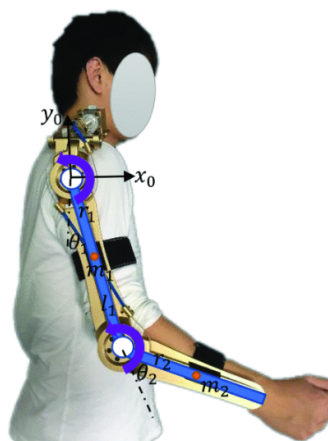


Figure 2.14: Upper-limb exoskeleton [27].

The authors were able to verify the effectiveness of the assistance on the patients' muscles by reading the variation in the intensity of the EMG signals when performing the tasks with and without the exoskeleton, obtaining an average of approximately 40% per muscle group that can be seen in Figure 2.15.

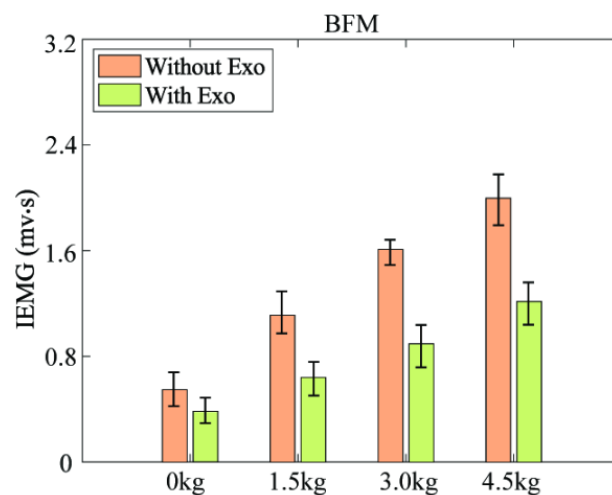


Figure 2.15: sEMG of BFM when bearing 0-4.5 kg objects with and without exoskeleton [27].

The results showed that the EMG signal amplitude, when lifting a 4.5 kg load with the exoskeleton, was the same when lifting 1.5 kg without the exoskeleton in the (biceps femoris muscle) BFW, so it was calculated that the exoskeleton was lifting 3 kg, then at the elbow joint it was producing around 9 N m of torque.

The corresponding DoFs and primary movements for this system are summarized in Table 2.7.

Table 2.7: Assistive Upper-Limb Exoskeleton for Manual Handling Tasks DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	1	Flexion/Extension
Elbow	1	Flexion/Extension

Exoskeleton using a double parallelogram linkage

In their work published in 2018, Christensen *et al.* [28] developed a shoulder joint that could perform internal and external rotation of the shoulder to be used in an exoskeleton. To achieve this goal, a passive joint was created using a Double-Parallelogram Linkage (DPL) system, shown in Figure 2.16.

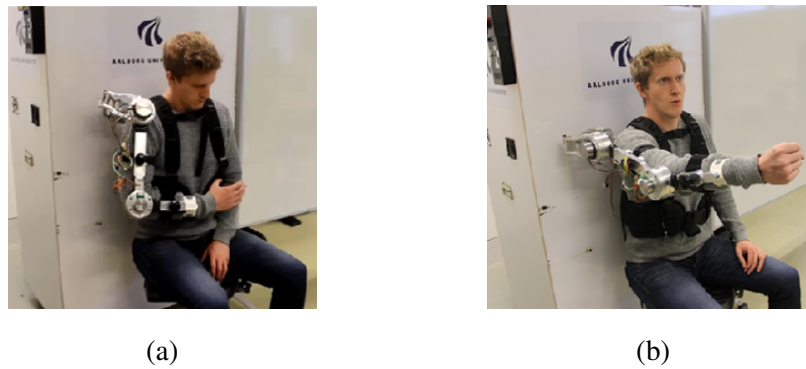


Figure 2.16: Exoskeleton motion: extension (a) and abduction (b) [28].

To this end, an exoskeleton was developed with 4-DoF, three of which are active and one of which, the DPL, is passive. BLDC motors were used for actuation, along with a harmonic gearbox and a force-sensing resistor as a main input. A study was carried out in which the authors simulated the daily activities of human beings with loads of up to 5 kg. Subsequently, they decided to scale it down to 50% of the max load tested. With this exoskeleton, they were able to perform the movements of flexion/extension, abduction/adduction, and medial rotation of the shoulder, as well as flexion/extension of the elbow. This exoskeleton is mobile, and the shoulder joint, as well as the rest of the exoskeleton, is made of 7075 aluminum alloy [29], with the weight of the shoulder joint being 2650 g.

With this installation of the shoulder joint in the upper body exoskeleton, the authors concluded that the joint has a great range and is a good choice for portable exoskeletons.

The corresponding DoFs and primary movements for this system are summarized in Table 2.8.

Table 2.8: Exoskeleton Using a Double Parallelogram Linkage DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	3	Flexion/Extension, Abduction/Adduction, Internal/External Rotation
Elbow	1	Flexion/Extension

Upper-limb exoskeleton robot for refractory construction

In 2018, Yu *et al.* [30] developed an upper-limb double arm exoskeleton with an air balancer and 7-DoF, shown in Figures 2.17 and 2.18. The exoskeleton was developed to help with refractory construction operations in furnaces, being designed to have great three-dimensional space mobility with the load and also able to help the operator move loads of up to 50 kg.

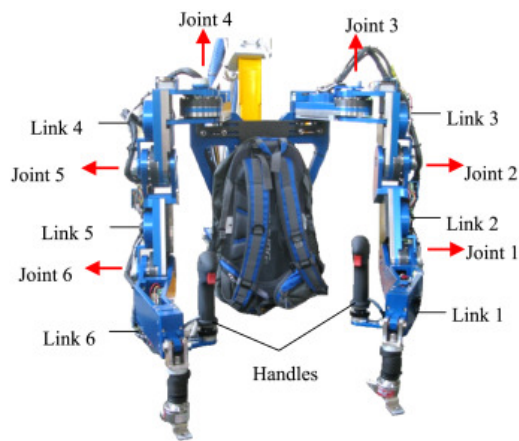


Figure 2.17: Double arm exoskeleton A [30].

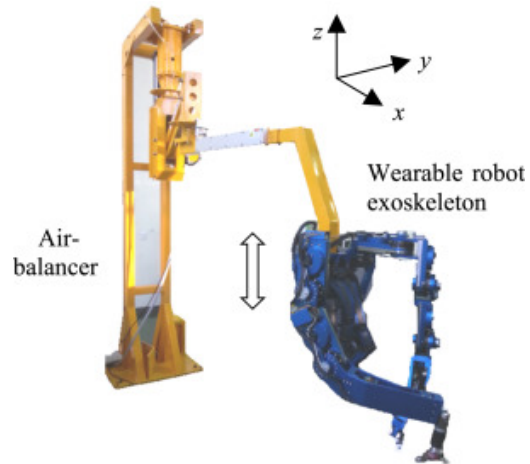


Figure 2.18: Double arm exoskeleton B [30].

In the development of the exoskeleton, 6-axis Force/Torque (F/T) sensors were used to obtain the link between the operator and the exoskeleton. After the final design of the exoskeleton was completed, it weighed 72.4 kg, and since it did not have support for the lower limbs, the exoskeleton had to be mounted on an air balancer. To perform the task of lifting 50 kg on the end effector, the actuators were required to produce 269.28 N m of peak torque. To obtain this value, DC motors were used with a harmonic box connected by a pulley reduction gear. The pulley-reduction gear allowed for better positioning of the motor and pulley due to its flexibility. Using F/T sensors to control the position of the exoskeleton, the authors found that they required a high gain, which caused responses that were very sensitive to sensor errors. For this reason, a speed-tracking torque control was developed, updating the Proportional-Integral (PI) references every 2 ms. To promote safety, limits were added to the joints, and the damped least-squares method was used to avoid singularities.

The authors carried out tests in simulated refractory construction operations, including lifting, transportation, and alignment. In the tests, the exoskeleton allowed the operator to transfer refractories weighing up to 50 kg without difficulty, and during these tests, the maximum displacements of the exoskeleton as well as its speed of movement could be obtained. In addition, the combination of movements in both arms enabled the performance of complex three-dimensional movements for aligning and manipulating objects. They also concluded that the dynamic control between the sensors and actuators was effective, ensuring adequate response without causing discomfort to the user, although the air balancer occasionally caused slight imbalances due to the repeated weight of the refractory.

With all these points, the authors concluded that the exoskeleton operator could easily move a load of up to 50 kg and perform repetitive tasks found in the refractory market.

The corresponding DoFs and primary movements for this system are summarized in Table 2.9.

Table 2.9: Upper-Limb Exoskeleton Robot for Refractory Construction DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	2	Flexion/Extension, Internal/External Rotation
Elbow	1	Flexion/Extension

Cable-driven exoskeleton with gravity compensation

In 2017, Sui *et al.* [31] developed a wearable exoskeleton to help workers in jobs that require them to move loads continuously for long periods, which can lead to shoulder and elbow injuries and serious on-the-job injuries. This reduction in workload improves worker health and costs for these companies. To this end, an exoskeleton with 5-DoF and a weight of 4.2 kg was developed, shown in Figure 2.19.

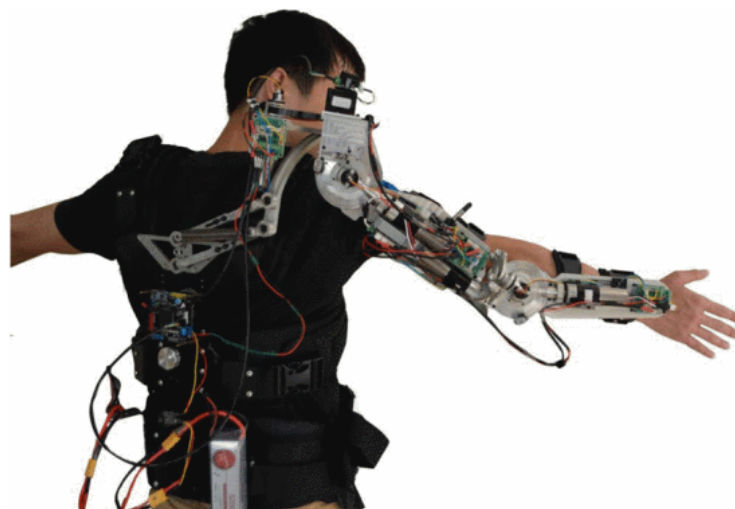


Figure 2.19: Daily exoskeleton [31].

To develop the exoskeleton, the authors used 2-DoF for the shoulder, 1-DoF for the elbow, 1-DoF for forearm rotation using a double parallelogram system, and finally a passive DoF for elevation and depression at the sternoclavicular joint with a gravity balance system. A cable-driven system and a belt reduction system were used to actuate the exoskeleton. A gravity balance method was also used to reduce the effort required from the exoskeleton actuator during movement. With the aim of reducing the weight of the exoskeleton, a spring system was chosen for the gravity balance system. To control the exoskeleton, the angular position of the joint was considered, accounting for the torque compensation due to losses, such as friction torque. This allowed the authors to conduct joint-tracking tests, which consisted of a sinusoidal reference of angle and angular velocity provided for the exoskeleton's elbow flexion and extension movement. It was checked whether the exoskeleton followed accurately to validate the efficiency and safety of their system. To confirm that the exoskeleton was helping while performing tasks, disposable electrodes were placed on the arm so the EMG could be read and a comparison of effort could be conducted between the absence and use of the exoskeleton when lifting 1.1 kg.

With this exoskeleton, the authors concluded that the application of the gravity balance reduced the stress on the motors and subsequently used smaller motors and gearboxes, thereby resulting in a lighter exoskeleton.

The corresponding DoFs and primary movements for this system are summarized in Table 2.10.

Table 2.10: Cable-Driven Exoskeleton with Gravity Compensation DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	2	Flexion/Extension, Internal/External Rotation
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

2.3.2 Rehabilitation exoskeleton

This section will analyze exoskeletons used for rehabilitation purposes.

Upper-body exoskeleton for stroke patients

In 2025, Talley *et al.* [32] developed a 3-DoF exoskeleton for the rehabilitation of patients suffering from arm function problems, such as people who have suffered a stroke. Plastic was used for the exoskeleton body, AK80-8 motors for actuation, as well as a servo motor and cable system for the elbow actuation. To control the exoskeleton, the authors used a mirror system, where IMUs were added to the patient's good arm and the exoskeleton attached to the arm that is blocked, then when the good arm is moved, the exoskeleton copies the movements, helping to rehabilitate the patient. After several tests, the authors concluded that the exoskeleton was able to copy the movement with a few deviations.

The corresponding DoFs and primary movements for this system are summarized in Table 2.11.

Table 2.11: Upper-Body Exoskeleton for Stroke Patients DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	2	Flexion/Extension, Abduction/Adduction
Elbow	1	Flexion/Extension

Reconfigurable 7-DoF upper-limb rehabilitation exoskeleton

In 2024, Wu *et al.* [33], developed an exoskeleton with 7-DoF to help patients who have suffered from strokes. To increase versatility, the exoskeleton developed can be modified to switch between the right and left arm; it also has a built-in gravity compensation system, helping to take strain off the electric motors. To control the exoskeleton, the authors used a system with six-dimensional force-torque sensors, allowing them to sense the patient's movement intentions. The exoskeleton can be used on different arms and can be adjusted to the physical structure of the patients, from height to arm length. The system used electric motors which, depending on the joint and movement, produced from 3 Nm to 25 Nm of nominal torque. To control the whole system, the authors used sliding mode control and dynamic movement primitives to achieve smooth control of the exoskeleton, and plan to add EMG readings in the future.

The corresponding DoFs and primary movements for this system are summarized in Table 2.12.

Table 2.12: Reconfigurable Upper-Limb Rehabilitation Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	3	Flexion/Extension, Abduction/Adduction, Internal/External Rotation
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

POWERUP exoskeleton

In 2024 Urendes *et al.* [34] developed a passive exoskeleton made of plastic. Using plastic gives the exoskeleton a mass of only 1.5 kg and simultaneously reduces monetary costs, making it ideal to be used in health clinics for the rehabilitation of children with neuro-motor dysfunctions. To this end, the authors developed a 5-DoF exoskeleton called POWERUP, shown in Figure 2.20, made entirely of Poly-Lactic Acid (PLA) filament and using elastics to perform the actuation.

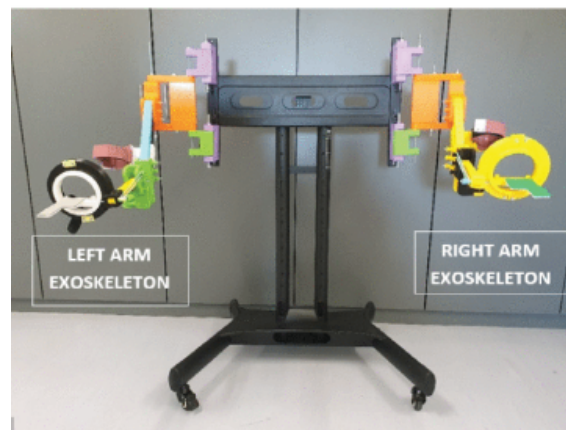


Figure 2.20: PowerUp exoskeleton [34].

Several exoskeleton modules were designed as it was to be used by children between the ages of 6 and 18 years old with different arm sizes. As a parameter, the authors decided that the exoskeleton should passively lift at least 2.5 kg. As the idea was to use it for therapy, it was fixed to mobile support. Two modes of operation were also developed, one that removes weight from the patient's arm, and one that generates resistance to movement to help the patient regain movement and strength.

Finally, to validate the exoskeleton, they used EMG signal readings and were able to confirm that the exoskeleton was indeed helping, thus validating the design.

The corresponding DoFs and primary movements for this system are summarized in Table 2.13.

Table 2.13: POWERUP Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	2	Flexion/Extension, Internal/External Rotation
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

5-DoF elbow-wrist exoskeleton

In 2019 Wu *et al.* [35] developed a 5-DoF elbow-wrist exoskeleton, shown in Figure 2.21, to facilitate the provision of repeated and progressive rehabilitation exercises that are essential for the effective recovery of patients with upper-limb disabilities. In this development, the authors opted to use smaller, simpler motors to avoid the weight, inertia, and volume issues of more powerful motors, so he was able to obtain a 3 kg exoskeleton.

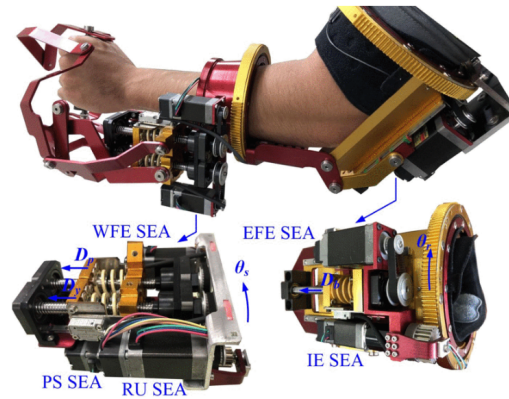


Figure 2.21: 5-DoF exoskeleton for elbow/wrist [35].

By integrating the positioning of the actuators, sensors, and transmission mechanism, the authors were able to develop a compact exoskeleton with minimal friction, thereby achieving effective performance for forearm rehabilitation through the use of an impedance controller to dynamically regulate the exoskeleton.

For actuation, the exoskeleton uses five SEA motors. These motors can provide accurate force/torque control obtained from the deformation of the linear SEA spring. In total, the five Linear SEA weighed only 0.48 kg.

The corresponding DoFs and primary movements for this system are summarized in Table 2.14.

Table 2.14: Elbow-Wrist Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	1	Internal/External Rotation
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

Exoskeleton actuated by the soft modules

In 2017, Oguntosin *et al.* [36] used soft actuators in an exoskeleton to make it ultra-light and to use computer vision to detect the movement and then control the actuators. This was achieved using plastic for the connections, a pneumatic system was used for the actuation. The exoskeleton was attached to an object such as a chair, as shown in Figure 2.22. The author's intention in creating the exoskeleton with these properties is to ensure that it can be used in a medical environment to rehabilitate patients, to keep the manufacturing cost low, to avoid the use of rigid robotic systems controlling the upper-limb, and to reduce the intervention by the medical professional.

With this project in mind, an exoskeleton was developed with four DoF, two passive and two active, and a video-based control architecture. With the printed parts made of Acrylonitrile Butadiene Styrene (ABS) plastic and the soft actuators made of Polyethylene, a weight of 957 g was achieved. As the actuators are pneumatic, it was decided that the acceptable pressure values

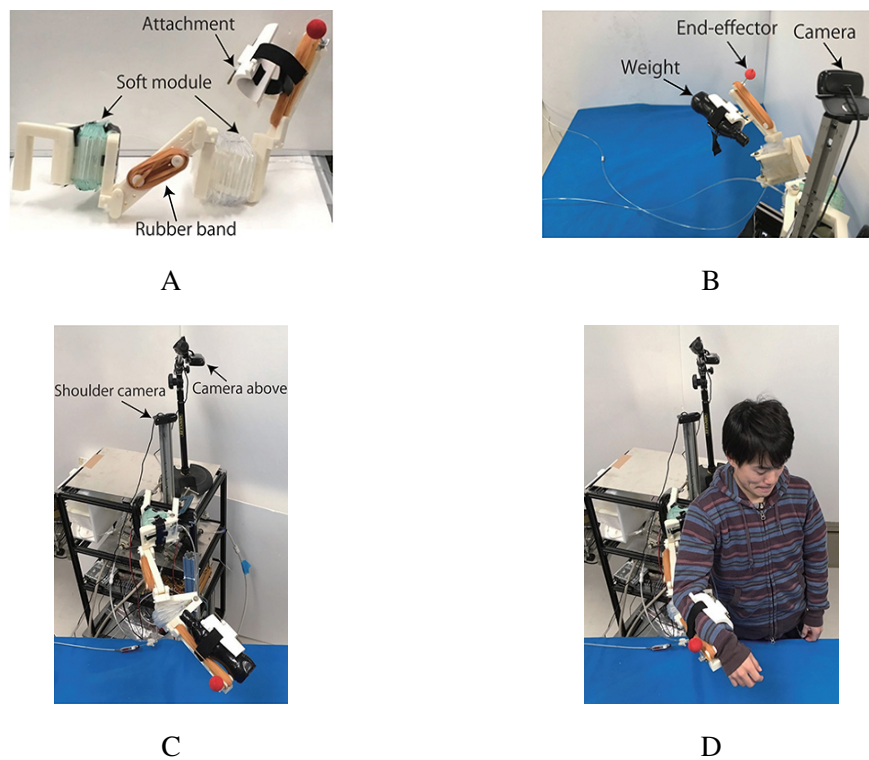


Figure 2.22: Soft rehabilitation exoskeleton [36].

would be -30 kPa to 30 kPa. With these values and the exoskeleton assembled, it could be verified that at the maximum positive pressure (30 kPa), the elbow joint of the exoskeleton produced 9 N m, and at the maximum negative pressure (-30 kPa), it produced -2.5 N m. Considering that the length of the forearm is 30 cm, the maximum load would be 3 kg when it produces 9 N m of torque and 0.8 kg when it produces 2.5 N m. As the exoskeleton is designed to help the person rehabilitate the arm in a post-stroke situation, these values are sufficient.

With this exoskeleton, the authors were able to achieve the proposed objectives: To have few DoF, to have precise control of movement, which was achieved through camera control, to be wearable and usable in everyday life, and finally, the assistance had to be compatible with muscle contraction to provide conformity in joint dynamics.

The corresponding DoFs and primary movements for this system are summarized in Table 2.15.

Table 2.15: Exoskeleton Actuated by the Soft Modules DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	1	Internal/External Rotation
Elbow	1	Flexion/Extension

Parallel actuated exoskeleton

In the same year, Hsieh *et al.* [37] designed a parallel actuated 2-DoF exoskeleton for post-stroke rehabilitation, as these patients require repeated and progressive training exercise and the use of an exoskeleton will reduce the cost of therapist labor, Figure 2.23, using linear SEA actuators with an impedance control to move the exoskeleton and force sensors to obtain the reference about the arm.

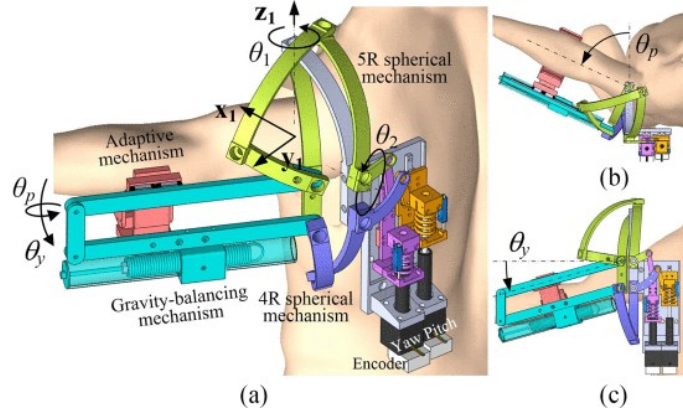


Figure 2.23: Computer-Aided Design (CAD) model of the shoulder exoskeleton [37]

Since this exoskeleton is for the upper-limb, it was necessary to study the displacement of the humeral head. The conclusion was that during abduction and adduction of the shoulder, the center point moved about 9 cm in the vertical z-axis and about 8 cm horizontally in the y-axis, which can be seen in the red line in Figure 2.24.

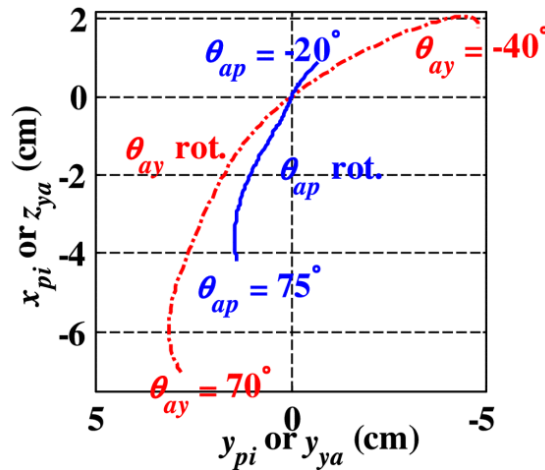


Figure 2.24: Displacement of the Humeral Head during shoulder motion [37]

With this study, the authors concluded that the displacement of the shoulder during movement is too high to be negligible and must always be taken into account when developing an exoskeleton that acts on the shoulder. To solve this, an adaptive mechanism was used, which meant that there was no need for precise alignment between the shoulder and the exoskeleton. So, therefore,

the exoskeleton had two active DoF for movement, and four passive DoF for the adaptive mechanism.

The prototype, weighing around 1.86 kg, was developed, but since the exoskeleton is for rehabilitation, it was fixed so that the patient does not need to support the exoskeleton. However, the exoskeleton was designed exclusively for the shoulder, and it was later necessary to develop the actuation of the shoulder internal/external rotation and elbow flexion/extension to achieve full control of the upper limb.

With the exoskeleton prototype built, the authors deployed it in a dummy arm made of aluminum so they could carry out some tests, starting with an impedance control test, where they had the exoskeleton follow a sinusoidal reference to move the dummy's arm, concluding that there was a slight misalignment caused by the motor due to a lack of power. They then carried out a kinematic misalignment experiment in which they calculated the misalignment of the passive joints and then measured them, obtaining the same results, thus validating their kinematics. Finally, they performed a test in which the passive joints were locked and compared them with unlocked joints. They observed a significant increase in force, resulting in dangerous and uncomfortable movements.

The corresponding DoFs and primary movements for this system are summarized in Table 2.16.

Table 2.16: Parallel-Actuated Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	6	Flexion/Extension, Abduction/Adduction

Neurorehabilitation exoskeleton

In 2017, Nam *et al.* [38] studied patients suffering from post-stroke with spastic elbow and/or wrist joints with the use of a 2-DoF exoskeleton to understand the reaction of the exoskeleton when it encounters spasticity during movement. The authors wanted the exoskeleton to be able to help rehabilitate patients with a high degree of spasticity.

For this purpose, a 2-DoF exoskeleton, shown in Figure 2.25, was used. This exoskeleton comprises 1-DoF in the elbow extension and flexion, and 1-DoF on the wrist dorsiflexion and palmar flexion. Furthermore, they used a mirror system in order for the patient or medical professional to force the arm that has reduced mobility to move. For actuation, two BLDC Motors were used, with enough torque to compensate for the patient's blocked movement, and torque sensors mounted on each of the joints to obtain torque data between the exoskeleton and the human arm during therapy. Having observed a torque of 22 Nm during the experiment implies that the motor has a value higher than this.



Figure 2.25: Exoskeleton used on the study [38]

With this study, the authors were able to obtain valuable data on the torque that the patient, with the arm blocked or limited due to a stroke, was able to produce, thus allowing future projects to be scaled according to these values.

The corresponding DoFs and primary movements for this system are summarized in Table 2.17.

Table 2.17: Neurorehabilitation Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Elbow	1	Flexion/Extension

Cable-driven arm exoskeleton

In 2016, Cui *et al.* [39] had the objective of improving the already developed CAREX [40] exoskeleton, to help people who suffer from movement disorders and reduced muscle strength, by building it with 7-DoF and actuated by cables, using it for complete arm rehabilitation, resulting in the CAREX-7, as illustrated in Figure 2.26.

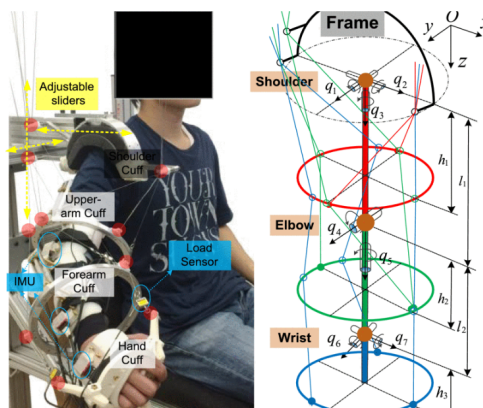


Figure 2.26: Exoskeleton used on the study [39]

The exoskeleton was fixed to a chair, and to achieve the 7-DoF, it uses 8 cables for actuation. Of the 7-DoF, three are for shoulder movement, one for elbow movement, and finally three for wrist movement. The exoskeleton is attached to the user via four cuffs. To detect the user's position, an IMU was used; furthermore, to receive feedback of the tension the cables were producing, load cells were used at the end of the cables.

To control the exoskeleton, the authors used a control scheme based on the “assistance as needed” paradigm, which has already been used by many researchers. This scheme evaluates the robot's required assistance to the user by measuring the trajectory tracking error of the end effector. The force field controller is a typical assistance-as-needed control scheme, which is applied in reach-movement training tasks.

The authors concluded that the CAREX-7 exoskeleton assists the seven joints while maintaining weight, and because the actuation is performed by cables, there is no need for great precision in the alignment of the joints. For future development, the authors want to collect EMG signal readings and increase the comfort of the exoskeleton.

The corresponding DoFs and primary movements for this system are summarized in Table 2.18.

Table 2.18: Cable-Driven Arm Exoskeleton DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Shoulder	3	Flexion/Extension, Abduction/Adduction, Internal/External Rotation
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

Rehabilitation exoskeleton for the elbow joint

In 2016, Copaci *et al.* [41] proposed an elbow exoskeleton, Figure 2.27, with 2-DoF. The device was actuated by a system based on Shape Memory Alloy (SMA), allowing the weight and noise of the exoskeleton to be reduced. It was developed for a person weighing 70 kg and with a height of 1.75 m.

The authors had already carried out other tests with the SMA based actuator, so they could conclude with a few more tests that the exoskeleton would only need four actuators and produce a torque of at least 3.5 Nm. With these values, a design can be defined for the exoskeleton, which will be made of plastic, and in a simple way for easy assembly. For patient safety, the exoskeleton also includes mechanical movement limitations to ensure it does not exceed the human limit. With this configuration, the exoskeleton weighs less than 1 kg.

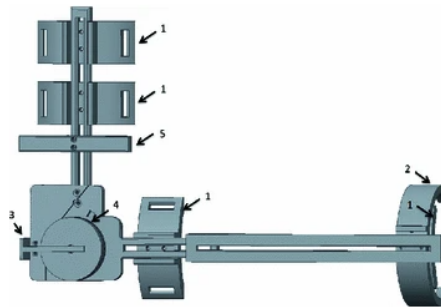


Figure 2.27: Exoskeleton model [41].

The authors concluded from the tests that the exoskeleton was very light and low-cost, and great for slow rehabilitation as it performs elbow flexion from 0° to 120° in 10 s and from 120° to 0° in 15 s.

The corresponding DoFs and primary movements for this system are summarized in Table 2.19.

Table 2.19: Rehabilitation Exoskeleton for the Elbow Joint: DoF and movements (data refers to a single limb).

Joint	DOF	Primary Movements
Elbow	1	Flexion/Extension
Forearm	1	Pronation/Supination

2.4 Discussion

After analyzing the various articles in the previous section, Tables 2.20 and 2.21 were constructed, providing an overview of the different exoskeletons, from the type of actuators to the construction material.

The torque values presented on Table 2.20 all refer to the max torque in the elbow flexion/extension movement, as this movement was acted on by all the exoskeletons presented, except the exoskeleton in Section 2.3.2.

Table 2.20: Assistive and rehabilitation exoskeletons — Table 1.

Name	DoF	Sensor Type	Actuator Type	Torque (Nm)	Weight (Kg)
Cable-driven [20]	3	Joint Angle	Cable-driven	17.37	7.000
Pick and place [22]	2	IMU	Cable-driven	12.00	4.000
Exosuit [24]	2	Air pressure	Cable-driven	6.00	3.200
Soft-actuated [25]	7	Goniometer	Pneumatic	5**	1.800
Dual-arm [26]	6	sEMG	Pneumatic	-	5.600
Manual tasks [27]	2	Joint Angle	Cable-driven	9.00*	2.000
Double parallelogram exo [28]	4	FSR sensor	BLDC	12.00*	>2.650
Construction [30]	7	F/T sensors	DC motors	270.00	72.400
Gravity compensation Exo [31]	5	Joint Angle	Cable-driven	8.00*	4.200
Stroke exo [32]	3	IMU	BLDC	10.00	-
Reconfigurable exo [33]	7	F/T sensors	BLDC	24.00	-
POWERUP exo [34]	5	None	Elastics (passive)	17.00*	1.500
Elbow-wrist exo [35]	5	F/T sensors	Linear SEA	-	3.000
EAsotM [36]	4	Visual-based control	Pneumatic	9.00**	0.957
Parallel-actuated [37]	6	F sensors	Linear SEA	-	1.860
Neurorehabilitation exo [38]	2	T sensors	BLDC	22.00	-
CAREX-7 [39]	7	IMU	Cable-driven	-	-
Elbow rehabilitation exo [41]	2	Joint Angle	Cable-driven	3.50	<1.000

Information not available in the article. * Estimated values. ** Maximum values in one direction.

Table 2.21: Assistive and rehabilitation exoskeletons — Table 2.

Name	Function	Structure Type	Material	Mobility
Cable-driven [20]	Assist	SemiRigid-Frame	Plastic	Portable
Pick and place [22]	Assist	Soft-Frame	-	Portable
Exosuit [24]	Assist	Soft-Frame	Nylon	Portable
Soft-actuated [25]	Assist	Soft-Frame	Plastic	Portable
Dual-arm [26]	Assist	Rigid-Frame	-	Portable
Manual tasks [27]	Assist	Rigid-Frame	-	Portable
Double parallelogram exo [28]	Assist	Rigid-Frame	Aluminum	Portable
Construction [30]	Assist	Rigid-Frame	Aluminum	Fixed
Gravity compensation Exo [31]	Assist	Rigid-Frame	Aluminum	Portable
Stroke exo [32]	Rehab	Rigid-Frame	Plastic	Portable
Reconfigurable exo [33]	Rehab	Rigid-Frame	Aluminum	Fixed
POWERUP exo [34]	Rehab	Rigid-Frame	Plastic	Fixed
Elbow-wrist exo [35]	Rehab	Rigid-Frame	Aluminum	Portable
EAsotM [36]	Rehab	Soft-Frame	Plastic	Fixed
Parallel-actuated [37]	Rehab	Rigid-Frame	Aluminum	Fixed
Neurorehabilitation exo [38]	Rehab	Rigid-Frame	Aluminum	Fixed
CAREX-7 [39]	Rehab	Soft-Frame	-	Fixed
Elbow rehabilitation exo [41]	Rehab	Rigid-Frame	Plastic	Portable

Information not available in the article.

Analyzing the different types of exoskeletons presented reveals some recurring trends in terms of portability, sensors, weight, and overall design. Assistive exoskeletons, for instance, tend to be portable, whereas rehabilitation exoskeletons are generally fixed. In terms of instrumentation, force or torque sensors are the most commonly used. Additionally, assistive exoskeletons tend to be heavier. In the examined designs, torque appears to be more closely related to the type of actuation and overall architecture than to the intended objectives. The same pattern applies to the number of DoF, which ranges from 2-DoF to 7-DoF.

The most commonly used actuation mode was the cable system, as it effectively addresses two main issues associated with placing electric motors directly at the joints: the first is the space constraint since motors can be bulky and limit joint mobility; the second is the additional load they impose, particularly critical when actuating shoulder flexion/extension and elbow flexion/extension, where mounting the motor at the elbow would result in extra weight that the shoulder joint must also support. An example of this design consideration can be found in the exoskeleton presented in [20]. Using electric motors with a gearbox directly in the joint is more efficient, as the adjustment of the cable system is not needed to operate it, and its control system is more direct. However, as previously stated, one of its problems is that the weight of the motor starts to influence the movement. The other issue regarding an electric motor with a gearbox is that to produce

a lot of torque, it can be too heavy to wear on the operator's back, so it has to be fixed, like the refractory construction exoskeleton.

A common feature observed in several of the exoskeletons presented in the Soft-actuated, Construction, Wearable upper-limb, Parallel-actuated exoskeleton, and Reconfigurable exo is an anti-gravity system that aims to “move” the weight of the exoskeleton from the arm to the operator's back, if it is portable, or to the support if it is fixed.

This system has several forms. For example, one could be like that of the exoskeleton from the article by Sui et al. [31], where in these systems, springs are used to support the weight of the exoskeleton. In other words, the spring assists the actuation system so that the motors do not have to exert so much force. The main limitation of this system is that if the exoskeleton becomes inverted, the spring may impede rather than assist movement. Another system that could be used is a counterweight system, where a counterweight would be added to the joint, performing the same task as the spring. The main defect of this system is that it increases the overall weight of the exoskeleton. For this reason, the system has to be evaluated on a case-by-case basis.

In Figure 2.28, it can be seen that the movements most covered by the exoskeletons shown are flexion/extension of the elbow and flexion/extension of the shoulder. There are two main reasons for this: the first is that these movements are the easiest to detect and perform, especially the elbow movement. Secondly, apart from their ease, the movements are practically identical, so the control will also be identical. Another relevant point is that both the Pick-and-Place [22] and the Exosuit [24] exoskeletons, although designed with only 1-DoF, allow the operator to perform two distinct movements, thanks to their flexible construction.

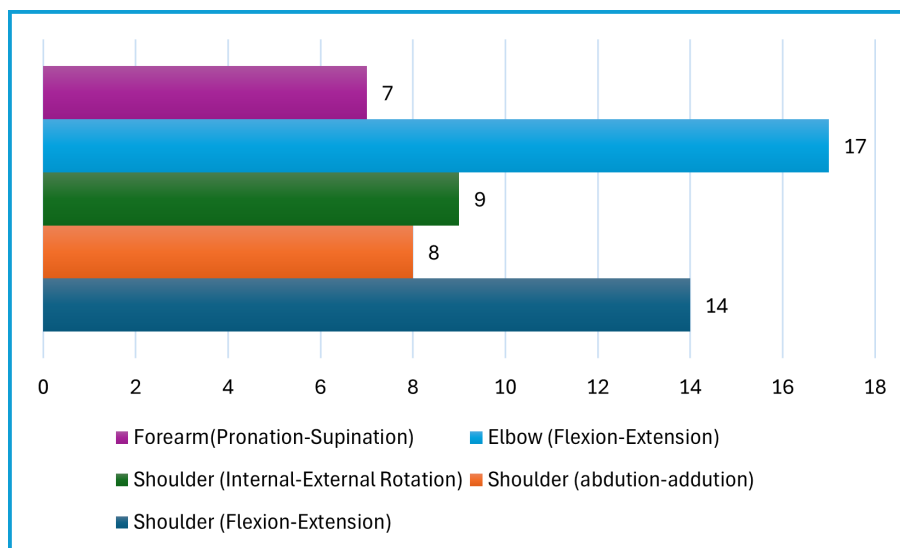


Figure 2.28: Number of exoskeletons targeting each joint movement.

To test the level of assistance provided by the exoskeleton for rehabilitation and assistance, the surface sEMG signal was measured, comparing the amplitude of the signal with and without the exoskeleton, where the amplitude of the signal is roughly equivalent to the operator's

effort [31]. Depending on the sensor system that relates the movement of the arm to the movement of the exoskeleton, the effectiveness of the exoskeleton can also be seen by measuring how much force is exerted on the operator's arm with the actuators switched off and comparing this to when they are switched on.

Table 2.21 shows the main material of each exoskeleton, when available. It is clear that the aluminum exoskeletons are heavier than the 3D-printed ones, as expected, except the cable-driven exoskeleton because it uses four motors which weigh nearly 2.5 kg. There is also a relationship between the torque the exoskeleton produces and the material, with aluminum ones tending to produce more torque. This is due to the great difference between the strength of aluminum compared to plastic, allowing for a greater output of power without the structure being damaged or even breaking.

Another growing issue, which is also the reason why several authors are opting for soft structures, is operator comfort. In a rigid structure, the center of action of the motors must be perfectly aligned with the operator's joint, which is often not possible with the necessary precision, and, as mentioned in Section 2.2.1, the advantage of soft structures is that they adapt to the operator's joint. This adaptation drastically increases operator comfort. As the idea of exoskeletons in the future is to use them for several hours, a high level of comfort is a point to be considered when building an exoskeleton.

2.5 Conclusion

For the purpose of developing an upper-limb exoskeleton for industrial environments such as agriculture, the previous study highlights two key aspects in its development: (i) exoskeleton design and (ii) testing and validation.

For design (i), portability is essential, since agricultural tasks are demanding and often in different locations. In addition, the exoskeleton must lift significant loads so that there is a high reduction in worker effort (for example, 10 kg requires motors that produce 70 Nm torque), and the exoskeleton must be light and have the load well-distributed over the operator's back. For the motors, gearboxes can be directly connected to the joints of the exoskeleton, allowing for a reduction in the torque loss, which is not the case with the cable system. It can also be seen that a more resistant material, such as aluminum, is necessary due to the high stress that the structure will have to undergo, and it is preferable to 3D-printing due to its low resistance. An anti-gravity system, which has been described in several of the documents reviewed above, could be implemented in order to prevent the weight from overloading the operator's arm. As presented in the various documents, the control system could be via sensors for precise interaction between the operator and the exoskeleton, as well as the use of safety measures such as movement limitations and speed/current limits to maintain realistic ranges of movement.

For testing and validation (ii), as with several studies, it can be performed using the sEMG signals and effort comparisons with and without the exoskeleton to obtain a methodical analysis of the benefit of the exoskeleton in the performance of tasks by the operator.

With these points in mind, a clear path for the initial development of the exoskeleton can be established, along with a widely used visual metric to assess its effectiveness in reducing effort across various tasks.

Chapter 3

Theoretical fundamentals

This chapter presents the fundamental theoretical concepts underpinning the dissertation, covering topics such as DC motors, sensors, microcontrollers, materials, and the kinematics and architecture of the exoskeleton.

3.1 BLDC motor and gearbox characteristics

There are several methods of operation, such as hydraulic systems, pneumatic systems, electric systems, in this project it will be explored electric motors, more specifically BLDC motors, to choose the right motor for the project, a study was carried out where it will be introduced the operation of BLDC motors, as well as the operation of gearboxes.

3.1.1 Characteristics of BLDC motors

BLDC motors are electric motors that work without mechanical brushes and commutators and instead use electronic controllers to manage the current in the stator, unlike traditional DC motors, so they don't suffer from friction and wear, thus guaranteeing greater precision, efficiency, and durability.

A BLDC motor, seen in Figure 3.1, consists of a stator (1), which houses the windings, a rotor (2), which contains permanent magnets and rotates in response to the magnetic field, and an electronic controller (3), which switches the current in the stator windings according to a specific sequence.

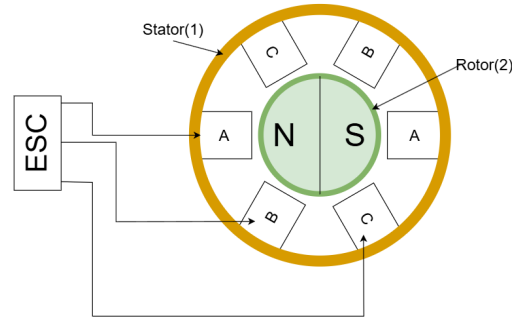


Figure 3.1: BLDC motor diagram.

The BLDC operation is based on electronic switching, in which the controller directs the current to the stator windings, generating a magnetic field that causes the rotor to rotate. Hall-effect sensors detect the position of the rotor and send signals to the controller, which adjusts the energization sequence of the windings to maintain efficient rotation.

In BLDC motors, the sequential activation of the stator windings generates a rotating magnetic field that interacts with the rotor's permanent magnets, causing it to rotate and transforming electrical energy into mechanical movement.

The motor's speed and torque are controlled by adjusting the power supply, regulating the time and duration of the current with the help of an electronic controller. This controller is essential for the motor's performance, as it uses sensors, such as Hall-effect sensors and rotary encoders, to monitor the rotor's position and ensure efficient switching of the current in the stator windings [42].

3.1.2 Planetary gearbox characteristics

Although there are several different types of gearboxes, for this work, planetary gearboxes are considered due to their small size and the distribution of effort among the various gears.

Planetary gearboxes consist of four essential components, as illustrated in Figure 3.2: the ring gear, the planet gears, the planet carrier, and the sun gear.

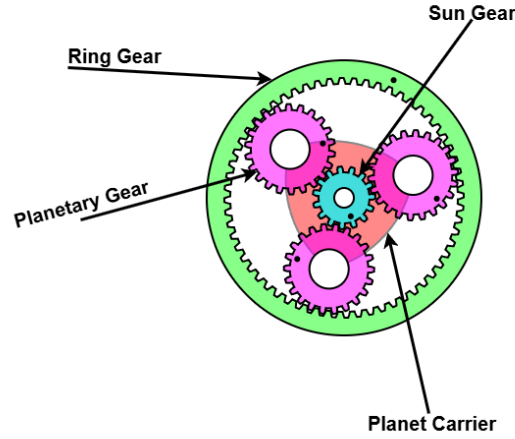


Figure 3.2: Planetary gearbox diagram [43].

When sizing planetary gearboxes, various configurations can be taken into account, but, for use in electric motors it is usually considered that the ring gear is fixed, the input is on the sun gear, and the output is on the planet carrier. In this case, the reduction ratio R is given by the equation 3.1 where Z_r is the number of teeth on the ring gear, and Z_s is the number of teeth on the sun gear.

$$R = 1 + \frac{Z_r}{Z_s} \quad (3.1)$$

In addition to the reduction ratio, it is essential to validate the correct number of teeth for the planetary gear set to ensure proper meshing and mechanical compatibility. The relationship between the number of teeth is shown in equation 3.2, where Z_p is the number of teeth on each planet gear.

$$Z_r = Z_s + 2Z_p \quad (3.2)$$

This condition ensures that the planet gears can mesh simultaneously with both the sun and ring gears without interference.

In order to properly design and adjust the gearboxes, it is also necessary to determine the number of planetary gears that can be used, as well as the positioning of their centers on the planet carrier. To achieve this, the equation 3.3 must yield an integer value for a given number N of planetary gears.

$$\frac{Z_s + Z_r}{N} \quad (3.3)$$

After validating the number of planetary gears N , their positions can be determined by first calculating the angular spacing between them using the equation 3.4.

$$\theta = \frac{360^\circ}{N} \quad (3.4)$$

where θ is the angle between adjacent planetary gears. This equation is valid when equal spacing between the gears is desired.

Next, the distance between the center of each planetary gear and the center of the sun gear must be calculated. As shown in the corresponding Figure 3.3, this distance is given by the equation 3.5.

$$a_1 = \frac{Z_s \cdot m + Z_p \cdot m}{2} \quad (3.5)$$

where m is the module of the gears.

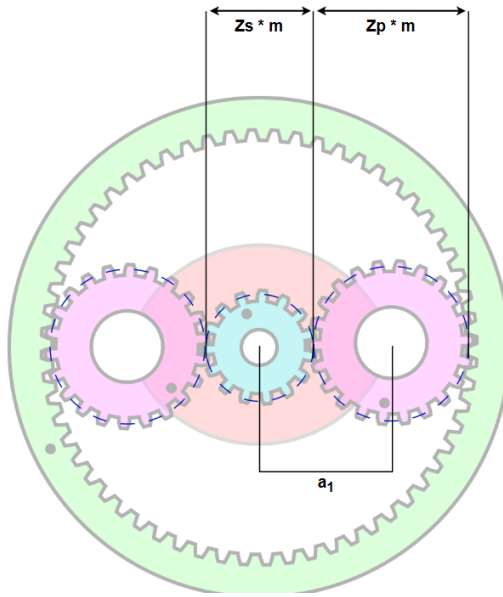


Figure 3.3: Planetary gearbox [43].

Once these steps have been validated, a mechanically feasible planetary gearbox can be designed. Following this, additional parameters such as load capacity, lifespan, materials, dimensions, and other design considerations must be analyzed [44].

3.1.3 BLDC motor selection

Following the theoretical analysis presented in the previous section, a study of potential motors is required. For this project, it was decided to use motors from CUBE MARS¹. The motors should provide sufficient torque to move the exoskeleton while remaining within safe limits to prevent injury. At this stage of the project, the selection of the motors was based on their peak torque, as it was considered the most relevant parameter for meeting the torque requirements of the system. This criterion was used to simplify the initial sizing process and is detailed in this

¹<https://www.cubemars.com/>

chapter. A critical review of this approach and its limitations is presented in Chapter 5. After checking various prices and specifications, two main options were obtained:

The RO100 motor [45], seen in Figure 3.4, is composed of a stator and a rotor with no additional hardware or embedded control system.



Figure 3.4: RO100 Motor.

A gearbox is required to use this motor and reduce the current output needed to produce the same torque. For that reason, price data was obtained from industrialized gearboxes offered by Neugart [46], and a design study was conducted to compare different gearbox configurations. Initially, the torque output requirements were calculated. Based on the sizing calculations presented above, several gearboxes using NYLON gears were dimensioned. A two-stage gearbox design was selected, with each stage providing a 2:1 reduction ratio, resulting in an overall reduction ratio of 4:1 and a nominal output torque of

Figures 3.5 and 3.6 show the two levels of one of the dimensioned gearboxes. Figure 3.5 shows a combination of 5 planetary gears that would be inside the RO100 BLDC motor. Figure 3.6 shows another combination with 3 planetary gears instead of 5, and a larger diameter, which would be under the motor connected to the planetary gearbox inside. Given the motor's peak torque of 12 Nm, the output of the first level would be a maximum of 24 Nm, which is why the second level would have to be larger.

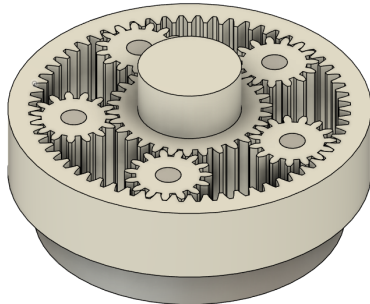


Figure 3.5: Designed planetary gearbox-Level 1.

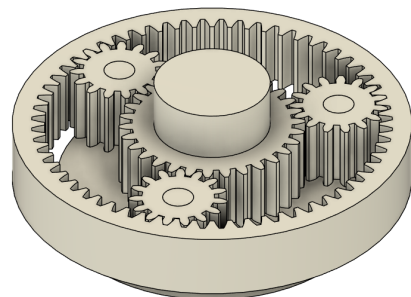


Figure 3.6: Designed planetary gearbox-Level 2.

Static simulation process

In order to identify whether gearboxes can withstand mechanical stress, a static simulation is carried out in Fusion 360. This section presents the process carried out and what the results mean.

First, the model in Figure 3.5 is simplified, resulting in the model in Figure 3.7, thereby reducing the computational effort.

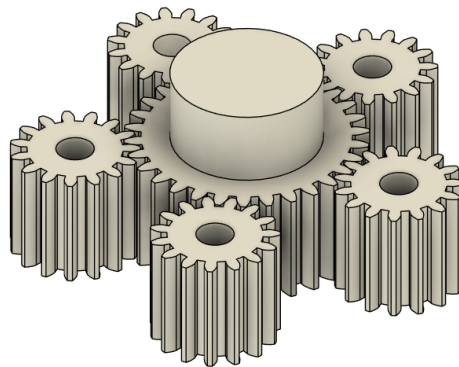


Figure 3.7: Simplified model.

After the simplification, the constraints are applied, in this case, the 5 planetary gears are blocked, Figure 3.8, and it is defined that the sun gear can rotate on itself, as seen in Figure 3.9.

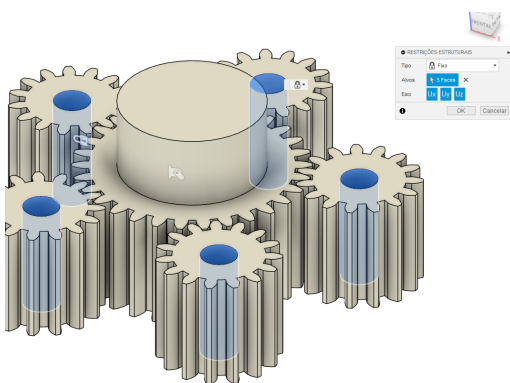


Figure 3.8: Planetary gears restriction.

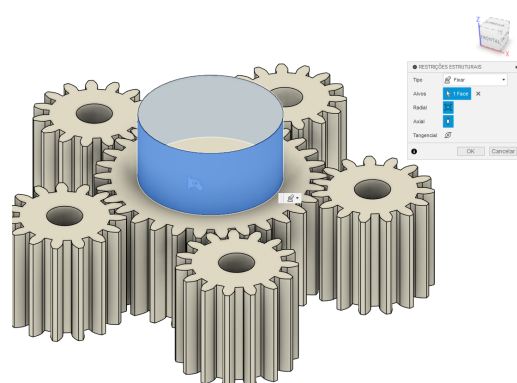


Figure 3.9: Solar Gear restriction.

With this defined, a moment value is applied to the sun gear, Figure 3.11. In order to carry out the study, it is also necessary to add the contacts, Figure 3.10, so that when the central gear tries to rotate, it will hit the external gears, which are currently immovable bodies.

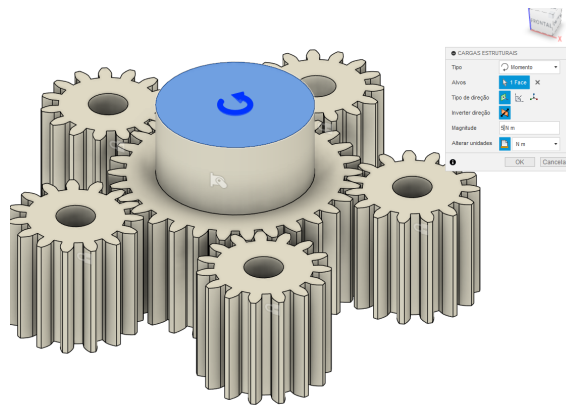


Figure 3.10: Solar gear moment.

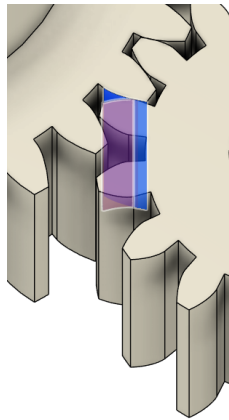


Figure 3.11: Contacts defined.

Subsequently, a mesh is generated, which the program uses to perform the force calculations (Figure 3.12), and the analysis is then conducted.

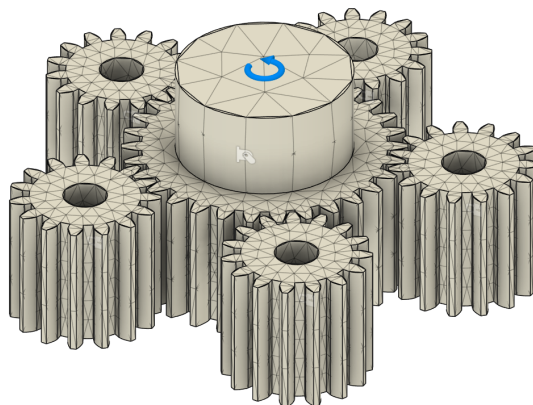


Figure 3.12: Model with generated mesh.

Figures 3.13 and 3.14 show the results of two studies. In Figure 3.13, a moment of 5 N m was applied, whereas in Figure 3.14, a moment of 30 N m was applied.

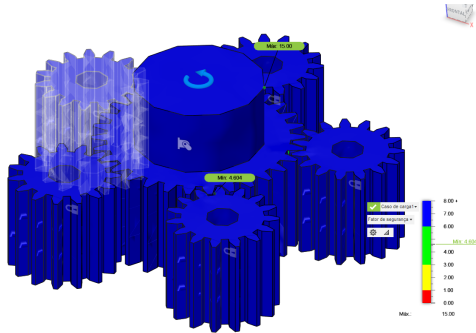


Figure 3.13: Study result With 5 N m moment

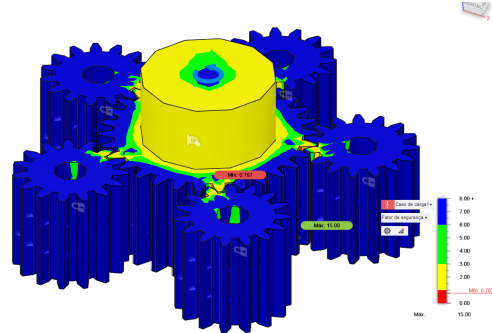


Figure 3.14: Study results With 30 N m moment

To interpret the results, it is essential to consider the meaning of the color scale and the safety factor, as illustrated in Figure 3.15, and to understand the safety factor values provided by Fusion 360. The safety factor is a metric used to evaluate whether a design is suitable for its intended application. It indicates whether a component can withstand damage, deformation, or failure under applied loads. This factor depends on the material used and must also account for criteria such as the manufacturing process and the final application [47]. In the case of colors, they mean whether the part is at risk of deforming or even breaking. In the case of blue, it will resist without problems, and in the case of red, it will probably break.



Figure 3.15: Safety factor scale.

In the case of Figure 3.13, with 5 N m of torque on the sun gear, the system will easily cope, with a minimum safety factor of 4.6. In the case of Figure 3.14, where an input of 30 N m is given, the system will not be able to cope, as the sun gear shaft will suffer deformations, and at the critical point, which is the teeth, it has a minimum safety factor of 0.767, which means that if this force were applied, the system would probably break or deform.

Static simulation results

In Figures 3.16 and 3.17, it can be seen the static test of level 1 and level 2, respectively. In the case of level 1, it would have to withstand 12 Nm of input; the simulation showed that it could withstand it with a safety factor of 1.5. In level 2, the box would have to withstand 24 Nm, which the simulation showed it could withstand with a safety factor of 2. This means that the box is mechanically validated, with the full system represented in Figures 3.18.

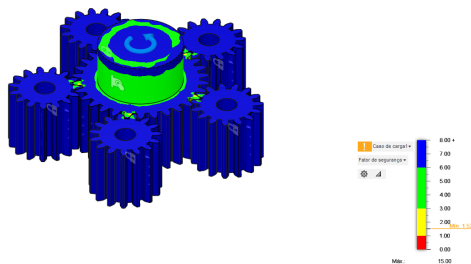


Figure 3.16: Static load planetary gearbox-level 1.

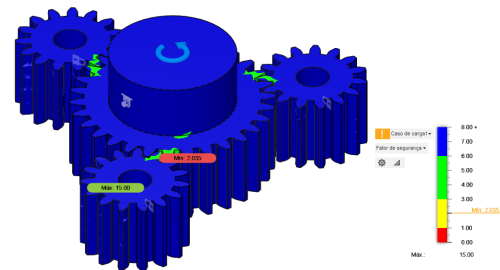


Figure 3.17: Static load planetary gearbox-level 2.

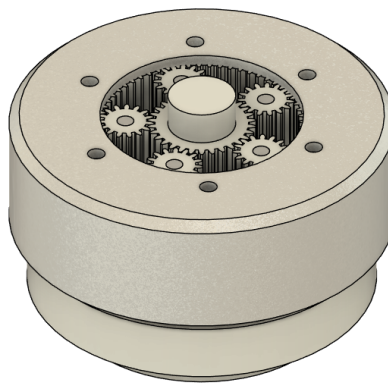


Figure 3.18: Full mounted system.

The second option was to use the Ak60-6 motor [48], shown in Figure 3.19, which is a BLDC motor with an integrated gearbox and driver, capable of producing 3 Nm nominal torque at 4 A, and 9 Nm peak torque at 13.5 A.



Figure 3.19: AK60-6.

After checking the two options, it was concluded that, with the RO100, it was possible to obtain more torque, either with the gearbox manufactured in the lab or with a purchased one with a price tag of around 400€ to 450€. However, the price would be much higher than the AK60-6, which only costs around 300€, and in addition to the price, there would still be the risk of failure in its construction. It was therefore decided to use the AK60-6 directly on the elbow, and an AK60-6 with a 3:1 reduction via a timing belt for the shoulder.

3.2 Load cell and rotary encoder characteristics

After studying the state-of-the-art, it was concluded that F/T sensors are commonly used, so a sensor from this category was chosen for this project. Due to their ease of acquisition and use, load cells were selected. Additionally, because of limitations with the chosen motor hardware, an external encoder was required. This section covers the theoretical background of the two sensors used in the project.

The load cell, Figure 3.20, are a device that transforms force into electrical signals. Its operation is based on four bridge sensors that form a Wheatstone bridge, Figure 3.21. These sensors are arranged by the load cell as in Figure 3.22, and have the particularity that when they are compressed or tensioned, their resistance varies; thus, through the excitation voltage and the output voltage, it is possible to obtain the force. To read these signals, an HX711 amplifier and an analog to digital converter is normally used. This board measures the variation in the output voltage and sends this signal via a data-clock channel [49].



Photo by ElectroPeak

Figure 3.20: Load cell [49].

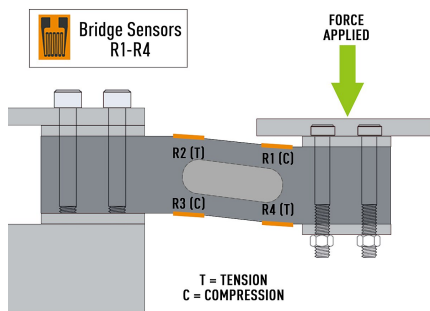


Figure 3.21: Wheatstone bridge [49].

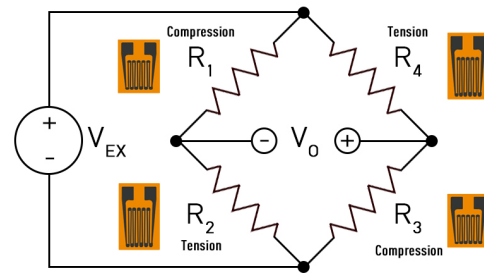


Figure 3.22: Load cell arrangement [49].

Even tho the chosen motor already has an internal encoder, its absolute position varies depending on the way it was connected, making it unsuitable due to safety measures. For this purpose, an absolute encoder using the AS5600² magnetic angle encoder was used. Its principle of operation is as shown in Figure 3.23, i.e. it has a hall sensor incorporated into the board, and a magnet that is incorporated into the motor shaft, so when the shaft rotates, the magnetic field rotates and the absolute position is obtained. This encoder features Controller Area Network (CAN) communication, making it easier to connect the exoskeleton system [50].

²https://pt.mouser.com/new/ams-osram/ams-as5600-sensor/?utm_id=22426705413&utm_source=google&utm_medium=cpc&utm_marketing_tactic=emeacorp&gad_source=1&gad_campaignid=22436688139&gbraid=0AAAAADn_wf1BaeOmial878xhUNP0hkee0&gclid=Cj0KCQjw-ZHEBhCxARIsAGGN96K5DzBnByONqAOaoX0WOPbrAB5BaYimMPfTvPqVOZhU8xbRFNH09LEaArypEALw_wcB

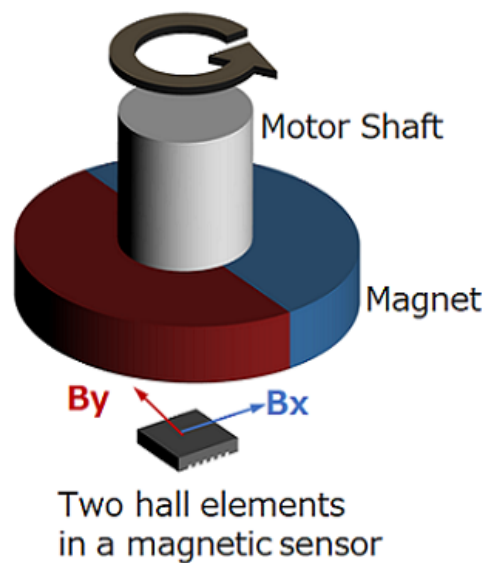


Figure 3.23: Encoder working principle [50].

3.3 Micro-controller

The core processing unit for this project is the microcontroller. The entire system architecture was developed around the RP2040³ microcontroller from the Raspberry Pi Foundation.

A microcontroller is a small computer integrated into a single chip. It has a processor (core), Random Access Memory (RAM) and Electrically Erasable Programmable Read-Only Memory (EEPROM) memory, which allows it to store the program to be executed even in the absence of a power supply [51]. In addition, microcontrollers offer digital input and output interfaces, and an Analog to Digital Converter (ADC), allowing real-world signals to be read. Because they are compact and efficient systems, they are widely used for specific tasks, such as controlling motors, reading sensors, or automating simple processes.

The RP2040, shown in Figure 3.24, is a low-cost microcontroller commonly used in prototyping and development projects. This microcontroller supports multiple communication protocols, including Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C), Universal Asynchronous Receiver-Transmitter (UART), and CAN bus, which is widely used in embedded and automotive systems. This compatibility facilitates the integration of various peripherals, simplifying system development and reducing prototype complexity [52].

³<https://www.raspberrypi.com/products/rp2040/>



Figure 3.24: RP2040 [52].

An example of this integration is the custom Printed Circuit Board (PCB) developed for this project, shown in Figures 3.25 and 3.26. The PCB combines an HX711 converter, the RP2040 microcontroller, and a CAN bus interface. This setup enables load cell data to be processed and transmitted via the CAN bus, improving system robustness against electromagnetic interference and making it suitable for industrial applications.

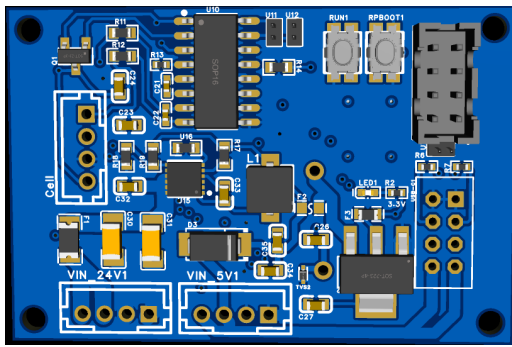


Figure 3.25: Smart HX711 - front.

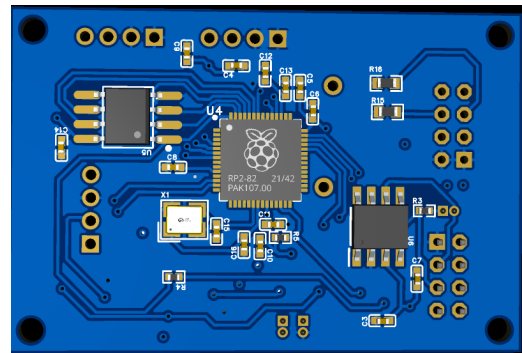


Figure 3.26: Smart HX711 - back.

The schematic of the PCB shown can be seen in the appendix A.

3.4 Exoskeleton architecture

This section will be presented the architecture of the exoskeleton, specifically the exoskeleton's control and communication architecture, and the exoskeleton's power supply architecture.

3.4.1 Control and communication diagram

To control the exoskeleton, it has three main microcontrollers: the control microcontroller, which manages all the information and sends command messages to the motor drives, and the other two microcontrollers, which read the data sent by the HX711 and send it to the control microcontroller. All the messages are sent by CAN bus.

Figure 3.27 shows the HX711 microcontroller system, where the load cells are read by the HX711, and then the HX711 sends the information to the microcontroller via the data-clock pins.

This system is necessary because the HX711's communication method, unlike CAN bus communication, is very sensitive to electromagnetic noise, creating reading errors.

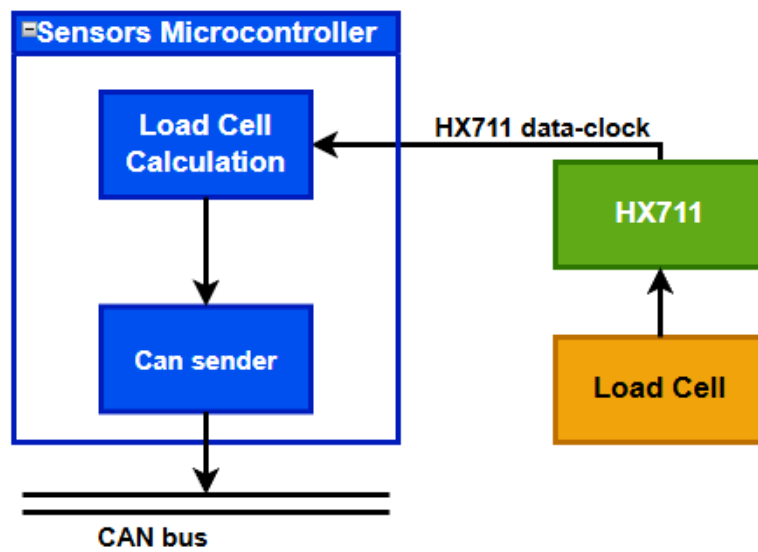


Figure 3.27: HX711 board diagram.

Figure 3.28 shows the diagram of the control microcontroller, which receives the information from the motors by CAN bus, the values of the load cells from the HX711 microcontroller, and the joint position values sent by the encoders. It takes all this information and calculates the reference speed in a PI for each motor, adjusts these reference values in the Control Validation block, and sends this information to the motor drives.

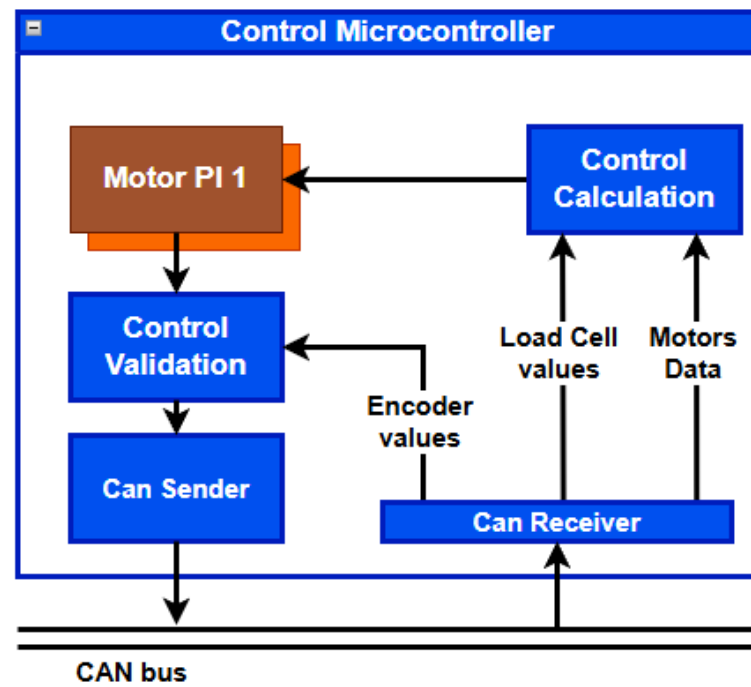


Figure 3.28: Control board diagram.

Figure 3.29 shows the inside of the validation block, which prevents movement beyond the limits imposed and limits the reference speed from -3000 to 3000 ERPM.

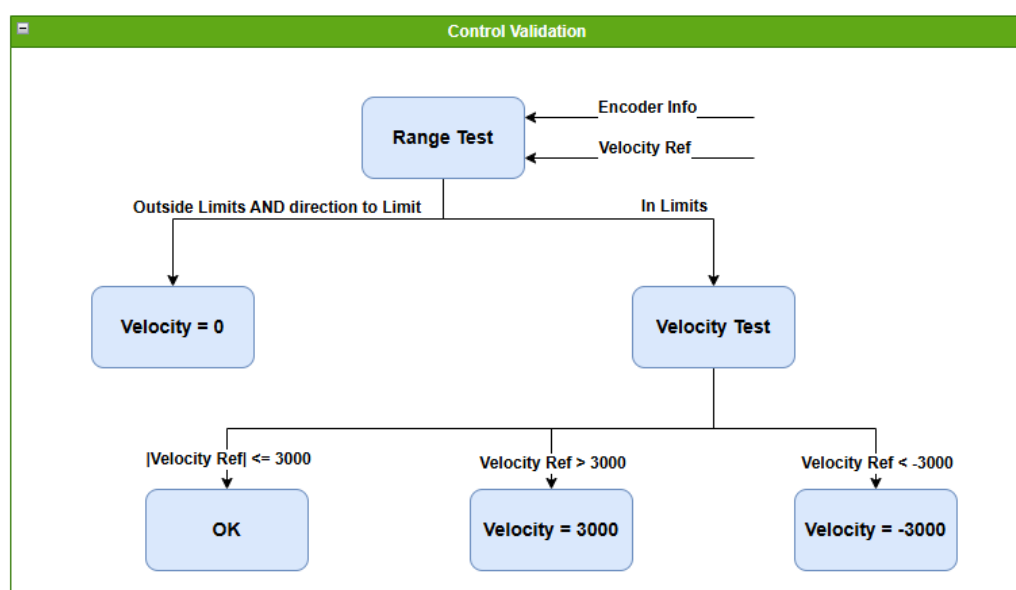


Figure 3.29: Control validation diagram.

3.4.2 Power Diagram

Figure 3.30 shows the system's power supply diagram, where a 24 V battery powers the control board, the safety buttons, and the motors. The control board then supplies 5 V to the HX711 microcontrollers and the encoders. The emergency button, when charged, only switches off the motors.

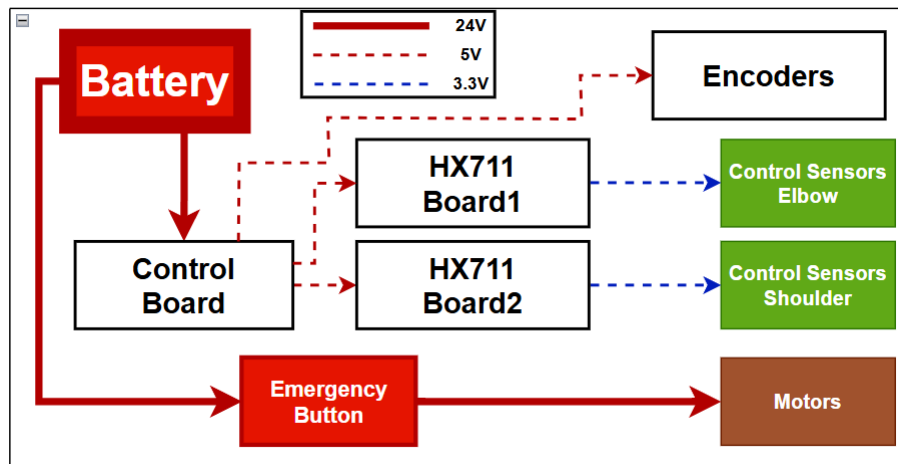


Figure 3.30: Power diagram.

3.5 Kinematics

Considering the movements of the upper-limb presented in subsection 2.2.2, a representation of the kinematics is shown in Figure 3.31.

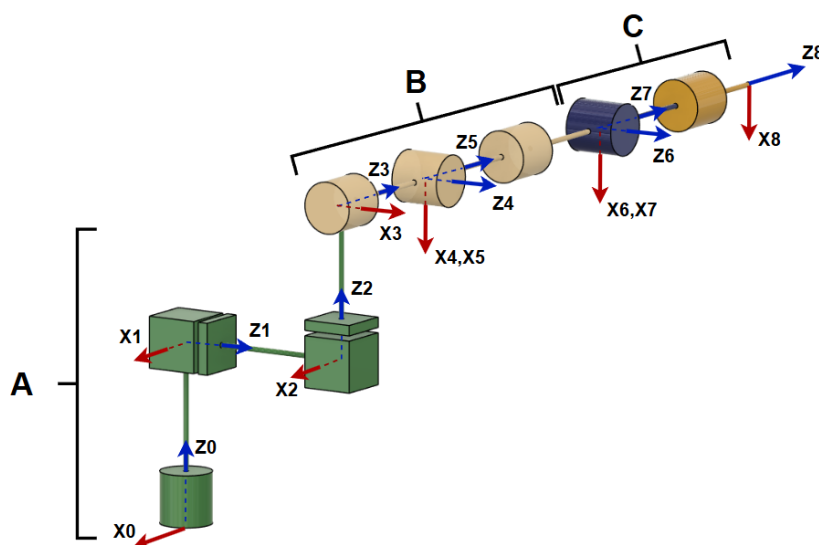


Figure 3.31: Upper-limb kinematic representation.

Three main sections can be identified in Figure 3.31. Section A shows the change in the instantaneous center of rotation of the shoulder. Section B represents the shoulder with its three degrees of freedom (3-DoF). Finally, section C illustrates elbow flexion and extension, as well as pronation and supination.

Simplified representation and exoskeleton representation

In the first phase of the exoskeleton's development, for the sake of simplicity, only the movements of shoulder extension and flexion, medial shoulder rotation, elbow flexion and extension, and elbow supination and pronation were considered, totaling four DoF. This representation can be seen in Figure 3.32. Also, the range of the angles is the same as the ROM of these movements. These values are shown in Table 3.1.

Table 3.1: Range of Motion (ROM) limits for the manipulator joints.

Theta	Movement	Min (°)	Max (°)
θ_1	Shoulder flexion/extension	-60	180
θ_2	Shoulder internal/external rotation	-90	90
θ_3	Elbow flexion/extension	0	140
θ_4	Forearm pronation/supination	-80	80

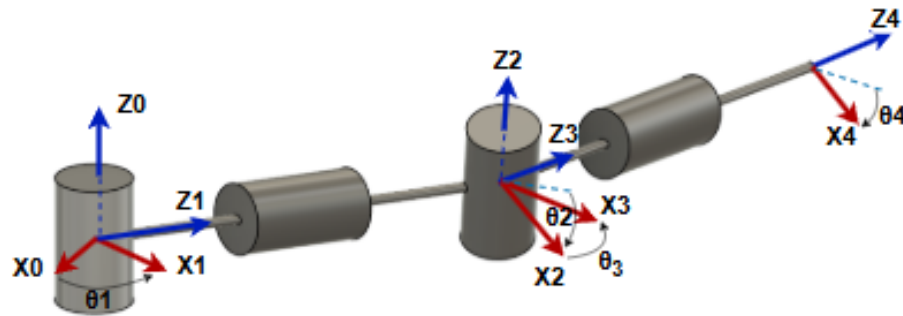


Figure 3.32: Simplified upper-limb representation with positive angles.

Using the Denavit-Hartenberg (DH) method [53], the z_i and x_i axes were defined, which made it possible to systematically apply this method to calculate both the direct and inverse kinematics.

Starting with the direct kinematics and following the rules established in Table 3.2 for assigning the DH parameters, it was possible to determine the values shown in Table 3.3, which describe the transformations between the manipulator links.

Table 3.2: DH parameter definitions.

Parameter	Description
a_i	Link length — distance from o_i to z_{i-1}
α_i	Link twist — angle from z_{i-1} to z_i around x_i
d_i	Link offset — distance from x_i to o_{i-1}
θ_i	Joint angle — angle from x_{i-1} to x_i around z_{i-1}

Table 3.3: Direct kinematics.

i	a_i	α_i	d_i	θ_i
1	0	-90	0	θ_1
2	0	90	d_2	θ_2
3	0	-90	0	θ_3
4	0	0	d_4	θ_4

To obtain the position and orientation of the end-effector, it is necessary to calculate the final homogeneous transformation matrix, $\mathbf{T}_n^0$, where n represents the number of joints.

This matrix results from the successive product of the individual matrices obtained using the Denavit-Hartenberg method:

$$\mathbf{T}_4^0 = \mathbf{A}_1 \cdot \mathbf{A}_2 \cdot \mathbf{A}_3 \cdot \mathbf{A}_4$$

Each $\mathbf{A}_i$ matrix is constructed on the basis of the $a_i, \alpha_i, d_i, \theta_i$ parameters defined in the DH table.

To calculate the inverse kinematics, since it can be seen that the last three actuators form a spherical wrist, the manipulator was decoupled in order to simplify the problem. Thus, a point $\mathbf{W}$ is considered, which is coincident with the origin of the referential frame 2 and 3, and the end point of the end effector, $\mathbf{p}$ is coincident with the origin of the z_4 and x_4 axes.

Given an end point $\mathbf{p}$ and an orientation $\mathbf{R}$, the final homogeneous transformation matrix $\mathbf{T}_4^0$ can be expressed as:

$$\mathbf{T}_4^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

In this matrix, the elements r_{ij} correspond to the orientation of the end-effector in relation to the base reference (i.e., the components of the rotation matrix $\mathbf{R}$)

$$\mathbf{R}_4^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

And p_x, p_y, p_z represent the position of the end point $\mathbf{p}$ in three-dimensional space.

All the values of the matrix $\mathbf{T}_4^0$ are considered to be known (position $\mathbf{p}$ and orientation $\mathbf{R}$), from which the inverse kinematics is calculated.

It is also possible to understand that the point $\mathbf{W}$, which represents the center of the spherical wrist, is obtained from the following vector equation:

$$\mathbf{W} = \mathbf{p} - \mathbf{R} \cdot \begin{bmatrix} 0 \\ 0 \\ d_4 \end{bmatrix}$$

where d_4 corresponds to the displacement along the z axis of the last joint. This displacement is applied in the direction of the z axis of the final orientation.

With Figure 3.33 and knowing the point $\mathbf{W}$ and considering the trigonometric relationship, it can be seen that θ_1 is calculated by equation 3.6.

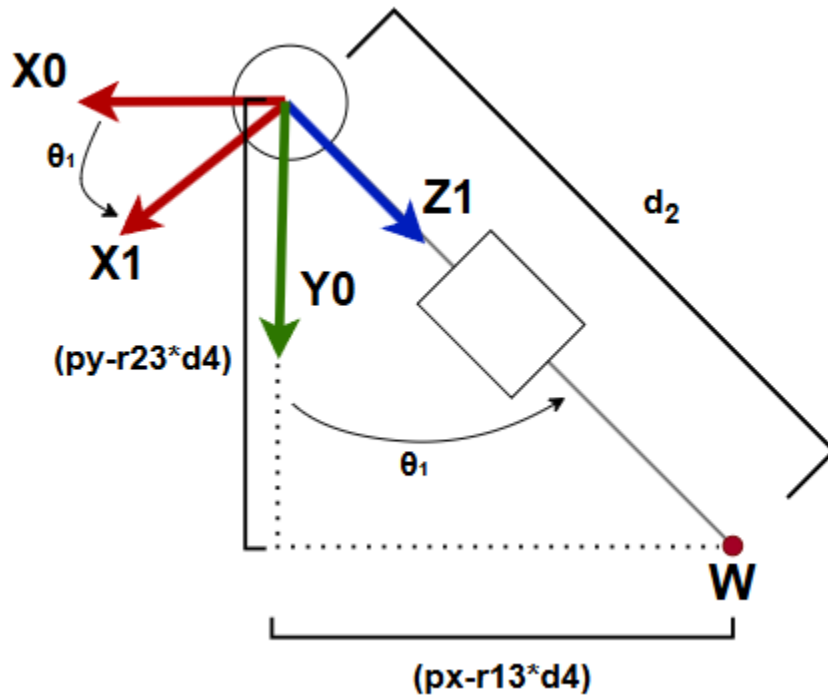


Figure 3.33: Top view.

$$\theta_1 = \text{atan2}((p_y - d_4 r_{23}), -(p_x - d_4 r_{13})) \quad (3.6)$$

To calculate θ_3 , the top view of the third DoF was used, Figure 3.34. Since point $\mathbf{P}$ and point $\mathbf{W}$ are known, obtaining the angle of θ_3 is equal to calculating the angle between vectors $\overrightarrow{O_0W}$ and $\overrightarrow{WP}$, which can be obtained by Equation 3.7.

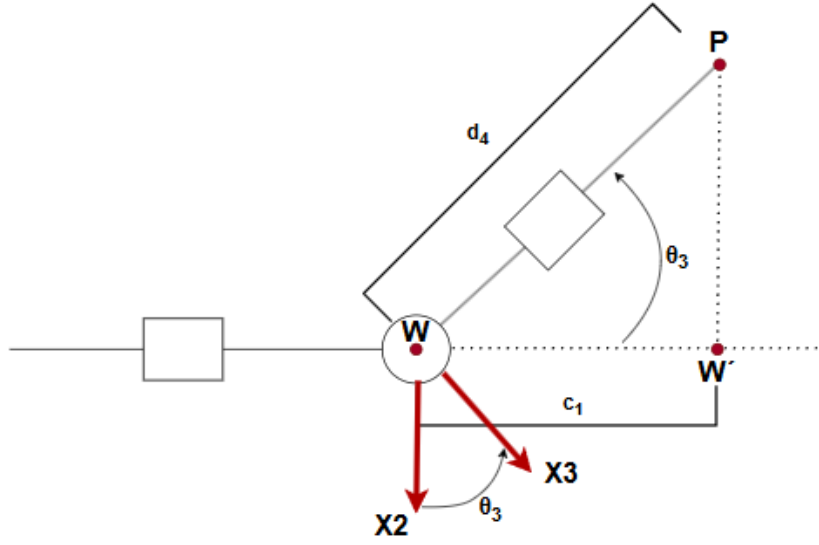


Figure 3.34: Top view third DoF.

$$\theta_3 = \arccos \left(\frac{\mathbf{u}_{WP} \cdot \mathbf{u}_W}{\|\mathbf{u}_{WP}\| \|\mathbf{u}_W\|} \right) \quad (3.7)$$

It is also possible to see from Figure 3.34 that the distance c_1 can be calculated using Equation 3.8.

$$c_1 = d_4 \cdot \cos(\theta_3) \quad (3.8)$$

Once the distance c_1 is known, it is possible to obtain the point $\mathbf{W}'$ through the vector calculation of Equation 3.9, where $\mathbf{u}_w$ is the unit vector of vector $\overrightarrow{O_0 \mathbf{W}}$.

$$\mathbf{W} = \mathbf{W} + u_w * c_1 \quad (3.9)$$

After obtaining $\mathbf{W}'$, and based on Figure 3.35, θ_2 is calculated. Equation 3.10 is used for this purpose.

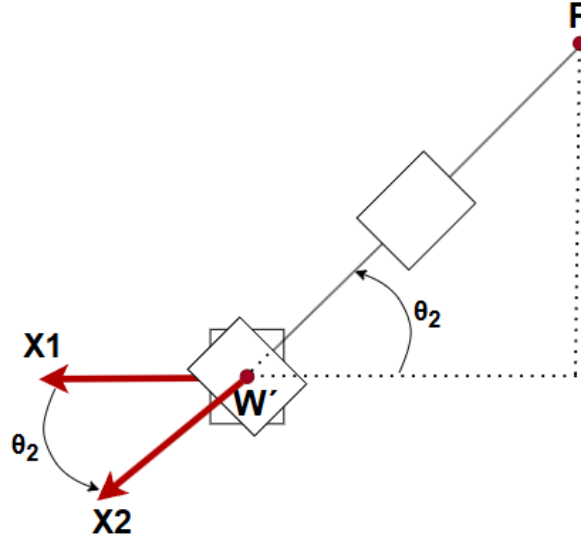


Figure 3.35: Front view third DoF.

$$\theta_2 = \arccos \left(\frac{p_z}{\|\vec{W'P}\|} \right) \quad (3.10)$$

Finally, having θ_1 , θ_2 , and θ_3 , and the direct kinematics table, it can be calculated $\mathbf{T}_1$, $\mathbf{T}_2$, and $\mathbf{T}_3$. When multiplied, the transformation matrix $\mathbf{T}_3^0$ is obtained. The matrix $\mathbf{T}_4^0$ is known, as it is the final position and final orientation.

So the matrix $\mathbf{T}_4^3$ is calculated with equation 3.11.

$$\mathbf{R}_4^3 = (\mathbf{R}_3^0)^T \cdot \mathbf{R}_4^0 \quad (3.11)$$

Since θ_4 is a rotation about the Z axis, it is known to be of the following type:

$$\mathbf{R}_4^3 = \begin{bmatrix} \cos \theta_z & -\sin \theta_z & 0 \\ \sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

So, obtaining the rotation matrix $\mathbf{R}_4^3$, it is possible to calculate θ_4 using Equation 3.12.

$$\theta_4 = \text{atan2}(r12(\mathbf{R}_4^3), r11(\mathbf{R}_4^3)) \quad (3.12)$$

To validate the obtained kinematics, a Python script was developed in which arbitrary angles were applied for the forward kinematics, yielding the resulting end-effector position and orientation.

To validate the direct kinematics, an identical model was designed in Fusion with the same dimensions and angles, as seen in Figure 3.36 and 3.37, and the $\mathbf{T}_4^0$, with all θ equals to 30° ,

was obtained with the script, Figure 3.38, where it can be observed that the same end points were obtained, thus validating the direct kinematics.

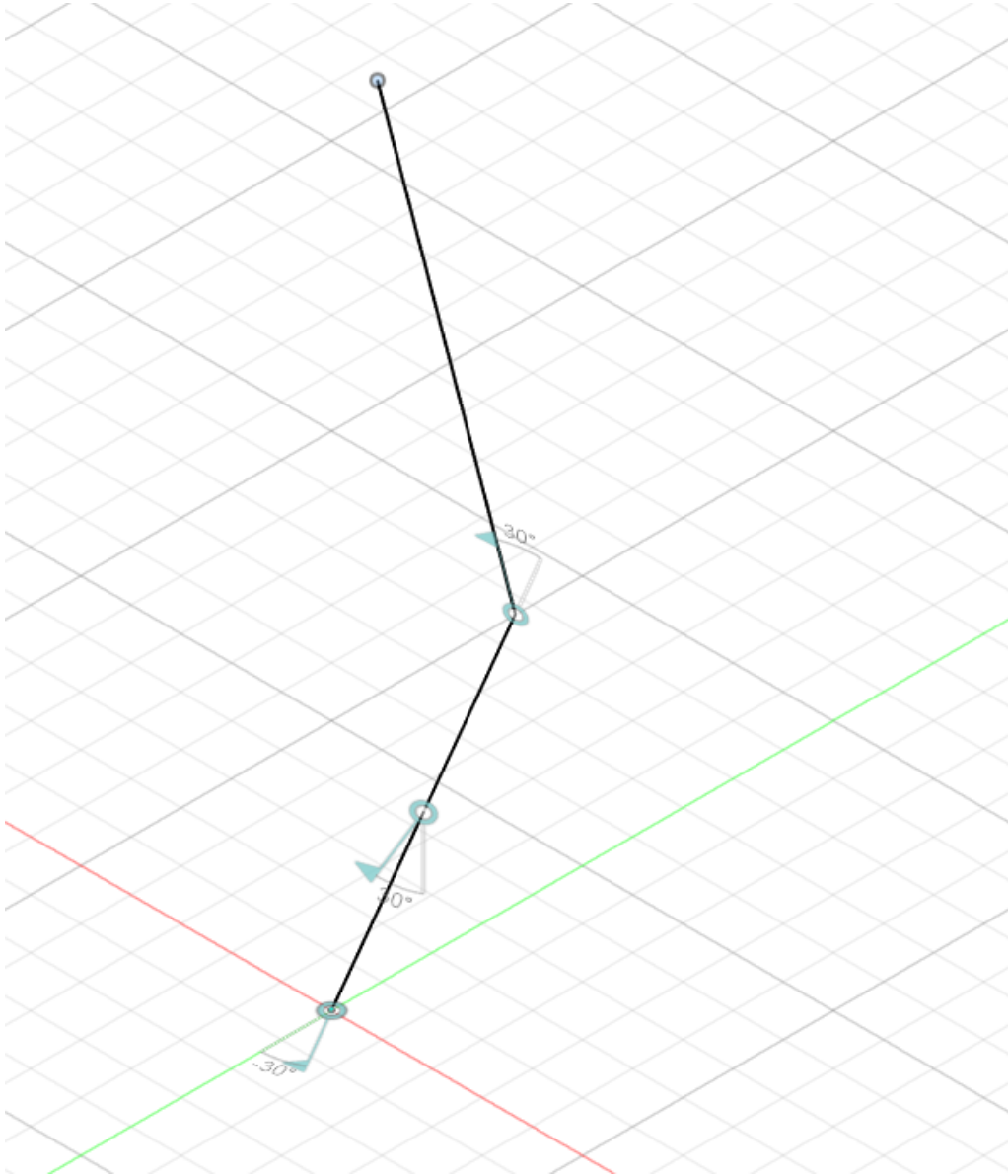


Figure 3.36: Fusion representation.

Vértice | X: -1307.996 Y: 1399.24 Z: 251.15 mm

Figure 3.37: Fusion representation final point.

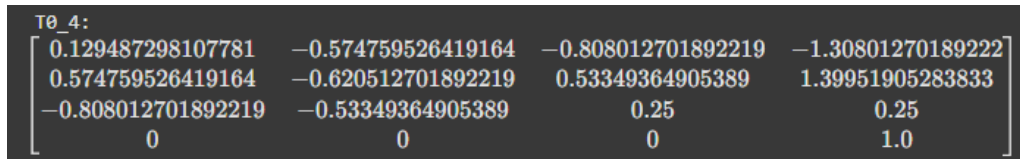


Figure 3.38: Points obtained with the script.

For the inverse kinematics, and within the ROM of the upper-limb, the final values given by the direct kinematics were used and passed to the inverse kinematics, obtaining the same defined angles. For example, using the same final positions as obtained in Figure 3.38, it is obtained the angles seen in Figure 3.39.

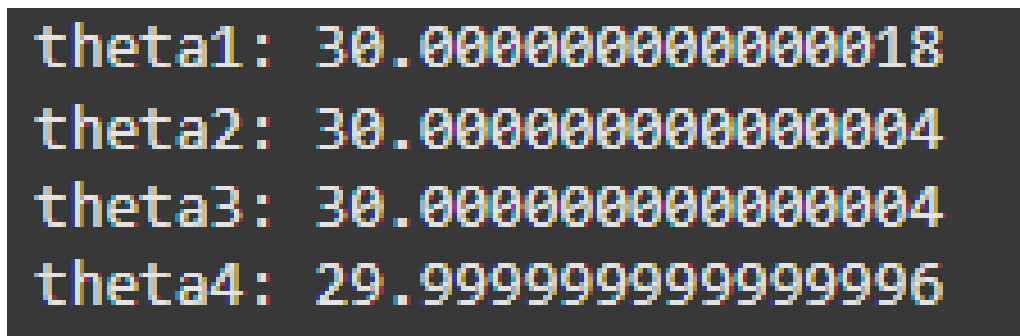


Figure 3.39: Calculated angles.

The inverse kinematics obtained is valid within the defined ROM values, except angle $\theta_3 = 0$, as it implies the arm is stretched, giving θ_2 infinite values, since regardless of the value of θ_2 , the final position does not vary.

For the exoskeleton, a model capable of geometrically replicating the movement of the human shoulder is required. To this end, the model illustrated in Figure 3.40 was adopted.

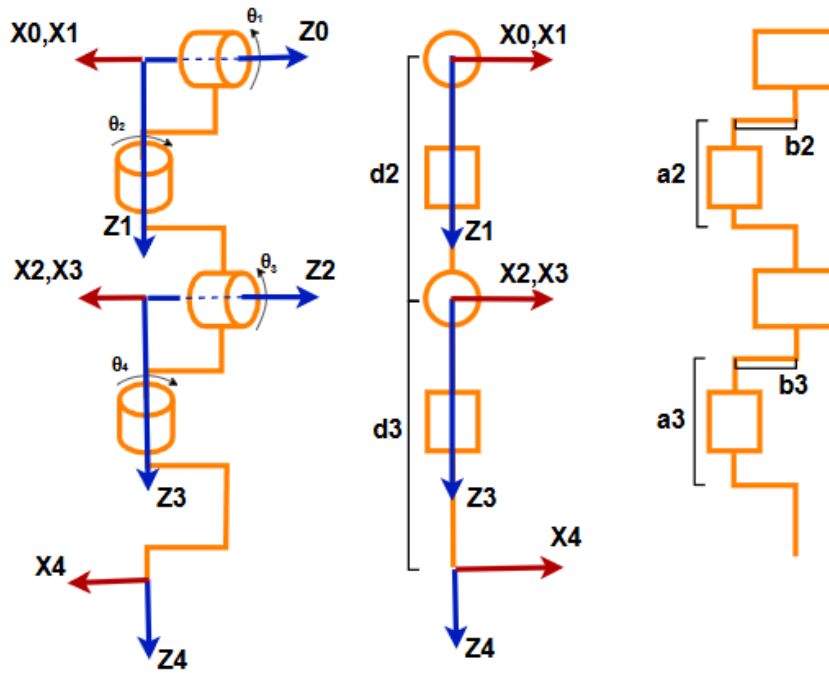


Figure 3.40: Exoskeleton kinematic diagram.

Considering that at the end of the human upper-limb there is a tool that expands its length to match that of the exoskeleton, it can be said that the two systems are geometrically similar. In other words, they have the same direct and inverse kinematics, which can be seen both from the position and orientation of the vectors and their origins, which coincide with those of the human arm, and from Figure 3.41, where the two models appear superimposed.

In practice, this means that, given certain values for θ_1 , θ_2 , θ_3 and θ_4 , both models will have the same orientation and final position at the end effector.

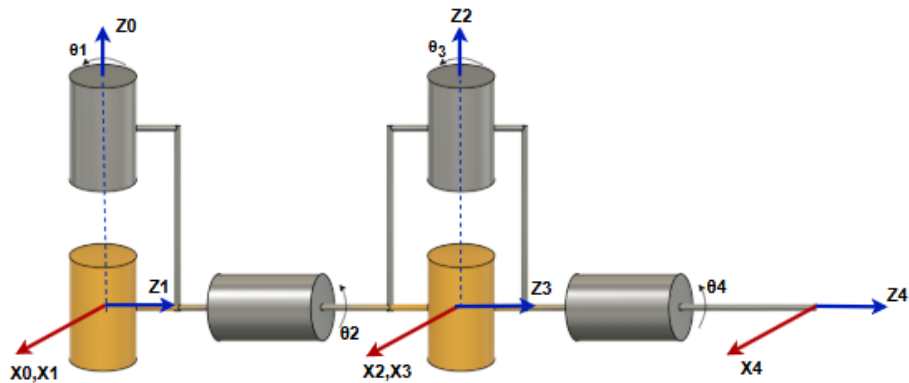


Figure 3.41: Overlapping kinematics diagrams.

This result is not only expected, but also mandatory, since the same number of DoF is used in both models. Otherwise, the exoskeleton would not be able to follow the movements of the human arm correctly.

Chapter 4

Prototype construction and implementation

This chapter will cover three main topics: the construction and validation of the control system in a simplified prototype, the application of the results learned on the construction of the exoskeleton for the upper-limb, and a study on different design configurations for various payloads, to improve understanding and support the development of exoskeletons in future work.

4.1 Validation prototype

Before developing the exoskeleton, a system was developed and built to validate the concept and create a base code that could be adapted to the final prototype.

Firstly, the operating principle of the system was defined. Figures 4.1 and 4.2 show the 3D model of the conceptual prototype and the final validation prototype after construction, respectively. The system consists of a motor and two load cells. To generate the control signal based on the load cell measurements, a control vector approach was implemented. In Figure 4.3, it is possible to see how the system reacts when a force is read. Using a vector makes the system more robust: if both load cells are accidentally triggered simultaneously, the resulting movement will still be directed towards the cell registering the higher force.

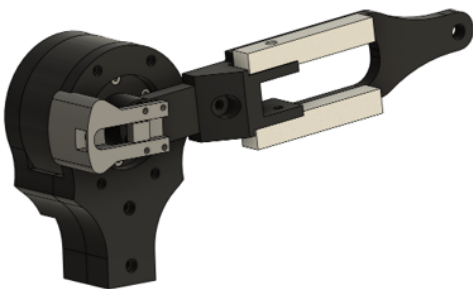


Figure 4.1: 3D model prototype.

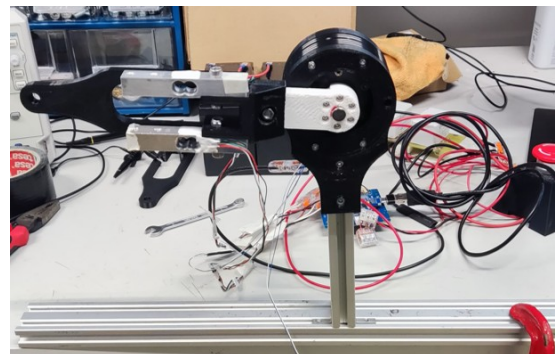


Figure 4.2: Constructed prototype.

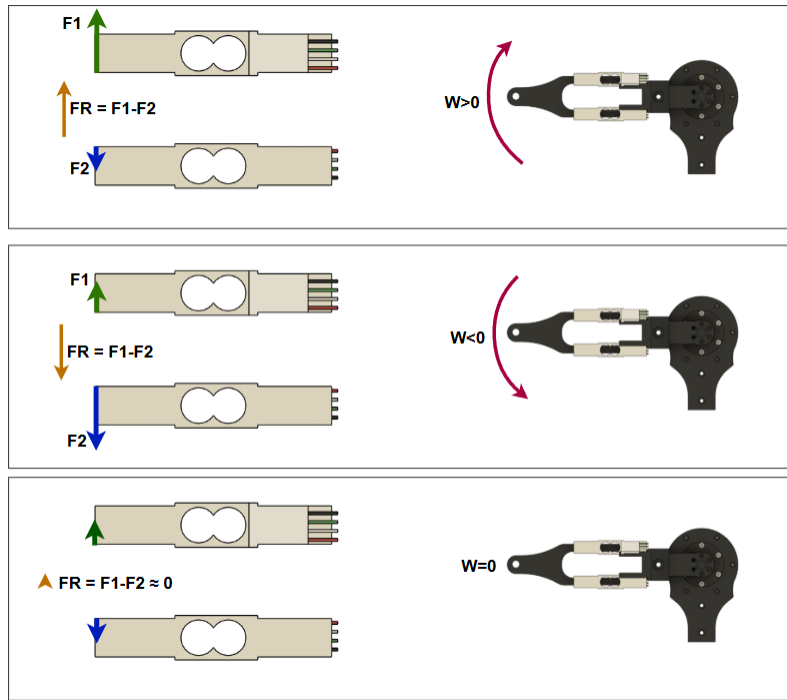


Figure 4.3: Control output based on load cell force difference.

Initially, a PI controller, shown in Figure 4.4, was implemented with the goal of the load cell's force vector to be 0. This control returned the current, which was then limited and sent to the motor controller. However, this method had to be modified for two reasons: The first reason is that, in this prototype, since the weight of the arm where the load cells would be mounted was very low, the motor would operate under near no-load conditions, making it unstable, as the control system could not react quickly enough based on the load cell feedback. The second problem was related to the motor's firmware. When the motor was idling, it often required a small initial current to start moving. However, the motor driver did not accept current commands lower than 0.5 A or higher than -0.5 A. As a result, when the control system reacted, it would already apply an excessive current, preventing the system from stabilizing.

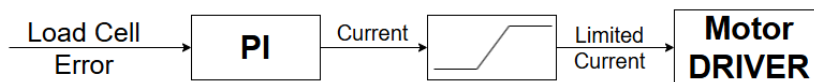


Figure 4.4: Current PI control diagram.

To solve this, the PI controller, shown in Figure 4.5, which instead of generating a current output, generates a speed output. As the loop speed was internal to the motor firmware, the motor was able to react very quickly and maintain very stable speed control. That way, the greater the force exerted on the load cell, the higher the output speed. To avoid accidents, the PI controller's output also has a speed limit.

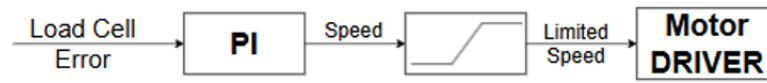


Figure 4.5: Velocity PI control diagram.

The control system in Figure 4.5 created another problem: the driver's current control, when stalled, corrected with as much current as possible. This was problematic because given that the ideology of the system is to work with the motor in stall, and to give assistance to a certain point, i.e. if the motor, operating at its nominal current of 4.5 A, can support 2 kg at the tip, adding 10 kg would ideally produce the behavior shown in Figure 4.6. However, in practice, the response is more similar to that shown in Figure 4.7, where the current quickly reaches the motor's peak limit and remains there, which can only be sustained for a very short time before risking motor damage. Given this, without a current limit, the system would work far above the nominal and would heat up quickly. For this reason, two solutions could be used: either make a control system like the one in Figure 4.8, where the command to control the cells gives rise to a limited speed, and this limited speed would be the reference for a PI that gives rise to a current value. But as explained earlier, this method could not be used because of the driver's limitations. For this reason, it was used the second solution was used, which is using the driver's tools to limit the maximum current to 5 A, thus obtaining a system like the one in Figure 4.6.

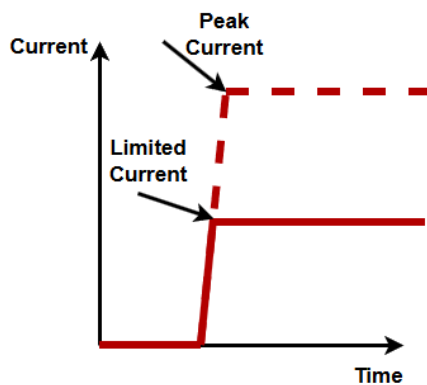


Figure 4.6: Expected current graphic.

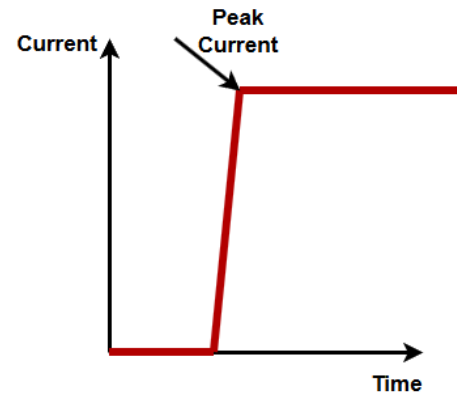


Figure 4.7: Real current graphic.

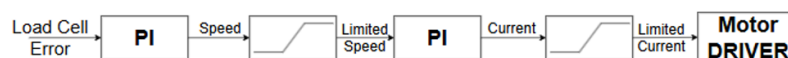


Figure 4.8: Velocity PI plus current PI control diagram.

Before moving on to the development and construction of the exoskeleton, another problem was detected: with the rotor blocked, even at the rated current, it heats up quickly. One of the reasons for this is that the motor chosen is closed, with only a small air inlet, and there is a low air flow to the copper. Another issue that worsens the problem is that the driver also heats up with the current flowing through it, and it's inside the motor housing. In an attempt to mitigate the problem, the design shown in Figure 4.9 and 4.10 was made to install a fan at the back of the motor.

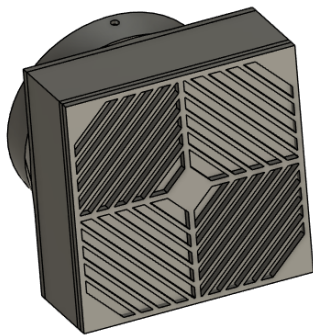


Figure 4.9: Cooling system front view.

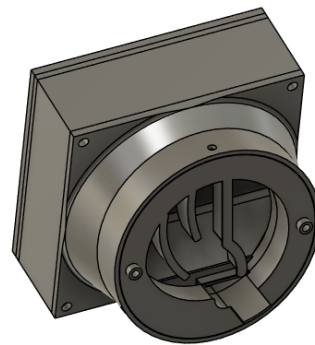


Figure 4.10: Cooling system rear view.

The design intent was to redirect part of the airflow to the back of the motor and then inside the motor, and part of the airflow directly into the motor, as can be seen in Figure 4.11.

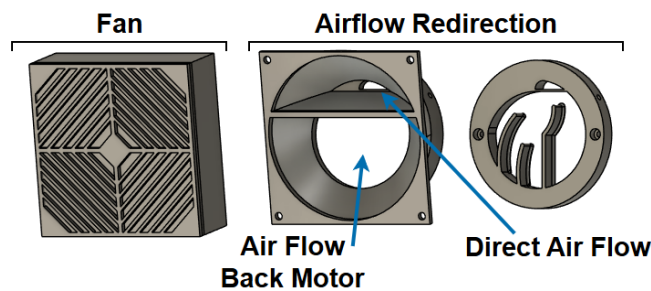


Figure 4.11: Cooling system parts.

After designing the cooling system, three tests were carried out to see if there was a significant improvement in the system. For this, the motor was placed in stall, i.e. zero speed, and a constant load was applied so that the motor used about 4 A continuously, slightly less than the 4.5 A nominal current. With the current stabilized, the temperature value sent by the driver was read, and once it reached 45 °C, the time taken for the system to reach 50 °C was measured. These tests were carried out with three configurations: Without a fan, with a fan and flow against the motor, and with a fan and flow pulling from the motor. These results can be seen in Table 4.1.

It's quite clear from the results that the air flow from the motors is much better, increasing the time needed to reach the target temperature by almost three times. With the flow directly against

Table 4.1: Time for the motor to reach 50°C starting from 45°C.

Condition	Time (s)	Relative Time
Without fan	140.5	-
With fan blowing against the motor	265	1.89x
With fan pulling air from the motor	408	2.91x

the motor also increased the useful time of the system; however, it is lower, this is because, against the motor and the plastic system, much of the flux of air is reversed. In the case of the pull, almost all the flow was useful flow.

4.2 Upper-limb exoskeleton

After developing the concept with the validation prototype, the development of the exoskeleton began. This section presents the initial model and then the individual development of each DoF of the exoskeleton.

4.2.1 First Concept

As described in Section 3.5, Figure 3.40, which represents the kinematic model of the exoskeleton, was used as a basis. Based on this model, a first sketch was made, which can be seen in Figure 4.12.

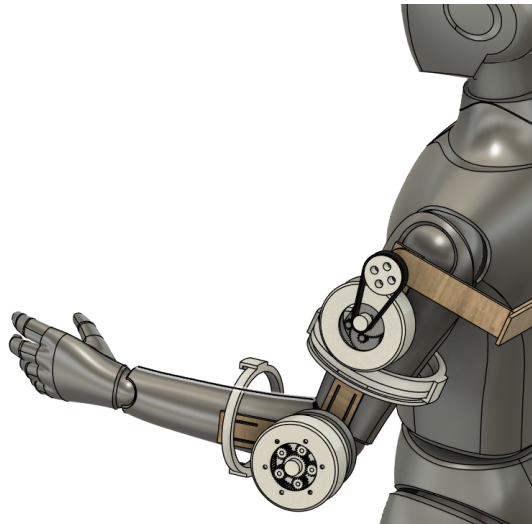


Figure 4.12: Exoskeleton first model.

It was also defined that of the 4-DoFs that exist in the kinematic model, for the sake of simplification, only two would be actuated, more specifically, the extension and flexion of the elbow, and the extension and flexion of the shoulder. Figure 4.13 shows the two active joints and the two passive joints for forearm rotation and medial shoulder rotation.

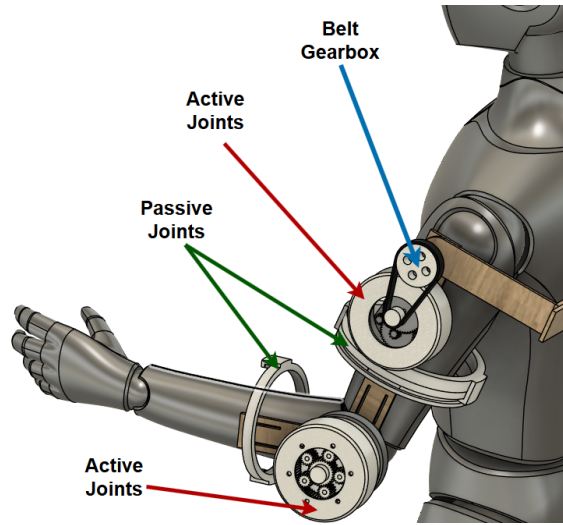


Figure 4.13: Exoskeleton constitution.

As mentioned above, the belt system is used to increase the torque produced by the motor. This system is necessary because, as the motors are equal, the shoulder motor always saturates first when the load is lifted. By increasing the torque, this problem is greatly reduced.

One issue with the chosen control method is that the arm forces the load cell, which makes the exoskeleton move in the direction of the arm, as shown in Figure 4.3 of the previous section. For this reason, and looking at Figure 4.14, if the force applied is on the arm, with the force F_2 , then the arm will be pushed downwards so that the exoskeleton does not try to compensate for this force and consequently does not help. For this reason, the load will always have to be applied to the exoskeleton. In the case of force F_1 , it will cause the exoskeleton to move downwards, and the load cell above will be forced against the arm, so the exoskeleton will try to compensate.

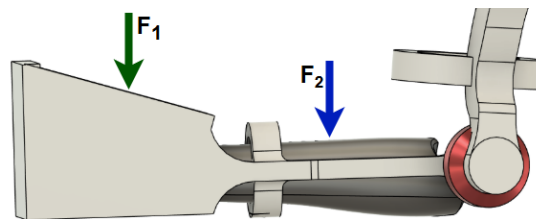


Figure 4.14: Load application exoskeleton.

4.2.2 Construction

After the initial design phase, each DoF was further developed using primarily plastic components produced through 3D printing, due to the ease and flexibility of the process. The main material used was Polyethylene Terephthalate Glycol (PETG), a durable and slightly flexible plastic that combines the strength of ABS with the ease of printing of PLA. For specific components that required greater flexibility, Thermoplastic Polyurethane (TPU), a highly elastic material, was

employed. This section highlights the key aspects of the development of each joint [54]. The construction process had to rely on practical testing rather than simulation due to the anisotropic mechanical properties of 3D-printed parts, where the strength varies significantly depending on the printing direction, making it difficult to obtain accurate results through conventional simulation tools [55].

Supination and pronation

For the rotational movement of the forearm, as mentioned in Section 3.5, it would have to have a staggered rotation, allowing the arm to stay inside the exoskeleton, and the exoskeleton to rotate around the arm. Taking this requirement into account, a first design of the joint was made, which can be seen in Figure 4.15.

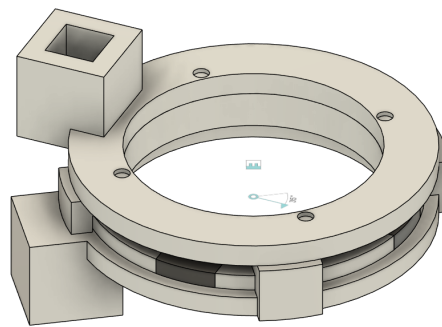


Figure 4.15: First version forearm rotation.

In this first model, Figure 4.16, the system consisted of two main parts, A and B, and four auxiliary parts, C, to close the system. After fitting the two main pieces, the other four were glued together, thus creating a simple rotation system. The problem with this first model was that there was a considerable amount of friction, and in addition, the parts were only held together by four pieces of plastic, which made it quite fragile.

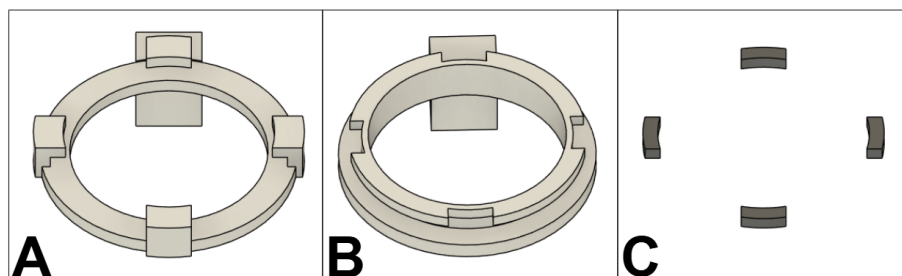


Figure 4.16: First version forearm rotation - components.

To solve the friction problem, the use of a bearing was considered. However, due to the specific dimensions of the system, it was extremely difficult to find a standardized version that

met the specifications, so it had to be customized. Another problem with using a commercial version is that a bearing of the required dimensions would be quite heavy. For these reasons, it was decided to build a simpler and custom bearing using steel balls, and a plastic enclosure. In this version, it would use 6 mm steel balls.

In the new version, Figure 4.17, a system was designed that could take balls to hold the two main parts together, so that the force would be distributed over several balls, greatly increasing the resistance compared to the previous system, where it was only distributed over small plastic parts. This new version also took into account another problem of the first version, which was that it was not possible to adjust the distance between the aluminum profile and the forearm, so the supports that hold the aluminum profile could slide to align the center of rotation with the center of the forearm as best as possible.

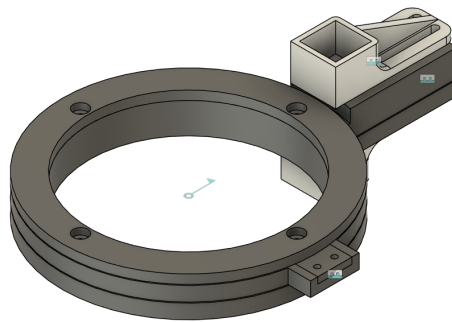


Figure 4.17: Second version forearm rotation.

In Figures 4.18 and 4.19, it can be seen what the ball system would look like, as well as the assembly system, where the balls would be placed in the space left in Figure 4.19, and when all the balls had been added, a piece of plastic would be placed to complete and close the system. However, this system had a serious flaw, as it was extremely difficult to place because there was no space to pass through the ball.

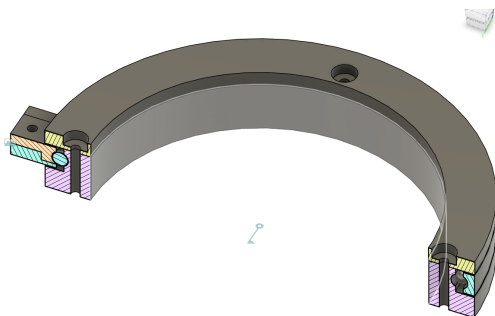


Figure 4.18: Second version - interior.

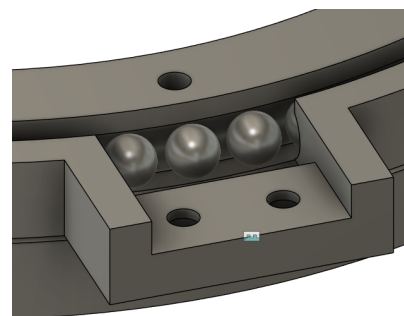


Figure 4.19: Second version - spheres input method.

After carrying out stress tests, several structural problems were found. First, tests were carried out on the aluminum profile support. Figure 4.20 shows the evolution of this support. The first version was an idealization of what was needed, a piece that allowed the distance between the aluminium profile and the arm to be adjusted. Still, it had three main problems: Firstly, the piece was extremely fragile in this configuration. Secondly, the place where the aluminum profile fits was very low, making it unable to withstand almost any lateral force without deforming or breaking. And finally, the third point was that the adjustment system only had two fixing points, which caused the part to rotate; in other words, the part could not be properly fixed to the rest of the system.

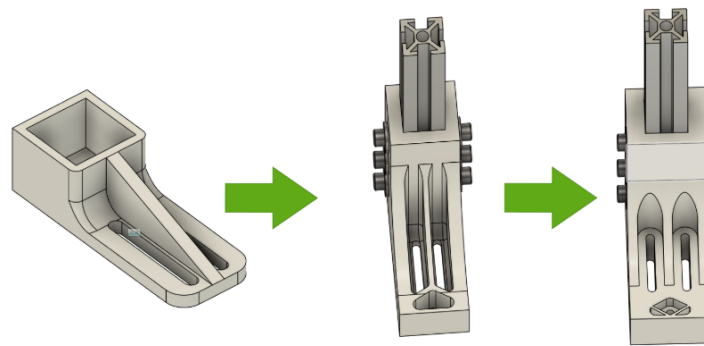


Figure 4.20: Aluminum profile support evolution.

A second version was developed to solve this, shown in Figure 4.20 in the center. In the case of this version, the part was already much thicker and much more robust. The area where the aluminum profile fits in was much larger and had a greater contact area, so that it could easily withstand stresses in various directions at the end of the aluminum profile. Finally, a third fixing point was added, making it very stable during rotation. However, this version had a serious flaw because the area where the nuts tightened, as seen in Figure 4.21, was very thin, and to make matters worse, only the nut area held the system together. As a result, when the nuts were stressed, they went through the plate due to the excessive pressure.

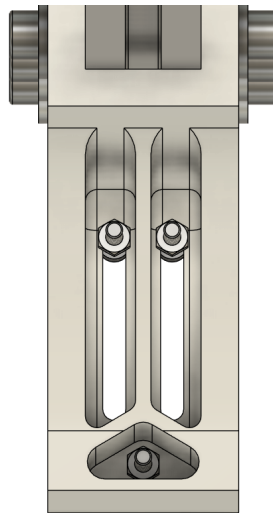


Figure 4.21: Support version 2 - fixation.

In the third and final version, shown on the right in Figure 4.20, the fixation problem was solved by thickening the part between the head of the bolt and the nut, and to reduce the pressure, it was widened so that a washer could be placed before the nut. This modification can be seen in Figure 4.22.

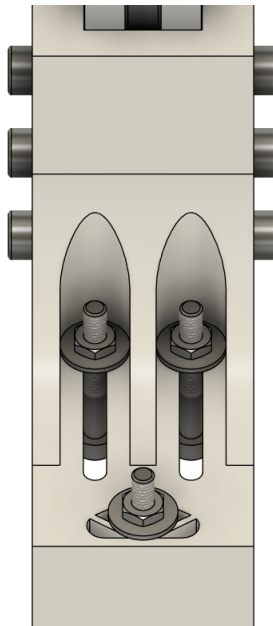


Figure 4.22: Support version 3 - fixation.

As a result, the piece that supports the aluminum profiles has become extremely robust, and has been reused several times throughout the project, its thickness measurements also becoming a point of reference for similar pieces.

With the aluminum profile support developed, the rotation system was then analyzed. The system shown in Figure 4.17 proved to be mechanically fragile, especially in the area where the

aluminum support was attached. So the new version of the system was much more robust to withstand the stresses, as can be seen in Figure 4.23. Another problem was that the system was initially designed to use a row of 6 mm steel balls, but obtaining a considerable number of balls of this size was not practical, as they were often sold in packs of 100 to 200 balls. One solution was to use 4.5 mm pressure gun balls, which are easy to come by in large quantities. The package purchased was the one shown in Figure 4.24, which contained 1500 balls, more than enough for the entire project. And even if the spheres weren't the most resistant, as they would be wrapped in plastic, their resistance wasn't a problem, as they would always be harder than the plastic.

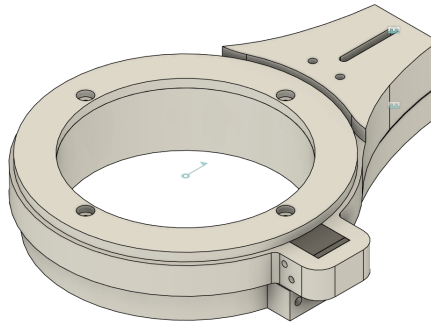


Figure 4.23: Third version forearm rotation.



Figure 4.24: Steel spheres of 4.5 mm.

As the balls were smaller and the part was thicker, three rows of balls were added instead of one. However, during assembly, it was concluded that two rows would be enough, so the middle row was left empty. The rows are shown in Figure 4.25. Another important point that was changed, which can be seen in Figures 4.25 and 4.26, was the closing piece of the system. In this version, it consisted of two parts: the first, which was fitted into the free space and then compressed against

the balls and screwed down, and the second, which served as a stop, closing the free space that was left. This can be seen better in Figure 4.25, on the left in orange.

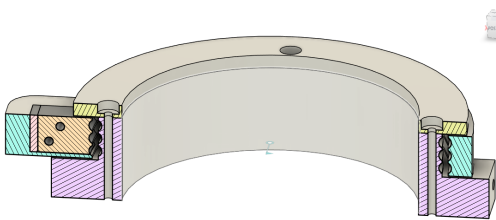


Figure 4.25: Third version - interior.

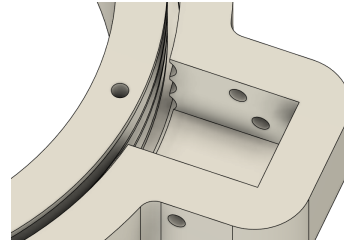


Figure 4.26: Third version - spheres input method.

At the end of this process, the final version of the forearm rotation joint was obtained as shown in Figure 4.27.

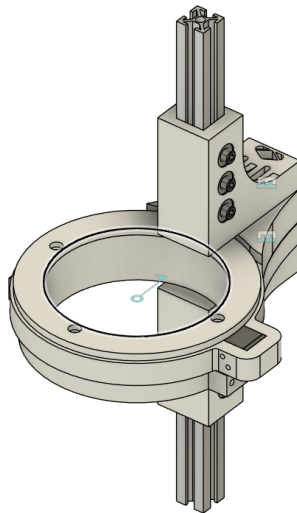


Figure 4.27: Final version forearm rotation.

Once the joint was built, two more important parts had to be developed in the forearm rotation area: the handle and hook of the exoskeleton, and the support for the sensors.

Starting with the hook and handle. In the case of the hook, it's a simple piece of plastic that sits on the end to help test, and can be seen in Figure 4.28. But it was not used in the final version of the prototype.

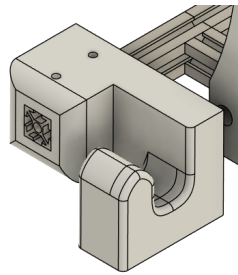


Figure 4.28: Hook 3D model.

In the case of the handle, it is positioned in a way that the forearm aligns with the center of rotation of the joint, allowing the user to rotate the forearm, as seen in Figure 4.29.

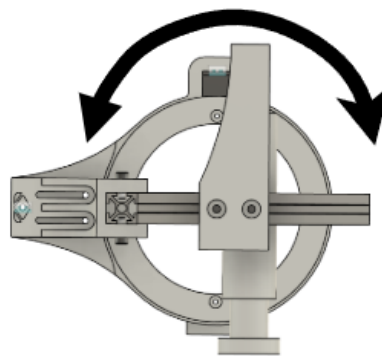


Figure 4.29: Handle positioning.

However, it also has another function. For the sensors to generate a control signal, they must meet two requirements: the first is that they must be as close to the forearm as possible, and may even be leaning against it, and the second is that force must be applied against them. Therefore, if the handle were fixed as in Figure 4.30, the person would not be able to push against the cell, and consequently, the exoskeleton would not detect movement.

To solve this situation, the system in Figure 4.31 was used, where the handle would move axially, so that if the operator moves his arm upwards, there will be a small space where the arm will rise and force the load cells, thus generating a control signal and activating the motors to compensate.

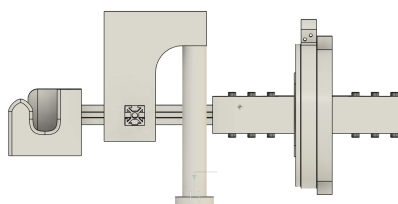


Figure 4.30: Fixed handle.

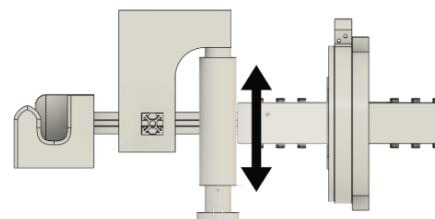


Figure 4.31: Movable handle.

For the development of the sensors, the bracket shown in Figure 4.32 was designed, allowing the load cell to be attached parallel to the aluminum profile as demonstrated in Figure 4.33. The design shown in Figure 4.32 allowed the distance to the arm to be adjusted, making it more versatile and not having to design a new bracket for each person, or in the case of thicker clothing.

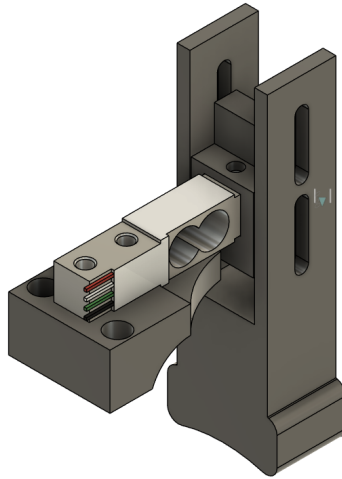


Figure 4.32: Sensor support.

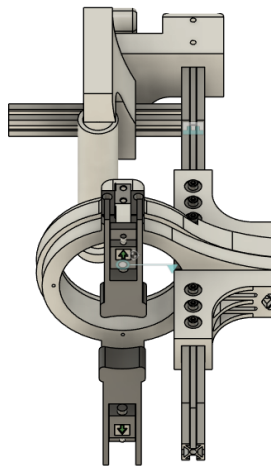


Figure 4.33: Load cells position.

The position in which it is positioned is very important, because as can be seen in Figure 4.34 and 4.35, even if the forearm rotates, the cells are always aligned with the movement of the elbow.

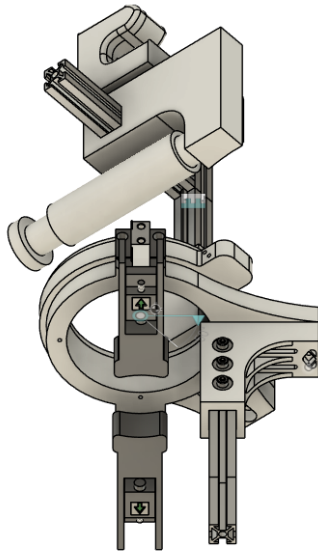


Figure 4.34: Load cells position - supination.

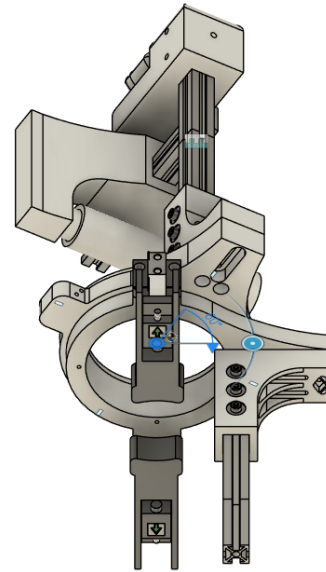


Figure 4.35: Load cells position - pronation.

Unlike other cases presented above, the parts did not need to be improved in terms of design, but rather in terms of material. More specifically, the part that connects the joint to the load cell. It was initially printed in PETG, which is rigid, but when moving the elbow there is still a considerable movement to reach the limit of the handle, and since the cell is made of aluminum, this connection broke. That's why it was decided to print the part in TPU, as it's a much more flexible plastic, allowing the position of the cell to move, thus avoiding breakage and continuing to generate the control signal.

Once all the parts presented in this section had been put together, the first joint was completed, shown in Figure 4.36, which allows the forearm to rotate and the control signal to be read so that the elbow motor can be actuated.

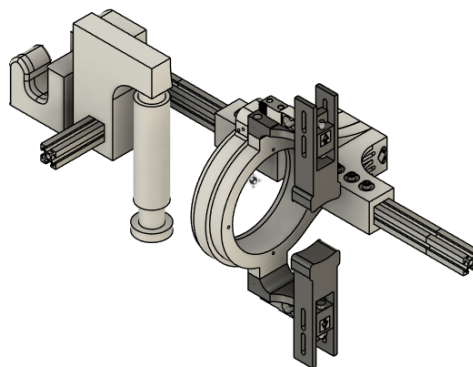


Figure 4.36: First DOF, Forearm rotation final version.

Extension and flexion of the elbow, and medial rotation of the shoulder

Initially, the second and third DoF were considered as separate developments. However, as described in this section, there was a need to combine the two movements into a single system.

In the case of the second DoF, which represents elbow extension and flexion, a system similar to the one developed in the validation prototype was developed, where the motor support design was adapted, and the cooling system also developed in that section was reused. In this system, the motor would be the link between the system developed in the previous section and the third DoF system, which represents the medial rotation of the shoulder. Figure 4.37 shows this first model.

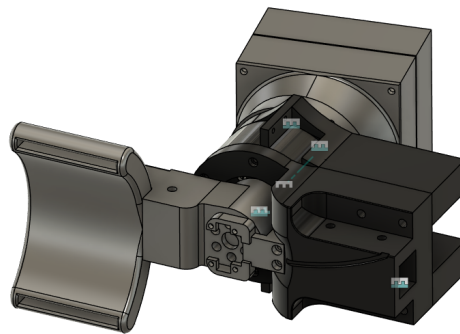


Figure 4.37: Elbow extension and flexion joint.

This system would have a motor support to which an aluminum profile would be attached, as seen in the Figure 4.37, and a plastic support connected to the motor rotor, which would also be connected to an aluminum profile. The design also included support for the forearm, with slots for attaching a strap to secure the arm to the exoskeleton. It also has the external encoder referred to in Chapter 3.2, for reading the position of the rotor.

Figure 4.38 shows the third DoF. Initially, the system was the same as the one developed for forearm rotation, but on a slightly larger scale.

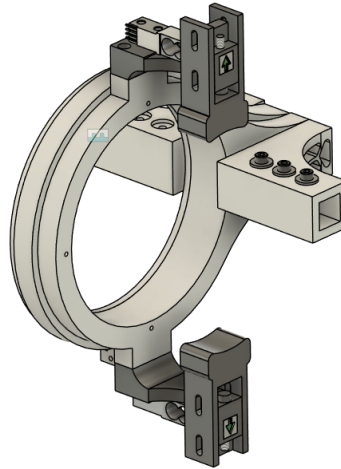


Figure 4.38: Medial rotation of the shoulder Joint.

This system for elbow flexion and extension, and medial rotation, as seen in Figure 4.39, had two problems that made it unusable. The first problem was that the elbow-wrist distance, approximately 33 cm, was much larger than the elbow-shoulder distance, approximately 22 cm, as seen in Figure 4.40, and in that short space, there would have to be the elbow motor support, the shoulder rotation system, and the shoulder extension and flexion system. The system in Figure 4.39 alone already measured around 30 cm.

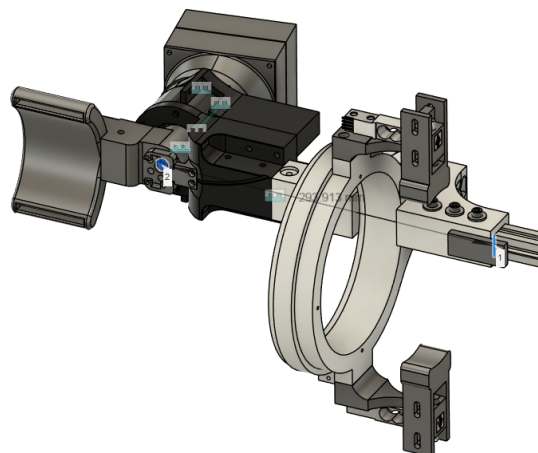


Figure 4.39: Second DoF and third DoF joints first version.



Figure 4.40: Upper-limb measure.

The second problem was that even if the system could be deployed, due to the fixed size of the load cells, the point of contact of the load cells would be very close to the shoulder, in which case the sensors would need a much greater angle to start detecting the movement, as seen in Figure 4.41 and 4.42.

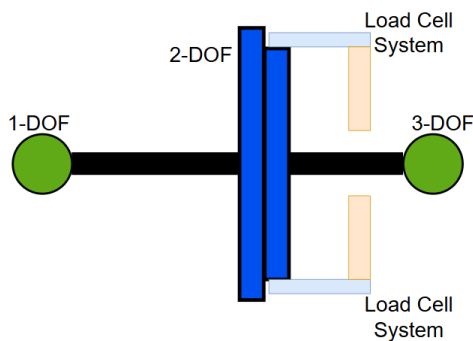


Figure 4.41: Load cell detection diagram A.

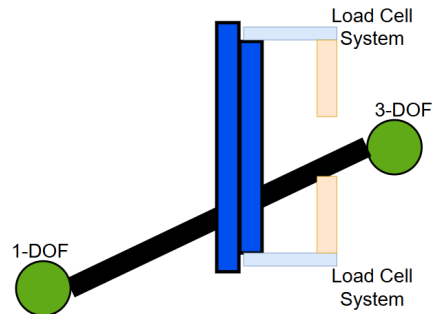


Figure 4.42: Load cell detection diagram B.

To solve these problems, a new and final design was made for the two joints, with two main requirements: to reduce the distance as much as possible so that the shoulder joint has room, and to bring the point of contact of the load cells as close as possible to the elbow. This led to the final design shown in Figure 4.43. The key point is that the part that supports the motor is also the third DoF, making it much more compact at 15.6 cm, a halving of the size, leaving enough room for the shoulder joint and enough space to detect movement with the load cells.

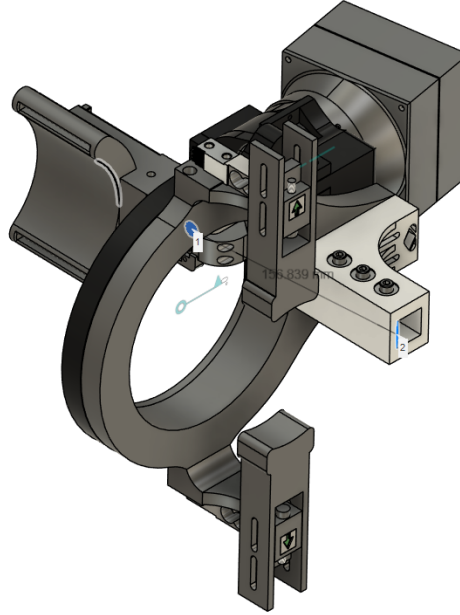


Figure 4.43: Second DoF and third DoF joints final version.

Extension and flexion of the shoulder

In this section, the development of the fourth DoF joint was presented, which allows the shoulder to perform extension and flexion movements.

As briefly mentioned in Section 3.1.3, the same type of motor was used for both joints in this prototype. Consequently, a higher gear reduction was required for the shoulder joint. This necessity arises from the relationship expressed in Equation 4.1, which describes the load capacity at the limb's endpoint as a function of the generated torque. In this equation, d represents the distance from the motor shaft to the endpoint, and g is the acceleration due to gravity.

$$TipWeight = \frac{T}{d \cdot g} \quad (4.1)$$

With the theoretical measurements of the exoskeleton, shown in Figure 4.44, and using the previous equation, disregarding the weight of the exoskeleton itself for simplicity, it was possible to calculate the torque needed for a given load at the end point, equations 4.2 and 4.3. And in equation 4.4, considering the same load for both motors, it was possible to obtain the ratio of how much more torque motor 1 needed compared to motor 2.

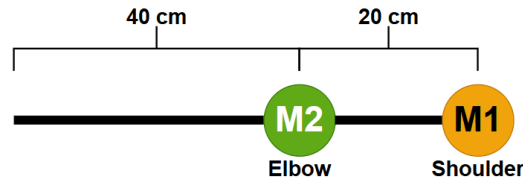


Figure 4.44: Exoskeleton measures diagram.

$$TipWeight_1 = \frac{T_1}{0.6 \cdot 9.81} = 0.17 \cdot T_1 \quad (4.2)$$

$$TipWeight_2 = \frac{T_2}{0.4 \cdot 9.81} = 0.25 \cdot T_2 \quad (4.3)$$

$$TipWeight_1 = TipWeight_2 \Leftrightarrow T_1 = 1.48 \cdot T_2 \quad (4.4)$$

With the calculated value plus a safety factor, it was decided that the reduction system would be 1:3, i.e., for three rotor rotations, the gear rotates one. A belt system was used because it was light and easy to obtain. Sizing a belt system is similar to sizing a two-gear gearbox. In this case, to get a 1:3 reduction, the number of teeth on the large gear divided by the number of teeth on the small gear would have to be three. For this reason, it was decided to use a 60-tooth gear and a 20-tooth gear. Due to the size and weight of the gears, it was decided to use High Torque Drive (HTD) 3M gears, where HTD is a type of timing belt tooth profile designed to transmit higher torques with less risk of teeth jumping and the number “3M” indicates that the belt pitch (center-to-center distance between two consecutive teeth) is 3 mm [56].

To calculate the belt dimensions, the ROLISA¹ catalog for 3M HTD belts was used in conjunction with the Pulley and Belt Calculator website². The distance between the pulleys was iteratively adjusted to select a standardized belt length available in the catalog, while ensuring an adequate distance for the project application.

Once the belt system had been dimensioned, it was necessary to design a way of attaching the gears to the motor. To do this, it was designed the shaft shown in Figure 4.45. It was designed to fit both gears so that when the drawing was sent to be machined on a Computer Numerical Control (CNC) machine, as this part could not be made of plastic, only one design was needed, thus facilitating the process. Figure 4.46 shows how the reduction system would be mounted on the motor.

¹<https://www.rolisa.pt/p2-c-185-correias-tipo-htd-3m-pt>

²<https://www.blocklayer.com/pulley-belt>

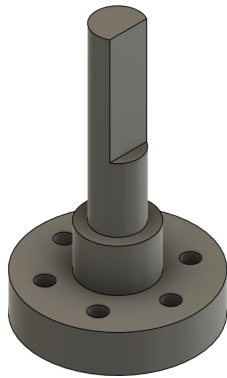


Figure 4.45: Shaft to hold the gears.

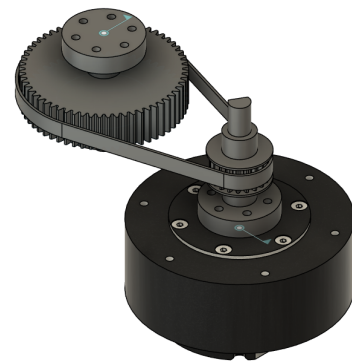


Figure 4.46: Belt reduction design.

Unlike the elbow joint, where the motor is also the joint, the shoulder, because of the reduction system, can't be the engine itself. To facilitate the process, utilizing the knowledge acquired from constructing passive joints (first DoF and third DoF), a bearing was designed for the joint that would provide space to attach one of the shafts of the reduction system. This system can be seen in Figures 4.47 and 4.48. The system was designed with three rows of spheres, but after testing, it was decided that only two rows were needed. However, it was not reprinted for this reason alone, and the three rows were kept.

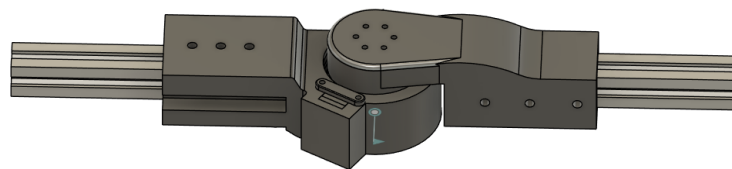


Figure 4.47: Shoulder joint system.

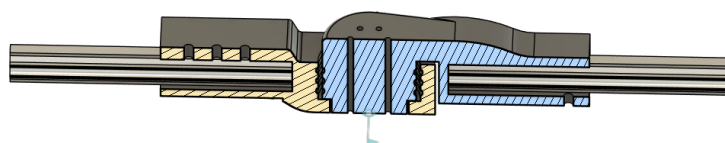


Figure 4.48: Shoulder joint system - inside.

With the bearing designed, a system was needed to stretch the belt system and simultaneously attach the motor to the frame. The system shown in Figure 4.49 was designed so that it could slide before being fixed to the aluminium profile, so that once the belt was fitted, the system was pulled back and fixed, adjusting the belt. A bracket was also added to help fix the large gear, which at the same time also serves to fix the magnet used in the encoder. As the entire structure that holds the motor is pulled back to stretch the belt, the system that holds the sensor has to be properly adjusted so that it can be placed in line with the magnet and the joint.

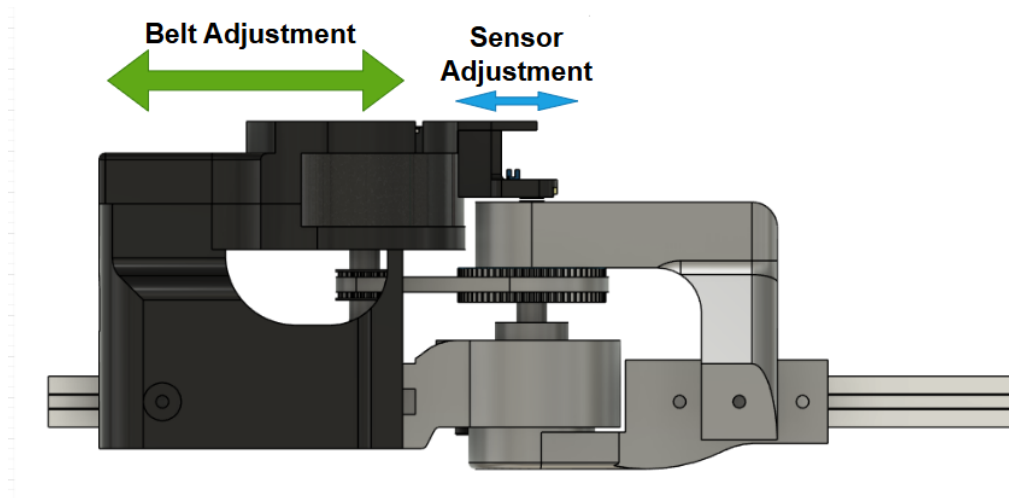


Figure 4.49: Belt adjustment system diagram.

With all this done, the final version of the shoulder joint was obtained in Figure 4.50.

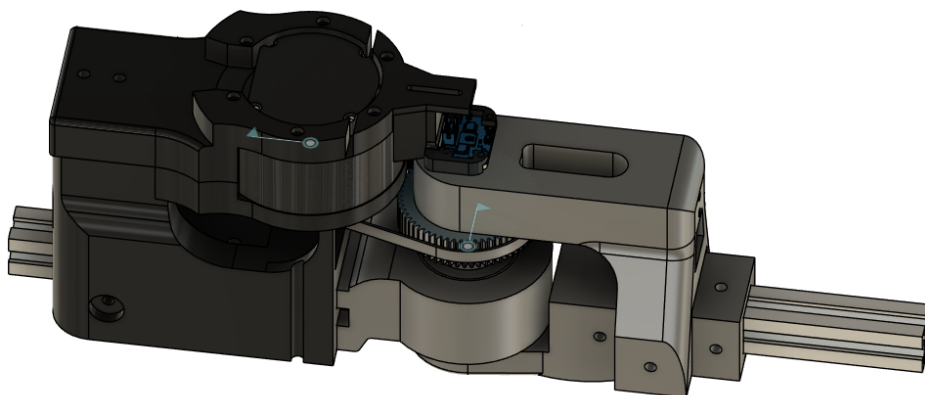


Figure 4.50: Final version shoulder joint.

4.2.3 Final Prototype

After the development and fabrication of all joints, the final exoskeleton prototype was assembled. This section will present the final construction, as well as all possible movements with the exoskeleton worn. To allow the attachment of the exoskeleton to the user's back, a diver backplate was used as the mounting structure. The assembled prototype is shown in Figures 4.51 and 4.52. The exoskeleton mounted on the back is seen in Figure 4.53.

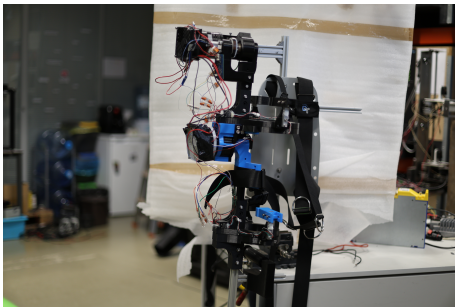


Figure 4.51: Final prototype - front side.



Figure 4.52: Final prototype - lateral side.

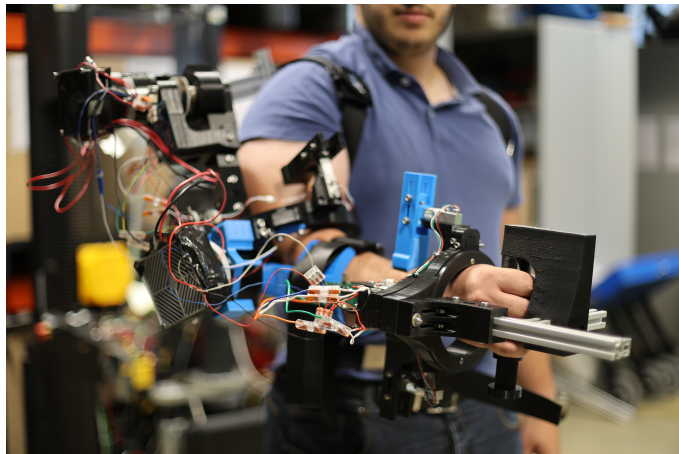


Figure 4.53: Worn exoskeleton prototype.

In Figures 4.54 and 4.55, it is possible to see the supination of the forearm and the pronation of the forearm, respectively.

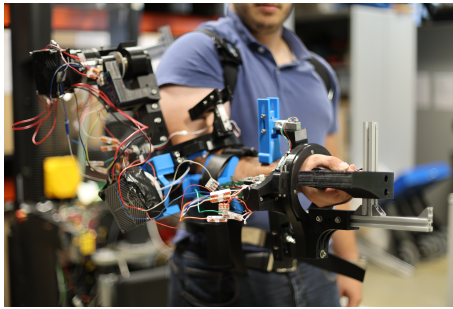


Figure 4.54: Forearm supination.

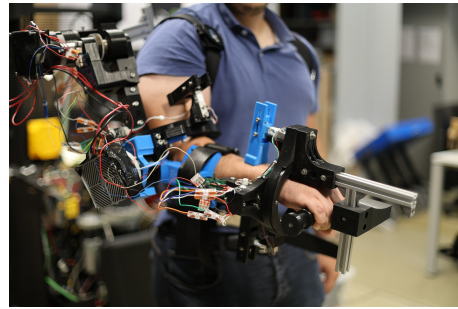


Figure 4.55: Forearm pronation.

In Figures 4.56 and 4.57, it is possible to see the external and internal rotation of the shoulder, respectively.

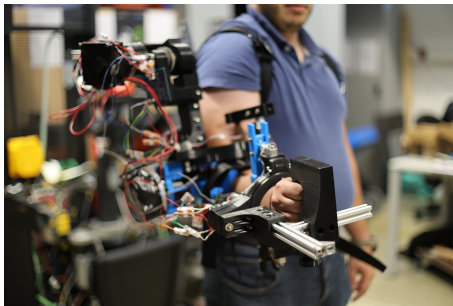


Figure 4.56: Shoulder external rotation.

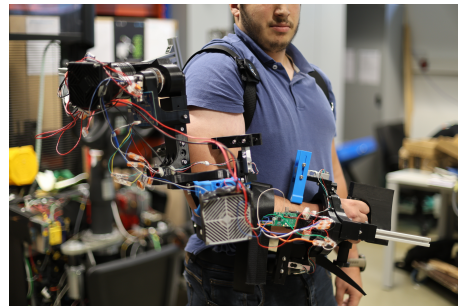


Figure 4.57: Shoulder internal rotation.

In Figure 4.58, it is possible to see the flexion of the elbow, and in Figure 4.59, it is possible to observe the flexion of the shoulder. In Figure 4.60, it is possible to see the extension of the shoulder and elbow, which consists of the arm being stretched out.

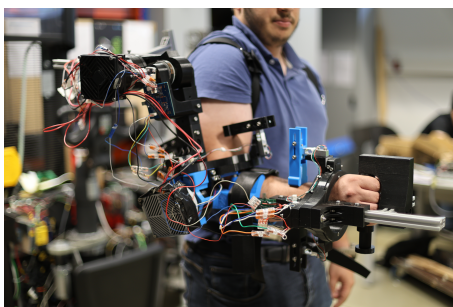


Figure 4.58: Elbow flexion.

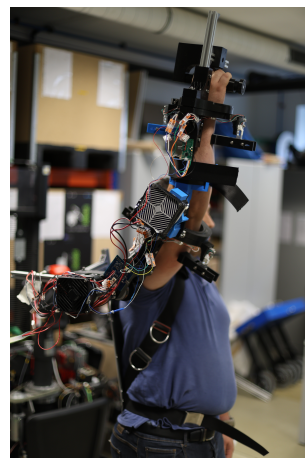


Figure 4.59: Shoulder flexion.

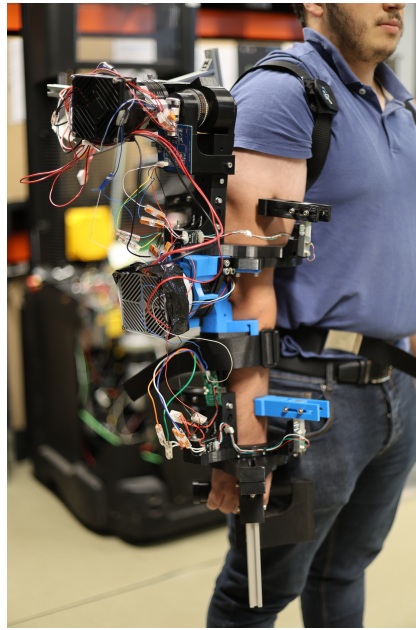


Figure 4.60: Elbow and shoulder extension.

During assembly and initial testing, an issue was identified. When the arm was positioned completely perpendicular to the floor, interference occurred between the third DoF and the operator's body. To address this, a cut was made in the aluminum profile, allowing the arm to be tilted at an angle of approximately 20° . This modification displaced the third DoF away from the operator's body, thereby improving clearance and facilitating movement. This is illustrated in Figure 4.61.

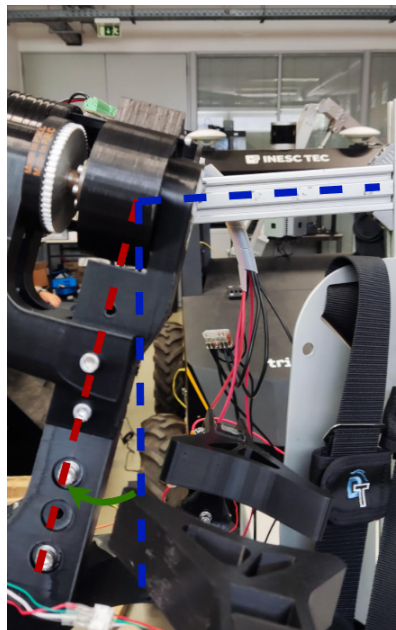


Figure 4.61: Arm tilt.

4.3 Theoretical dimensioning and performance analysis

This section will present possible gearbox-motor combinations, which together would be able to hold a given load in a position perpendicular to the ground. The aim of this section is: firstly, to obtain combinations that minimize the power consumed as much as possible. To understand the trend in weight and consumption of exoskeletons for various loads, such as whether the system is heavier than the load it is intended to lift. And finally, to verify whether the use of heavy reduction gearboxes would be more efficient than the use of motors alone.

The following criteria were used to select the combinations: First, only the nominal values of both the motors and gearboxes were considered. In other words, when a gearbox is used, its nominal torque must be greater than or equal to the motor's nominal torque multiplied by the reduction ratio. Secondly, the resulting output speed of the motor-gearbox combination must not be lower than 75°s^{-1} . This threshold is not mandatory and can be adjusted depending on the system requirements. Therefore, by taking the rated speed and dividing it by 75°s^{-1} , it is obtained the maximum reduction value that the motor can undergo is obtained. The third point is that the combination chosen will focus on minimum weight together with minimum power used, and there may be other combinations besides the one presented. This study also assumed that, when the motor is in stall conditions while supporting a load requiring nominal torque, the current drawn is equal to its nominal value. However, in practice, this assumption does not strictly hold due to the inherent electrical and mechanical characteristics of the motor. Finally, the worst case scenario will be considered, which can be seen in Figure 4.62, which is when the arm holding the load is parallel to the ground.

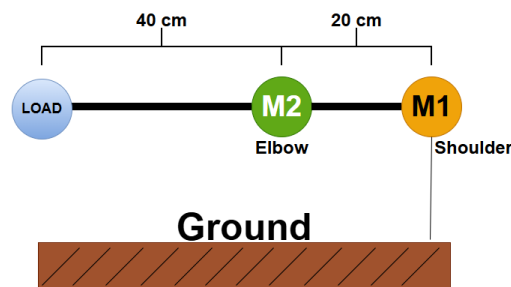


Figure 4.62: System diagram.

In this situation, the elbow system is independent of the shoulder combination, but the shoulder combination is dependent on the elbow combination, because it will be an extra weight that the shoulder system will have to support. For this reason, results will be presented for the 1-DoF and 2-DoF systems.

To calculate the torque required in the elbow system, equation 4.5 was used. To calculate the necessary torque to the shoulder system, equation 4.6 was used. For this study the efficiency of the gearbox will not be considered.

$$T_{\text{elbow}} = M_{\text{Payload}} \cdot 0.4 \cdot 9.81 \quad (4.5)$$

$$T_{\text{shoulder}} = M_{\text{Payload}} \cdot 0.4 \cdot 9.81 + M_{\text{elbow}} \cdot 0.2 \cdot 9.81 \quad (4.6)$$

For this study, NEUGART's PLE gearboxes, which are an economical range of gearboxes, were considered. The torque ratings for the gearboxes were taken from their datasheet. Depending on the model, the number of levels, and the reduction. Table 4.2 shows all this information. Table 4.3 shows the weight of the gearboxes, who also depends on the same characteristics as the nominal torque. The information on the datasheet was a range of values, but as the variation was small in relation to the total weight of the gearbox, the highest value was taken to represent the worst case.

Table 4.2: Nominal output torque T_{2N} (Nm) for PLE gearboxes at various ratios i and stages p .

PLE040	PLE060	PLE080	PLE120	PLE160	i	p
11	28	85	115	400	3	1
15	38	115	155	450	4	
14	40	110	195	450	5	
8.5	25	65	135	-	7	
6	18	50	120	450	8	
5	15	38	95	-	10	
16.5	44	130	210	-	9	2
20	44	120	260	800	12	
18	44	110	230	700	15	
20	44	120	260	800	16	
20	44	120	260	800	20	
18	40	110	230	700	25	
20	44	120	260	800	32	
18	40	110	230	700	40	
7.5	18	50	120	450	64	
20	44	110	260	-	60	3
20	44	120	260	-	80	
20	44	120	260	-	100	
18	44	110	230	-	120	
20	44	120	260	-	160	
18	40	110	230	-	200	
20	44	120	260	-	256	
18	40	110	230	-	320	
7.5	18	50	120	-	512	

Table 4.3: Relative weight (kg) values for PLE gearboxes depending on the number of stages.

Model	1-stage	2-stages	3-stages
PLE40	0.4	0.4	0.5
PLE60	0.9	1.1	1.3
PLE80	2.2	2.7	3.2
PLE120	5.9	7.7	9.5
PLE160	17.5	23.5	-

In this study, Cube Mars motors were also used for system sizing. The AK and AKE motor models were selected based on data from the manufacturer's official website. For the sizing

process, the nominal torque, nominal current, operating voltage, and nominal speed values were considered. As mentioned earlier, a minimum speed of 75°s^{-1} was set as a requirement. Using this, the maximum reduction ratios the motor could handle were calculated. To assist with configuration, the maximum nominal torque was determined by multiplying the nominal torque by the maximum reduction ratio. All this information is summarized in Table 4.4.

With all the information available, the study was carried out considering that the load, in the worst case scenario, would vary from 4 kg to 72 kg, in 4 kg intervals. With the motors and gearboxes presented, and taking these intervals into account, 72 kg was the maximum weight for which sizing could be carried out, taking into account the reduction limits of the motors.

Equation 4.5 was then used to calculate the torque required, and based on these values, the elbow was sized. The motor-reducer combinations used can be found in Table 4.5.

After defining this combination, Equation 4.6 was applied, including the weight of the elbow system, to obtain the torque required for the shoulder. With this data, the shoulder was sized, and the motor-gearbox combinations are shown in Table 4.6.

Finally, the total weight of the system and the power required were added up, resulting in the values shown in Table 4.7, corresponding to each payload value.

Table 4.4: Cube Mars Motors Specs.

Model	Rated Voltage (V)	Rated Torque (Nm)	Rated Current (A)	Rated Speed (Deg/s)	Weight (Kg)	Max Reduction	Max Torque (Nm)
AK45-36 KV80	24	8	2.0	240	0.34	3.20	25.6
AK45-10 KV75	24	2.5	2.1	900	0.26	12.00	30
AK40-10 KV170	24	1.3	2.7	2220	0.2	29.60	38.48
AK60-6 V3.0 KV80	48	3	3.8	2940	0.38	39.20	117.6
AK60-6 V1.1 KV80	24	3	3.8	1398	0.368	18.64	55.92
AKA60-6	48	3	4.0	2400	0.46	32.00	96
AKE60-39 V3.0 KV80	48	24	4.5	420	0.75	5.60	134.4
AKE80-8 KV30	48	12	4.8	900	0.57	12.00	144
AKE60-8 KV80	24	5	4.8	1080	0.26	14.40	72
AK70-9 KV60	48	8.5	6.25	1560	0.54	20.80	176.8
AK60-6 V1.1 KV140	24	3	6.5	2520	0.368	33.60	100.8
AK80-8 KV60	48	10	6.9	1458	0.57	19.44	194.4
AK80-64 KV80	48	48	7.0	288	0.85	3.84	184.32
AK70-10 KV100	48	8.3	7.2	1860	0.521	24.80	205.84
AK80-6 KV100	48	6	9.7	3618	0.485	48.24	289.44
AK80-9 KV100	48	9	10.3	2340	0.485	31.20	280.8
AK10-9 V2.0 KV60	48	18	10.6	1368	0.96	18.24	328.32
AKA10-9 KV60	48	18	10.6	654	1.06	8.72	156.96
AK10-9 V3.0 KV60	48	18	10.7	1410	0.94	18.80	338.4
AK80-9 V3.0 KV100	48	9	12.0	2340	0.49	31.20	280.8
AK10-9 V2.0 KV100	48	15	16.2	2526	0.96	33.68	505.2
AKE90-8	48	55	21.0	720	1.4	9.60	528

Table 4.5: Elbow Configuration per Tip Load.

Tip (kg)	Elbow Motor	Elbow Gearbox	Elbow Weight (kg)	Elbow Power (W)
4	AKE60-39 V3.0 KV80	-	0.75	216
8	AK80-64 KV80	-	0.85	115.2
12	AK80-64 KV80	-	0.85	230
16	AKE80-8 KV30	PLE80	3.27	230
20	AKE80-8 KV30	PLE80	3.27	230
24	AKE80-8 KV30	PLE80	3.27	230
28	AKE80-8 KV30	PLE80	3.27	230
32	AKE80-8 KV30	PLE80	3.27	230
36	AKE80-8 KV30	PLE80	3.27	230
40	AK80-6 KV100	PLE120	8.185	465.6
44	AK80-6 KV100	PLE120	8.185	465.6
48	AK80-6 KV100	PLE120	8.185	465.6
52	AK80-6 KV100	PLE120	8.185	465.6
56	AK80-6 KV100	PLE120	8.185	465.6
60	AK80-6 KV100	PLE120	8.185	465.6
64	AK10-9 V2.0 KV60	PLE160	24.46	508.8
68	AK10-9 V2.0 KV60	PLE160	24.46	508.8
72	AK10-9 V2.0 KV60	PLE160	24.46	508.8

Table 4.6: Shoulder Configuration per Tip Load and elbow weight.

Tip (kg)	Shoulder Motor	Shoulder Gearbox	Shoulder Weight (kg)	Shoulder Power (W)
4	AK80-64 KV80	-	0.85	336
8	AKE80-8 KV30	PLE80	2.77	230
12	AKE80-8 KV30	PLE80	3.27	230
16	AKE80-8 KV30	PLE80	3.27	230
20	AKE80-8 KV30	PLE80	3.27	230
24	AK70-9 KV60	PLE120	8.24	300
28	AK80-6 KV100	PLE120	8.185	465.6
32	AK80-6 KV100	PLE120	8.185	465.6
36	AK80-6 KV100	PLE120	8.185	465.6
40	AK10-9 V2.0 KV60	PLE160	24.46	508.8
44	AK10-9 V2.0 KV60	PLE160	24.46	508.8
48	AK10-9 V2.0 KV100	PLE160	24.46	777.6
52	AK10-9 V2.0 KV100	PLE160	24.46	777.6
56	AK10-9 V2.0 KV100	PLE160	24.46	777.6
60	AK10-9 V2.0 KV100	PLE160	24.46	777.6
64	AK10-9 V2.0 KV100	PLE160	24.46	777.6
68	AK10-9 V2.0 KV100	PLE160	24.46	777.6
72	AK10-9 V2.0 KV100	PLE160	24.46	777.6

Table 4.7: Total Weight and Power per Tip Load.

Tip (kg)	Total Weight (kg)	Total Power (W)
4	1.6	552
8	3.62	345.2
12	4.12	460
16	6.54	460
20	6.54	460
24	11.51	530
28	11.455	695.6
32	11.455	695.6
36	11.455	695.6
40	32.645	974.4
44	32.645	974.4
48	32.645	1243.2
52	32.645	1243.2
56	32.645	1243.2
60	32.645	1243.2
64	48.92	1286.4
68	48.92	1286.4
72	48.92	1286.4

Since the elbow is independent of the shoulder's weight, the results were divided into two systems: one with 1-DoF, represented by the data in Table 4.5, and another with 2-DoF, represented by Table 4.7. Using these two tables, two graphs were generated for each system. Figures 4.63 and 4.65 show the weight the system must lift for a given payload, while Figures 4.64 and 4.66 illustrate the power consumed for a given payload.

In Figure 4.63, the theoretical and actual values of the exoskeleton developed in this project were also included. For comparison purposes, the Guardian XO Alpha exoskeleton, developed by Sarcos Robotics, was added. It is a full-body system with 24-DoF, weighing approximately 113 kg and capable of repeatedly lifting about 45 kg.

To include this system in the analysis focused on a comparison of 2-DoF, it was assumed that the weight of one arm represents 10% of the total body weight, resulting in approximately 11.3 kg. It was also considered that each arm can support a nominal payload of 22.5 kg.

For the exoskeleton developed in this work, the theoretical value was calculated based only on the weights of the motors and their nominal torque, estimating the maximum payload it could lift under ideal conditions. The actual value corresponds to the actual weight of the system, including the two passive joints and structural components.

As mentioned in Section 3.1.3, the initial design was based on peak torque values, which led to an overestimation of the system's capabilities. Under realistic conditions, the payload is effectively zero, meaning that the system is only capable of supporting its own weight.

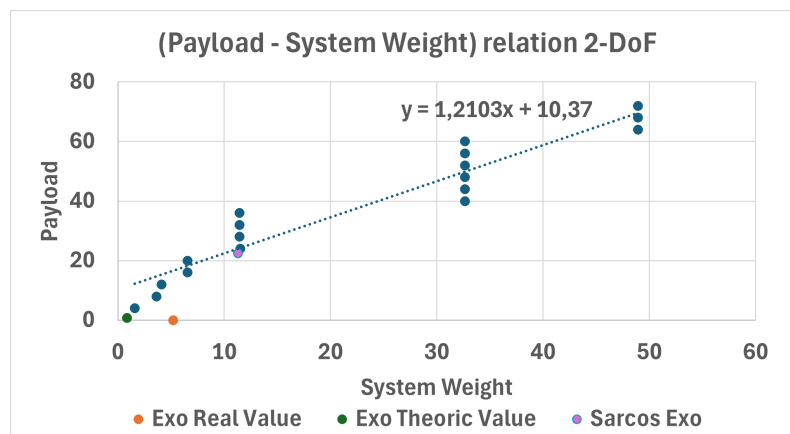


Figure 4.63: Relation weight tip to system with 2-DoF weight.

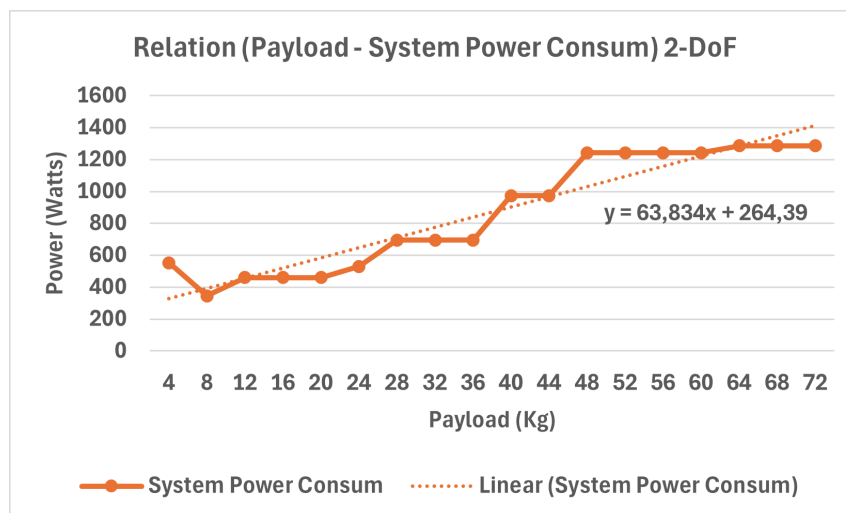


Figure 4.64: Power consumption to hold a payload on the tip in a system with 2-DoF.

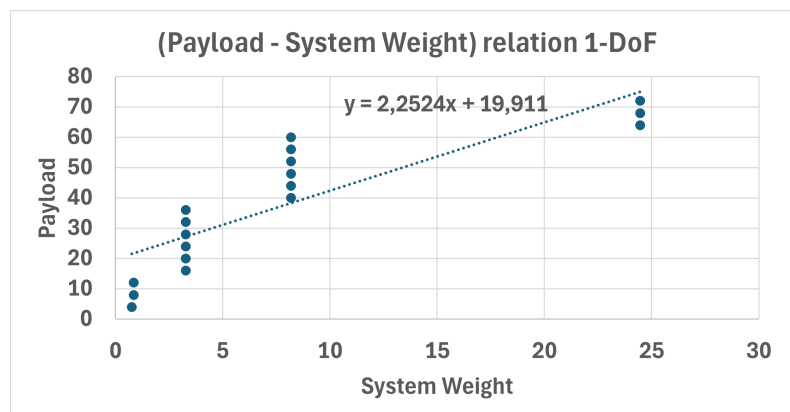


Figure 4.65: Relation weight tip to system with 1-DoF weight.

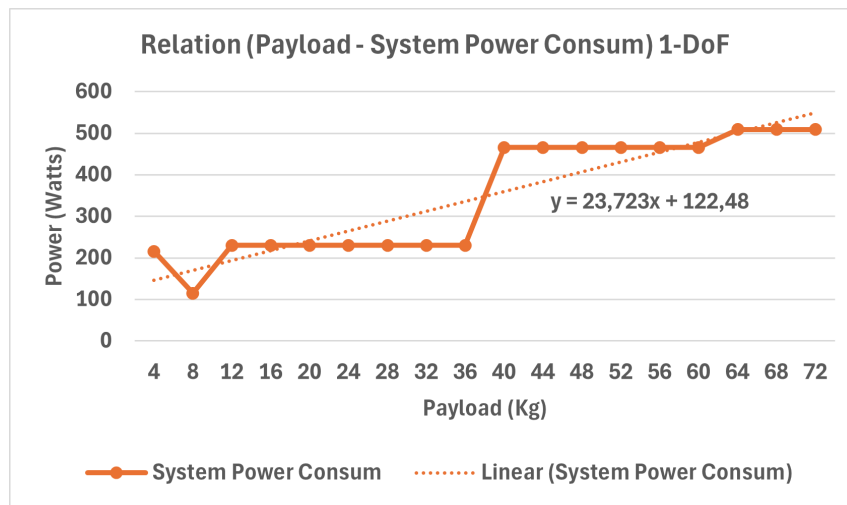


Figure 4.66: Power consumption to hold a payload on the tip in a system with 1-DoF.

After analyzing the graphs, several key observations can be made. The first point, evident in both Figure 4.63 and Figure 4.65, is that for the given dimensions, the system consistently weighs less than the payload it is capable of lifting. This is supported by the trend lines, which exhibit a slope greater than 1. However, it is important to note that this analysis only accounts for the weight of the motors.

When comparing the theoretical and actual values of the exoskeleton developed, a clear discrepancy becomes evident. This highlights the fact that the actual payload capacity will be lower than the theoretical estimates. Therefore, caution must be taken when interpreting these results.

To compensate for the considerable weight of the system, the power consumption graphs offer useful insights. For instance, when lifting a 72 kg load, the dual-motor system would consume approximately 1200 W. While this value may seem high, it also implies that with 1500 Wh batteries, the user could maintain a static position under maximum load for around 1 hour and 15 minutes. In practice, such a prolonged effort would rarely be required, making this a feasible scenario for most use cases.

Another clear difference in requirements can be observed between the single-motor and dual-motor systems, since the shoulder motor must support not only the payload but also the weight of the elbow motor, resulting in a significant discrepancy in design considerations.

Additionally, Figure 4.63 and Figure 4.65 reveal that some motor-gearbox combinations have similar overall weights but different maximum payload capacities. This occurs because the weight of the gearboxes is considerably greater than that of the motors. Therefore, in many cases, as long as the gearbox size and number of stages remain the same, changing the motor model results in only minor variations in total system weight.

A particularly notable observation is the substantial weight difference between larger gearboxes, especially when moving from the PLE120 to the PLE160 model, where the weight increases from 5.9 kg to 17.5 kg, almost tripling. This significant jump explains the clustering of

data points in the graphs, with transitions between clusters corresponding to the need for larger gearboxes.

For this reason, selecting a combination designed for a 40 kg payload would be inefficient, since another system with the same weight can support up to 62 kg with only about a 250 W increase in power consumption.

Finally, it is important to note that certain motors, such as the motor AKE90-8 with a theoretical max torque of 528 Nm, could not be utilized due to fixed reduction ratios and nominal torque limits, restricting their applicability in this context. But if the value of 75°s^{-1} was too high for the context, it could be adjust so that the motor could be used with an even higher torque.

To enable a more detailed analysis of the designs, a study was carried out focusing on the dimensioning of 2-DoF exoskeletons using only motors, without any additional reduction gearboxes. In this analysis, payloads ranging from 1 to 8 kg were considered, in increments of 1 kg. The maximum payload of 8 kg was the highest value achievable when considering all the motors listed in Table 4.4. The resulting motor combinations are presented in Table 4.8. For better analysis, the results are presented in the graphs shown in Figures 4.67 and 4.68.

Table 4.8: System Configuration per Tip Load without extra gearbox.

Tip (kg)	Elbow Motor	Shoulder Motor	System Weight (kg)	System Power (W)
1	AK45-36 KV80	AK45-36 KV80	0.68	96
2	AK45-36 KV80	AKE60-39 V3.0 KV80	1.09	264
3	AKE60-39 V3.0 KV80	AKE60-39 V3.0 KV80	1.5	432
4	AKE60-39 V3.0 KV80	AKE90-8	2.15	1216
5	AKE60-39 V3.0 KV80	AKE90-8	2.15	1216
6	AKE60-39 V3.0 KV80	AKE90-8	2.15	1216
7	AKE90-8	AKE90-8	2.8	2000
8	AKE90-8	AKE90-8	2.8	2000

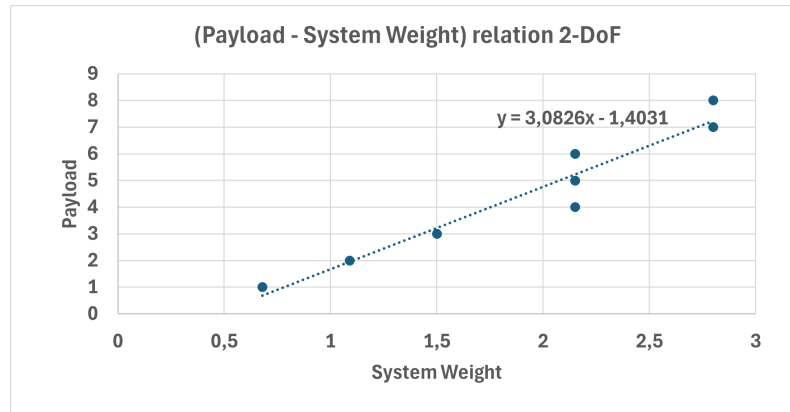


Figure 4.67: Relation weight tip to system with 2-DoF weight without extra gearbox.

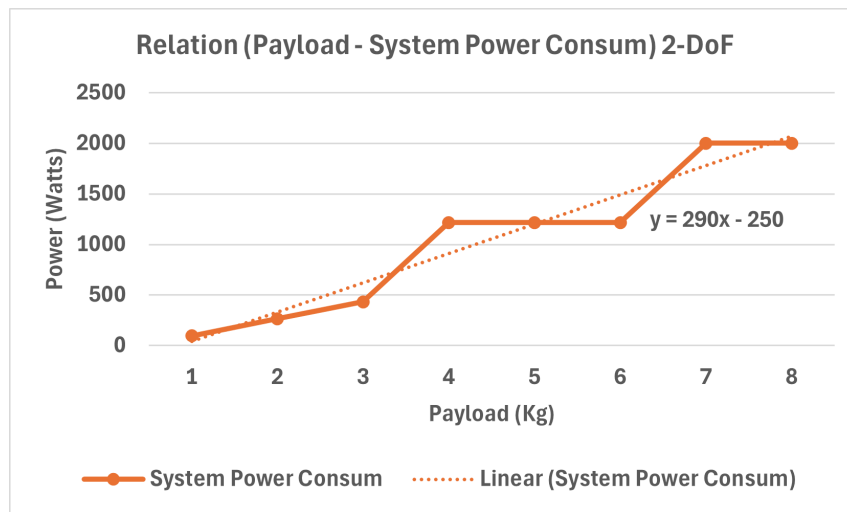


Figure 4.68: Power consumption to hold a payload on the tip in a system with 2-DoF without an extra gearbox.

From the presented graphs, a clear difference in system capacities can be observed. With the use of reduction gearboxes, the maximum achievable payload under the current requirements is 72 kg, whereas using only motors without additional gearboxes limits the maximum payload to 8 kg. Furthermore, the power required to sustain the 8 kg payload is almost twice that needed to maintain the 72 kg payload. Another important observation is that, when employing reduction gearboxes to lift 8 kg, the system weight is slightly higher while power consumption is only 345 W, compared to 2000 W consumed by the motor-only system.

Chapter 5

Results

This section presents the results related to the control and operation of the developed exoskeleton, including its ROM.

5.1 Exoskeleton results

After the development and construction of the exoskeleton presented in the previous chapter, tests were conducted on the final prototype. However, some design limitations are present.

The first major limitation was the use of the peak torque value during the exoskeleton's design process. The initial assumption was that the motor would operate continuously at stall torque; however, tests on the validation prototype revealed that using a current above the nominal level leads to very rapid motor overheating. In the final prototype, a current of 5 A is still being used, above the nominal 4 A, although well below the peak of 13.5 A, primarily because this was the minimum required for the motors to lift the exoskeleton's weight.

Another limitation in the design process was the simultaneous selection and dimensioning of both motors. As discussed in Chapter 4, a large portion of the exoskeleton was in plastic, which made physical testing necessary, as many of the structural properties (especially weight and resistance) could not be accurately simulated. This created a dependency on having the actual components fabricated before accurate dimensioning could be performed.

Another aspect briefly addressed in the state-of-the-art is user comfort. As shown in Table 5.1, which compares the exoskeletons ROM with that of the human body, restricting one of the shoulder's natural movements, in this case, abduction and adduction, results in noticeable discomfort during use.

Table 5.1: Comparison between human and exoskeleton range of motion (ROM).

Joint	Movement	ROM (°)	Exoskeleton ROM
Shoulder	Flexion	180	125
Shoulder	Extension	60	0
Shoulder	Internal Rotation	90	∞
Shoulder	External Rotation	90	∞
Elbow	Flexion	140	80
Elbow	Extension	0	0
Forearm	Pronation	80	∞
Forearm	Supination	80	∞

Table 5.1 also shows that certain joints, such as shoulder internal/external rotation and forearm rotation, have an effectively infinite ROM due to the use of full rotary bearings. This indicates a significant oversizing of the system, which could be optimized to allow only the necessary range of motion. For instance, in the case of forearm rotation, instead of using a full bearing that allows continuous rotation, a semicircular mechanism would suffice, as this movement typically requires only 180°. Reducing this to the functional ROM would decrease both the weight and volume of the system, thereby improving its overall efficiency.

5.1.1 Elbow control

To validate the control's operation at the elbow, the control signal, position, speed, and motor current were retrieved, and three tests were performed on the exoskeleton's operation.

The first test validated was the movement of the arm to various positions, as shown in the graph presented in Figure 5.1. In the graph, the blue line illustrates the current consumed by the motor, the green line depicts the elbow angle, the red line indicates the speed, and the black line represents the control signal transmitted by the load cells.

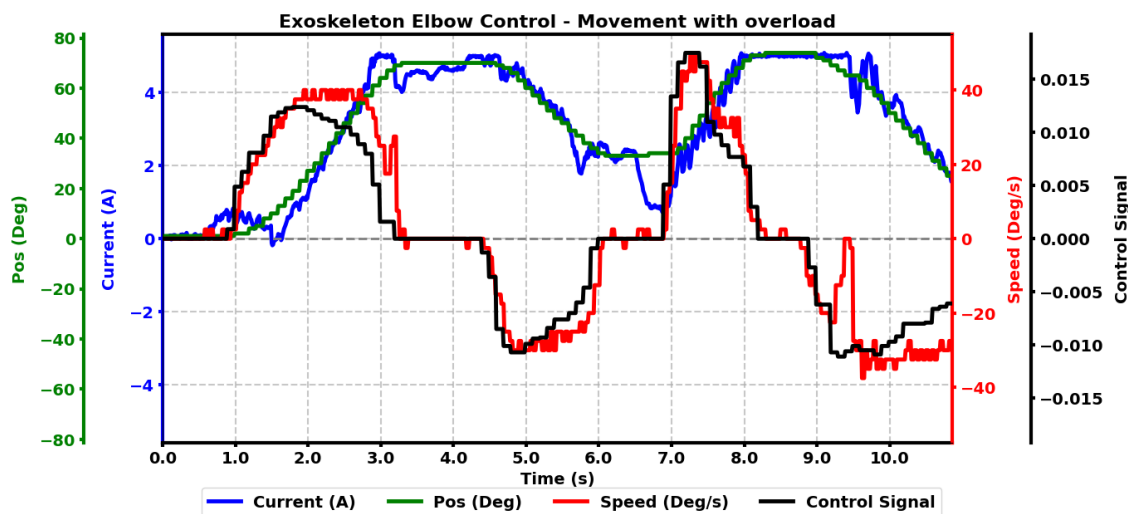


Figure 5.1: Elbow Movement.

The first thing that can be gleaned from the graph is that there is a similarity between speed and control signal, and between angle and current. The control signal has no units; it is just a linear value depending on the force exerted on the load cells, and not necessarily a weight value. As the system control is PI-based, where the proportional component has a very significant value, this causes the speed value to be similar to the control signal value with a difference in magnitude. In the case of the angle with the current value, the reason for the similarity of the curves is that when the angle increases, the effect of gravity rises, requiring greater effort on the motor.

The sequence of movements occurs as follows: the operator initiates arm movement while the exoskeleton remains stationary. As a result, the load cells then detect contact with the operator's arm, and the control signal becomes positive. This prompts a speed signal to be sent to the motor driver. The motor begins to actuate, causing the exoskeleton arm's position to increase. At a certain point, the operator stops the movement, but the exoskeleton continues in deceleration until the control signal reaches zero. Once this occurs, the system becomes stationary again. When the operator subsequently performs a downward arm movement, the same sequence is repeated; however, in this case, both the control signal and the speed are negative.

This complete sequence is performed again; however, in the second ascent, the operator moved the arm more quickly, resulting in a steeper increase in the control signal. As a consequence, a higher motor speed was required to follow the movement.

The second test complements what happened during the previous scenario, as shown in the graph in Figure 5.2. The graph shows the motor current in blue, the elbow angle in green, the speed in red, and the control signal from the load cells in black.

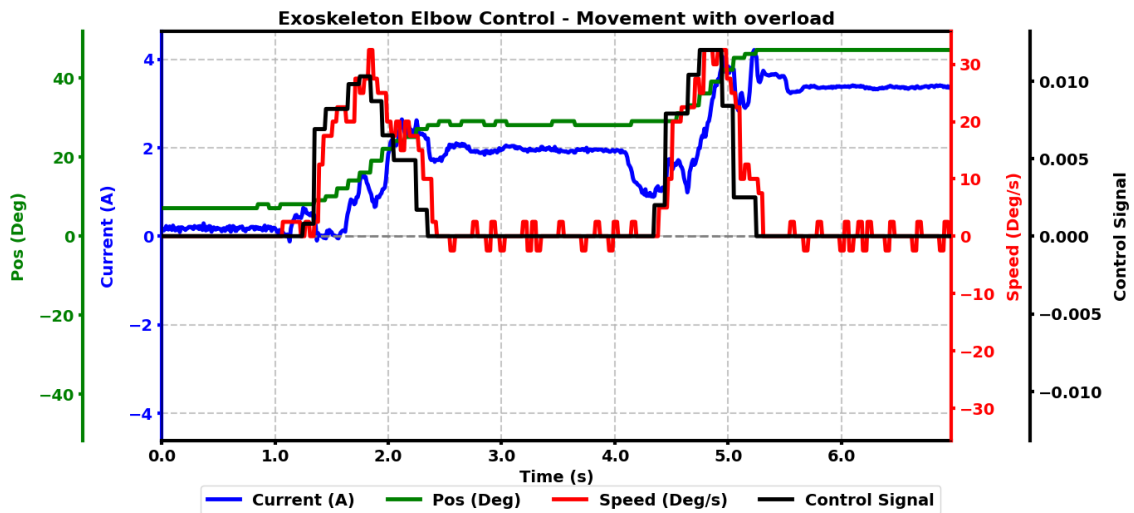


Figure 5.2: Exoskeleton control stabilization.

It is possible to see from the graph that the load cells detect contact, and the speed consequently increases as well. As soon as the forearm begins to move away, the control signal tends toward zero and stabilizes. In this system, with the current gains, it takes about 2 s to stabilize.

However, depending on the need, this value can be easily changed by increasing or decreasing the proportional gain.

And finally, the last test represents the behavior of the system when a load above the maximum payload of the exoskeleton is used. The graph in Figure 5.3 shows that behavior. In the graph, the blue curve corresponds to the motor current, the green curve to the elbow angle, the red curve to the speed, and the black curve to the control signal sent by the load cells.

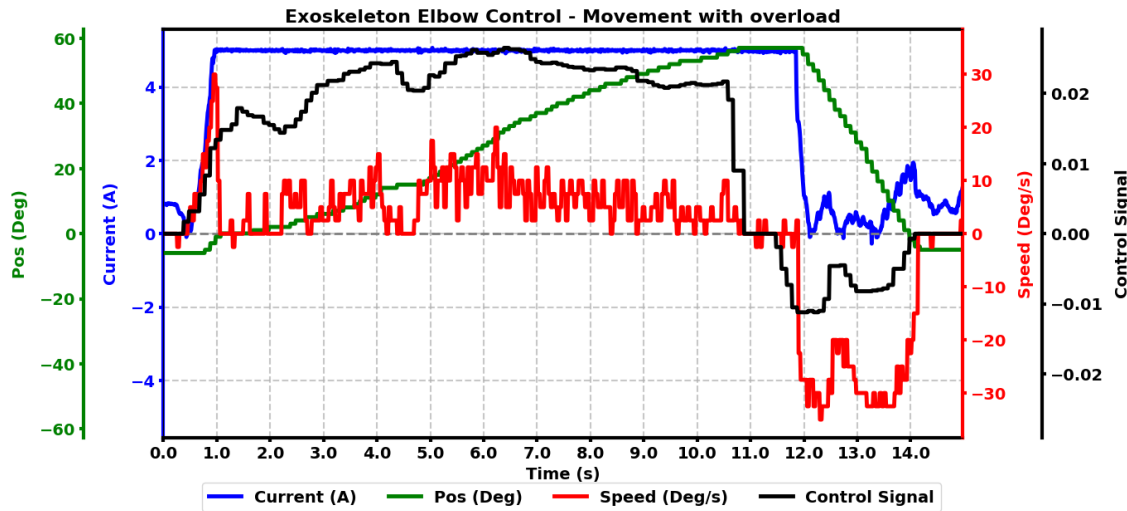


Figure 5.3: System behavior when in overload.

As demonstrated in the validation prototype, the primary objective of the exoskeleton is to assist the user as much as possible. For this reason, it is necessary to limit the motor current, as discussed during the development of the validation prototype. In the graph, it can be seen that a control signal is generated by the load cells; however, in certain situations, the arm may become blocked, for instance, when attempting to lift a heavy load. In such cases, the exoskeleton will deliver the maximum allowable current, and movement will only occur if the operator contributes to the effort.

In the case of the developed exoskeleton, due to its limited payload capacity, the help it provides may not be perceptible. However, in a more powerful exoskeleton using the same control strategy, such as one capable of lifting 20 kg at the end-effector, if the operator attempts to lift a 21 kg load, the system would still behave similarly. The operator would only feel the additional 1 kg, and the control signal graph would resemble that of the current prototype.

5.1.2 Shoulder Control

The method for controlling the shoulder motor is the same as the method for controlling the elbow motor. In the previous section, it was demonstrated that the control method for the elbow works well and as expected. However, due to mechanical limitations and the complexity of the shoulder, the same method is not as effective.

Four main factors make it difficult to use the same control method:

- i) Position of the shoulder's center of rotation.
- ii) Involuntary control signal
- iii) Movement blocked when the elbow is fully flexed
- iv) Belt loses tension due to plastic deformation.

The factor i) concerns the position of the shoulder's center of rotation. As described in Section 3.5, this center varies throughout shoulder movements. Since both the exoskeleton structure and the sensor mounting system are rigid, changes in the center of rotation during shoulder flexion alter the points of contact with the sensors, making it more difficult to activate the load cells properly.

The factor ii) appears during elbow flexion. Since the load cells used to control the shoulder motor are positioned in the biceps and triceps region, elbow flexion causes the biceps to contract, increasing their volume and generating a signal in the load cells that does not correspond to actual shoulder movement. This problem is also amplified by the misalignment between the human elbow joint and the exoskeleton's elbow joint. As illustrated in Figure 5.4, when, for example, the human elbow's center of rotation is located behind that of the exoskeleton, the human joint effectively rotates around the exoskeleton's rotation point. This misalignment generates unintended contact at the back of the user's arm. Due to the rigid nature of the exoskeleton structure, achieving perfect alignment throughout the entire range of motion is extremely challenging.

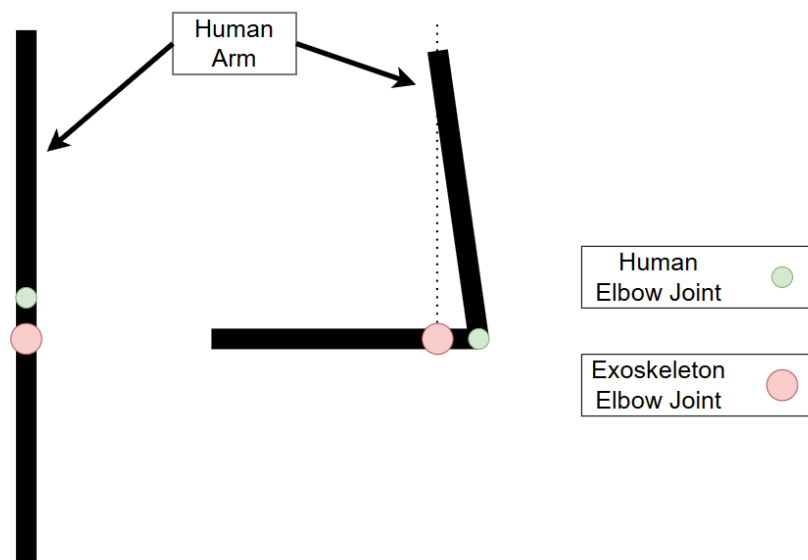


Figure 5.4: Misalignment problem.

To mitigate this issue, the signals from both load cells were recorded during elbow flexion. For each load cell, a graph was generated as a function of the elbow angle, and a trend line was fitted to represent the observed values best, as shown in Figures 5.5 and 5.6.

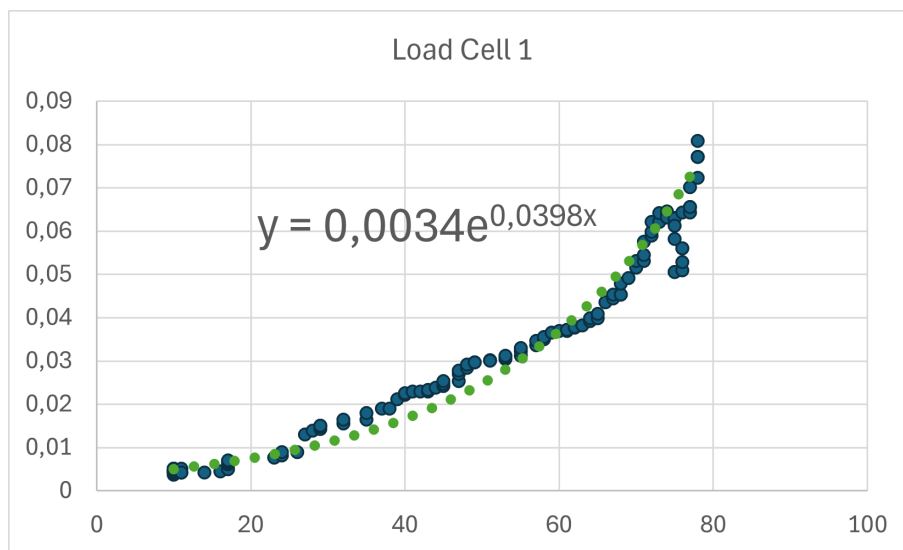


Figure 5.5: Load cell 1 error during elbow flexion.

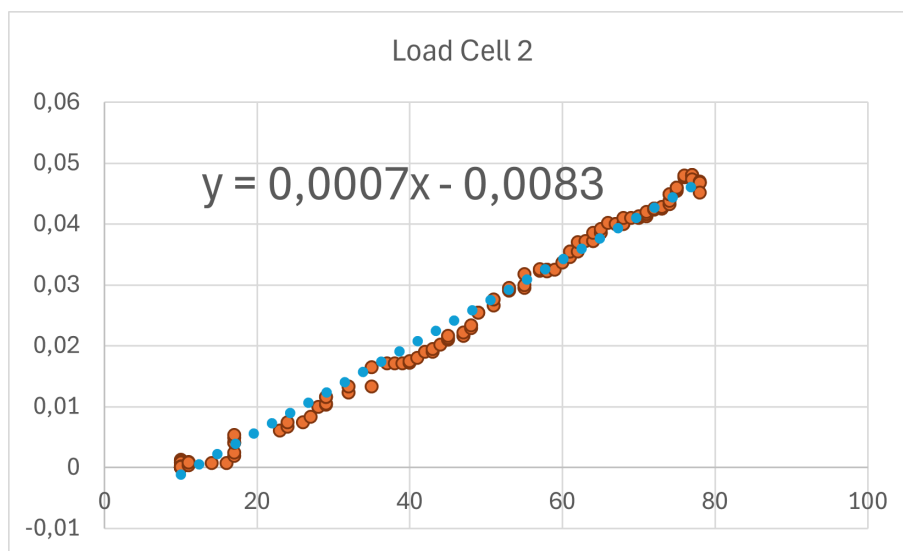


Figure 5.6: Load cell 2 error during elbow flexion.

The graphs present a distinct curve. In Figure 5.5, the curve follows an exponential trend, which occurs because, when the biceps contract, they quickly approach their maximum volume. As a result, during movement, the muscle expansion reaches a point where it no longer increases significantly. In contrast, Figure 5.6 shows a linear trend. This is explained by the issue described in Figure 5.4: due to the misalignment of the rotational axes, the arm comes into contact with the rear sensor, generating the linear error observed. In Figures 5.7 and 5.8, the results of implementing the equations in both load cells are presented, where the maximum value in both graphs does not exceed 0.015 and remains constant throughout the movement.

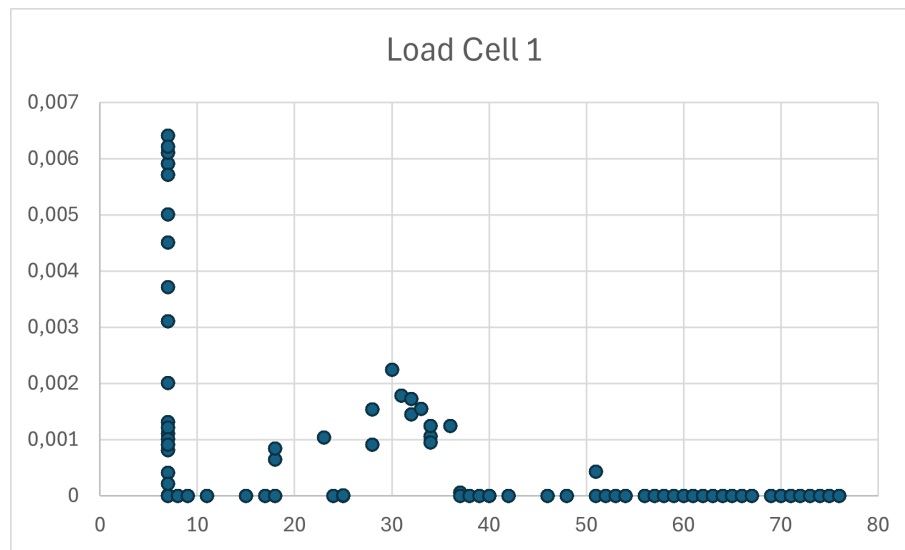


Figure 5.7: Load cell 1 error during elbow flexion after correction.

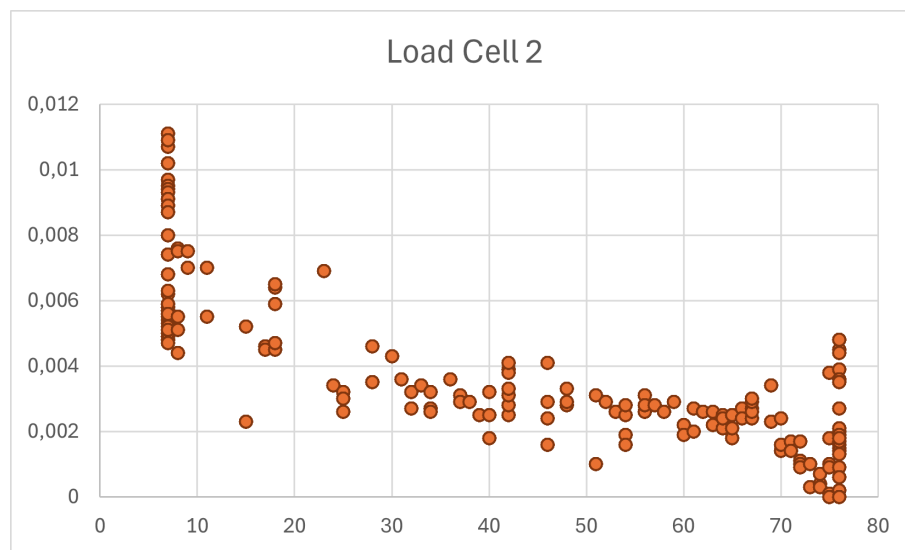


Figure 5.8: Load cell 2 error during elbow flexion after correction.

The factor iii) arises from the rigid structure of the exoskeleton. When the elbow is fully flexed, as shown in Figure 5.9, movement in that direction becomes mechanically constrained, making it more difficult to generate a reliable control signal.

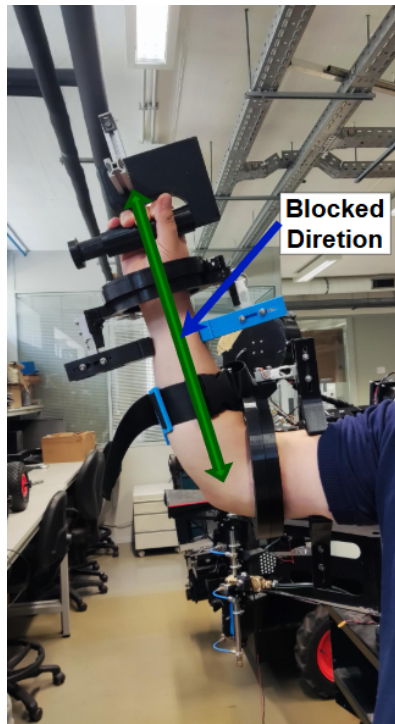


Figure 5.9: Movement limitation.

Finally, the limitation iv) arises from the material used in the motor mount. Since the component was manufactured in plastic, even when fully tensioned, the force exerted by the belt during movement is sufficient to deform the material, as shown in Figure 5.10, causing the system to skip teeth. To mitigate this issue, the motor current was limited to a level at which this failure no longer occurred. However, this restriction reduced the available torque to approximately 5 Nm, which is significantly below the requirement for lifting. As a result, the system cannot operate autonomously and requires external assistance to move. This limitation could be effectively addressed in future iterations by replacing the motor with a more powerful unit and redesigning the mount in a more resistant material.

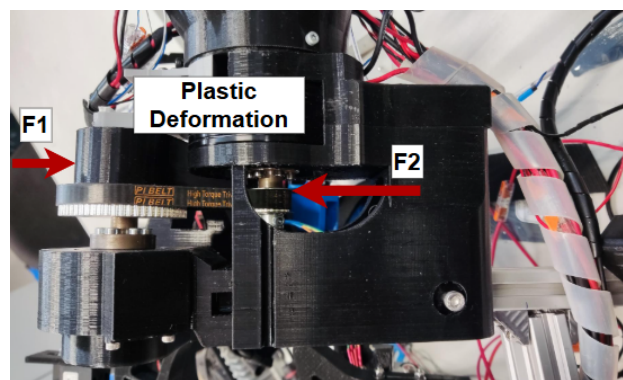


Figure 5.10: Plastic deformation problem.

Despite the limitations described, the system, although less effective than the one implemented

for the elbow, still performed according to expectations, as illustrated in Figure 5.11. The figure illustrates the system behavior, with the motor current represented by the blue line, the elbow angle by the green line, the speed by the red line, and the control signal from the load cells by the black line.

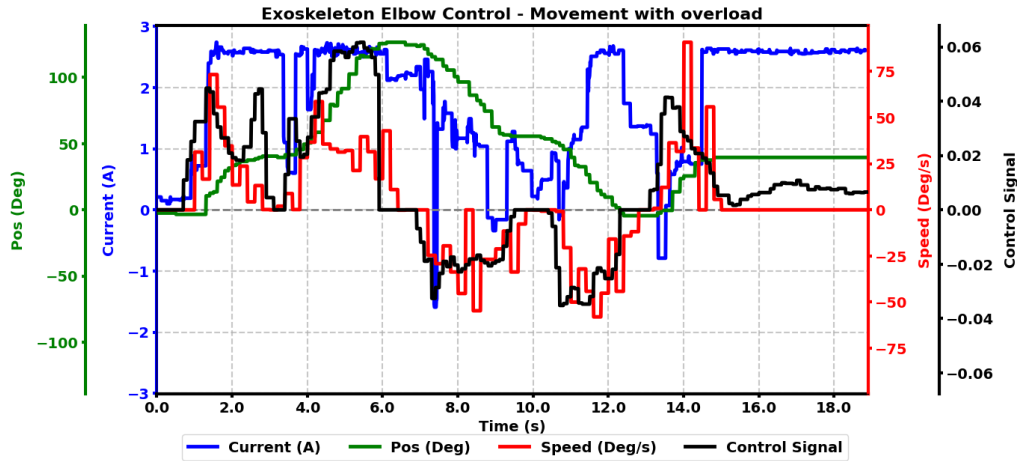


Figure 5.11: Shoulder movement.

5.1.3 Conclusions

Based on the obtained results, it can be concluded that the control system using load cells is effective for managing elbow flexion/extension movements and, although with some limitations, shoulder flexion/extension. One of the main advantages of this control strategy is its low computational demand, requiring only two PI controllers. This makes it feasible to implement the entire control logic on a simple microcontroller.

The use of load cells as a HMI method was also validated through this prototype. Nevertheless, several limitations were identified, such as the fragility of the load cells, the considerable physical space they occupy, and the need for an ADC with an amplifier, such as the HX711. The integration of the HX711 introduces additional challenges, since its communication protocol is highly susceptible to noise, complicating reliable data acquisition.

It was also acknowledged that, during construction, a more effective approach to dimensioning the exoskeleton would have been to proceed incrementally, designing and building each part before selecting the corresponding motor. In practice, this would involve designing the first DoF, fabricating all related components, including the motor mount, and then weighing the complete structure. With this data, along with the intended payload, the required torque could be calculated, allowing for appropriate motor selection. The same process would then be followed for the second and third DoFs. Finally, once the entire structure up to the fourth DoF was assembled, its total weight could be measured, and the second motor could be dimensioned based on this value. This step-by-step method would ensure that each motor selected had the required torque capacity to meet the actual system demands.

Another potential improvement to enhance efficiency would be the implementation of a mechanical locking mechanism when the PI controller's speed reference is zero. In such cases, if the joint is intended to remain static, the mechanical lock could hold the position without requiring continuous motor torque. This would reduce the current draw of that motor to nearly zero. Consequently, when a joint is not actively moving but only maintaining its position, no electrical power would be required, leading to a significant increase in the system's energy efficiency.

Overall, while the approach proved effective for simpler movements, such as those of the elbow, its application to the shoulder remains more challenging due to the complexity of shoulder kinematics.

A video of the exoskeleton in full operation is provided in Appendix [B](#).

Chapter 6

Conclusion

This chapter presents the conclusions drawn from the work developed and the results obtained. It confirms the accomplishment of the proposed goals. Finally, it outlines potential directions for future research and improvements to be explored in subsequent developments.

6.1 Conclusion from results

The work carried out in this dissertation and the results obtained have provided valuable insights into the development of exoskeletons.

One important finding, which was not addressed in any of the state-of-the-art exoskeletons analyzed, is the issue of motor heating. Since the motors often need to operate in a locked state to maintain position, significant heat is generated. Therefore, implementing effective cooling solutions should be considered a fundamental aspect in future exoskeleton designs.

The use of load cells as part of the control system demonstrated positive results for force-based interaction. However, their application presents certain limitations, particularly for rotational movements such as internal and external shoulder rotation. Their physical size also poses a challenge, as they occupy a considerable amount of space within the system.

Comfort is another critical factor identified during the development of this project. The rigid structure of the exoskeleton restricts natural movements, highlighting the need for additional DoF. Furthermore, precise alignment between the exoskeleton's joints and the user's anatomical joints is essential, as misalignments were found to cause discomfort during use.

An important conclusion from the work carried out is the demonstration of the system's scalability and the feasibility of an upper-limb exoskeleton. However, regarding comfort, achieving a more natural interaction would require additional DoF. For a fully functional upper-limb exoskeleton, using, for example, five actuators per arm, resulting in a total of ten motors for both arms. If each motor required 10 A to operate, the total current consumption would reach around 100 A, which is impractically high. This highlights the need for a more efficient system architecture to enable scalability.

The results obtained in Section 4.3 further support this conclusion, as they showed that using motors coupled with high-reduction gearboxes is far more advantageous. Such configurations can generate higher torque while consuming less power. Nevertheless, this approach introduces significant limitations in terms of space and weight, as gearboxes occupy substantial volume and add considerable mass to the system.

These findings suggest that developing an exoskeleton exclusively for the upper-limbs may not be practical or advantageous with the current solutions. In the configurations studied, even with only four DoFs (two per arm) to lift a reasonable payload of 8 kg per arm, the actuators alone would weigh around 8 kg. When the weight of the supporting structure, batteries, and other components is added, the total mass of the system would easily exceed 16 kg. Consequently, this weight would be borne by the operator, potentially aggravating the very problem the exoskeleton is intended to solve.

These conclusions indicate that, for an agricultural exoskeleton to provide sufficient strength to be truly useful, a full-body design would be required. In such a configuration, if the system is properly dimensioned, the weight of the upper-limb mechanism, even if it reached 50 kg, would be supported entirely by the exoskeleton's structure rather than by the operator. This load distribution would make the solution feasible and practical, as it would prevent the added mass from increasing the physical burden on the user.

6.2 Accomplishment of the proposed goals

Throughout this dissertation, all proposed objectives were achieved. A comprehensive state-of-the-art review on exoskeletons was conducted, followed by the design and construction of an exoskeleton. A functional control method was developed and validated, and a study was carried out to determine the dimensions of various motor and gearbox combinations to support future work in this field.

6.3 Future work

For future work, it is intended to further explore HMI systems for the control of the exoskeleton, as this is a key aspect of such devices. Another objective is to design and develop a more powerful exoskeleton by applying all the knowledge acquired in this dissertation.

This includes the development of a hand actuation system and a complete actuation mechanism for the shoulder. Furthermore, the development of a full-body exoskeleton will be explored, as this approach would allow the weight of the device and payload to be supported by the structure itself rather than by the operator, making the solution more practical and effective.

It is also intended in future work to use EMG signals as a method of validating the support provided by the exoskeleton. This will provide a clear metric of the reduction in effort required by the operator.

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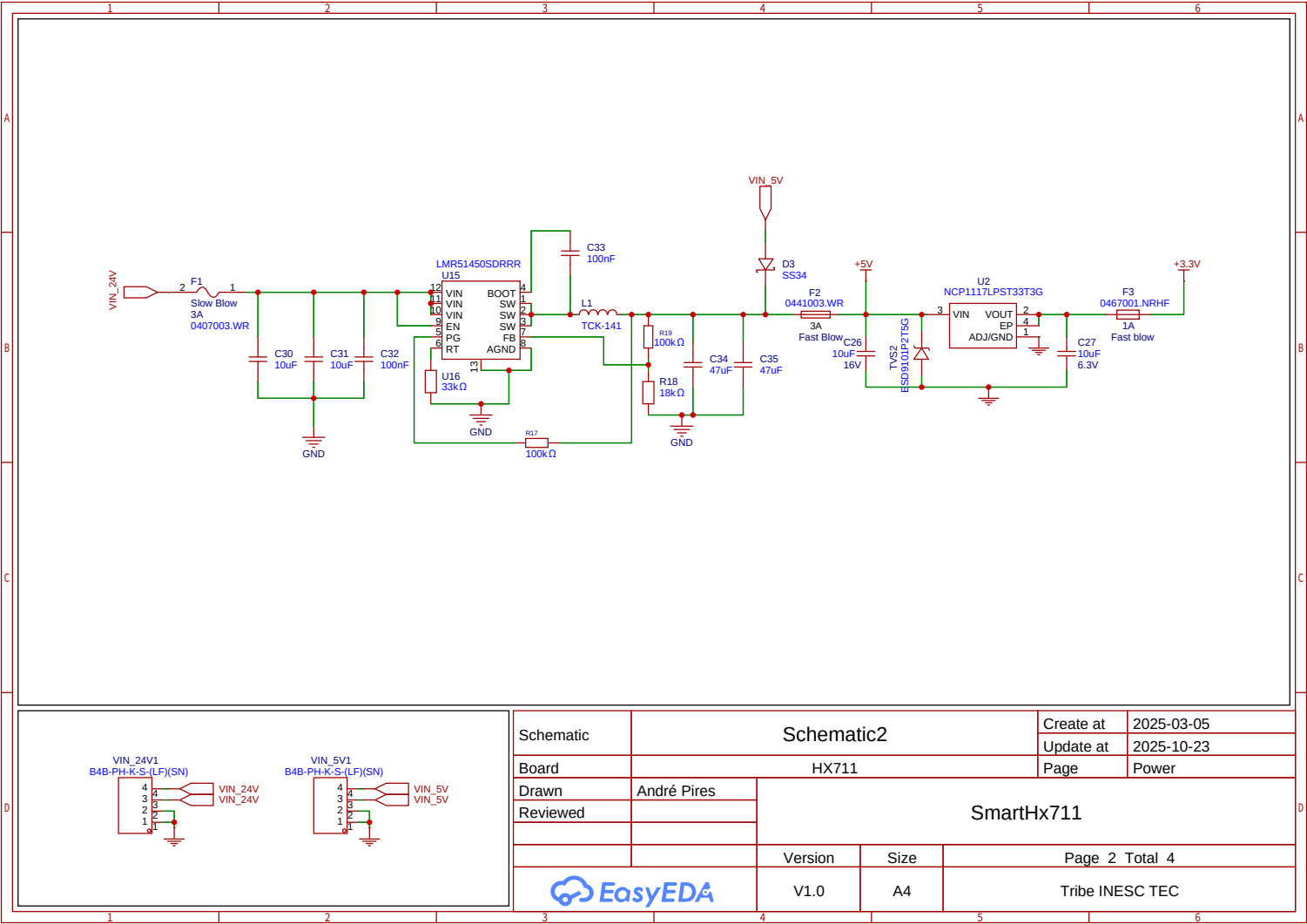
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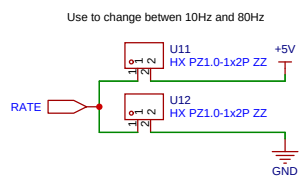
Appendix A

Smart HX711 - Schematic

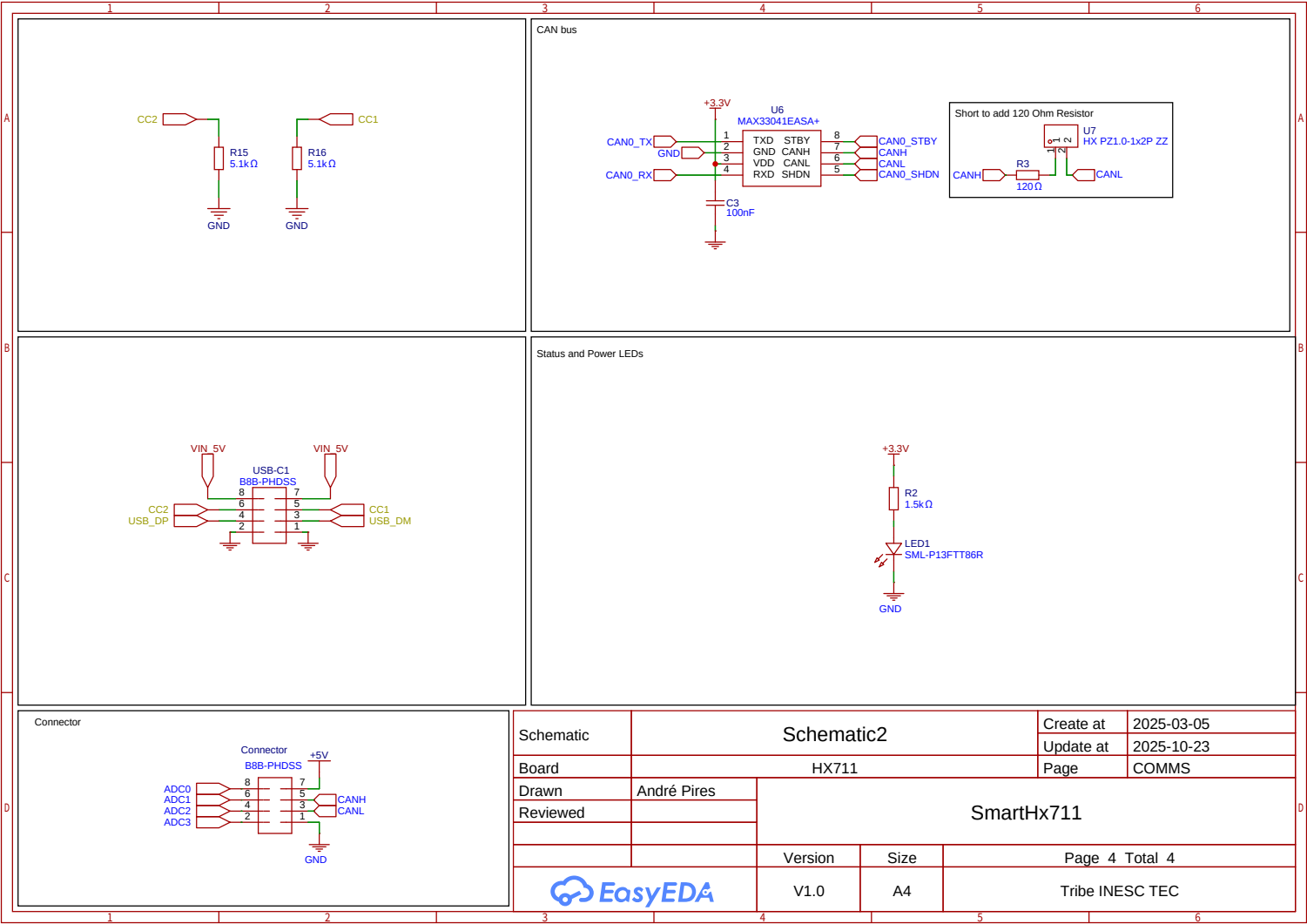
Schematic diagram of the designed PCB







Schematic	Schematic2			Create at	2025-03-05
				Update at	2025-10-23
Board	HX711			Page	HX711
Drawn	André Pires	SmartHx711			
Reviewed					
		Version	Size	Page 3 Total 4	
		V1.0	A4	Tribe INESC TEC	



Appendix B

Videos

This appendix contains videos recorded during the development and testing of the exoskeleton prototype.

B.1 Full Movement Demonstration

Videos:

- 1: <https://youtu.be/LeDhdkymNEY>
- 2: <https://youtu.be/aKwuXOMVWD0>