Design and Prototyping of Parsimonious Technologies for Upper-Limb Muscle Activation

MASTER REPORT

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Strasbourg, February, 2024

Abstract

The present research project, which is the start of my Master's thesis work is dedicated to search for low-cost technologies aimed at activating upper-limb muscles through the design and prototyping of an exoskeleton structure for rehabilitation and assistance, especially for people who have suffered a stroke. Extensive research has been conducting, first exploring the medical context surrounding the illness, particularly its consequences in the neuromotor domain, and a description of some medical imaging techniques utilized for identifying regions of the brain that are impacted. Then, a detailed review of rehabilitation methods, both robotic and non-robotic, shows specifications and complexities to design an exoskeleton for this purpose. Subsequently, the project conducts an in-depth exploration of various types of robotic actuators used in exoskeletons for physical therapy, presenting the state of the art of suitable mechanisms for assisting upper-limb rehabilitation.

Additionally, the paper introduces the concept of compliance mechanisms and their significance in enhancing the functionality and comfort for exoskeleton devices, bringing examples such as the classical serial elastic actuators and the novel Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA). Moreover, the report presents the concept of gravity compensation systems and details the mathematical model of the basic equilibrator mechanism, showing examples of recent research and explaining its importance to develop lighter and lower-cost systems. The project also summarizes the current state of the research, describing the general objectives and the mainly contributions of previous master's thesis work. As well as highlighting the general and specific objectives of the current Master's thesis work, presenting the project management, progress and milestones.

Finally, the work proposes an innovative, low-cost and light upper-limb exoskeleton with a gravity compensation system for the shoulder joint, allowing flexion/extension and abduction/adduction movement. Furthermore, there is an elbow joint compliance actuator based on MACCEPA, enabling control over the angular position of the elbow for flexion/extension movements. The proposal consists of a step-by-step description of the dimensioning of the parameters of the gravity compensation system, such as spring stiffness and maximum elongation, as well as its mathematical model. Subsequently, mathematical modeling of elbow actuator torque is demonstrated. Lastly, the work that will be carried out during the internship in the spring semester is evoked.

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Chapter 1

State Of The Art

1.1 Medical Context

1.1.1 Stroke

Stroke is defined by the World Stroke Organization as the interruption of the blood supply to part of the brain (Martins 2023). This interruption occurs either when the blood vessel is obstructed, known as ischemic, or when the blood vessel ruptures, termed hemorrhagic (Rosamond et al. 2008), as it is shown in Figure 1.1. The ischemic stroke is the most common type, normally provoked by fatty deposits or blood clots that build up in blood vessels from the heart. Preliminary studies indicate that contracting COVID-19 may elevate the likelihood of experiencing an ischemic stroke (Clinic 2023). In the other hand, several factors are associated with the hemorrhagic type, such as high blood pressure out of control, overtreatment with anticoagulants, head trauma, etc.

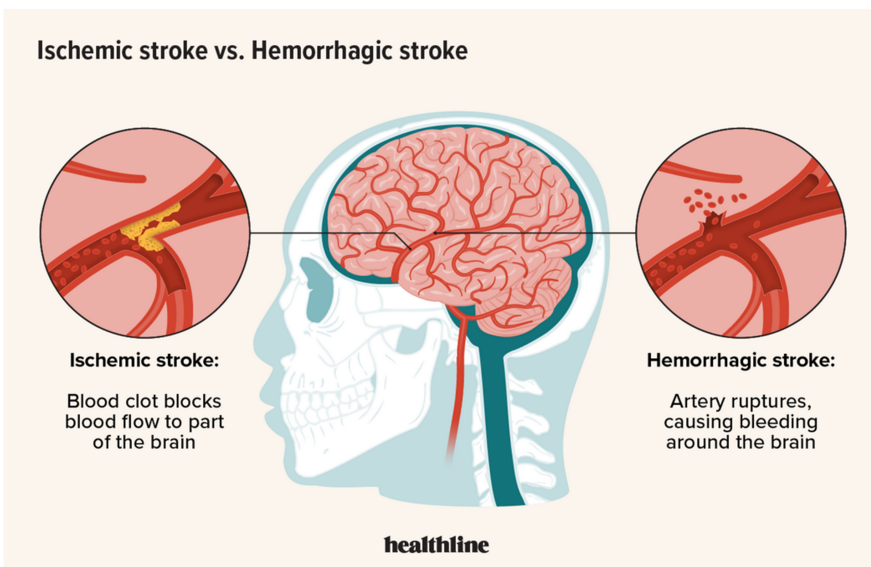


Figure 1.1: Ischemic Stroke and Hemorrhagic Stroke (HealthLine 2023).

The Global Burden of Diseases, Injuries, and Risk Factors Study estimated that from 1990 to 2019 the absolute number of incident stroke increased by 70%, with 12.2 million cases only in 2019 (VALERY FEIGIN 2021). In France, according to (Inserm 2017), one case occurs every four minutes. These numbers have drawn the attention of the scientific world in the healthcare sector to understand and find all the factors that can contribute to this medical condition to prevent it, as well as to evaluate and determine what are the best treatments post-incident. In that way, studies highlight lifestyle risk factors such as overweight or obesity, lack of physical activity, and excessive alcohol consumption, among others. As medical risk factors, high blood pressure, high cholesterol, diabetes, and cigarette smoking are key risk factors (Clinic 2023; Inserm 2017).

1.1.2 Sequelae of a stroke

The consequences of a stroke may include temporary or permanent disabilities, and the complications vary based on the duration of insufficient blood flow to the brain and the particular region affected. A common effect is the loss of muscle movement, known as paralysis, normally associated to the weakness or the inability to move on one side of the body, called hemiparesis. This condition hinders everyday tasks, including coordination, fine motor skills, and movement precision (SALMAN 2022), making stroke the primary cause of acquired disability in adults (Inserm 2017). The impaired voluntary muscle motion is provoked by the alterations in motor unit (MU) activation, where it can be observed an initial decrease in the number of MUs within 4 hours after the stroke. This reduction is probably associated with the function inactivity, since the diminution of electrical signals send by the nerves produces a certain atrophy during this interruption time (Huang et al. 2021).

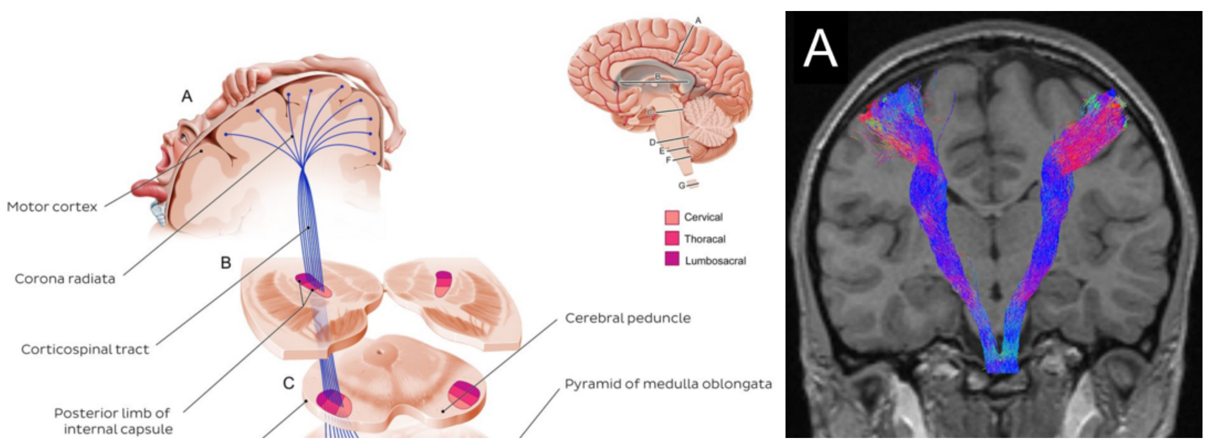
The weakness of the muscle is the most common stroke consequence, where Around 80% of stroke survivors experience movement problems, according to the Stroke Association in the United Kingdom (Association 2013). However, there are several other effects, such as the drop foot, this condition is characterized by the toes catching on the ground during a forward step, a result of weakened muscles responsible for toe elevation. Besides that, felling pain on the body due to physical weakness, memory loss, difficult to swallow and feeling less sensitive to pressure and temperature are also the sequelae of the stroke. The prospects for functional recovery differ across neurological disorders and between upper and lower limbs. A stroke with damage to the CST can result in enduring impairments in hand and finger function, coupled with imbalanced muscle tone, contributing to the challenge of executing hand opening movements (SALMAN 2022).

The aftermath of a stroke brings about diverse psychological challenges as well, since all the biological consequences bring the loss of autonomy and self-esteem, besides the diminution of the ability to endure physical and mental efforts, called stamina. All these points combined result in the most frequent psychiatric complication of stroke, the Post-stroke depression (PSD). The estimated prevalence is around 30–35%, with a range varying from 20% to 60%. Stroke patients experiencing PSD have increased mortality rates and exhibit less improvement in rehabilitation programs compared to non-depressed stroke patients. An important point observed is the lack of motivation and resistance to leaving home, both for medical consultations and rehabilitation sessions. As a result, they face poorer functional outcomes and diminished quality of life (G.L. Lenzi 2008).

1.2 Rehabilitation

1.2.1 Generalities

Rehabilitation stands as the primary foundation in facilitating the recovery of individuals post-stroke. The efficacy of rehabilitation interventions depends on several factors, such as the patient's age, the specific body part affected, the extent of neurological damage, and various other individual factors. An essential first phase in the rehabilitation journey is to evaluate the patient's condition accurately for predicting potential outcomes. This evaluation encompasses clinical assessments, neurophysiological measurements, and brain imaging techniques, such as transcranial magnetic brain stimulation and diffusion tensor imaging. The objective is to assess the integrity of the corticospinal tract (CST), as its preservation indicates a promising potential for recovery despite initial impairments (Prabhakaran et al. 2008). The corticospinal tract is directly associated with the motor cortex in the brain (Figure 1.2(a)) and can be seen using imaging of the neural tracts with T1-weighted MRI scan, this technique reconstructs and visualizes the pathways of nerve fiber bundles (Figure 1.2(b)).



(a) Overview of the CST.

(b) CST tractography projected on a T1-weighted MRI scan in coronal plane.

Figure 1.2: Corticospinal Tract - Adapted from (Physiopedia 2024).

Over the past 50 years, the field of rehabilitation has evolved significantly, transitioning from just an orthopedic-centric approach to a more comprehensive understanding regarding the movement patterns and pondering the different components that form the normal, organized movements (Wolf et al. 2002). Ongoing research continually contributes to refining rehabilitation methods and adapting them to the unique needs of patients. Demonstrated by (Patten et al. 2006), the integration of functional training and high-intensity resistance training reveals positive clinical effects, offering potential improvements in the quality of upper limb movements. Despite the widespread acknowledgment that post-stroke therapy should encompass task-oriented training and strengthening interventions, a comprehensive understanding of hemiparetic weakness, especially in upper limb rehabilitation, remains elusive (SALMAN 2022).

1.2.2 Challenges of Rehabilitation Process

Conventional therapeutic practices predominantly focus on the recovery of fundamental functions of impaired limbs in the early stages post-stroke. However, patients often face discharge without complete recovery and lacking recommendations for sustaining existing activity levels (Ivey et al. 2005; SALMAN 2022). Therefore, the efficacy of traditional rehabilitation and its duration are still a subject of investigation. In (X. Wu, Smith, and Brown 2016), motor benefits from intensive therapy compared to standard care were observed at 12- and 36-weeks post-therapy, suggesting the importance of task frequency right after the stroke.

In (George Hornby et al. 2011) is shown that high doses of task-specific locomotor training over a 6-week intervention improved other lower-limb tasks that were not practiced and were functionally distinct from the trained task, suggesting the skill transfer, where it occurs a gaining proficiency in one motor task due to practice in other motor tasks. Task-specific training is emerging as a promising neuro-rehabilitative approach for enhancing motor function after stroke. Hence, it is crucial to design rehabilitation training and devices around specific and meaningful tasks from daily life. Increasing, in that way, the specifications and constrains for the development of devices aimed at rehabilitation.

Presently, the primary obstacle confronting long-term rehabilitation is the economic burden. In 2017, a University of Oxford team conducted a study to estimate the cost of stroke in 32 countries within the European Union, along with Iceland, Israel, Norway, Switzerland, and the UK (Fernandez 2017). The findings indicated that stroke incurred approximately 60 billion euros in 2017, encompassing healthcare costs, social care (nursing), unpaid care (by relatives or loved ones), and the loss of productivity (SALMAN 2022).

1.2.3 Home Therapy

The home therapy presents a fascinating approach, where patients follow a rehabilitation program in the comfort of their homes under regular therapist supervision. The purpose of this strategy lies in the possibility to perform highly intensive exercises with larger task duration and frequency, since there exists evidences that suggest its correlation with improved motor function during chronic stages (SALMAN 2022). Besides that, recognizing the profound impact of emotional well-being on the overall recovery journey, it becomes imperative to address not only the physical but also the emotional aspects of rehabilitation. Considering the often challenging logistics of frequent hospital and clinic visits, home-based rehabilitation devices emerge as valuable tools, providing patients with a convenient and accessible means to continue their rehabilitation efforts. However, establishing and implementing an effective home therapy program and devices poses considerable challenges, both for technology incorporation, given that a majority of stroke patients are aged 70 and above, necessitating special training in advanced technologies, and the frequent need to have the assistance of a caregiver (such as a nurse or relative) to support the patient in adhering to their prescribed program.

1.2.4 Non-Robotic Rehabilitation

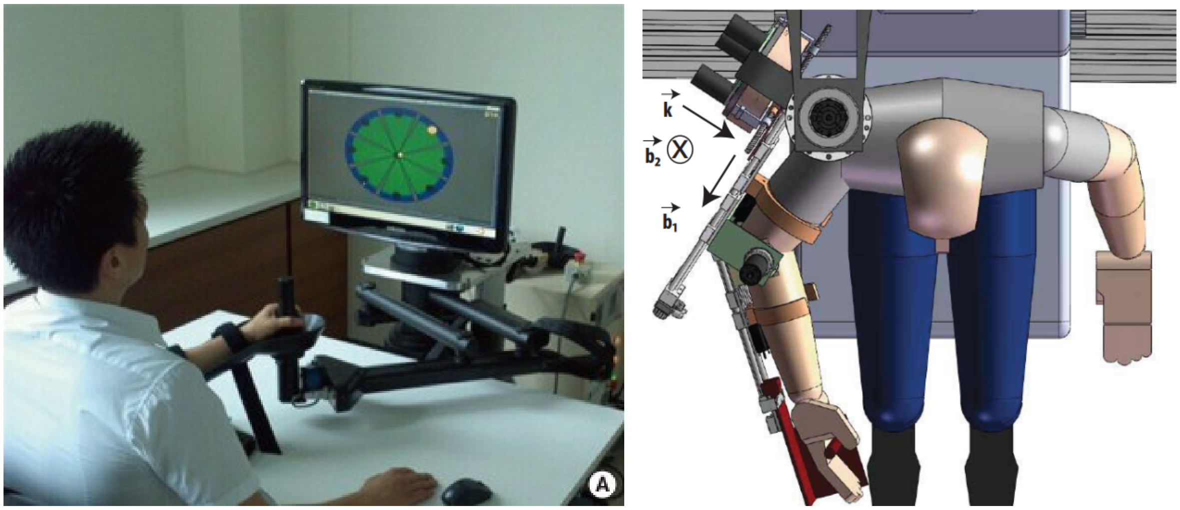
Post-stroke rehabilitation with a physiotherapist, without robotic interventions, includes functional and high-intensity resistance training to enhance upper limb movement, mitigating the motor impairments, as well as task-oriented training and strengthening interventions. Besides that, other techniques are used, such as the bilateral training, where simultaneous movements of both limbs are performed, the affected and the unaffected, to enhance coordination and motor function after stroke. As well as the Constraint-Induced Movement Therapy (CIMT) method, where the unaffected upper limb is restricted, emphasizing a high-intensity, task-oriented rehabilitation program for the affected limb (Christie, McCluskey, and Lovarini 2019). These approaches within physiotherapy, focusing on adaptive learning and specific impairments, underline the comprehensive nature of post-stroke non-robotic rehabilitation.

1.2.5 Robotic Rehabilitation

With the advancement of robotics in the 20th century, rehabilitation robots originated with Theodor Büdingen's 1910 patent for a *movement cure apparatus*, a device powered by an electric motor to assist and guide stepping motions in individuals with heart disease (Koh 2022). However, it wasn't until 1989 that commercial rehabilitation robots entered the market, marked by the MIT-MANUS, with the first clinically test in 1994 (Krebs et al. 1998). Since then, these devices aid in upper or lower limb movements, supporting motor relearning, proprioception, cognitive functions, and attention (Khalili and Zomlefer 1988). The significance of this approach lies in the robot's ability to offer quantitative and continuous monitoring during training, aiding in comprehending recovery mechanisms in repeated tasks, enhancing functional recovery in a shorter time. Nonetheless, the philosophy is not to replace therapists, but to expand treatment options, reducing the physical efforts from the physiotherapist and augment the number of patients being seen by the professional at the same time.

Currently, there exists two main categories of rehabilitation robots, the end-effector-based devices and the exoskeleton-based devices. The first type is characterized by a robotic manipulator, where the human limb – typically the hand – is connected to the machine at a single point – typically on the robot end-effector – and force is applied solely at this location (Frisoli et al. 2007). This approach was the first one developed, and the end-effector robot utilized in rehabilitation guides the human arm, executing movements along paths specified by therapists (D'Ambrosio 2023). An example of this strategy is the InMotion 2.0 (Figure 1.3(a)), designed by Interactive Motion Technologies, that allows patients to perform reaching movements through a control strategy that offers flexible assistance.

The second classification, the exoskeleton-type, shares a similar structure with the human arm and is affixed to the side of the human arm at multiple locations. The joint axis of the exoskeleton robot aligns with the human limb joint axis. The multi-location attachment of the exoskeleton makes it easier to accurately determine posture during movement, in addition to enable both the control of torque applied to each joint and the measurement of torque or position responses. Being also possible to cover the entire range of upper limb motion (D'Ambrosio 2023). The AssistOn-SE is a self-aligning shoulder-elbow exoskeleton that shows this type of configuration (Figure 1.3(b)). Post-stroke rehabilitation using robots presents both significant advantages and drawbacks. On the



(a) End-Effector-Based Device. (b) Exoskeleton-Based Device.

Figure 1.3: Robot rehabilitation main categories (Chang and Kim 2013; Ergin and Patoglu 2012a).

positive side, robotic devices offer consistent and precise movements, ensuring patients are provided with therapy customized for motor recovery. They can provide repetitive exercises, crucial for neural plasticity and functional improvement. Moreover, robots can reduce the physical strain on therapists, allowing them to focus on personalized care plans and patient motivation.

However, there are drawbacks to consider. Affordability is a key concern, as many advanced robotic devices are expensive, limiting accessibility. Portability is another issue, since most devices available on the market are large and heavy. Additionally, customization is essential, as stroke survivors exhibit diverse needs, demanding an adjustable and comfortable device, instead of a one-size-fits-all approach. End-effector-based robots provide advantages such as simpler mechanics and ease of use. They are generally more affordable, but they may lack the biomechanical complexities of human movement. Exoskeleton-based devices, attached to the limb segments, provide a more natural range of motion, but normally tend to be heavier, bulkier, and costlier.

1.2.6 Conclusion

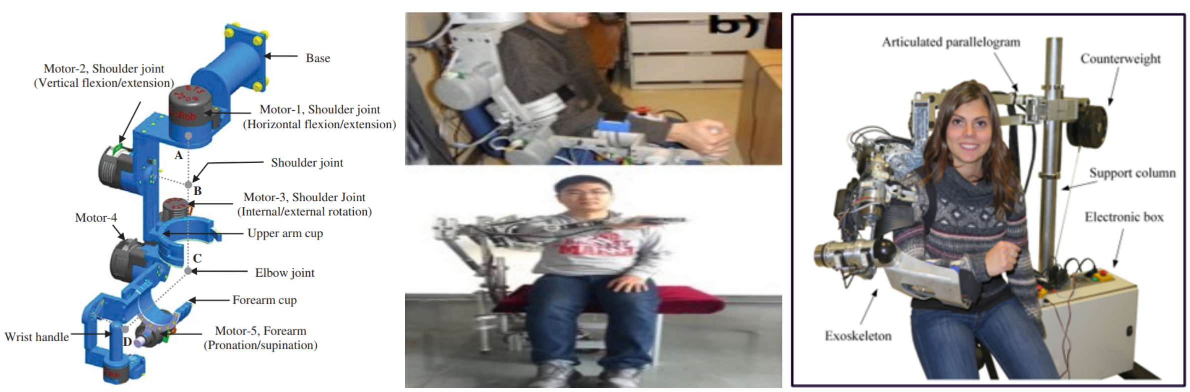
Ensuring affordability, portability, weight, and customization for rehabilitation robots is paramount. Sadly, many existing devices on the market fail to meet these criteria, being expensive, heavy, and non-adjustable. This situation emphasizes the pressing need for cost-efficient approaches in rehabilitation robotics, ensuring that the benefits of these technologies are accessible to a broader stroke survivor population. Research efforts should focus on developing devices that are not only technologically advanced but also practical, cost-effective, and adaptable to the diverse needs of stroke patients. Thus promoting better outcomes and more accessibility.

1.3 Robot Actuators

Robotic actuation refers to the mechanism or process by which a robot's components, such as joints or limbs, are set into motion or controlled. It involves the generation and application of forces or torques to enable the desired movement or manipulation of the robot. Normally an actuator is composed by an electric motor coupled with mechanical transmission to adjust the torque and velocity. In recent years, extensive research has explored various types of actuators for exoskeleton robots. This growing field aims to enhance the development of advanced robotic systems that can effectively assist individuals, optimizing performance, adaptability, and safety, mainly for rehabilitation purposes. Unlike traditional robotic manipulators, actuators for exoskeleton systems demand a collaborative configuration, emphasizing compliance mechanism and low velocity in order to align the device with the specific characteristics of the arm joints, such as DOFs and RoMs. And also to prevent potential harm, such as arm breakage. The intricacies of developing these actuators extend beyond mechanical structures, necessitating adaptive control systems that ensure a harmonious and safe interaction with the human body during rehabilitation processes, such as impedance control and some security codes in the software programming. All these points should be considered when during the actuator design project.

1.3.1 Types of Actuators

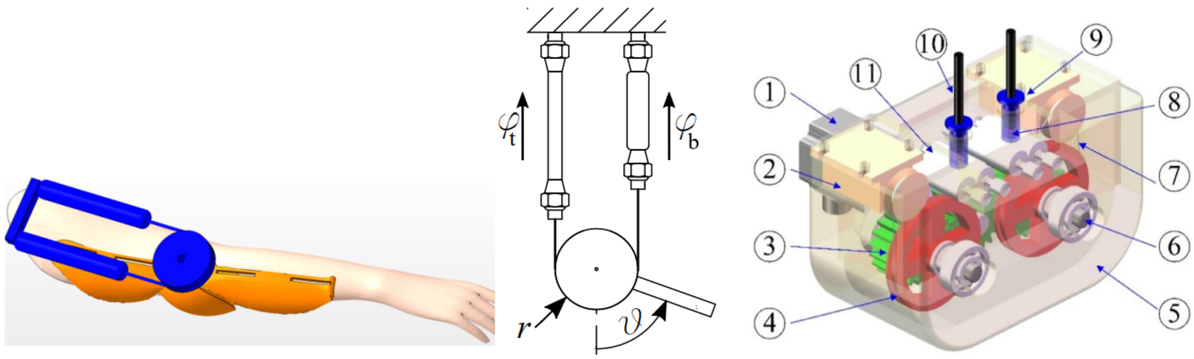
Given the specifications described in section 1.3, the most common and first to be explored approach in the papers was the direct adaptation of a classic robotic manipulator coupled in parallel to the arm structure. In this setup, the actuator, comprising an electric motor and gears, is directly aligned and fixed to the joints. As demonstrated in the works of (Rahman et al. 2012; Ergin and Patoglu 2012b; Trigili et al. 2019), shown at Figure 1.4. Furthermore, some review articles, such as (Cornejo et al. 2021), where various traditional projects are evaluated. Also in studies that explore and analyze the importance of precise alignment between the system and the human arm, as seen in (Malosio et al. 2011).



(a) (Rahman et al. 2012). (b) (Cornejo et al. 2021). (c) (Trigili et al. 2019).

Figure 1.4: Traditional actuators directly aligned and fixed to the joints.

However, in recent years, several actuation techniques have been investigated, such as Pneumatic Artificial Muscles (PAMs) (Figure 1.5(a)), classified as soft actuators, can be configured antagonistically to leverage their variable mechanical compliance for optimal adaptation of robot performance during therapy. Moreover, it can mimic the biomechanical characteristics of human muscles, enhancing coordination and safety in human-robot interaction. Exoskeleton actuators based on PAMs have been tested in the elbow joint (Zhang et al. 2008; Vitiello et al. 2012; Dragone et al. 2022), shoulder joint (Thompson 2019), lower limb application (Głowiński 2022; Zhong et al. 2020), or even for automatic evaluation of Nociceptive Thresholds in the hands of rheumatic patients (Randazzini et al. 2020). Furthermore, recent works also have designed, tested and analyzed the antagonistic configurations utilizing cables directly attached to gears and motors (Figure 1.5(b)), instead of using PAMs, as can be seen in (Wu 2019; Liu et al. 2018).



(a) PAM used in (Capace et al. 2020) (b) Cable attached to actuator unit (Wu 2019)

Figure 1.5: Alternative Actuation Techniques.

1.3.2 Compliance Mechanism

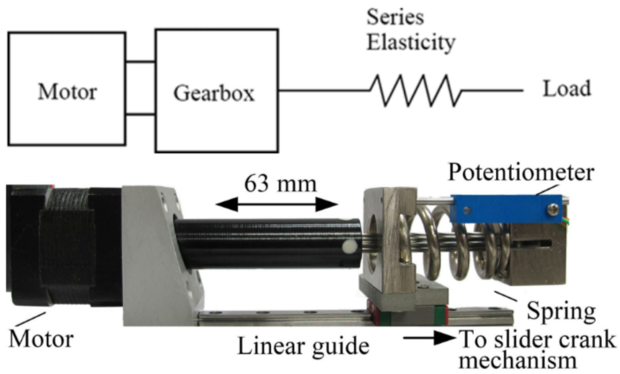
As mentioned in section 1.3, the compliance mechanisms in exoskeleton devices act as a dynamic bridge between human biomechanics and robotic assistance, seamlessly blending safety and comfort. To do so, some robot actuators have been developed and studied, for instance the classical Serial Elastic Actuator (SEA) and a novel mechanism called MACCEPA presented in the following sections.

Serial Elastic Actuator (SEA)

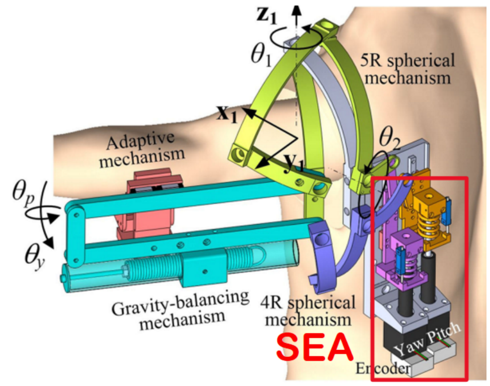
Serial Elastic Actuators (SEAs) represent an innovative approach in robotics, emphasizing compliance and energy storage. In these systems, a compliant element is serially arranged between the motor and the load, providing inherent elasticity (Figure 1.6(a)). This design choice offers several advantages. SEAs enable safer human-robot interactions as the compliance helps absorb shocks, reducing the risk of injury. The compliance in SEAs also mimics the compliant behavior of biological muscles, contributing to smoother and more natural movements in robots. In (Hsieh, Chen, et al. 2017), this system was chosen to control an actuated exoskeleton for shoulder rehabilitation (Figures 1.6(b)).

MACCEPA Mechanism

In (Vanderniepen et al. 2007) is presented a novel compliance system, named as Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA). The working



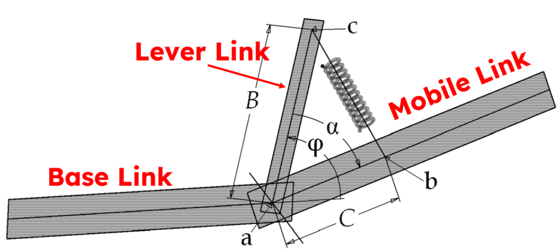
(a) SEA diagram (Junior et al. 2016) and SEA used in (Hsieh, Chen, et al. 2017).



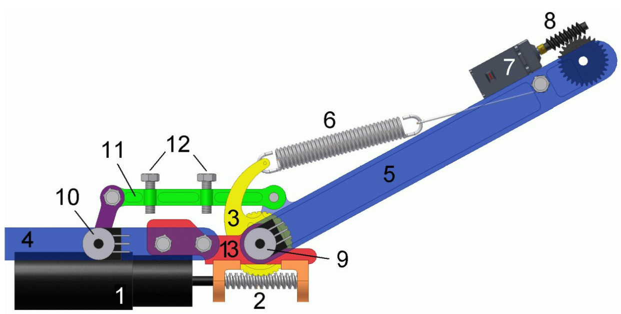
(b) SEA in (Hsieh, Chen, et al. 2017) structure.

Figure 1.6: SEA system applied in exoskeleton structures.

principle of this system can be seen at Figure 1.7(a), where three bodies pivot around a common rotation axis. The base link, acting as the grounded element, generates actuator torque. The lever link, functioning as a lever arm, rotates around the same axis. Point c on the lever link serves as the attachment point for a cable connected in series with a spring that wraps around point b, a fixed location on the mobile link. Consequently, when torque is applied, pulling the lever link, it, in turn, pulls the mobile link through the spring. The Figure 1.7(b) shows the CAD design model of this mechanism, where the left motor (1) is linked to a non-backdriveable worm gear (2), propelling the lever arm (3). Considering the left element (4) as the reference, the lever arm sets the desired position for the right element (5). The spring (6) subsequently pulls the right element towards alignment with the lever arm and the desired position. Online adjustment of the spring's pre-tension and its constant is achievable through the second motor (7) and a non-backdriveable worm gear (8). Therefore, the MACCEPA allows to control both position and compliance of the system, i.e., the variation of spring's pre-tension by the second motor (7) increase or decrease the relationship between the torque and the angle α.



(a) MACCEPA schematic drawing.

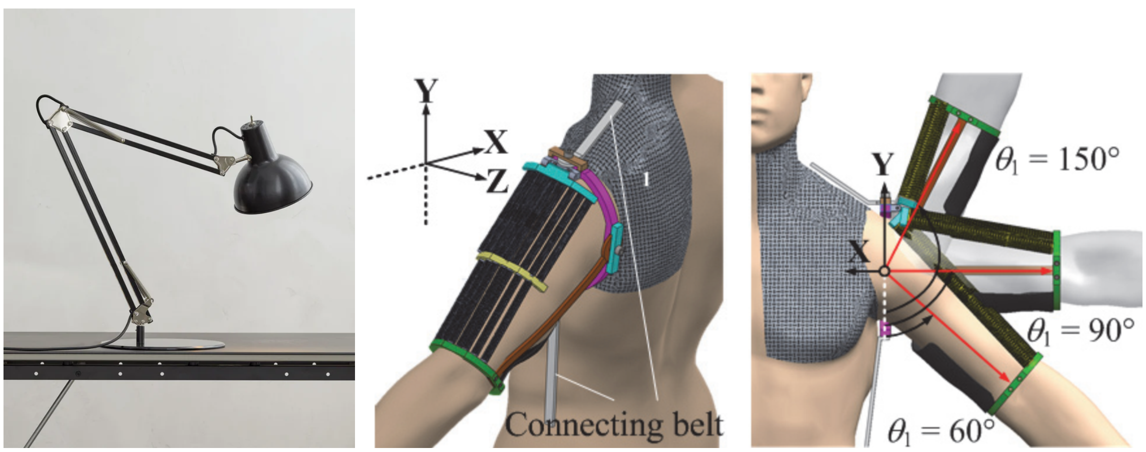


(b) MACCEPA CAD design.

Figure 1.7: MACCEPA working principle and CAD design (Vanderniepen et al. 2007)

1.4 Gravity Compensation System

A Gravity Compensation System is a mechanism designed to balance the effects of gravitational forces on a system or object. There are two primary types: a counterweight system, where an opposing mass is used to counterbalance the gravitational forces acting on the target object, and elastic element system, in which a device performs the same task by storing potential energy, normally using springs or rubber bands. A common application of these systems lies in some desk lighting (Figure 1.8(a)), where the globe can be adjusted in various static orientations, meaning it remains stable without variations in gravitational potential energy. In the context of exoskeletons, it is a mechanism designed to counterbalance the effects of gravity on the user's limbs, reducing muscular effort and fatigue (Figure 1.8(b)). The significance lies in its capacity to use lighter motors and batteries, since the torque required to move the user's limbs reduces, thereby decreasing the overall weight of the exoskeleton. This design optimization not only contributes to a more ergonomic and user-friendly device but also lowers production costs and extended battery life, enhancing the accessibility and environmental sustainability of exoskeleton technology.



(a) Spring Balanced Lighting.

(b) A Gravity-Balanced Exoskeleton.

Figure 1.8: Gravity compensation System applied to a lighting (Midgard 2023) and exoskeleton (Hsieh and Lan 2014)

1.4.1 Basic Equilibrator

A basic equilibrator system (Figure 1.9(a)) is a simple mechanical arrangement designed to maintain balance or equilibrium within a system (W. Van Dorsser et al. 2008). In this configuration, the potential energy U_p remains constant and is equal to the sum of the mass's potential energy U_m and the energy stored in the spring U_s. For the depicted gravity equilibrator in Figure 1.9(b), this relationship can be expressed as follows.

$$U_p = U_m + U_s = mgL\cos\varphi + \frac{1}{2}k(a^2 + r^2 - 2ra\cos(\varphi)). \tag{1.1}$$

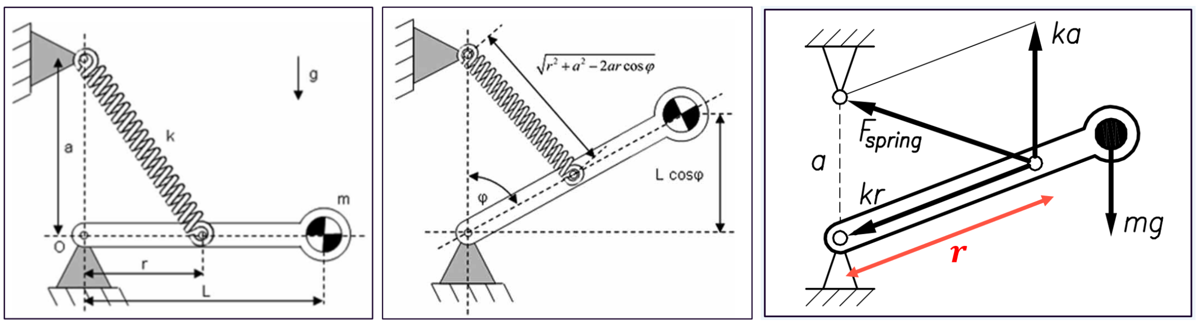
Here, m denotes the payload mass, g is the gravity acceleration, L is the length of the weight arm, φ is the angle between the vertical and weight arms, k is the spring stiffness, a is the distance from the pivot to the fixed spring attachment point, and r is the distance from the pivot to the spring attachment point on the weight arm. For equilibrium, the energy function must reach a local minimum, thus

$$\frac{\partial U_p}{\partial \varphi} = -mgL\sin\varphi + rka\sin\varphi = 0, \tag{1.2}$$

therefore, the condition for static balancing, for any φ, lies in following relationship

$$mgL = kar, \tag{1.3}$$

in which, it represents the equality between the torque from the mass and the torque from the spring (Figure 1.9(c)).

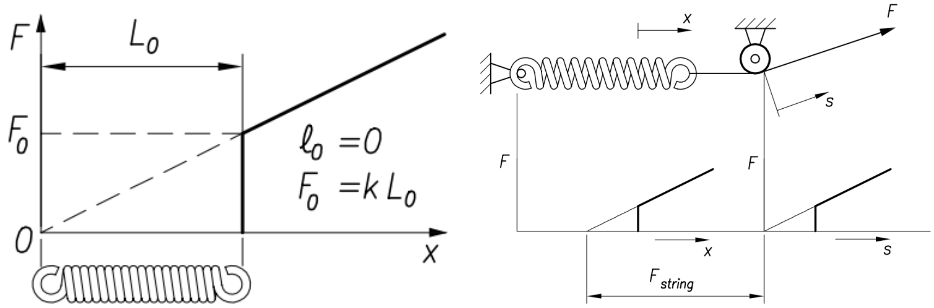


(a) (b) (c)

Figure 1.9: Basic Equilibrator (Herder 2001; W. Van Dorsser et al. 2008).

Note that the classical elastic energy equation, given by $U_s = \frac{1}{2}k\Delta x^2$, is dependent on the variation in the spring length Δx. However, in equation (1.1) the elastic energy is formulated as a function of the current length of the spring x, given by the cosine law $x = \sqrt{a^2 + r^2 - 2ra\cos(\varphi)}$. This mathematical imposition results in the need to use a spring whose applied tension matches exactly the current length x, i.e. the elastic force must be given by $F = kx$, instead of the classical Hook law $F = k\Delta x$ (Herder 2001). A spring that behaves in this way is known as zero-free-length springs (Figure 1.10(a)). To achieve this special behavior, during manufacturing, the metallic wire is wound around the bobbin with precision, ensuring an exact pre-tension is applied. This process establishes that the intrinsic force F_0 is inherently proportional to the spring's initial length (Figure 1.10(a)). Nevertheless, these springs are not readily available on the market, since it depends on the values of k, a and r, being too specific for each project and expensive to order it. Hence, the cost-effective alternative is to emulate the behavior using some techniques, for instance by storing the free length behind a guiding element, like passing a string through a guide eye or a pulley (Figure 1.10(b)). This configuration enable pre-tension the system and use a cable to match the spring length x, ensuring that the free end of the string initiates force buildup upon leaving the guide eye or pulley.

In that way, given a constant mass m and center of mass L, by using a zero free length spring and equation (1.3), it is possible to project a basic equilibrator by choosing the spring stiffness k and the two lengths a and r. For systems in which the mass and/or the center of mass vary with time, it is necessary to adjust online at least one of these parameters (k, a or r), aiming to keep the equality of equation (1.3). In (Hsieh, Chien, and Lan 2015), the basic equilibrator using pulleys is implemented in its exoskeleton structure (Figure 1.11(a)). In addition, it is suggested that an adjusting motor with a coil-constraining screw be used with the objective to change the spring stiffness (Figure 1.11(b) in the right). To do so, a certain number of spring coils are constrained by a screw with the same spring pitch distance, changing in that way the number of active coils of the spring.



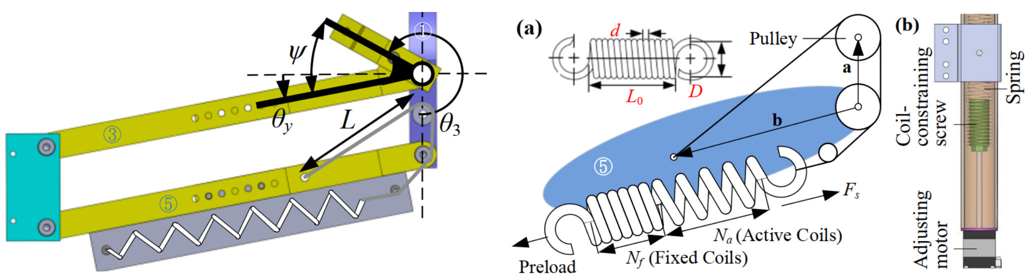
(a) Zero Free Length Spring (b) Zero Free Length Spring emulated by a guiding element

Figure 1.10: Zero Free Length Spring (Herder 2001).

Figure 1.11(b) shows that given a total coils number N, it is possible to constrain a certain number of coils N_f and release the rest of coils N_a, maintaining it actives. Doing that, the adjusted stiffness is given by the ratio between the active number of coils and total number of coils, as follows

$$K_a = \frac{N}{N_a}K, \tag{1.4}$$

where K is the spring original stiffness, and K_a is the actual modified spring stiffness. Furthermore, in (W. Van Dorsser et al. 2008), a novel mechanism is introduced wherein a specialized screw and nut achieve the same adjustment of spring stiffness as described, but without consuming energy, i.e., without the use of any motor or active device. Other energy-free adjusting mechanism is presented in (Wouter D Van Dorsser et al. 2007), where the equality of equation (1.3) is maintained by altering the value of a and r simultaneously. In recent years, gravity compensation systems,



(a) (b)

Figure 1.11: Basic Equilibrator used in (Hsieh, Chien, and Lan 2015).

particularly basic equilibrators, have been used in various exoskeletons designed for rehabilitation purposes. The integration of these systems in exoskeleton structures has become a pivotal strategy to optimize weight and cost in the development of devices. In (Hsieh, Chen, et al. 2017) this strategy is implemented, as can be seen in Figure 1.6(b), as well as in (Hsieh and Lan 2014), where a full passive mechanism based in basic equilibrator is designed, shown in Figure 1.8(b). Moreover, (Sui et al. 2017) present a complete upper-limb exoskeleton where two gravity compensation system is designed, one of these mechanisms incorporates an active system for real-time adjustment of the length a, where a motor modifies the spring's attachment point. This dynamic adjustment of a accommodates changes in weight or center of mass, keeping the torque balance.

1.5 The Present Research Context

1.5.1 General Objectives

The rising demand from stroke patients and the necessity for cost-effective robotic devices prompted the iCube laboratory, led by Professor Bernard Bayle, in partnership with the Politecnico Milano, led by Professor Marta Gandolla, to research and develop parsimonious technologies and methods for upper limb rehabilitation. The team also includes the Engineer Benoit Wach and the PhD student Beatrice Luciani, with past collaboration of Dr. Maciej Bednarczyk. In pursuit of this goal, the supervisors of the current project have assembled an interdisciplinary team of researchers, comprising specialists in neuroengineering and experts in mechatronics engineering. The project started in 2022-23 and involved two Master's theses. One thesis focused on developing a robotic exoskeleton structure, while the other centered on designing bracelets to detect the onset of patient muscular activity.

The current research aims to investigate, from the mechatronic's point of view, the state of the art of new mechanisms, such as compliance structure, gravity compensation system using springs in conjunction with compact torque motors, low-cost sensors to detect muscle activation, and others. In addition to evaluate the robotic strategy from a biomechanical point of view, focusing to examine which strategy will bring better rehabilitation, prioritizing compact and light devices with affordability and usability principles. Therefore, the research has designed and prototyped a novel parsimonious exoskeleton structure, aiming to achieve the diverse needs of a wide range of users. It should be user-friendly, intuitive, and efficient, making it suitable for home therapy as well.

1.5.2 Biomechanical Point of View

As mentioned in the subsection 1.5.1, the current project profits from contributions made by other master's thesis. In (D'Ambrosio 2023), an excellent biomechanical study was made analyzing the arm degrees of freedom (DOFs), as well as the range of motion (RoM) of each joint, where some alignment mechanisms were proposed. In addition, the dissertation presents a study of estimating the length and weight of the arm based on the total mass and height of the patient, bringing important specifications for the exoskeleton prototyping (Figure 1.12 and Appendix A).

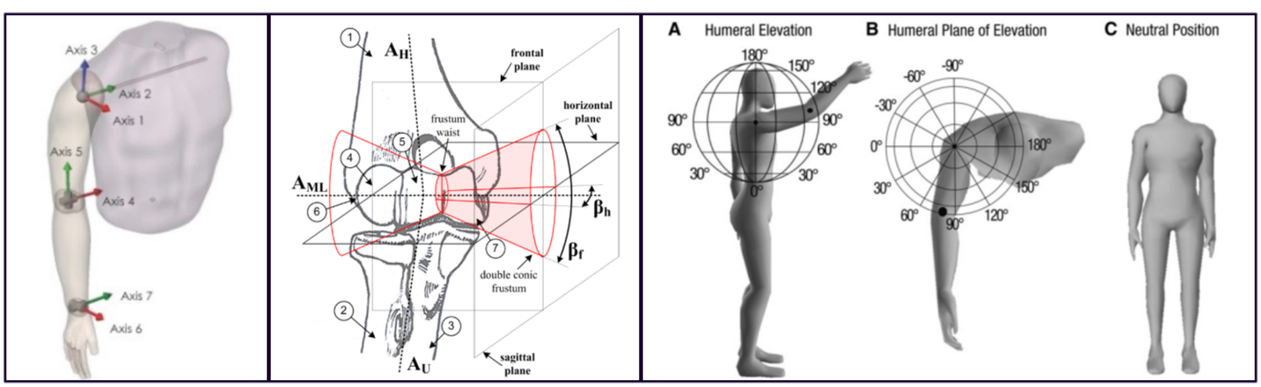
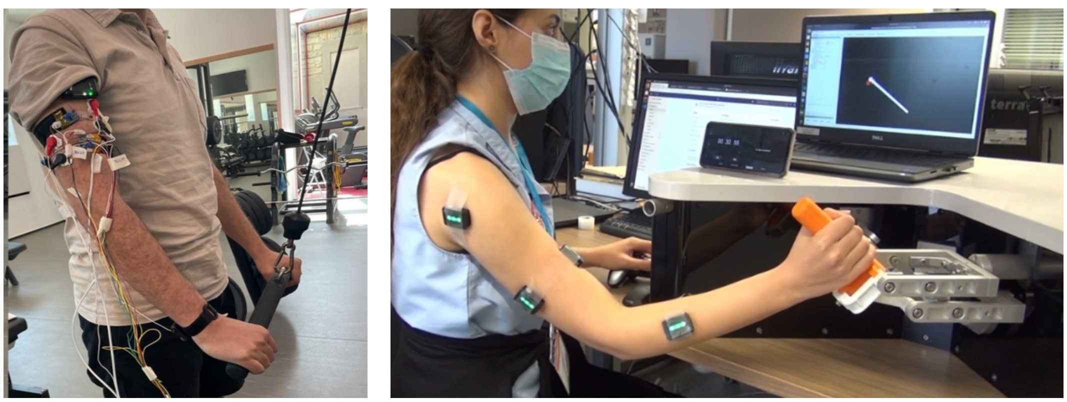


Figure 1.12: Biomechanic Study of the Arm - Adapted from (D'Ambrosio 2023).

1.5.3 Muscle Contraction Detection and ROS2 Environment

The development of low-cost technologies to detect muscle activation in patients with hemiparesis remains a key challenge in advancing robot-assisted therapies. Recent works frequently employ surface electromyography (sEMG), known as the gold standard due to their excellent ability to detect the electrical signals that initiate muscle contraction (Casaccia et al. 2015). However, these devices are often expensive, limiting widespread accessibility. Therefore, the present research has investigated alternative sensing options that can validate devices with sufficient performance to control the exoskeleton and execute rehabilitation tasks. In (Azhar 2023), the study investigates four different sensing systems based on low-cost sensors, including Force Sensing Resistor, Strain Gage, Commercial Flex Sensor, and a purpose-designed Flex Sensor using the piezoresistive material Velostat (Figure 1.13(a)), in which the signals were processed, analyzed and also compared with the sEMG signals. Moreover, in (SALMAN 2022), a well-reviewed bibliography of the medical context is presented as well as the development of an impedance control in ROS2 Environment to handle an end-effector device (Figure 1.13(b)). In addition, a cost-effective bracelet using FSR sensors and a microcontroller was designed and prototyped (Figure 1.14), where the signals acquired were capable to mimic a manipulator robot in the ROS2 environment (Alves 2023).



(a) Experimental Set-up of Azhar. (b) End-Effector device of Salman.

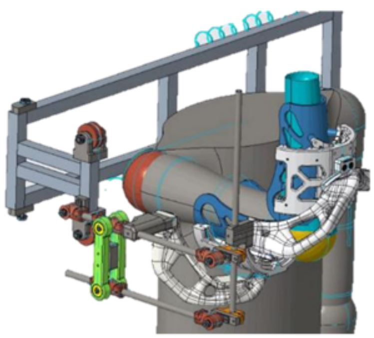
Figure 1.13: Thesis Contribution from (Azhar 2023; SALMAN 2022).

(a) Cost-Effective Bracelet Prototype. (b) Data sending to ROS2.

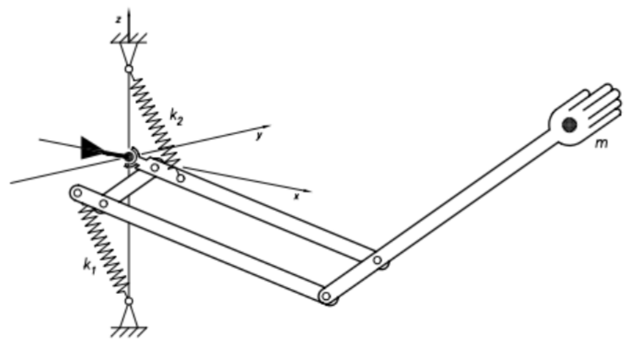
Figure 1.14: Cost-effective Bracelet using FSR sensors (Alves 2023).

1.5.4 Mechanical Structure

With regard to the mechanical structure of the exoskeleton, in (D'Ambrosio 2023) was proposed the passive system in Figure 1.15(a), in which a gravity compensation system was designed, based on the anthropomobile arm (Figure 1.15(b)) defined by (Herder 2001). This system is able to keep the arm statically – with zero potential energy – in different positions by using an arrangement of springs. Additionally, the thesis recommends employing a slider-crank mechanism for the actuation of the system. However, despite the simplicity and linearity of the system, the proposed project faces challenges in implementing a lightweight actuator on the structure, which complicates the development of future compact versions of the device. Thus, the current master's thesis will propose an actuation system with alterations in the mechanical structure to improve overall performance and functionality.



(a) Exoskeleton Structure.



(b) Anthropomobile arm.

Figure 1.15: Exoskeleton Structure proposed by (D'Ambrosio 2023) based on Anthropomobile arm, defined by (Herder 2001).

1.5.5 Current Master Objectives

Given this context, the main contribution of the present Master thesis project is to design and control a parsimonious exoskeleton prototype for upper-limb rehabilitation and assistance, emphasizing the principles of affordability and user-friendliness. The device should be capable to actively perform, i.e. using electrical motors, the flexion and extension movement at the elbow joint based on the monitoring of the patient intention to move. In addition, a passive gravity compensation system for the shoulder must be implemented. To accomplish that, the work plan comprises two work packages: one for the Fall semester and another for the Spring semester, each one subdivided into two stages as shown in the Table 1.1. The project management of this thesis is available in the Appendix B.

Table 1.1: The Project Work Plan

Stages	**Tasks**	**Work Packages**
Stage 1	Study the state of the art, both medical context and robot's actuator	**Fall Semester**
Stage 2	Propose an Actuation with CAD design and Math Model.	
Stage 3	Build Robot with the muscle activation device	**Spring Semester**
Stage 4	Control system using ROS2.	

Chapter 2

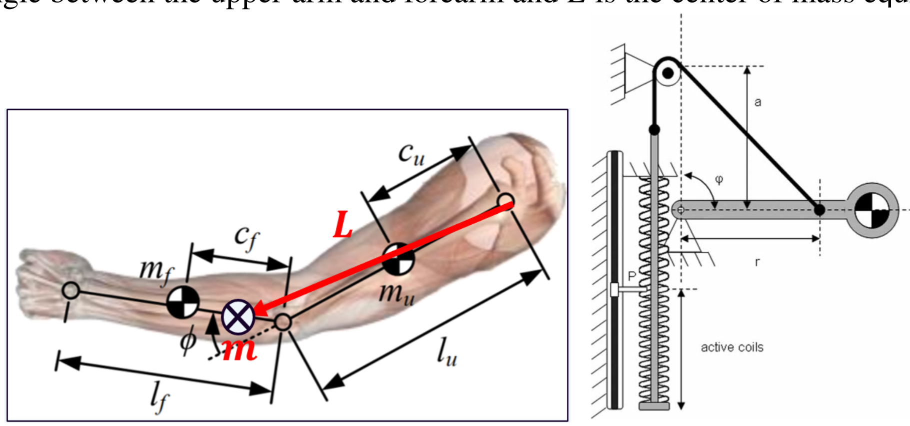
Actuator Proposal

2.1 Modeling of the Gravity-Balancing Mechanism

In the development of a Gravity-Balancing Mechanism for an upper-arm exoskeleton, the initial step involves precise measurement or estimation of the weight and length of the user's arm. These parameters are pivotal in computing the equivalent mass and center of mass, crucial factors for designing an effective balancing torque equation. To do so, (Frigo et al. 2018) provides a table with an estimation, in terms of percentage, of the arm mass and length based on the total mass and height of the individual. This biomechanical study is well-reviewed in the work of (D'Ambrosio 2023), shown in Figure A.1. Once the weight and length of upper-arm and forearm are estimated, it is possible to compute the equivalent mass and center of the mass by following the Figure 2.1(a), where m_f and m_u are the masses of the forearm and upper arm, respectively, l_f and l_u are the total lengths of the forearm and upper arm, respectively, and c_f and c_u are the center of masses of the forearm and upper arm, respectively. Therefore, the equivalent mass and center of mass is given by

$$m|L| = m_u c_u + m_f(l_u + c_f \cos(\phi)), \tag{2.1}$$

where ϕ is angle between the upper-arm and forearm and L is the center of mass equivalent.



(a) Parameters of a human's upper limb. (b) Basic Equilibrator.

Figure 2.1: Modeling of the Gravity-Balancing Mechanism - Adapted from (Hsieh, Chien, and Lan 2015; W. Van Dorsser et al. 2008).

Thus, replacing equation (2.1) in equation (1.3), the basic equilibrator parameters can be chosen in order to project the gravity-balancing mechanism, as follows

$$kar = g(m_u c_u + m_f(l_u + c_f \cos(\phi))). \tag{2.2}$$

It can be seen, that the balancing changes depending on the angle ϕ. Figure A.2 shows that the elbow range of motion (RoM) for flexion-extension movement is an average of 9° ± 7 until 137° ± 7. Thus, considering the maximum possible values of this study, the feasible range of ϕ will be considered

($2° \leqslant \phi \leqslant 144°$). Hence, considering the mass and height of the user, the gravity compensation system can be projected as follows:

1. Estimate the masses and lengths of upper-arm and forearm using the table shown in Figure A.1. For the lengths it is also possible to simply measure them with a measuring tape.

2. Consider an initial value of ϕ as an intermediate value of its range, for example $\phi_0 = 73°$.

3. Choose a feasible initial value for the length r, typically 30% of the upper-arm length (l_u), based on previous works.

4. Define that $a = r$. Doing this, when the weight arm is in the upright position, i.e. $\varphi = 0°$ (Figure 2.1(b)), the spring is fully relaxed. Since the current spring length is given by the cosine law $x = \sqrt{r^2 + a^2 - 2ar\cos(\varphi)}$, as can be seen in Figure 1.9(b). As well as the maximum spring elongation occurs when $\varphi = 180°$, thus $x_{max} = 2.r$.

5. Then, the initial value of spring stiffness k_0 can be computed by applying the arm values estimated and the values of a and r in equation (2.2).

6. Once the spring stiffness is computed and the range deflection is defined ($0 \leqslant x \leqslant 2.r$), it is possible to look for an off-the-shelf spring available on the market that has a k value close to that designed and a deflection range greater than or equal to the defined one.

7. Then, the final k of the commercial spring is considered and the values of r and a are finely adjusted to maintain the equality of equation (2.2).

8. Finally, a range of r or k can be computed by varying ϕ inside its range ($2° \leqslant \phi \leqslant 144°$). In that way, it is possible to project one mechanism to compensate online the variation in the center of mass caused by the flexion movement of the forearm. The same reasoning can be applied if the user holds 1 or 2 kg of weight in their hand.

2.2 Modeling of the Elbow Joint Actuator

To model the elbow joint actuator, the initial step involves determining the maximum torque demand. Subsequently, an assessment of the operational torque required by the system is conducted. For the present application, the maximum torque can be defined the sum of arm weight torque and the torque from some load used during the rehabilitation, thus

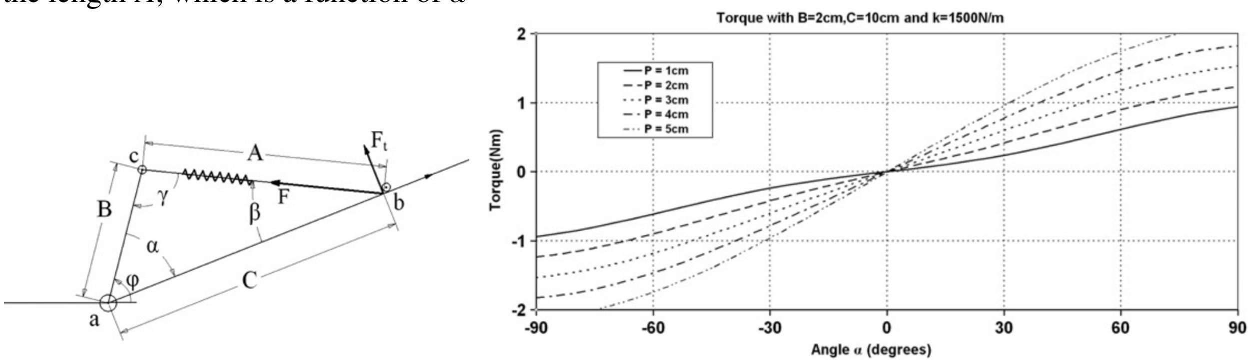
$$T_{max} = (m_f.g.c_f) + (m_{max\_load}.g.l_f), \tag{2.3}$$

where the m_{max_load} is the maximum mass of the load used and held in the user hand. Computed this, the torque of the system projected should be greater than this maximum torque required

$$T_{sys} > T_{max}. \tag{2.4}$$

The actuator chosen will be based on the MACCEPA system described in subsection 1.3.2. Therefore, to model the torque applied the mechanism scheme is shown in Figure 2.2(a). Where here a is the rotation point, b the fixed point on right body, the cable connecting the spring to the pre-tension mechanism is routed around this point. The c is the fixed point on lever arm, where the spring is attached, T_{sys} the Torque applied by MACCEPA, F the Force due to extension of the spring, F_t

the Component of F orthogonal to line ab, that generates torque. K is the spring constant, B is the length of the lever arm, C is the distance between point a and point b. α is the angle between the lever arm and right body and β is the angle between A and C. And P is the extension of the spring caused by pre-tensioning, that it is the total extension of the spring when $\alpha = 0$. Observe that $|C - B|$ is constant and equals the length A when $\alpha = 0$, and that the total spring extension is given by $A - |C - B| + P$, where two independent causes produce the spring elongation, the variation of the length A, which is a function of α and the setting of the pre-tensioning P (Van Ham et al. 2007).



(a) MACCEPA scheme.

(b) Torque as a function of angle α with varying pre-tension.

Figure 2.2: MACCEPA system (Van Ham et al. 2007).

Hence, the torque of the system is given by:

$$T_{sys} = CF_t = CF\sin(\beta), \tag{2.5}$$

where $F = K(A - |C - B| + P)$, thus

$$T_{sys} = C\sin(\beta)K(A - |C - B| + P). \tag{2.6}$$

Finally, using the sine rule $\frac{\sin(\beta)}{B} = \frac{\sin(\alpha)}{A}$ and the cosine law $A = \sqrt{B^2 + C^2 - 2BC\cos(\alpha)}$, the generated torque is then:

$$T_{sys} = KBC\sin(\alpha)\left(1 + \frac{P - |C - B|}{\sqrt{B^2 + C^2 - 2BC\cos(\alpha)}}\right), \tag{2.7}$$

as can be seen in Figure 2.2(b). It is shown mathematically in (Van Ham et al. 2007) that for small values of α the equation (2.7) can be linearized resulting in equation (2.8). And it is shown graphically that this linearization works well for α up to 45°.

$$T_{sys} = \alpha\left(\frac{KBC}{|C - B|}\right)P. \tag{2.8}$$

Therefore, the MACCEPA can be projected by choosing the values of K, B and C, respecting the constraint shown in equation (2.4) and considering that $(0 \leqslant \alpha \leqslant 45°)$. As mentioned, the torque also varies depending on the spring pre-tension P given in centimeters, as shown Figure 2.2(b).

2.3 Initial CAD Design

The Figure 2.3 shows the initial skeleton for the envisioned CAD design of the exoskeleton proposed. The project has been developed using skeleton structure in PTC CREO CAD software, with collaboration of engineering Benoit Wach. In Figure 2.3, UA, FA and HA represent the coaxial line of Upper-Arm, Forearm and Hand, respectively. The Base is the robot ground that can be fixed at the user's back or on the floor. The gray spherical link is fixed on the base and the green mobile spherical link moves around the revolute joint 1. The blue structure attached to the upper-arm moves around the revolute joint 2, and the orange link attached to the forearm moves around the revolute joint 3. The kinematic chain of the robot is shown in Figure 2.4. Spring 1 is associated to the gravity-balancing mechanism projected in section 2.1, and Motor 1 is responsible to change the r value of the basic equilibrator to keep the torque balance when there is variation in the angle of the elbow ϕ. Finally, the Motor 2 and Spring 2 are the part of the MACCEPA mechanism Figure 1.7(b). Moreover, another small motor will be added at the right end of the orange link, with the objective to pre-tension the Spring 2.

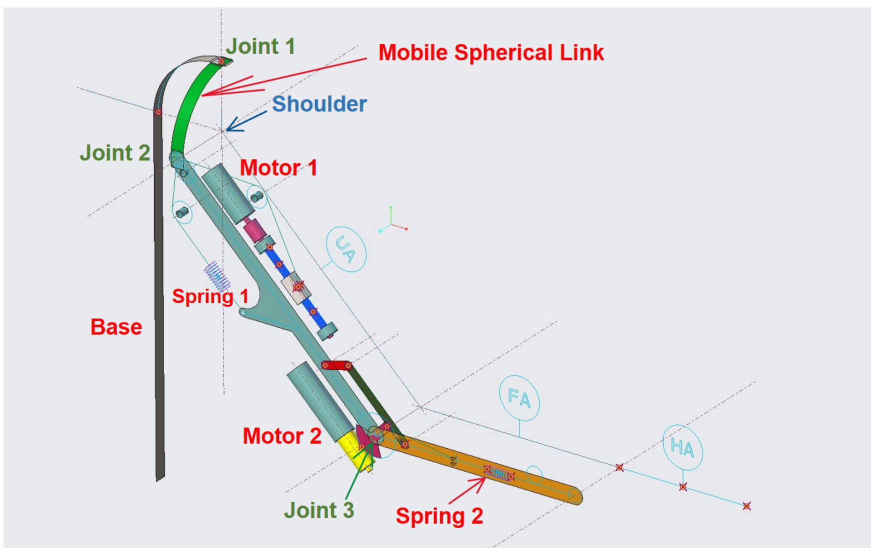


Figure 2.3: The initial skeleton for the envisioned CAD design.

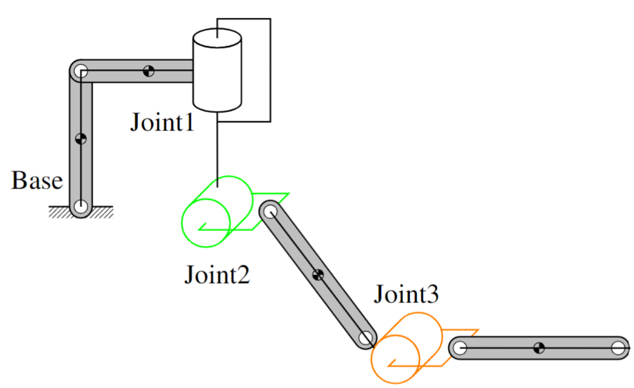


Figure 2.4: Exoskeleton kinematic chain.

Chapter 3

Conclusions

In this Master thesis project, the primary aim was to design and prototype a parsimonious exoskeleton structure for upper-limb rehabilitation and assistance, focusing on affordability, user-friendliness, and adaptability. The project is divided into two main phases, spanning the Fall and Spring semesters, each comprising two stages, with project management details provided in Table 1.1 and Figure B.2. Extensive research was conducted in the medical context, rehabilitation and robotic actuators. Moreover, training in CREO CAD software is included in the Fall semester curriculum.

Robotic rehabilitation offers precise and repetitive movements beneficial for neural plasticity and therapist strain reduction, yet concerns over affordability, portability, and customization persist. Conversely, non-robotic approaches emphasize task-oriented training but may overlook the intricate biomechanical nuances of human movement. The proposed exoskeleton incorporated a passive gravity compensation system for the shoulder and an active system for elbow flexion and extension, driven by monitoring the patient's movement intention. Addressing these challenges with its cost-effectiveness, ease of use, and adaptability. The mechanism designed for the shoulder offers low cost, lightness and mathematical simplicity, even allowing abduction/adduction movement. On the other hand, it lacks coverage for all shoulder degrees of freedom and lacks an active actuator to move the limb directly, particularly on the shoulder joint. The elbow system is characterized by its affordability, lightweight design, compactness, and compliance mechanism. Additionally, it enables adjustment of the system's torque by modifying the spring pre-tension, which can be synchronized with forearm muscle contraction. For example, when the user lifts a load, requiring increased arm torque, this can be detected by measuring forearm muscle contraction and translated into heightened spring pre-tension within the MACCEPA system. However, it also acknowledges limitations regarding biomechanical intricacies, constraining the elbow DOFs. Thus, further research and development to enhance performance and functionality are necessary. Ultimately, this project contributes to the advancement of affordable rehabilitation robotics, investigating new parsimonious technologies to bring accessibility for stroke survivors.

3.1 Future Developments

In future development, several tasks will be undertaken, including finish the CAD design. Then, the exoskeleton weight will be considered in simulation, evaluating its significance in the gravity compensation system and elbow actuation, despite often being neglected in general works when compared to the arm weight. Furthermore, the energy-free approach to adapt the gravity compensation system will be evaluated, aiming to optimize the cost and energy consumption. Subsequently, the robot will be constructed, followed by the integration of the sensor system with the exoskeleton structure. A control strategy will be projected and implemented within the ROS2 environment to enable the voluntary movement of the user. Experimental validation of rehabilitation tasks using parsimonious technologies will be conducted to assess effectiveness and usability.

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Appendix A

Biomechanic Study of the Arm

Body part	Length (% of the height)	Mass (% of the total mass)	COM (% of the body segment's length)
Upper arm	18.6	2.71	57.72
Forearm	14.6	1.62	45.74
Hand	10.8	0.61	21.00

Figure A.1: A study of estimating the length and weight of the arm based on the total mass and height of the individual (Frigo et al. 2018; D'Ambrosio 2023).

	Elevation		Plane of Elevation	
Shoulder Task	Mean	SD	Mean	SD
Flexion(elevation at 90°horizontal flexion)	152°	10°	58°	22°
Extension(elevation at 90°horizontal extension)	54°	10°	-82°	6°
Abduction(elevation at 0°horizontal flexion)	151°	10°	71°	16
Horizontal flexion	84°	9°	126°	8°
Horizontal extension	78°	7°	-22°	13°
External rotation A	16°	6°	92°	24°
External rotation B	89°	8°	84°	9°
External rotation C	85°	11°	11°	8°
Internal rotation B	85°	9°	81°	10°
Internal rotation C	87°	10°	-3°	10°
	Flexion		Forearm rotation	
Elbow and Forearm Task	Mean	SD	Mean	SD
Flexion	137°	7°	34°	26°
Extension	9°	7°	6°	23°
Pronation	84°	9°	160°	19°
Supination	82°	11°	-13°	18°

Figure A.2: Shoulder and Elbow Range of Motion (D'Ambrosio 2023).

Appendix B

Project Management

The current master thesis project has been managed by sharing a specific google calendar with the supervisor and co-supervisors, to schedule laboratory workdays and meetings. Additionally, a shared Trello workspace using Kanban method has been used Figure B.1. And the progress and milestones shown in Figure B.2 of this work were presented and validated to the supervisors.

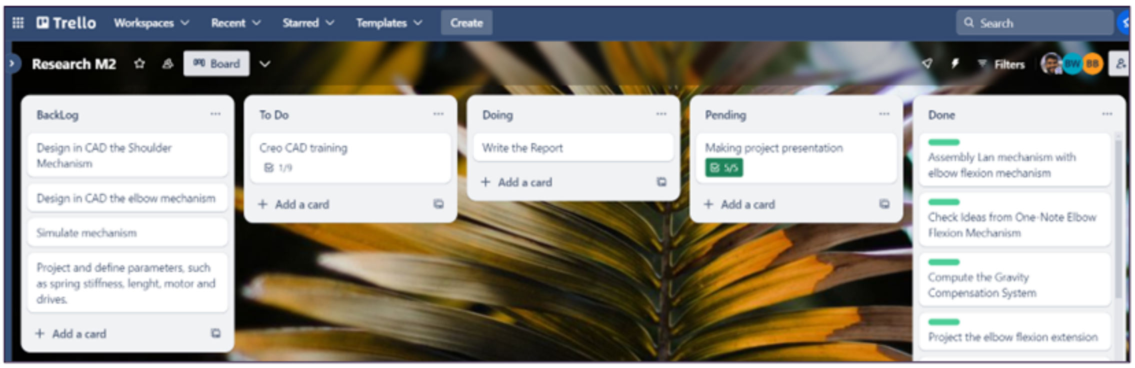

Figure B.1: The Kanban method used in Trello workspace shared with supervisors.

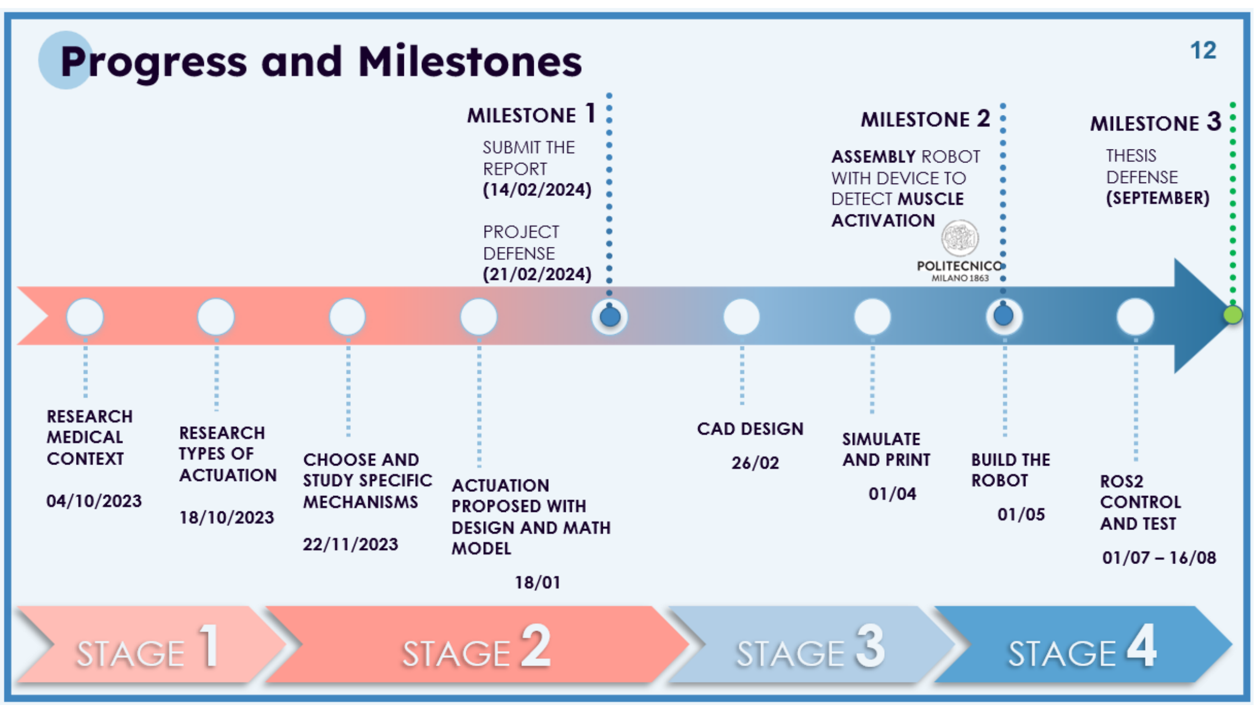

Figure B.2: The Project Progress and Milestones.