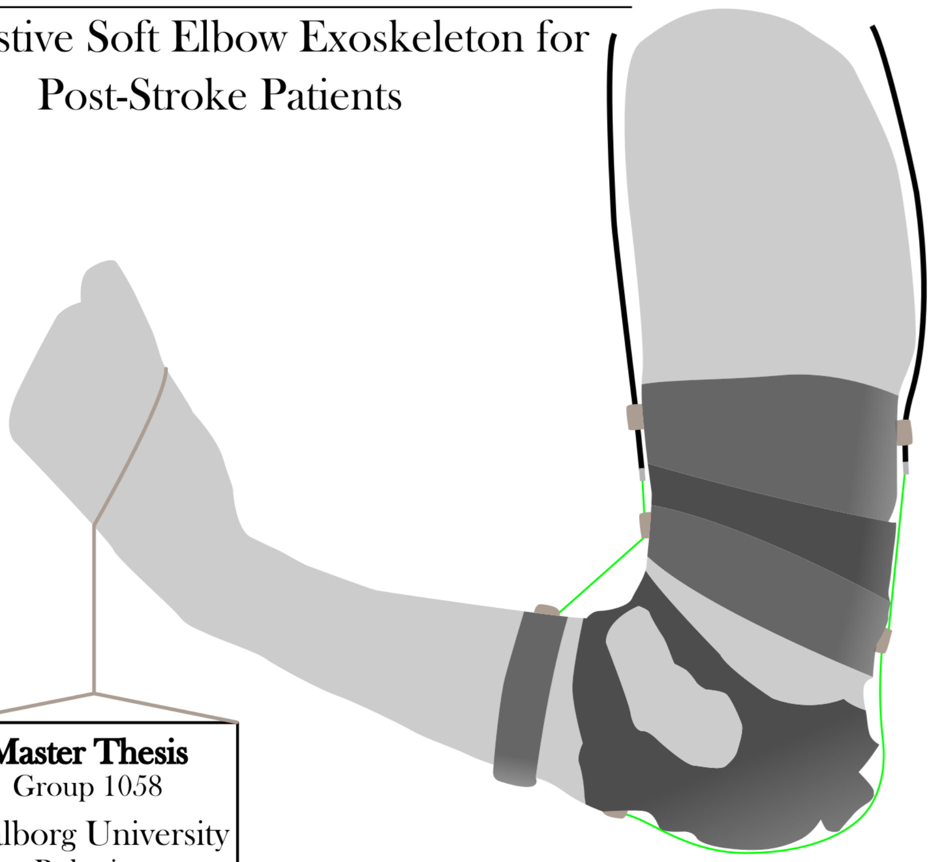
Rehabilitation through Daily Activity

An Assistive Soft Elbow Exoskeleton for Post-Stroke Patients



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William Tolstrup

Supervisor:
Mostafa Mohammadi

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Abstract

Introduction: Stroke is a leading cause of long-term disability, significantly impairing a person's ability to perform daily activities due to hemiparesis, which causes weakness in one side of the body. Some control can be regained with rehabilitation, with typical rehabilitation happening in a clinical setting with a physical therapist or a stationary rehabilitation device. Methods like task-oriented exercises and constraint induced movement therapy are resource intensive and not suitable for home use.

Methods: This thesis develops a soft exoskeleton for the elbow joint, with a focus on user comfort in the form of being lightweight and discrete. The device integrates electromyography (EMG) and accelerometer data from an inertial measurement unit (IMU) to detect user intent with a support vector machine (SVM) model predicting the intended movement. Both flexion and extension are actively actuated using a cable that is controlled on the back of the user and routed to the insertion points on the forearm.

Results: The exoskeleton demonstrated potential in assisting with daily activities, particularly lifting a grocery bag. The SVM model showed different accuracies for the two participants who tested the system, with 82% and 69%. The effective range of motion while using the exoskeleton was also limited in both participants. The average response time from intended motion to actual movement was 0.94 seconds. These are all areas for improvement, in addition to the fit of the straps.

Discussion: The findings indicate that the soft exoskeleton can effectively support the arm, flex and extend the arm within the limitations caused by the exoskeleton, and help with daily activities such as lifting a grocery bag. There are multiple areas in need of improvement, specifically the fit and tightness of the straps which can slip and reduce the effective range of motion. Future work should focus on improving the device's responsiveness and fit, and expand on its capabilities to include wrist and finger movements for more comprehensive and useful assistance. Testing with post-stroke patients is recommended to evaluate the device on its target user group.

Danish Summary

Introduktion: Blodpropper er en af de førende årsage til langvarig handikap, hvilket nedsætter en persons evne til at udføre daglige aktiviteter på grund af hemiparese, som forårsager svaghed i den ene side af kroppen. Noget kontrol kan genvindes med rehabilitering, som foregår i en klinik med en fysioterapeut eller en stationær rehabiliteringsmaskine. Metoder som opgaveorienterede øvelser og constraint-induced movement therapy er ressourcekrævende og ikke egnede til hjemmebrug.

Metoder: Denne rapport udvikler et blødt exoskelet til albueleddet med fokus på brugernes komfort i form af at være diskret og ikke tung. Enheden integrerer elektromyografi (EMG) og accelerometerdata fra en inertial measurement unit (IMU) for at finde brugerens intention med en support vector machine (SVM) model, der prøver at forudsige den ønskede bevægelse. Både fleksion og ekstension aktiveres aktivt ved hjælp af et kabel, der kontrolleres på brugerens ryg og føres til punkter på underarmen.

Resultater: Exoskelettet demonstrerede potentiale til at assistere med daglige aktiviteter, især med at løfte en indkøbspose. SVM-modellen viste forskellige nøjagtigheder for de to deltagere, der testede systemet, med henholdsvis 82% og 69%. Den effektive bevægelse ved brug af exoskelettet var også begrænset hos begge deltagere. Den gennemsnitlige responstid fra ønsket bevægelse til faktisk bevægelse var 0,94 sekunder. Disse er alle områder, der kan forbedres.

Diskussion: Resultaterne indikerer, at det bløde exoskelet effektivt kan støtte armen, bøje og strække armen inden for de begrænsninger, der er forårsaget af exoskelettet, og hjælpe med daglige aktiviteter såsom at løfte en indkøbspose. Der er flere områder, der har behov for forbedring, specifikt pasformen og stramheden af stropperne, som kan glide og reducere den effektive bevægelse. Fremtidigt arbejde bør fokusere på at forbedre enhedens responsivitet og pasform samt udvide dens kapaciteter til at inkludere håndleds- og fingerbevægelser for mere omfattende og nyttig assistance. Test med patienter, der har haft en blodprop anbefales for at evaluere enheden på dens egentlige målgruppe.

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Preface

Aalborg University, May 30, 2024

This is the master thesis project written by Robotics engineering students in group 1058 at Aalborg University. The project has been written between February and June 2024. All the code used in this project is freely available on the public github

William Tolstrup
<wtolst19@student.aau.dk>

1 Introduction

Stroke is a leading cause of long-term disability, with hemiparesis significantly impairing a person's ability to do normal daily activities they used to do before the stroke, as they experience weakness in one side of their body. It can especially be difficult to use the arm and hand due to difficulty of extending the arm and opening and closing the hand. Rehabilitation is crucial for post-stroke patients to regain as much functionallity of their limbs as possible, which typically involves repetitive use of the affected limbs usually in a clinical setting.

Current rehabilitation methods include task-oriented exercises and constraint-induced movement therapy, which are proven effective, but are also very resource intensive therapies. The use of different machines that are impractical for home use as well as human physical therapists makes it very costly. Given these constraints, there is a gap in the available methods for accessible, home-based rehabilitation.

This research aims to explore home-based rehabilitation solutions for the elbow joint, which may offer a more sustained, regular and routine-based training that is based on real-life tasks. This can be a cost-effective method for rehabilitation as it can free up time for the therapists or allow group sessions if each patients has their own device.

This leads to the initial problem statement:

Initial Problem Statement

How can the elbow joint be supported to aid with rehabilitation, while assisting with daily activities?

2 Problem Analysis

This chapter goes into detail regarding different elbow conditions, exploring their causes and common treatments. Subsequent sections will explain the anatomy of the elbow, and the latest technology for rehabilitation.

Injuries and illnesses that can lead to reduced function or disability in the elbow are many and not far between. Common elbow injuries are caused by repetitive motion, overuse and sports, typically resulting in muscle, ligament and/or tendon sprains or tears. [1] Some conditions resolve within a few weeks with treatment, while reduced function caused by diseases may take a lot longer to resolve, if resolvable at all. An overview of diseases and injuries that can cause long-term elbow complications are listed below.

- **Cerebral Palsy (CP)**: A permanent movement disorders appearing in childhood. Upper-limb disorders in CP are caused by spasticity and can be seen as concractures in the shoulder, elbow, wrist or hand. [2]. Common treatments for CP is physical therapy and rehabilitation, involving exercises to maintain or improve muscle function, orthotic and assistive devices, and in some cases surgery. [3]
- **Elbow Contracture**: Often called "Stiff Elbow", it is a relatively common condition, reducing the range of motion of the elbow, caused by prolonged immobilization, elbow injury, elbow surgery, and inflmmatory diseases such as arthritis. Mild elbow contractures can be treated non-surgically with stretching and physical therapy exercises. More severe cases can be treated surgically and in the worst case scenario, a total elbow replacement can occur.[4]
- **Spinal Cord Injury (SCI)**: A traumatic injury resulting in either complete SCI where no nerve communication is present below the injury site or incomplete SCI where some nerve communication is present below the injury site. Depending on the injury site, paralysis may affect the lower body (paraplegia) or the whole body (tetraplegia), excluding the head. Treatment in the form of rehabilitation consists of physical therapy combined with skill-building exercises alongside counseling.[5]
- **Brachial Plexus Injury**: It is a traumatic injury caused when the shoulder and neck are forced away from each other, causing either the lower or upper nerves to stretch, compress or in severe cases rupture from the spinal cord. This can cause numbness, weakness, or in severe cases paralysis in the affected arm, as well as muscle atrophy and stiff joints as the nerves heal. Treatments include surgery and physical therapy post-surgery to maintain range of motion. [6]
- **Stroke**: Occurs when something blocks the blood supply to parts of the brain. Depending on the part of the brain that was damaged, the effects of stroke can be

different. The most common disabilities after a stroke are weakness or paralysis on one side of the body, as well as changes to speech, learning and understanding. [7] Treatment consists of rehabilitation in the form of speech-, physical-, and occupational therapy. [8]

There are more injuries and diseases that affect the elbow joint, but those mentioned above cover the majority of conditions. Untreatable conditions such as muscular dystrophy has not been mentioned.

2.1 Stroke

Henceforth, the focus will shift to strokes, as it is the leading cause of serious long-term disability [9]. Every year, 15 million people suffer a stroke worldwide. Of the 10 million who survive, 5 million are left with permanent disability as a direct effect of having a stroke [10]. The most common type of stroke is ischemic stroke, which occurs when blood vessels are blocked, reducing oxygen flow to the brain, either from blood clots or other build-up such as plaque. As mentioned, the effects of a stroke can vary depending on where in the brain, the blockage occurred, and there are three main structures of the brain in which strokes occur: cerebrum, cerebellum, and brainstem. And based on the paper by Nichols, L. et al. [11], the most frequently affected area is the cerebrum, with $44,5\%$ of strokes occurring in this region. For further clarification on this number, see Appendix A. The cerebrum is divided into two hemispheres, the right and the left. The hemispheres control the opposite side of body in terms of feeling and movement, so if the left hemisphere is affected with a stroke, movement and feeling can be affected on the right side of the body, where weakness in one side of the body is called hemiparesis, while paralysis on one side of the body is called hemiplegia. Symptoms can recover spontaneously, but most of the time only partially and inconsistently, leaving many with impaired upper-limb movement. Symptoms can be categorized in positive and negative symptoms, with negative symptoms including weakness and loss of control of individual joints, while positive symptoms include excessive muscle contractions such as spasticity, dystonia, and pathological synergies, which is an abnormal co-activation muscle pattern that reduces degrees of freedom during motor control. This all result in reduced hand dexterity and weakened goal-oriented upper-limb movements. [7, 12, 13, 14].

2.1.1 Spasticity

Spasticity affects 25% of stroke survivors, and causes stiff or rigid muscles. Commonly affecting the elbow, wrist, and ankle, the condition causes involuntary muscle contractions when moving, often making it difficult to move within full range of motion. And when the muscle cannot complete its full range of motion, tendons and tissue around it can become tight, making it difficult to stretch the muscle. If the condition is left untreated, spasticity can lead to contracture, where the joint becomes stuck in an abnormal position. Other than surgery and medicine, treatment options include physical exercise and stretching to help maintain full range of motion, and in some cases, braces can be used to hold a muscle in a normal position. [15]

2.1.2 Treatment

The study by Takaaki, K. et al. [16] which examines data from 7,491 stroke patients, highlights that patients with a higher care-need, i.e. needs more assistance after discharge from the hospital, have a higher risk of negative outcomes, specifically, a greater need for assistance need correlates with a higher likelihood of being bedridden as well as increased mortality rates. Conversely, patients requiring less assistance after discharge tend to have lower mortality rates and are less likely to be bedridden. The paper confirms the intuitive thinking that more severe strokes will increase care-need and mortality rates than less severe strokes. The study emphasizes the importance of reducing the patients' dependency on care through rehabilitation efforts, noting that care-needs of lower levels are associated with positive long-term health effects. The paper by Dobkin, B. [17], suggests that intensive task-oriented rehabilitation strategies are the most effective in post-stroke recovery, emphasising that intensive therapies in specific skills show greater benefit than general rehabilitation over several times a week. For upper-limb rehabilitation, strategies involve task-based reaching and grabbing exercises such as reaching for a book on a shelf with the affected limb with intensity and challenge increasing over time. The paper also outlines the use of constraint-induced-movement therapy (CIMT), where the healthy limb is constrained, forcing the patient to use the affected limb. This helps counter the effects of a learned nonuse, a common effect post-stroke, where patients neglect using their affected limb, opting to use their unaffected limbs. Given enough time of nonuse, muscles become weaker and function can be lost completely, resulting in greater effort required to perform tasks with the affected limb. CIMT emphasises intensive task-oriented exercises, for multiple hours every day for weeks. Patients may see increases in the use of the affected limb by 20- to 50% using this approach. Limitations for this approach is that patients need an adequate amount of finger and wrist extension, at least 10 degrees, which is a fairly good motor control, limiting the number of patient who can participate. In another paper by Dobkin, B. [18], while he still supports the positive increase in limb usage, he comments on how the focused use of CIMT can negate other approaches, such as bimanual arm practice. Furthermore, he mentions - based on a published study - that the intensive training over a relatively short period of time could lead to less skill retention, as there is less need for memory retrieval over the period of training. Instead, he mentions that task-oriented training in spaced practises with more interval between exercises could lead to better skill retention.

In conclusion, strokes represent a significant medical challenge because of their often severe long-term disabilities, such as hemiparesis and hemiplegia. The impact to motor functions can be profound, affecting their ability to perform everyday tasks. The most effective strategies for post-stroke rehabilitation include intensive task-oriented physical therapy and CIMT, reducing the likelihood of muscle atrophy and functional deterioration. But it is also important to take personalized rehabilitation plans into account as each patient has different capabilities and therefore different needs.

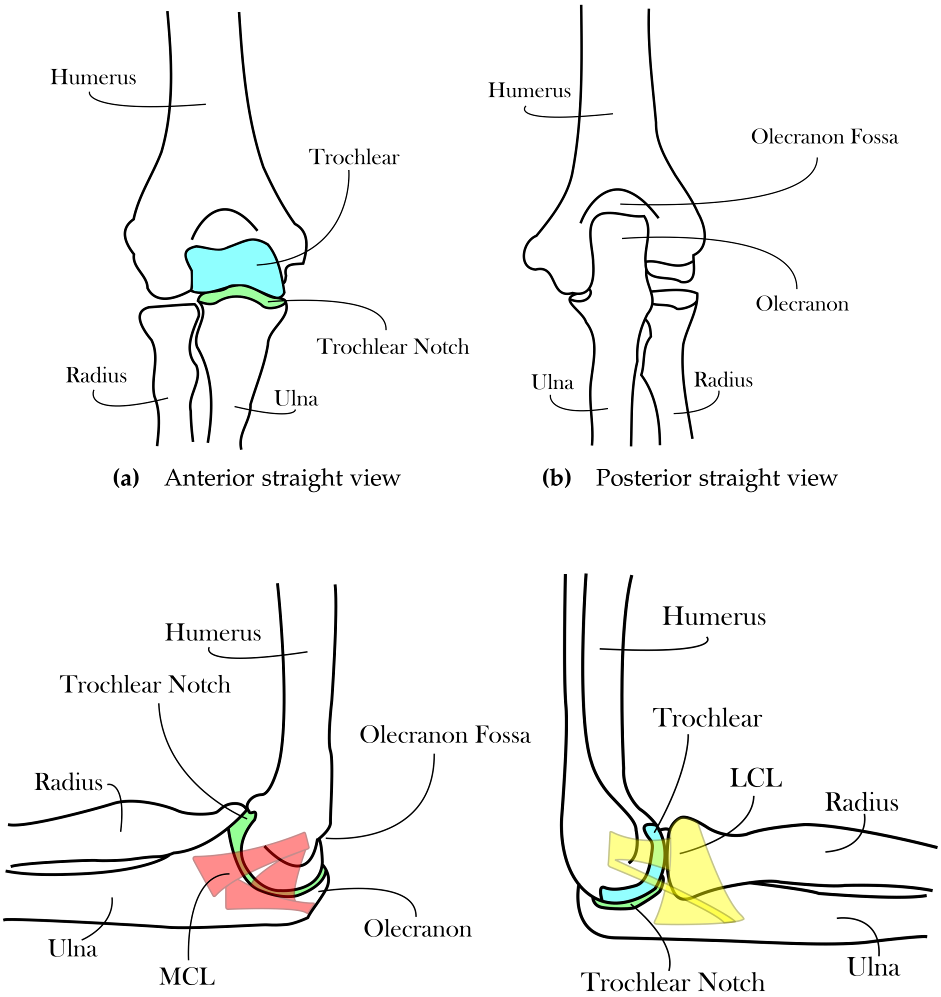
2.2 Elbow joint

The elbow is a synovial hinge joint, meaning that bones move against each other to create motion. It is made up of primarily the distal humerus and the proximal ulna, although movement between the proximal radius and the humerus and the ulna and radius is possible for different motion. The terms distal and proximal refers to the distance to the torso, and is present on all bones in the body. In the case of the humerus, the bone in the upper arm, the distal end refers to the end of the bone which is furthest from the torso, and thus closest to the elbow. The proximal end of the humerus is then closest to the torso, being as it is near the shoulder. The elbow joint allows for flexion (moving the forearm closer to the upperarm), extension (moving the forearm away from the upper arm), pronation and supination (the rotation of the wrist in both directions). Based on a study from Zwerus, E. et al. [19], the mean active range of motion (aROM) of these movements are as follows:

Movement		**Flexion**	**Extension**	**Pronation**	**Supination**
aROM		146°	-2°	80°	87°

2.2.1 Stabilization

The elbow joint gets its stabilizing attributes from both static and dynamic sources. Primarily, the connection trochlear on the humerus slots into the trochlear notch on the ulna bone, acting as a sort of open socket, and the primary pivot for extension and flexion of the elbow. Think of the trochlear notch as the inside of the socket while the olecranon is a protrusion that wraps around the humerus and acts as a pin that slots into the olecranon fossa on the humerus during extension movements. The articulation between these bones ensures smooth and stable movement. Furthermore, the strong ligaments medial collateral ligament (MCL) and lateral collateral ligament (LCL), provide the rest of the major static stability, as the MCL helps connect the humerus to the ulna on the inside of the joint, while the LCL is on the outside and helps connect the humerus to the ulna and radius bones. Both of these ligaments are made up of three smaller ligaments each, forming triangles. While there are other ligaments in the elbow, these are the main ones for providing static stability, and prevent dislocations. [20, 21]



(a) Anterior straight view **(b)** Posterior straight view

(c) Anterior side view **(d)** Posterior side view

Figure 2.1: Illustrations of the elbow bone structure with ligaments from 2 angles. Illustrations adapted from [22, 23]

Muscles

For dynamic stabilization, muscles crossing the elbow are the prime stabilizers. Many of the muscles that are attached to the elbow joint provide motion for the wrist and fingers, such as supination and pronation, as well as flexing and extending the fingers.

The primary muscles for inducing movement in the elbow joint are the bicep brachii, brachioradialis, and brachialis which are responsible for flexion motion. For extension, the tricep brachii muscle is by far the most contributing muscle, assisted by the anconeus muscle. The muscle that is performing a motion is called the agonist, while the reverse motion is called the antagonist. In the case of the elbow, the bicep brachii is the primary agonist in flexion, while the tricep brachii is the antagonist as it extends while the bicep contracts. If multiple muscles work to do the same motion, they are called synergists. In the case with flexion, the bicep brachii is the primary muscle while the synergists are the brachioradialis and the brachialis.[20, 21, 24]

Looking at the simplified diagram in Figure 2.2, the bicep can be seen attached to the radius, enabling it to both aid in flexion of the elbow and supination of the forearm. The other end is attached at the shoulder joint. The brachialis is located under the bicep and aids in the flexion of the forearm. The brachioradialis also aids in the flexion of the forearm, but it is located primarily in the forearm with origin on the humurus. The tricep brachii likewise is attached to the humurus and on the olecrannon of the ulna bone. [25]

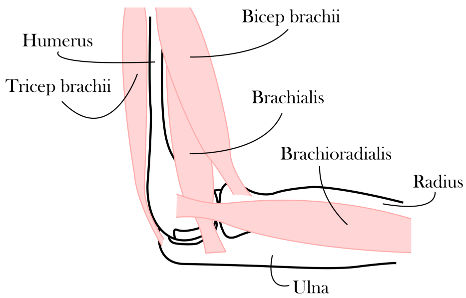


Figure 2.2: Illustration of the main muscles associated with elbow flexion and extension overlayed on the previous illustration of the elbow bone structure

There are three main parts of a lever system: The effort or force applied, the fulcrum, and the load. In the case of the arm, the elbow joint is the fulcrum, the insertion point of the bicep brachii is where the effort or force is being applied, and the load is normally applied in the hand, or at the very end of the lever. This arrangement between the fulcrum, effort, and load means that the arm is a third class lever system. The efficiency of a lever is based on the length of the effort arm in relation to the load arm, which is the distance from the fulcrum to the point of effort or load respectively. For the arm, the effort arm is the distance from the elbow joint to the bicep brachii insertion point, and the load arm is the distance from the elbow joint to the hand. The advantage of a lever system like this is a greater range of motion and speed of the end of the lever (the hand), because the effort is applied closer to the pivot point of the fulcrum, meaning that small contractions of the muscle moves the hand a lot more, increasing dexterity and precision. The downside of this system is that it requires more effort to move a weight at the end of the lever, meaning that the system does not provide any mechanical advantage. [26, 27] This is illustrated in Figure 2.3.

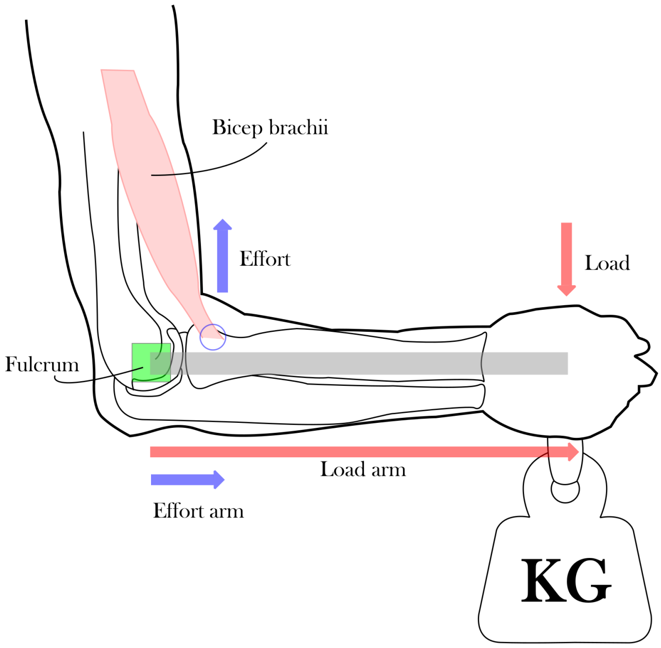


Figure 2.3: Illustration of the arm as a lever system overlayed on the bone structure of the elbow and arm. Based on images from [26]

2.3 Current Solutions

In general, there are two types of robotic upper-limb rehabilitation devices: End-effector robot and an exoskeleton. The end-effector offers a simple design and works with patients with different arm lengths, but it does not allow for individual joint control and the exercises associated with it are limited as well. Exoskeleton rehabilitation robots, on the other hand, matches the structure of the human limb, allowing for isolated joint exercises, and a greater range of motion, at the expense of being more complicated, and harder to adapt to individual patients and differing arm lengths.[28] As end-effector rehabilitation devices cannot focus on individual joints such as the elbow, exoskeleton solutions will be covered in this section.

In a recent study from Xiong, F. et al.[29], several new technologies based on neurological rehabilitation to restore movement in stroke patients are reviewed, to reduce the burden on clinical staff and improve rehabilitation efficiency from traditional rehabilitation therapy which typically includes electrical stimulation, physical therapy, massage and acupuncture. The robot-assisted therapy (RAT) are divided into two categories: Exoskeletons and end-effector robots. A study from Terranova, T, et al. [30] mentions that CIMT is the gold-standard due to robust results, but that RAT showed similar results as CIMT. In the study, an InMotion ARM robotic device was used, which is a system that supports the affected limb against gravity, and enables isolated exercises for the hand and arm as well as combined exercises, all while monitoring movements. It enables intensive and adaptive therapy, reducing the burden on clinicians. As the results of CIMT and RAT are nearly identical, there are some considerations that falls in favor of RAT. Specifically, the time involvement for a therapist is substantial for CIMT at 3-6 hours per day for 10-15 days, which is expensive and locks up a lot of therapist time. Comparing to RAT where the protocol for rehabilitation is 1 hour sessions 3 times a week, which enables more patients to undergo an equally as effective rehabilitation. A disadvantage for the use of RAT is the initial high cost of the equipment, as well as specialized training to use it. The study concludes that while each method had similar results, a combination of the two might be beneficial, with RAT focusing on the elbow and shoulder joints, while CIMT focuses more on the hand and fingers. This is because the repetitive training with adjustable resistance is effective for regaining strength and aROM in the larger joints, while fine motor control is improved with task-specific training.

In a study by Dobkin, B. et al. [31], he notes that extensive restraint may not be as important as the intensive practice, as positive results have been observed with only 2 hours of daily practice without total restraint of the affected hand. Related, he notes that bimanual practice can lead to more functional use of the arm and hand, and trials have showed recovery is similiar to CIMT. Commenting on the use of mechanical devices, he notes that they may play a part of practicing normal limb kinematic movements, which is a key factor in achieving better gains, emphasizing that most devices are too expensive for home use.

All rehabilitation exoskeletons are interfaced with the user on the affected arm through a rigid exoskeleton setup, with a large structure supporting the arm against gravity. This is unsuitable for home use. The exercises are based on performing tasks on a screen, with the arm moving the cursor. Gamifying the rehabilitation is effective to help keep patients motivated, although multiple studies suggest that task-oriented rehabilitation shows the greatest results. [18, 17, 31]

Based on a paper by Bardi, E. et al [32], soft robotic exoskeletons have recently been proposed as an alternative to the rigid exoskeletons, as a soft exoskeleton can support movement without constraining the joints and reduce complexity by the fact that precise joint alignment is not required as it uses the wearers skeletal structure, acting more as an exomuscle than an exoskeleton. This reduces the amount of force that can be exerted as well as limits in terms of accuracy. Despite this, they may provide daily assistance and home rehabilitation outside of the clinic. The paper has reviewed the most prominent soft exoskeleton solutions in the last 20 years, and found that over 50% uses pneumatic actuation, with cable-driving actuation coming in second, and most soft exoskeletons support either 1 or 2 degrees of freedom.

2.4 Final Problem Statement

After reviewing the current main treatment options for post-stroke hemiparesis patients, with task-oriented exercises and repetition ranking as the most effective physical rehabilitation and comparing that to current solutions that do not offer much for home rehabilitation, there seems to be a gap in rehabilitation for post-stroke patients. Therefore, based on the importance of keeping patients from learned nonuse, while enabling them to perform daily activities with their affected arm has lead to the following final problem statement:

How can a soft exoskeleton, focusing on the elbow joint, be designed and controlled to assist post-stroke patients with daily activities, enabling natural rehabilitation through increased use of the affected arm?

3 Requirements

The design and control requirements for the soft exoskeleton are important for ensuring its effectiveness and usability for post-stroke patients. These requirements are derived from the final problem statement and insights gathered from users of the MyoPro device [33], an elbow-specific exoskeleton designed for individuals with weakness or paralysis of the arm.

- Range of motion: The exoskeleton should not interfere with the natural range of motion of the elbow joint between $0° - 150°$. This is based on the table in section 2.2.
- Assistance: The exoskeleton should enable assistance in daily activities, and provide active assistance when holding items of around 2 kg. Therefore, a requirement for the system is to be able to lift a grocery bag weighing around 2 kg from the floor to the table.
- Correlation between estimated and actual movement: The correlation between the actual movement and the predicted movement should be at least 90%, with the majority of the miss classifications being false negatives. This is so the user does not become frustrated when using the exoskeleton and miss classifications should not endanger the user.
- Weight: The weight of the exoskeleton attached to the arm should be low enough to be comfortable to wear for an entire day, therefore it should not weigh more than 200 grams.
- Response time: The exoskeleton should have a fast response time (less than 0.5 seconds) from user intention to movement.
- Ease of use: It should be feasible to put on and take off the exoskeleton with just one hand.

4 Concept and initial idea

This chapter outlines the fundamental concepts and initial ideas behind the design of the exoskeleton and its control system. Including the available hardware, the theoretical background for electromyography and inertial measurement unit, and finally the overall mechanical and control system concept.

4.1 Hardware

The hardware for this project includes a Shimmer3 EXG Unit, which can record electromyography (EMG) signals over two channels while also having a reference electrode. It also has a built-in 9-axis Inertial Measurement Unit (IMU) encompassing two accelerometers (a wide-range and a low-noise variant), a gyroscope and a magnetometer. It is a wireless device, connecting and emitting data via bluetooth, which is beneficial for a low-profile attachment. The data emitted from the device can be processed using Shimmer software, or it can be processed more directly using python.

For the actuation, a large 12V brushed DC motor equipped with a planetary gearbox with a reduction of 49:1 is available. This allows it to have an operating torque of 1.8 Nm, with a maximum momentary torque tolerance of 5.3 Nm. This large gear reduction means that the maximum output speed without a load is 143 rpm. [34] It is controlled by a ZK-BM1 dual DC motor driver, which can provide both forward and backward direction control with the use of Pulse Width Modulation (PWM). It has a duty cycle of 0%-100%, allowing fine control of the motor.[35]

A Raspberry Pi 4 is used for computation, and will be used as the interface between the control system and the motor driver. It runs on Linux 22.04 as well as having a headless installation of ROS2 Humble.

4.2 Electromyography

EMG is a biomedical signal measurement that captures the electrical potential generated by muscle contractions. Surface EMG (sEMG) is then the method of recording this electrical signal from muscle contractions by using a non-invasive approach of electrodes placed on the skin. However, sEMG only measures activity of surface muscles, while being more prone to noise as the signal travels through the different tissues to the EMG electrode on the skin. Furthermore, sEMG cannot distinguish between which muscle signals are picked up, which can lead to mixing of different muscle signals.[36, 37]

The intensity of EMG activity is measured in microvolts and correlates linearly with both the strength of muscle contractions and the number of muscles involved, which further amplifies the chances of mixing diffent muscle signals. Looking at a single muscle, stronger contractions of that muscle results in higher voltage amplitudes in the recorded EMG signal.[38]

4.2.1 Electrode placement

As per Hermens, H. J. et al, [39], the largest percentage of authors place the electrodes on the center of the muscle belly or on the most prominent bulge of the muscle belly. Likewise, in this report, the electrodes have been placed on the most prominent belly of the tricep and bicep muscle. The neutral or references electrode is likewise placed on a bony part of the body, for example near the olecranon on the ulna bone, and serves as a baseline or zero voltage point against which the active electrode recordings are compared.

4.2.2 Filtering the sEMG

Following the approach outlined in Lotti, N. et al, [40], and findings from Rose, W [41], the most common filtering approach is as follows:

- Low-pass filter: Used to remove high-frequency noise and aliasing. Usually around 450-500 Hz, as the sEMG signal typically lie below this.
- High-pass filter: Removes movement and other artifacts. Usually around 20-40 Hz.
- Notch filter: Removes electrical powerline noise. In Europe, this is 50 Hz.
- Full rectification: Converts all negative values to positive, simplifying the signal by only looking at the magnitude of muscle activations without looking at the direction of the signal.
- Low-pass filter: Removes the rapid fluctuations and smooths out the rectified signal to extract the signal envelope, which is the pattern of muscle activation over time. Usually below 5 Hz.

The EMG envelope is the smooth curve that outlines the force of which the muscle is contracting. It is useful for visualizing the muscle activity and to use as a pattern for when the muscle is activated.

For the actual implementation, the frequency for the different filters are as follows:

- Low-pass filter: 350 Hz with 4^{th} order Butterworth
- Notch filter: 50 Hz
- High-pass filter: 10 Hz with 10^{th} order Butterworth
- Post-rectification low-pass filter: 4 Hz with 4^{th} order Butterworth

The raw, filtered, rectified, and the EMG envelope can be all be seen in Figure 4.1 over a period of rest, flexion, static hold, and extension.

Figure 4.1: Graph of the raw, filtered, rectified, and EMG envelope of the bicep and tricep EMG data over a period of rest (white), flexion (green), static hold (yellow), and extension (blue)

As evident in the figure, a third envelope is present and is the combination of both channel envelopes. This will be explained in subsection 6.2.2.

4.3 Inertial Measurement Unit

An IMU is a component that operates with an accelerometer that measures linear acceleration, a gyroscope that measures angular velocity, and a magnetometer that provides a reference direction relative to the Earth's magnetic field, as well as determining the heading of the device. The accelerometer detects changes in translational motion and helps to capture acceleration dynamics in the human body, depending on where it is placed. The gyroscope measures rate of rotation around one or more axes, and is crucial for detecting and calculating orientation changes. The integration of these sensors enables sophisticated motion detection and orientation capabilities.[42]

4.3.1 Shimmer IMU

Unfortunately, there were problems regarding getting reliable data from the gyroscope and the magnetometer on the Shimmer device, and therefore the project will rely solely on the accelerometer data from the Shimmer IMU. Figure 4.2 shows the calibrated accelerometer data.

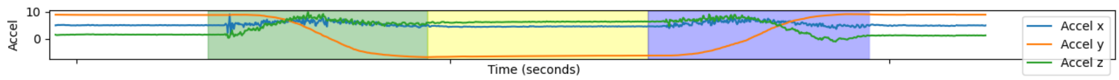


Figure 4.2: The calibrated accelerometer data from all three axes over a period of rest (white), flexion (green) static hold (yellow), and extension (blue)

As can be seen, the y-axis data changes indicates a correlation between the axis of rotation of the elbow and the y-axis of the accelerometer.

4.4 Concept

The purpose of the exoskeleton is to facilitate out-of-clinic rehabilitation by enabling users to perform more daily activities. It functions as both an assistive and rehabilitative device, with rehabilitation occurring naturally as users use their affected arm more frequently, supported by the assistive capabilities. The key idea is to stave off learned nonuse while enabling users to perform daily tasks.

To facilitate rehabilitative use, it is important that users actually use the exoskeleton and are not physically or mentally burdened by it. This means that the design should be as discreet as possible, allowing it to be worn underneath clothing, which could make it easier to perform daily activities outside of the house, without feeling different from their peers.

As discussed in section 2.3, many existing solutions use pneumatic actuation. While effective, these setups are often too bulky for daily use, typically requiring a backpack to store a compressor. To address this, the proposed concept will employ a cable-driven mechanism using high-strength fishing line. This approach aims to utilize the agonist/antagonist nature of muscles to actively control both flexion and extension with a single actuator.

Actively controlling both cables that simulate the bicep and tricep muscles will require careful attention to tensioning, as the lengths of the cables may vary in an agonist/antagonist configuration, for example if flexing the elbow retracts the cable 10 cm, the cable for extension may extend 12 cm. And since there is only a single motor to actuate both directions, there needs to be a dynamic tensioning system in place for it to work properly.

While mimicking the muscles as close as possible is the goal, there may arise complications depending on the insertion point of the bicep and tricep cables, depending on the strength of the motor and the leverage of the cables. It is also important to consider the pinch point inside the elbow as well as the outside of the elbow, where the cable may rub against the bone.

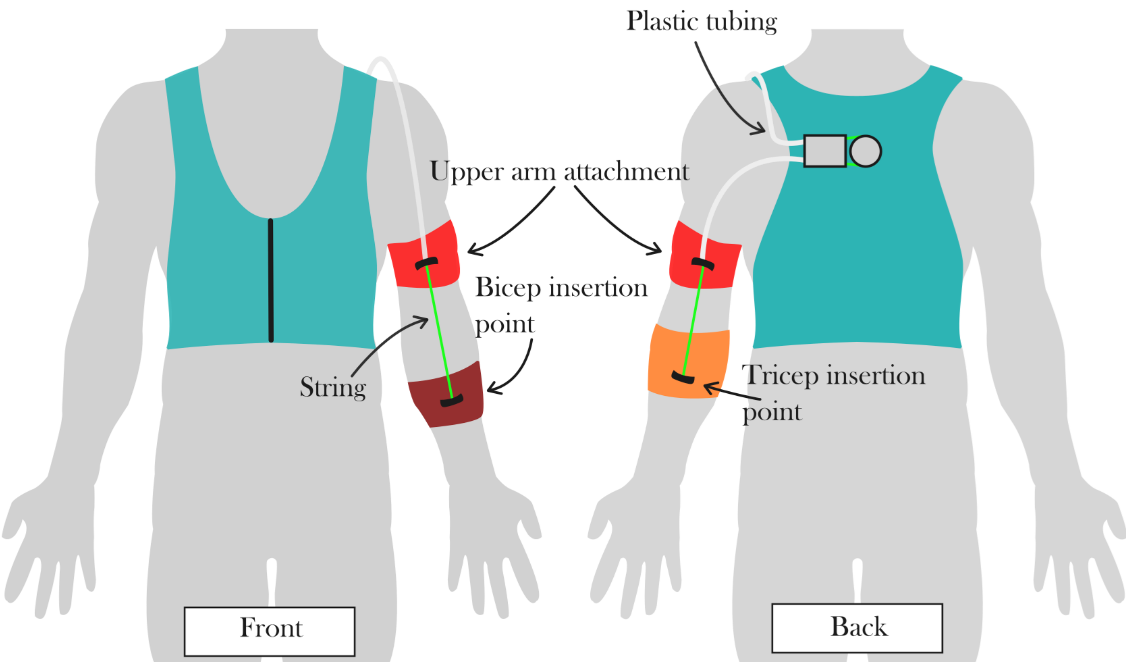


Figure 4.3: Front and back view of the exoskeleton concept on the body

4.5 Control System Concept

To control the exoskeleton, a robust and reliable system is needed to not irritate the user, while being quick and responsive. Therefore, the concept for this exoskeleton is to use sEMG and the accelerometer from the IMU to capture the intent of the user. Using a machine learning (ML) algorithm in conjunction with a velocity control paradigm, a responsive and useful control strategy could be achieved. Critical for the velocity control, is the possibility for a feedback loop. If this is not possible, explained more in subsection 6.4.4, the control strategy will be to utilize a fixed-speed control paradigm.

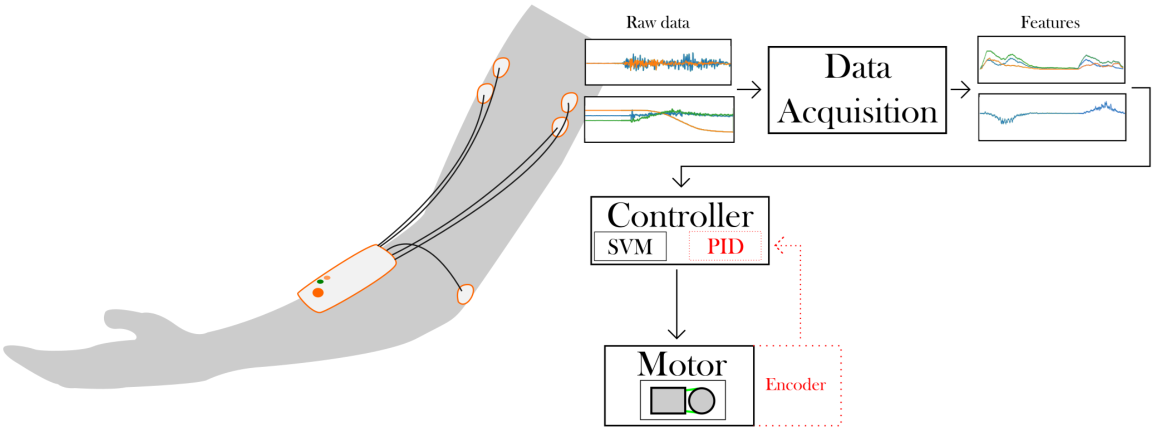


Figure 4.4: Flowchart over the control system, with the feedback dotted in red, as it may not be implemented.

5 Mechanical design

The mechanical, and in part also the control system design, is limited by the hardware which is available, and can be split into these three parts: cable routing, control box, and physical attachments.

5.1 Cable Routing

The routing of the cables is an important aspect of the setup, as excessive bends could increase friction of the cable and reducing the efficiency of the device. It is also important to consider user comfort when routing the cable to avoid any pinch points or discomforts when using the device.

For the exoskeleton, high-strength braided fishing line is used as the cable material due to its flexibility and strength. The fishing line is routed through bowden tubing with the inner steel cable removed, which helps guide the cable while reducing friction and wear on the cable. Two separate tubes extend from the control box which is mounted on the back, to the midpoint of the upper arm, one for the flexion cable on the bicep, the other for the extension cable on the tricep. The tubing also reduces the risk of friction burn, if the cable was to run along skin.

From the midpoint of the upper arm, the cable runs free until the insertion point on the forearm. While this does not follow the natural muscle dynamics, it is needed for increased leverage.

5.2 Control Box

The control box houses the electronics necessary for operating the exoskeleton while being compact enough to be worn on the body. As shown in Figure 5.2, an exploded view of the control box reveals the spool component and tensioning system. The spool and enclosure design is inspired by Xiloyannis, M. et al [43], where they use a single motor to actuate two cables also to flex and extend the elbow. The tensioning system allows small amount of movement in the cable, with the idea being that the cable on the spool is always tight, so when it turns, the cable will not unspool, but rather be pulled out. Simultaneously, it should also allow the two cables to move with slight differences in length, which could benefit the agonist/antagonist movement.

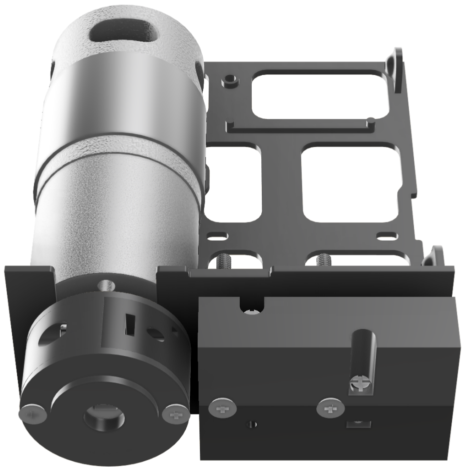


Figure 5.1: Assembled control box, with the actuation wheel enclosed in a casing. Raspberry Pi and motor driver are not pictured

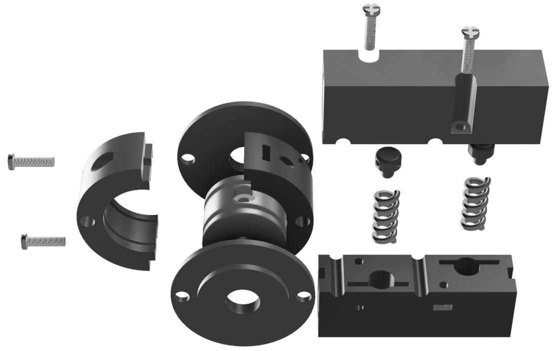


Figure 5.2: Exploded view of the control box, showing the actuation wheel and the springs inside the tensioning system

Given the large size of the DC motor, the control box is designed to enclose both the motor driver and the Raspberry Pi as shown in Figure 5.1. Following the example from [43] and mounting the control box on the back, offers advantages in terms of weight distribution, and reducing interference with daily activities. Having it on the back also allows a form of modularity, as another motor could be added to help with hand and finger motions, or to assist both arms at the same time. Additionally, mounting the control box on the back keeps it out of sight for the user, and could effectively be hidden by a backpack or a loose fitting shirt.

The actual control box can be seen in Figure 5.3 with the tensioning system and spool covered up by a front cover that also acts as the attachment point for the tubes.

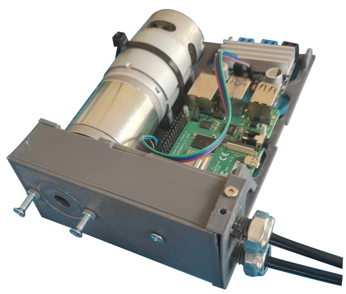


Figure 5.3: The control box with the front cover and tubes attached. The Raspberry Pi and motor controller is visible inside, missing the back cover.

5.3 Physical attachment

The physical attachment of the exoskeleton is important for user comfort while keeping the device discreet and secure.

The physical attachments of the exoskeleton consists of straps and bands with plastic guides sown into it that helps to guide and attach the cable to the body, as can be seen in Figure 5.4

Figure 5.4: Image of the exoskeleton worn on the body from a front and back view. The cable is guided from the control box on the back to the attachment points on the forearm, through plastic guides sown into the fabric.

Since the straps have to be quite tight to not move when the cable acts on them, padding is used underneath so that it does not hurt when tightening them.

The blue vest that can be seen in the above figure, has the control box mounted on the back with a secondary strap that wraps around the body and can be tightened on the chest.

The padding on the outside elbow is provided by a repurposed elbow protector with the plastic cover removed. This prevents the cable from running against the body and the bone of the elbow. As stated before, one of the main goals of this solution is to keep the exoskeleton as subtle and minimally visible as possible, which pairs with the importance of the cable routing around the body. It should first and foremost not impair natural movement, while keeping the bends to a minimum with the largest radius possible. The goal is to wear the device under a loose fitting sweatshirt or similar clothing without it being noticeable.

5.4 Mechanical actuation

For the actuation of the exoskeleton, one end of the cable is attached to the spool on the motor, and the other end is affixed to the insertion point on the forearm. This is replicated for the other cable, although it is pre-coiled around the spool to allow it to be pulled out while the other is pulled in. So if the arm is fully extended, the extension cable is wound around the spool, while the flexion cable is not.

The insertion points on the forearm are the points where the force of the cable pulls, which means that the force from the pulling of the cable goes in a straight line from the insertion point to the guide attachment on the upper arm. In Figure 5.5, the insertion points can be seen as well as the cable through which the force is exerted, the lever arm, and the pivot point. The lever arm is the perpendicular distance from the axis of rotation, that being the elbow joint, to the line of action, that being the cable. The longer the lever arm, the more leverage the cable can pull, thus needing less force to pull it. This means that when the arm is fully extended, the cable is effectively parallel to the forearm, making the perpendicular distance from the elbow joint to the cable very small. This means that since the lever arm is so short, more force is required to actuate the arm, meaning that it is more difficult to actively flex the arm when it is fully extended.

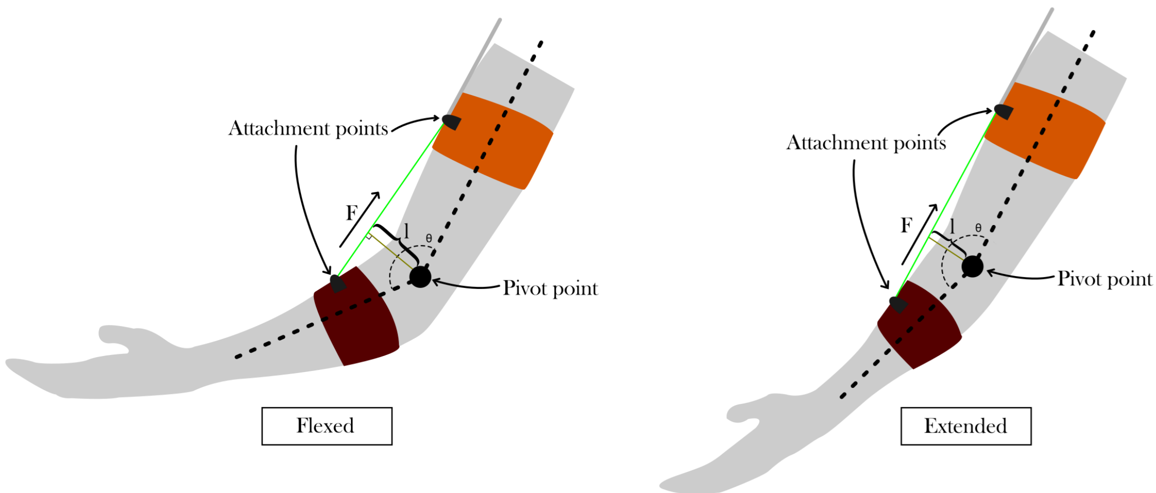


Figure 5.5: Illustration of the change in length of the lever arm *l*, depending on if the arm is flexed or extended. Adapted from [40]

Based on static torque calculations that can be found in Appendix C, the torque required to actuate the elbow joint with no additional load is **2.2 Nm**, with an estimated forearm weight of 1.5 kg and length of 30 cm. This means the torque required is higher than the operational torque of the motor at 1.8 Nm.

The cable tension required to flex the arm from full extension without any additional weight is 220 N, which is also higher than the force the motor can output, considering the spool radius of 1 cm. The force output of the motor at operational torque is $\frac{1.8\,\text{Nm}}{0.01\,\text{m}} = 180\,\text{N}$, however the maximum momentary torque is 5.3 Nm, which is sufficient to flex the arm from full extension. And, already at a 10° bend, the cable tension falls to 147 Nm, which only decreases as the arm is flexed, meaning the motor should be able to provide the necessary cable tension to actuate the elbow.

6 Control system

The control system is designed to enable seamless, real-time control of the exoskeleton using EMG and IMU data from the Shimmer3 device. The goal is to train a Support Vector Machine (SVM) model to predict user intentions of elbow flexion and extension, providing effective assistance for out-of-clinic rehabilitation.

6.1 Support Vector Machine

A SVM is a supervised ML algorithm that is very flexible since it, other than linear classification, can also be used to classify on non-linear datasets by using different kernels, which maps the input into a higher dimensional space, at the risk of overfitting.

SVM seeks to separate classes with the best decision boundary hyperplane while keeping the margin as large as possible, which is the distance between the optimal hyperplane that separates the classes and the nearest data-points. While this may not always be possible, there are parameters in the classifier that can alter its rules.

- **C**: C is the penalty term, and it determines how strict the SVM is regarding violations to the margin. Therefore, a large C value will force the model to search for a better hyperplane in favor of a larger margin, which may ultimately lead to overfitting.
- **Kernel:** The kernel takes as input the original data and computes the output as if it had been mapped to a higher-dimensional space, which is very useful if the data is linear inseparable in the original form, as the algorithm may find a space where the data is linearly separable.
- **Gamma:** Influences the reach of a single training example. High gamma can lead to overfitting, while low gamma can result in underfitting.

There are many other hyperparameters in the SVM, such as class weights, if some classes are underrepresented in the dataset, it is possible to increase their weight to even it out. Tuning these parameters is important for getting the best possible classifier. Since there are multiple different kernels to test and C-values to try, it can be useful to use an automatic, iterative approach such as GridSearchCV, which systematically works through multiple combinations of parameters and cross-validates them as it goes to determine the best set of parameters. It uses pre-determined lists of values for each parameter, for example $C = [0.1, 1, 2, 4]$, which are used as the grid for its search. While it does not guarantee the best possible parameters as the grids have to be defined, it is automatic and systematic and finds the best combination of the defined parameters.[44]

6.2 Data acquisition

6.2.1 Protocol

To reduce chances of artifacts and excessive noise in the EMG signals, it is important to prepare the skin before applying the electrodes. Shaving excess hair, wiping with an alcohol pad and let it dry off completely before attaching the electrode is common practise.

For this report, the protocol is based on a person standing up, with a weight available to be picked up from a comfortable position.

The states useful for flexion and extension for training the SVM consist of the following:

- Rest: Baseline for no muscle activity, in a relaxed position with the arm hanging by the side.
- Flexion: Grasping the weight and flexing the arm.
- Static hold: Holding the weight still at a non-resting position.
- Extension: Extending the arm to maximum extension, down by the side of the body, and releasing the grasp of the weight.

Each state will last for 4 seconds, which was found to be a natural, comfortable speed for flexion and extension movement.

The protocol continues until stopped by the user, around 20 repetitions is enough for a dataset.

Individual calibration protocol

Before recording the dataset, a brief calibration recording is needed to extract the maximum voluntary contraction (MVC), a baseline for no activity (NA), and the maximum and minimum values for the accelerometer y-values over the full range of motion of the user.

MVC and NA
The MVC is when the user produces the maximum contraction of the bicep and tricep muscle respectively, while the NA is when no movement occurs. Both are used for normalizing the EMG envelope to values between 0 and 1 as in Equation 6.1

$$\text{Envelope}_{\text{norm}} = \frac{\text{Envelope} - \text{NA}}{\text{MVC} - \text{NA}} \tag{6.1}$$

Which maps the MVC to 1 and NA to 0.

The MVC and NA are also used to create a threshold to determine if the muscle is active or not as in Equation 6.2

$$\text{Threshold} = \text{NA} + k \cdot (\text{MVC} - \text{NA}) \tag{6.2}$$

With k being the threshold percentage. The threshold is then k percent above the NA towards the MVC.

Minimum and maximum accelerometer y-values
The maximum and minimum values for the accelerometer y-values over the full range of motion from full flexion to full extension is used to estimate the angle of the arm. It needs to be as precise as possible as it can change significantly from slight variations in the placement of the Shimmer3 device on the forearm.

6.2.2 Features

Selecting relevant features is critical for optimizing the performance of the SVM model.

However, feature engineering requires a lot of trial and error to find relevant features. Initially, following the approach from [45], and using the Mean Absolute Value (MAV), Root-mean square (RMS), and standard deviation (SD) for both the EMG and accelerometer data, resulted in a decent classification accuracy, but testing on new data proved futile. Adding more relevant features such as the 8 largest coefficients from a wavelet transform on the 'db4' daubechies wavelet for both EMG channels, totalling 37 features (14 raw emg, 14 filtered emg, 9 accelerometer) this still did not improve the real-time classification. Experimenting with a lot of different features, the following were found to be the most useful for real-time classification.

Accelerometer

The accelerometer provides information regarding the orientation and movement of the arm. Key features that can be extracted from the accelerometer y-data include:

1. **Angle Estimation**: Looking at the upper graph in Figure 6.1, the minimum and maximum amplitude of the accelerometer y-data can be mapped to the minimum

and maximum arm angle (0-150°) of the arm to estimate the current angle. Linear interpolation can be used as in Equation 6.3 and Equation 6.4 to estimate the angle based on current accelerometer y-data as in Equation 6.5

$$a = \frac{\text{Angle}_{min} - \text{Angle}_{max}}{\text{Sensor}_{max} - \text{Sensor}_{min}} \tag{6.3}$$

$$b = \text{Angle}_{max} - a \cdot \text{Sensor}_{min} \tag{6.4}$$

And these can be used to estimate the arm angle like so:

$$\text{Angle} = a \cdot \text{S} + b \tag{6.5}$$

With S being the current accelerometer y-data sensor value. The estimated angle can be seen in the lower graph of the above-mentioned figure. However, this does not provide good feature data. The thought was to use it to train the model that an increasing angle (moving towards 150) would correspond with flexion and reversely a decreasing angle would correspond with extension. But, the effect was that the model would attribute specific angle ranges to flexion and extension and would predict those classes despite the arm being stationary.

2. **Derivative of y-data**: Given that the change in the angle is relevant for the model to understand if the arm is being flexed or extended, using the derivative of the y-axis accelerometer data indicates the speed and direction of arm movement. This feature helps the model distinguish between flexion and extension movements.

   To smooth out the derivative graph, a moving average-like 4-data size buffer is made, where the oldest value is replaced by new data, and then the derivative is taken over this circular buffer. This removes the spikes that occur, as the accelerometer y-data may not be 100% noise free, and this helps to smooth out the derivative and avoid sudden spikes from negative to positive.

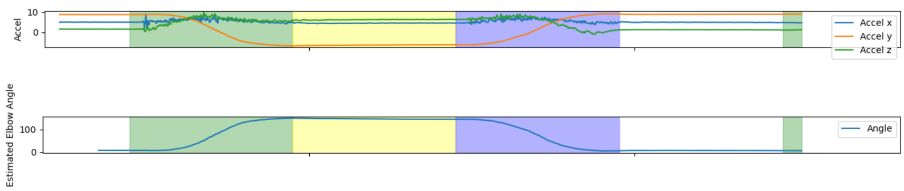


Figure 6.1: Accelerometer data (top) and the estimated arm angle derived from the accelerometer y-data (bottom)

EMG

Since the output of the filtered EMG data is the EMG envelope, it gives a good picture of the muscle activity, but commonly a threshold is set so that when the EMG envelope exceeds this threshold, the muscle is seen as being active. Since the EMG envelope can drop even while performing an action, a combined envelope that is the sum of both bicep and tricep envelope is made, which will be used to determine if the arm is being moved. The argument for combining these is that both muscles are active during both types of movements, flexion or extension. Since post-stroke patients have different levels of strength, the threshold should be dynamic and based on the individual. Therefore, the threshold is set as 25% above the NA towards the MVC for the combined envelope. In Figure 6.2, a sequence of rest, flexion, and extension of the EMG envelope can be seen, with the threshold overlayed in a dotted line. Below, the correlating muscle activation can be seen.

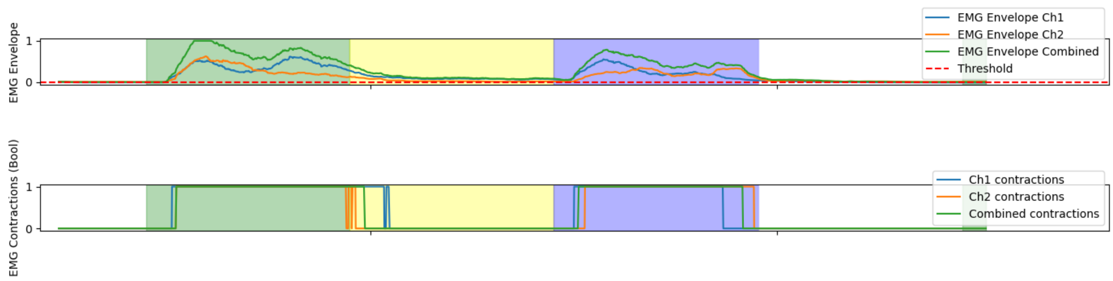


Figure 6.2: Graph of the EMG envelope with the 25% threshold (top) and the correlating muscle activation (bottom)

This returns a boolean value (true of false) about whether the muscles are active or not. This value, alongside the channel 1 and channel 2 envelopes are used as features in the SVM model.

Chosen features

The chosen features can be seen in Table 6.1.

EMG	Accelerometer
Combined contractions	y-data derivative
Ch1 envelope	
Ch2 envelope	

Table 6.1: Table of the chosen features

The argument for including the combined contraction instead of the two individual contraction based on channel 1 and channel 2 envelopes, is that the envelope may not stay above the threshold for the entire duration of the movement, resulting in spikes and fluctuations that may confuse the model.

Since both muscles (bicep and tricep) are active during either movement, combining their envelopes could help with the instability of staying above the threshold, and then having a seperate threshold on the combined envelope could provide a more consistent and stable signal throughout the entire movement.

6.3 Training the model

As SVM is a supervised ML model, it needs labelled data. This is built into the protocol, as each instruction given to the user to either rest, flex, hold, or extend their elbow, is also recorded as a class and labelled accordingly, automatically labelling the feature data.

Before supplying the SVM with the feature data, it is critical to standardize the data, to ensure that each feature contributes equally. To do this, StandardScaler is used, which normalizes each feature individually by removing the mean, i.e. centering the data around 0, and scaling the data to have unit variance. This step is important as omitting it, the model may have a bias against features with smaller scales.

As stated in section 6.1, the SVM model is tuned and evaluated using cross-validation, specifically k-fold cross-validation with $k = 5$. This involves dividing the data equally into k subsets and iteratively training the model on $k - 1$ subsets and using the last for testing purposes. This helps in assessing the performance of the model. The hyperparameter tuning searches through the parameter grid that can be seen in Table 6.2. Since the protocol records are 20 samples long, 80% (or 16 samples) are used for training and the remaining 20% (or 4 samples) are used for testing, and since $k = 5$, this is done 5 times, where each subset is used exactly once as the testing subset.

C	0.1	1	2	5	10	20
Gamma	1	0.1	0.01	0.001		
Kernel	Linear	RBF	Polynomial	Sigmoid		

Table 6.2: Parameter grid for hyperparameter tuning

With the optimal parameters being determined by the *accuracy* metric, which help the model generalize better on unseen data.

The model is evaluated in a classification report and a confusion matrix, examples of both can be seen in Figure 6.3 and Figure 6.4 respectively.

```
Best SVM Parameters:
{'C': 1, 'gamma': 0.1, 'kernel': 'linear'}
Best SVM Accuracy: 0.8248490077653149

Best SVM Classification Report:
               precision    recall  f1-score   support

   extension       0.95      0.80      0.86       581
     flexion       0.93      0.75      0.83       556
        rest       0.76      0.87      0.81       584
 static hold       0.73      0.88      0.80       597

    accuracy                           0.82      2318
   macro avg       0.84      0.82      0.83      2318
weighted avg       0.84      0.82      0.83      2318
```

Figure 6.3: Classification report, showing best SVM parameters and performance metrics

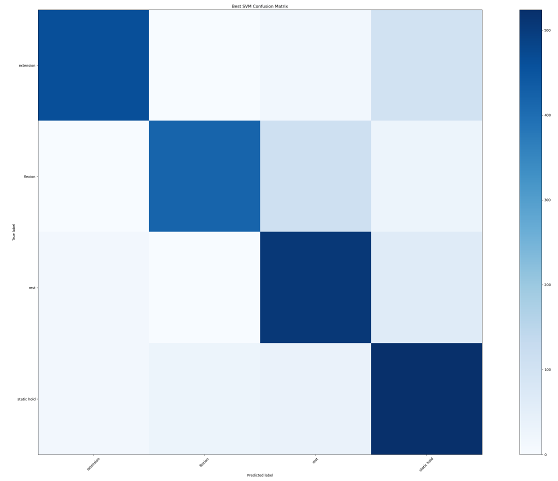


Figure 6.4: Confusion matrix with correct predictions in the diagonal, and misclassifications outside of the diagonal. The deeper the color, the more predictions of this type

The classification report provides insight into metrics such as:

- **Precision**: Ratio between correctly predicted positive observation and the total predicted positives.
- **Recall**: The ratio between correctly predicted positive observation and all observations in the actual class.
- **F1-score**: The weighted score of **precision** and **recall**, it is a way of combining both metrics, useful if classes are imbalanced.
- **Support**: The actual number of occurrences of the classes in the dataset. Useful for checking if there classes are equally represented
- *Accuracy*: The ratio between correctly predicted observations to the total observation.
- *Macro avg*: The average of **precision**, **recall**, or **F1-score** for each class without taking into account if each class is represented equally.
- *Weighted avg*: Same as *macro avg*, but takes into account the representation (**support**) of each class before averaging.

And the confusion matrix visualizes the accuracy of predictions, where the correct predictions are on the diagonal, and a darker color means that more predictions of that class versus the actual class. The squares outside of the diagonal give information regarding misclassifications.

6.4 Applying the model

This section describes the integration of the SVM ML model into the real-time control system for the exoskeleton on the Raspberry Pi 4.

6.4.1 Model and scaler

The trained model is saved alongside the specific instance of the StandardScaler and loaded on the Raspberry Pi. It is important that it is the same scaler that processes the new incoming data, so that it corresponds with the training data.

6.4.2 Real-time control strategy

The SVM prediction is used to determine the direction of the motor.

- Flexion ⇒ forward
- Extension ⇒ backward
- Rest or Static hold ⇒ stop

To reduce erratic motion if a few predictions happens to be incorrect, a moving average of the prediction is taken over a buffer of 5, meaning the most occurring prediction in the buffer is used as the actual prediction. This strategy makes the system less responsive, but also less frustrating to use.

To further reduce the chance of misclassifying flexion or extension, a prerequisite check is made before either of these predicted classes actually are accepted. That is, if the prediction is flexion the channel 1 contraction must be true (the bicep muscle must be active) in order for the system to accept it as a flexion class. The same applies to extension with the tricep being active.

6.4.3 Safety stop

For safety, the elbow angle estimation feature is also used as a digital stop to halt the motor if the angle moves outside of the predefined safe range of $0 - 150°$. This ensures that the movement does not exceed the physical limits of the user.

6.4.4 Encoder feedback and PID controller

Ideally, including feedback from the motor and incorporating it into a PID controller would make a more robust a reliable system. However, since the motor does not have a hall sensor or encoder natively, the only possibility is to attach one after the 49:1 gear reduction, which is not ideal. And since the encoder available is already low resolution, determining the actual speed of the motor based on the output shaft is going to be difficult.

The reason for including a PID controller is that since the lever arm changes depending on the angle of the arm, the force acting on the elbow joint likewise changes. This means that despite the control system sending a specific PWM signal, the motor may not maintain a consistent speed due to the varying load on the motor. When the arm is fully extended, the lever arm is at its maximum, which means it will require more force to move the arm, which can cause the motor to slow down for the same PWM value. Conversely, if the arm is halfway flexed, the lever arm is shorter, which means it will require less force to move it, and the motor will move faster at the same PWM value.

Utilizing a PID controller could counter this issue by adjusting the PWM signal dynamically based on feedback from the system, most commonly using an encoder on the motor shaft. There are three parts of the PID controller:

- Proportional term (**P**): The difference between the desired and actual speed.
- Integral term (**I**): Accumulated past errors.
- Derivative term (**D**): Predicted future errors.

Integrating a PID controller allows the control system to compensate for changes in the load and maintain the desired motor speed, providing smoother and more reliable operation of the exoskeleton across its range of motion.

The encoder attached to the motor shaft after the gear reduction proves ineffective, and thus will not be implemented. This also means that the control paradigm will remain a fixed-speed control.

6.4.5 Conclusion

In summary, the control system is designed to enable the user to initiate a desired movement and the control system will detect this and act accordingly. The Shimmer3 device captures both EMG and accelerometer data, which are then processed to derive the features for the SVM model.

For the EMG data, envelopes from channels 1 and 2 are combined and compared against an activation threshold to determine muscle activity. This combined activation, along with the individual channel envelopes, are used as features for the SVM model.

The accelerometer data is smoothed using a moving aver window of size 50, and the derivative of the y-data is calculated. This is used as a feature for the SVM model.

The four features: muscle activation, channel 1 envelope, channel 2 envelope, and the derivative of the accelerometer y-data, are then published to the motor control script. These features are processed by the trained SVM model, which predicts whether the user intends to flex or extend the elbow. Based on this prediction, the motor direction is set.

Additionally, the estimated angle is used a digital safety stop if it exceeds the maximum thresholds of $0 - 150°$. The bicep and tricep muscle activity, based on the EMG envelope compared against a threshold, is used to confirm that the predicted motion is the intended one.

7 Testing

In this chapter, a standard protocol for testing the exoskeleton with different participants is set up, and the requirements from chapter 3 are tested, either directly or through a questionnaire answered by the participants.

7.1 Testing protocol

As noted, this protocol outlines the steps each participant will follow before, during, and after testing the exoskeleton.

- **Skin preparation**: The area where the electrodes will be placed will be shaved, wiped with an alcohol wipe and let to air dry before placing the electrodes.
- **Calibration**: The participant will perform MVC and NA, as well as move their arm through the full range of motion, from full flexion to full extension.
- **Data collection and model training**: The participant will record a series of 20 samples of rest, flexion, and extension. This data will be used to train the SVM classifier, and the classification report and confusion matrix will be extracted and analysed. The trained SVM classifier and the corresponding scaler will be transferred to the Raspberry Pi.
- **Equip the exoskeleton**: The participant will put on the exoskeleton, ensure it is worn securely and is comfortably attached, and then turned on.
- **Tests**: Four tests will be performed by the participant, with procedures explained in each test.
- **Questionnaire**: The participant will answer a short questionnaire regarding the comfort of wearing the device during the tests.

7.2 Range of motion

Objective

The objective is to verify that the exoskeleton allows for natural range of motion of the elbow between $0 - 150°$

Procedure

The participant will move the elbow from full extension to full flexion. The estimated angle is recorded and an sideview image is taken to measure the angle.

7.3 Assistance

Objective

The objective is to ensure that the exoskeleton can assist with daily activities, specifically lifting a grocery bag weighing approximately 2 kg from the floor to a table.

Procedure

The participant will be asked to lift a 2 kg grocery bag from the floor to the table with the assistance of the exoskeleton.

7.4 Movement correlation

Objective

The objective is to test the correlation between the participant's intended movements and the actual movements classified by the exoskeleton.

Procedure

The participant will be asked to move their arm up or down at random 10 times. The participant will start at a midways position at around a 90° bend. The participant will return to this position after each command. The command and the corresponding movement is recorded and compared.

7.5 Response time

Objective

The objective is to test the response time of the exoskeleton from the command to the activation of the motor.

Procedure

The participant will be asked to move their arm up or down at random 10 times, and the time from the command is given until the motor is activated is recorded and averaged.

7.6 Questionnaire

Objective

The objective is to gather feedback on user comfort and overall experience with the exoskeleton.

Procedure

The participant will answer a short questionnaire regarding the comfort and usability of the exoskeleton during the tests. The questionnaire can be found in Appendix B.

8 Results

This chapter compiles the results from the tests and compares the results against the initial requirements. The goal is to evaluate the effectiveness of the device in assisting with daily activities, and thus helping rehabilitate post-stroke patients.

There are a total of two participants for testing the exoskeleton and the control system:

- **Participant 1**: A 25-year-old male. He is able-bodied with no weakness or paralysis of the arms. He is right hand dominant, with the exoskeleton mounted on his left arm.
- **Participant 2**: A 24-year-old female. She is able-bodied with no weakness or paralysis of the arms. She is right hand dominant, with the exoskeleton mounted on her left arm.

The results will come in the same order as the tests in chapter 7.

8.1 Classifier accuracy

Participant 1

The classification report and confusion matrix for the trained SVM model based on the 20 sample protocol can be seen in Figure 8.1 and Figure 8.2 respectively.

```
Best SVM Parameters:
{'C': 1, 'gamma': 0.1, 'kernel': 'linear'}
Best SVM Accuracy: 0.8248490077653149

Best SVM Classification Report:
              precision    recall  f1-score   support

   extension       0.95      0.80      0.86       581
     flexion       0.93      0.75      0.83       556
        rest       0.76      0.87      0.81       584
 static hold       0.73      0.88      0.80       597

    accuracy                           0.82      2318
   macro avg       0.84      0.82      0.83      2318
weighted avg       0.84      0.82      0.83      2318
```

Figure 8.1: Classification report for **participant 1**, showing best SVM parameters and performance metrics

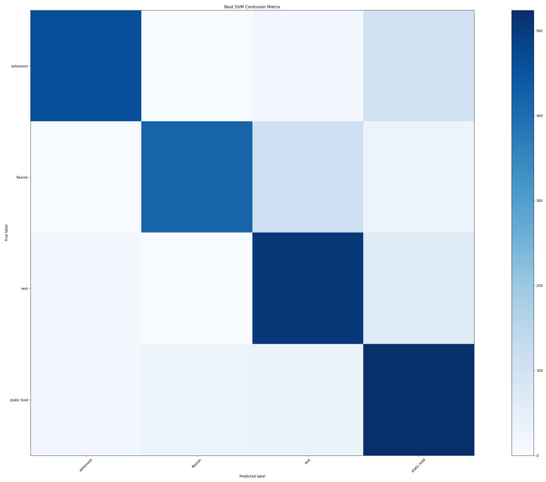


Figure 8.2: Confusion matrix for **participant 1**

As can be seen in the classification report, the best parameters are:

- **C**: 1
- **Gamma**: 0.1
- **Kernel**: Linear

The accuracy score is at **82%**, which initially is not very good.

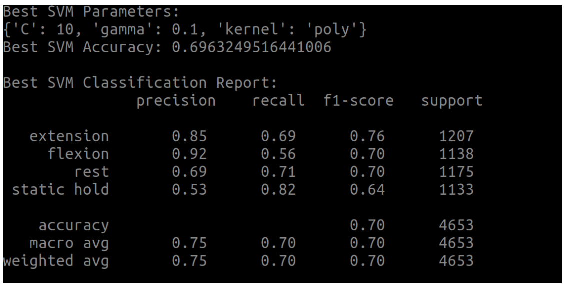
Focusing on the precision and recall metrics:

- The **extension** class has high precision and medium recall of 95% and 80% respectively, which means the model predicts this class very well, but misses 20% of the actual instances.
- For the **flexion** class, the precision is high at 93%, but the recall is lower at only 75%, which indicates that the model is accurate when predicting the class, but it misses about 25% of the actual instances.
- The **rest** class has lower precision at 76% than recall at 87%, which means that it often predicts this class even if it may not be correct.
- The **Static hold** class is similar to the rest class, with 73% precision and 88% recall, meaning it also wrongly predicts this class

Participant 2

Despite following the same steps for preparing the skin, the EMG electrodes on participant 2 experienced a lot of noise from external movement, e.g. touching the backside of the electrodes, magnitudes larger than what was true for participant 1.

The classification report and confusion matrix for participant 2 can be seen in Figure 8.3 and Figure 8.4 respectively.



```
Best SVM Parameters:
{'C': 10, 'gamma': 0.1, 'kernel': 'poly'}
Best SVM Accuracy: 0.6963249516441006

Best SVM Classification Report:
               precision    recall  f1-score   support

   extension       0.85      0.69      0.76      1207
     flexion       0.92      0.56      0.70      1138
        rest       0.69      0.71      0.70      1175
 static hold       0.53      0.82      0.64      1133

    accuracy                           0.70      4653
   macro avg       0.75      0.70      0.70      4653
weighted avg       0.75      0.70      0.70      4653
```

Figure 8.3: Classification report for **participant 2**, showing best SVM parameters and performance metrics

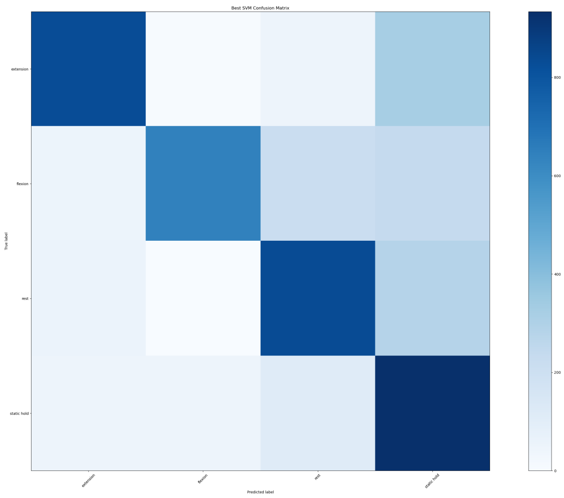


Figure 8.4: Confusion matrix for **participant 2**

As can be seen in the classification report, the best parameters are:

- **C**: 10
- **Gamma**: 0.1
- **Kernel**: Polynomial

The accuracy score is at **69%**, which is quite bad.

Focusing on the precision and recall metrics:

- The **extension** class has high precision and medium recall of 85% and 69% respectively, which means the model predicts this class well, but misses 31% of the actual instances.

- For the **flexion** class, the precision is very high at 92%, but the recall is lower at only 56%, which indicates that the model is accurate when predicting the class, but it misses about 44% of the actual instances.
- The **rest** class has a lower precision at 69% compared to its recall at 71%, which means that it often predicts this class even if it may not be correct.
- The **static hold** class is similar to the rest class, with 53% precision and 82% recall, which similar to the rest class means that it wrongfully predicts this class frequently.

8.2 Range of motion

Participant 1

The sideview images have been overlapped and the angle of the full flexion has been measured using an online protractor tool [46]. The found angle can be seen in Figure 8.5.

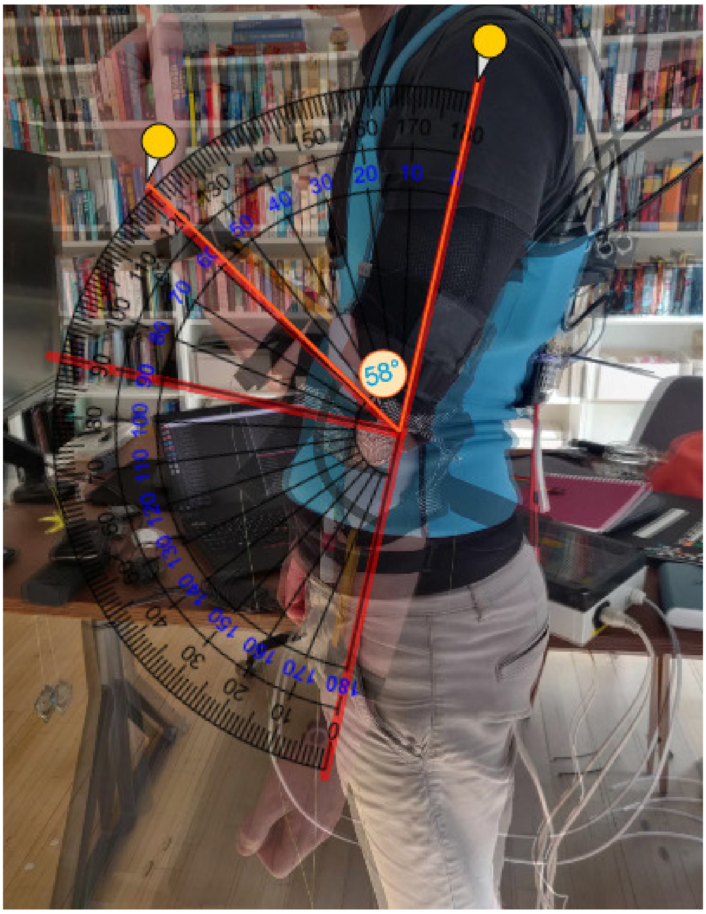


Figure 8.5: Measured angle between full extension and full flexion for **participant 1**

Given this angle is the acute, the obtuse angle is $180 - 58 = \mathbf{122°}$.

The estimated angles as measured by the accelerometer can be seen in Table 8.1

	Extension	**Flexion**
Degrees	-0.33	134

Table 8.1: Table showing the minimum and maximum angle measured by the angle estimation based on the accelerometer data for **participant 1**

Participant 2

The participant did not give permission to use the images or videos captured during testing to be used in the report. Therefore, just the results from the images will be provided here.

The results from the images and from the estimated angle are compiled in Table 8.2 below.

	Estimated Angle	Measured Angle
Max (degrees)	63.3	90
Min (degrees)	3.4	10

Table 8.2: Table showing the maximum and minimum angles from the estimated angle based on the accelerometer data, and the measured angle from sideview images for **participant 2**

8.3 Assistance

The grocery bag was the same for both participants and it weighed 2421 g.

Participant 1

The participant successfully lifted the grocery bag from full extension to full flexion (as allowed by the exoskeleton). The assistance was constant during movement and it was able to hold the grocery bag at various angles during the flexion and extension movements.

Participant 2

The participant was able to lift the bag from full extension to full flexion, but not from full flexion to full extension.

8.4 Movement correlation

Participant 1

The 10 random commands and the corresponding observed movements can be seen in Table 8.3.

Command	Observed action
Up	Up
Down	Down
Up	Up
Up	Up
Down	Down
Up	Up
Down	Down
Down	Down
Down	Down
Up	Up

Table 8.3: Table for commanded action and observed action for **participant 1**

All 10 of the commands were successfully repeated by the participant.

Participant 2

The predictive capabilities on participant 2 were subpar, and despite the intent to extend the arm, this was near impossible for the participant to do. Flexing and holding the arm still worked fine, but extending the arm again was not possible.

Therefore, this test is void, as movement correlation would be a maximum of 50%.

8.5 Response time

Participant 1

The participant performed 10 actions while being recorded. The intent is expressed by a command word either "up" or "down" and the time from this word being spoken until the motor activates is measured from the video. The 10 actions and their corresponding response times from word till motor activation can be seen in the response time test video.

The average response time of the 10 actions is 0.94 seconds

Participant 2

As mentioned, the test video for this participant will not be included in the report, and just the average response time of the 10 actions, all being flexion movements after being manually extended.

The average response time of the 10 flexion actions is 1.20 seconds

8.6 Questionnaire

The full questionnaires can be found in Appendix B for both participants. This section will summarize the findings based on the answers from the participants.

- **Comfort**: Both participants experienced some discomfort while using the exoskeleton. Participant 1 found it uncomfortable, noting issues such as pinching during full flexion and tight straps that caused discomfort. While participant 2 did not explicitly state it was uncomfortable, they mentioned burning on the skin during flexing and tightness on the upper arm when fully flexed.
- **Ease of use**: Both participants found the exoskeleton easy to put on and take off.
- **Stability**: The exoskeleton felt secure for both participants with participant 1 rating "secure" and participant 2 rating it "very secure". However, issues such as the upper arm strap slipping during use was noted by participant 1.
- **Assistance**: Both participants felt that the exoskeleton provided decent or good assistance while lifting the grocery bag. Participant 1 appreciated its strength and participant 2 noted restrictions in the range of motion. Both participants did not question its ability to support the arm.
- **Responsiveness**: Participant 1 found the exoskeleton responsive, while participant 2 rated it as "very unresponsive".

9 Discussion

This chapter provides a comprehensive analysis of the results discussed in the previous chapter. It discusses the implications of the results, highlights successes and limitations, and finally touches on possible future research.

To reiterate the final problem statement, the goal was to design and control a soft exoskeleton for the elbow joint that would assist post-stroke patients with completing daily activities, while simultaneously enabling rehabilitation through increased use of the affected arm.

Classification accuracy

Given that the classification report for both participants reveal the same pattern between precision and recall of the four classes, albeit with different percentages, it indicates that when the model predicts flexion or extension, it is usually correct given the high precision metric. The lower precision of the rest and static hold classes indicates that there are more false positives for these classes, meaning that the exoskeleton will sometimes predict rest or static hold despite an intent to move.

As a result, the model is more likely to remain stationary when there is an intent to move, rather than moving without an intent to do so. This, while not optimal, is safer as unexpected movement is reduced, but it may lead to frustration if the exoskeleton does not respond to intended movements.

Comparing with the requirements, the average prediction accuracy is **75.5%**, which is lower than the requirement of **90%**, but there is more false positives for non-movement than movement, which is a positive.

Range of motion

The significant difference between the measured and estimated angles highlights a need for more precise calibration and better attachment for the shimmer device on the forearm.

The limited range of motion experienced by the participants fails the requirements of the exoskeleton not affecting the active range of motion. This may be improved by mounting the upper arm strap higher on the upper arm, and fastening it better so it does not slip.

Assistance

The requirement for lifting a grocery bag from the floor to a table was successful since both participants were able to lift the grocery bag, although the height was limited by the range of motion.

Movement correlation

The movement correlation test was successful for participant 1, while it was deemed void for participant 2. Participant 1 performed each action without any misclassifications, although this may be skewed by the fact that most misclassifications are non-movement, so there may be a lot of misclassifications that resulted in non-movement before the intended action was predicted.

Response time

Participant 1 had a faster average response time compared to participant 2, with the average of them being 1.07 seconds.

This does not live up to the requirement for the response time at 0.5 seconds. This may also be affected by the system incorrectly predicting either rest or static hold.

User comfort

The user comfort requirements are up for debate as it is technically not possible to put on the exoskeleton alone, as the cable must be tied after putting it on. Other than that, the exoskeleton can be put on alone, but it is difficult to do so one-handed, as straps around the chest needs to clasped and the vest needs to be zipped up. Other than that, it is fairly easy to put on one-handed, but all together, this does not fulfil the requirement of being able to put on the exoskeleton one-handed.

The weight of the part that is attached to the arm is measured to be 68 grams, which is below the requirement of 200 grams. This does not take into account the control box on the back.

Limitations

There are multiple interesting challenges that have limited the project.

Given the operational torque of the motor at 1.8 Nm is lower than the torque generated by the elbow at 2.21 Nm, the lifespan of the motor may be reduced due to having to continuously work harder than it was made for. Additionally, given that the cable tension needed to flex the arm while fully extended is close to the maximum force the motor is able to generate even momentarily, adding an additional 2 kg in the hand, effectively extending the distance from the elbow to the center of mass, should not be possible for the motor to lift alone. The discrepancy may be generated by the muscles, or momentum may play a role in aiding the motor with the flexing action.

The results may not be entirely accurate as they were performed by able-bodied individuals, and more accurate results would be available if it was tested by post-stroke patients.

Since the SVM uses only a few features, it may be influenced a lot by the derivative of the y-data of the accelerometer. And thus, it may not be necessary to have an SVM model and instead use a switch statement looking at the sign of the derivative and the muscle activations. Another factor playing into this is that when the exoskeleton is active, and say in the flexed position, there is little to no play in the cable, meaning it is completely taut. This makes it difficult to cause a change in motion of the accelerometer if that were to be the defining factor for control.

The shimmer device turned out to be a time-sink and a lot of time was used to try to allow simultaneous EMG and IMU data to be transmitted from it. Custom calibration methods for the accelerometer, gyroscope, and magnetometer were created and applied through a graphical user interface, which also enabled recording from the device. Ultimately, none of this was used in the final version.

Lastly, while the wet EMG electrodes provided good EMG data, they did irritate the skin after prolonged wear, to the point of developing a rash from using it multiple days in a row. In a real product, dry, reusable electrodes would be recommended for user comfort.

Future research

While the elbow joint is an important joint to assist and rehabilitate, as the bicep muscle helps with more than just flexion, the product would be a lot more useful if more degrees of freedom were included such as the wrist and/or the fingers.

Overall, the exoskeleton shows promise with assisting with daily activities, but there are several areas that need improvement:

- Improve user comfort by addressing strap tightness and slipping.
- Improve the fit to be usable with mutliple different sizes of arms, especially the upper arm strap.

- Improve the responsiveness and consistency of the control for the exoskeleton.
- Enable calibration while wearing the exoskeleton to account for any limitation in range of motion.

10 Conclusion

This thesis successfully developed a soft elbow exoskeleton that can assist in daily activities.

The exoskeleton was designed with a focus on user comfort, lightweight construction, and a discrete form, to allow wearing it underneath clothing. Testing protocols were established to evaluate the effective range of motion, assistance capability, control effectiveness, and the user satisfaction. The device demonstrated potential in assisting with daily activities, specially with flexing and extending the arm, as well as lifting items with the affected arm. However, testing also highlighted areas for improvement in response time and fit.

Future research should work to enhance the responsiveness of the exoskeleton and refine the fit to accommodate a broader range of users. Additionally, expanding the capabilities of the device to include wrist and finger movements could provide more comprehensive support that may be more useful for post-stroke patients than solely actuating the elbow. Testing involving post-stroke patients is recommended to test if it viable for use for this group and whether it promotes natural rehabilitation through increased use of the affected limb.

This thesis contributes to the field of assistive robotics by providing a working prototype for home-based assistive use with the goal of natural rehabilitation. It integrates EMG and IMU data for user intent detection and applies a SVM model to predict the intended movement of the user.

In conclusion, the development of the soft elbow exoskeleton is a step in the direction of affordable and accessible post-stroke assistance and theoretically helps with rehabilitation, all outside of a clinical environment. It could provide the user with a more sustained, regular and routine-based training that, while it may not be as immediately intensive as the CIMT method used in clinics, could still provide effective rehabilitation over time without the constraint of scheduled therapy sessions.

Appendices

A Part of the brain affected by stroke

An exact excerpt from the paper:

Results: During the one-year study period, there were 418 acute ischemic strokes, and 54.6% (228/418) were in the territory of a single large vessel. Of the single large vessel strokes, 62.3% (142/228) were in a middle cerebral artery (MCA) territory, 12.1% (29/228) in a posterior cerebral artery (PCA) territory, 8.8% (20/228) in a basilar artery distribution, 7.5% (17/228) in a posterior inferior cerebellar artery (PICA) distribution, 6.6% (15/228) in an anterior cerebral artery (ACA) distribution, 1.8% (4/228) in a superior cerebellar artery (SCA) distribution, and 0.4% (1/228) in an anterior inferior cerebellar artery (AICA) territory. Internal capsule lacunar strokes accounted for 17.7% (74/418) of the total, brainstem lacunar strokes for 8.1% (34/418) and thalamic lacunar strokes for 5% (21/418) of the infarctions. Watershed infarctions accounted for 2.9% (12/418) of the strokes, 9 in the MCA/PCA watershed area and 3 in the MCA/ACA watershed area.[11]

Categorizing this data into the three main parts of the brain, cerebrum, cerebellum, and brainstem, the calculated percentages can be extracted as such:

	Relevant arteries	**Cases**	**% of total cases (418)**
Cerebrum	MCA, PCA, ACA	142+29+15 = 186	44,5%
Cerebellum	PICA, SCA, AICA	17+4+1 = 22	5,3%
Brainstem	Brainstem lacunar	34	8,1%

B Questionnaire

User comfort questionnaire

1. **Personal information**

    - **Age:**
    - **Gender:**
    - **Dominant Hand:**

    ### Comfort and usability

2. **How comfortable was the exoskeleton to wear?**
    - Very uncomfortable
    - Uncomfortable
    - Neither comfortable or uncomfortable
    - Comfortable
    - Very comfortable
3. **How easy was it to put on and take off the exoskeleton?**
    - Very difficult
    - Difficult
    - Neither difficult or easy
    - Easy
    - Very easy
4. **Did you experience any discomfort or pain while using the exoskeleton?**
    - Yes
    - No
    - If yes, please elaborate: ______________
5. **Did the exoskeleton feel securely attached during use?**
    - Very secure

- Secure
- Neither secure or loose
- Loose
- Very loose

6. **Did the weight of the exoskeleton cause any discomfort?**
   - Yes
   - No
   - If yes, please elaborate: ______________

7. **Were there any pressure points where the exoskeleton felt too tight or too loose?**
   - Yes
   - No
   - If yes, please elaborate: ______________

Functionality

8. **How well did the exoskeleton assist you in daily activities (lifting the grocery bag)?**
   - No assistance
   - Barely any assistance
   - Slight assistance
   - Decent assistance
   - Good assistance

9. **Did you feel any restriction in your natural range of motion while using the exoskeleton?**
   - Yes
   - No
   - If yes, please elaborate: ______________

10. **How responsive did the exoskeleton feel to use?**
    - Very unresponsive
    - Unresponsive
    - Neither unresponsive or responsive
    - Responsive
    - Very responsive

General feedback

11. **What did you like most about the exoskeleton?**
12. **What did you like least about the exoskeleton?**
13. **Do you have any suggestions for improving the exoskeleton?**

==

Participant 1 questionnaire

1. **Personal information**
   - **Age:** 25
   - **Gender:** Male
   - **Dominant Hand:** Right

Comfort and usability

2. **How comfortable was the exoskeleton to wear?**
   - Very uncomfortable
   - <u>Uncomfortable</u>
   - Neither comfortable or uncomfortable
   - Comfortable
   - Very comfortable
3. **How easy was it to put on and take off the exoskeleton?**
   - Very difficult
   - Difficult
   - Neither difficult or easy
   - <u>Easy</u>
   - Very easy
4. **Did you experience any discomfort or pain while using the exoskeleton?**

- <u>Yes</u>
- No
- If yes, please elaborate: During full flexion, the skin got slightly pinched on the edge of the fabric.

5. **Did the exoskeleton feel securely attached during use?**

   - Very secure
   - <u>Secure</u>
   - Neither secure or loose
   - Loose
   - Very loose

6. **Did the weight of the exoskeleton cause any discomfort?**

   - Yes
   - <u>No</u>
   - If yes, please elaborate: ______________

7. **Were there any pressure points where the exoskeleton felt too tight or too loose?**

   - <u>Yes</u>
   - No
   - If yes, please elaborate: To keep the straps from running up the arm during flexion, they had to be quite tight, which was not pleasant. The upper arm strap also was slightly loose, and slowly made its way down towards the elbow.

Functionality

8. **How well did the exoskeleton assist you in daily activities (lifting the grocery bag)?**

   - No assistance
   - Barely any assistance
   - Slight assistance
   - Decent assistance
   - <u>Good assistance</u>

9. **Did you feel any restriction in your natural range of motion while using the exoskeleton?**

- Yes
- No
- If yes, please elaborate: Due to the upper arm strap slipping, the effective maximum flexion varied throughout the tests, as the further down towards the elbow it went, the less maximum flexion became.

10. **How responsive did the exoskeleton feel to use?**

    - Very unresponsive
    - Unresponsive
    - Neither unresponsive or responsive
    - Responsive
    - Very responsive

    General feedback

11. **What did you like most about the exoskeleton?**
    It's strength. While it could not lift a heavy toolbox, it had no problems lifting the grocery bag, and it easily supported the weight of a relaxed arm.

12. **What did you like least about the exoskeleton?**
    The forearm straps. They had to be tight to avoid slipping, which was uncomfortable.

13. **Do you have any suggestions for improving the exoskeleton?**
    General increase in responsiveness. Also additional functionallity such as opening and closing the hand, which seemed to be an important asset from the MyoPro users.

==

Participant 2 questionnaire

1. **Personal information**

    - **Age:** 24
    - **Gender:** Female
    - **Dominant Hand:** Right

Comfort and usability

2. **How comfortable was the exoskeleton to wear?**
   - Very uncomfortable
   - Uncomfortable
   - Neither comfortable or uncomfortable
   - Comfortable
   - Very comfortable
3. **How easy was it to put on and take off the exoskeleton?**
   - Very difficult
   - Difficult
   - Neither difficult or easy
   - Easy
   - Very easy
4. **Did you experience any discomfort or pain while using the exoskeleton?**
   - Yes
   - No
   - If yes, please elaborate: A little burning on the skin during flexing
5. **Did the exoskeleton feel securely attached during use?**
   - Very secure
   - Secure
   - Neither secure or loose
   - Loose
   - Very loose
6. **Did the weight of the exoskeleton cause any discomfort?**
   - Yes
   - No
   - If yes, please elaborate: ______________
7. **Were there any pressure points where the exoskeleton felt too tight or too loose?**
   - Yes
   - No
   - If yes, please elaborate: It was tight on the upper arm.

Functionality

8. **How well did the exoskeleton assist you in daily activities (lifting the grocery bag)?**
    - No assistance
    - Barely any assistance
    - Slight assistance
    - Decent assistance
    - Good assistance
9. **Did you feel any restriction in your natural range of motion while using the exoskeleton?**
    - Yes
    - No
    - If yes, please elaborate: The upper arm piece should be mounted higher on the arm.
10. **How responsive did the exoskeleton feel to use?**
    - Very unresponsive
    - Unresponsive
    - Neither unresponsive or responsive
    - Responsive
    - Very responsive

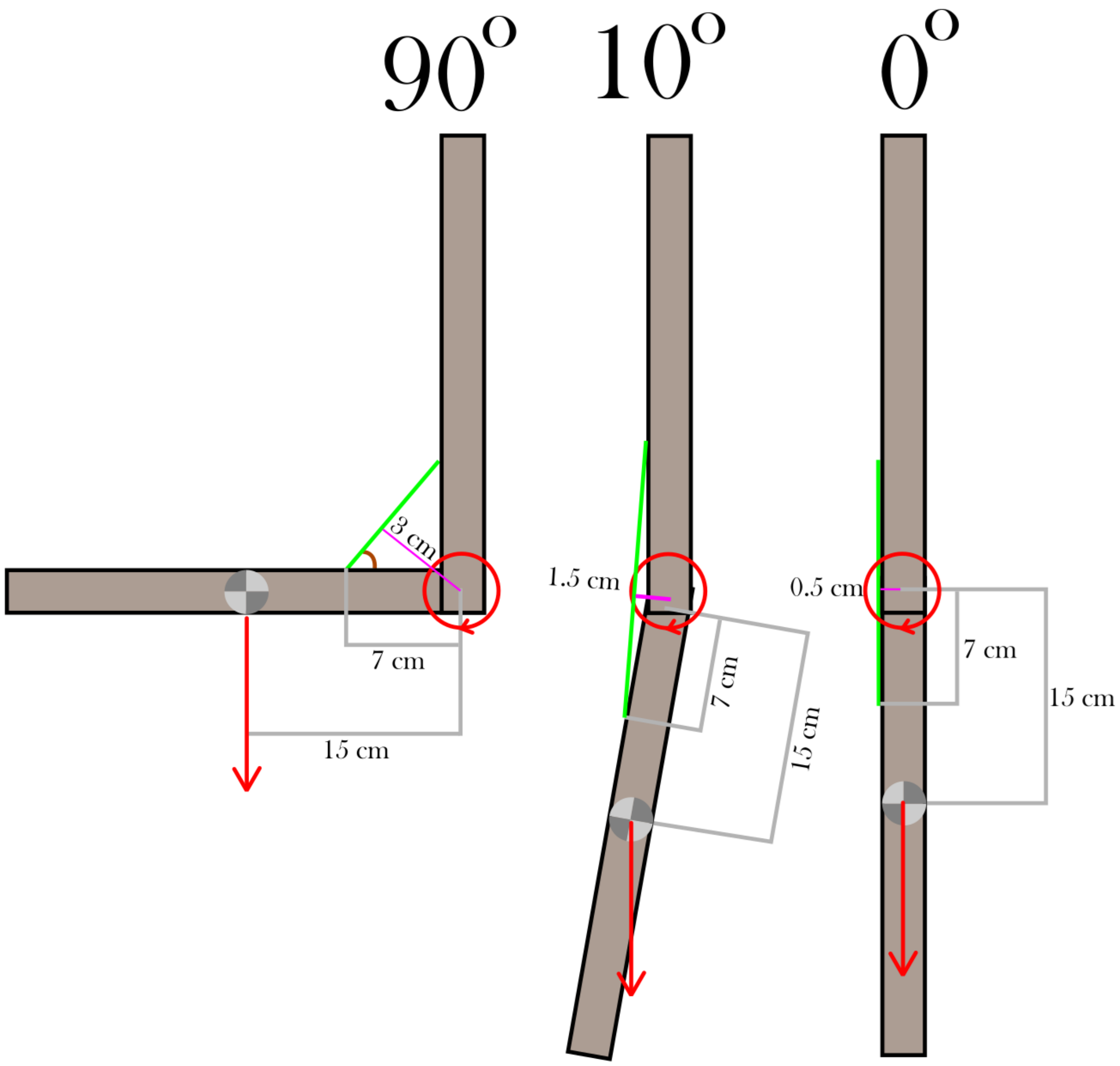
General feedback

11. **What did you like most about the exoskeleton?** That is felt secure and was relatively easy to use. I was not worried that my hand would suddenly drop.
12. **What did you like least about the exoskeleton?** It was tight on the upper arm, which caused a bit of pain when fully flexed.
13. **Do you have any suggestions for improving the exoskeleton?** Different size pieces for the straps.

C Torque and cable tension calculations

Parameters

- Weight of forearm: $m_f = 1.5\,\text{kg}$
- Length of forearm: $l_f = 0.30\,\text{m}$
- Distance to attachment point (from elbow): $l_a = 0.07\,\text{m}$
- Distance to center of mass (from elbow): $l_{com} = \frac{0.30\,\text{m}}{2} = 0.15\,\text{m}$
- Motor operational torque: $1.8\,\text{Nm}$
- Motor maximum momentary torque: $5.3\,\text{Nm}$
- Spool radius: $r_s = 0.01\,\text{m}$
- Additional weight: $m_a = 2\,\text{kg}$
- Gravity constant: $g = 9.82\,\text{m/s}^2$
- Lever arm distances:
  - Fully extended (0°): $l_0 = 0.01\,\text{m}$
  - Slightly bend (10°): $l_{10} = 0.015\,\text{m}$
  - 90° bend: $l_{90} = 0.03\,\text{m}$



Equations

The force due to the weight of the forearm can be calculated like so

$$F_{forearm} = m_f \cdot g \tag{C.1}$$

And torque can be calculated by this equation:

$$\tau_{elbow} = F_{forearm} \cdot l_{com} \tag{C.2}$$

As the torque is dependent on the weight of the forearm and the distance from the axis of rotation to the center of mass, which is roughly half of the length of the forearm.

It therefore remains constant despite a change in the angle of the elbow:

$$\tau_{elbow} = 1.5\,\text{kg} \cdot 9.82\,\text{m/s}^2 \cdot 0.15\,\text{m} = 14.73\,\text{N} \cdot 0.15\,\text{m} = 2.21\,\text{Nm} \tag{C.3}$$

Calculating the tension of the cable acting on the arm, the lever arm, which is the perpendicular distance from the string to the axis of rotation, is used.

Since the arm is stationary, the string must create an equal but opposite torque to the torque of the elbow, thus the torques are at an equilibrium and $\tau_{string} = \tau_{elbow}$ is true.

And since torque can also be calculated like so:

$$\tau = F \cdot d \cdot \sin\theta \tag{C.4}$$

with d being the distance from the pivot point (elbow) to where the force is applied (string), and θ is the angle between the force vector (running along the string) and the arm. In this case, the lever arm distance l replaces the product $d \cdot \sin\theta$.

With this, the unknown tension force can be found:

$$\tau_{string} = F_{tension} \cdot l \Leftrightarrow \tau_{elbow} = F_{tension} \cdot l \tag{C.5}$$

So, with the elbow at 90°:

$$\tau_{elbow} = F_{tension} \cdot l_{90} \Leftrightarrow 2.21\,\text{Nm} = F_{tension} \cdot 0.03\,\text{m} \Leftrightarrow F_{tension} = \frac{2.21\,\text{Nm}}{0.03\,\text{m}} = 73.58\,\text{N} \tag{C.6}$$

And following the same structure, with the elbow fully extended at 0°:

$$F_{tension} = \frac{2.21\,\text{Nm}}{0.005\,\text{m}} = 441.45\,\text{N} \tag{C.7}$$

Since the operational torque of the motor is 1.8 Nm, with a maximum momentary torque of 5.3 Nm, and the radius of the spool on which the string is wound, the force the motor can exert using the spool can be calculated like so:

$$F_{motor} = \frac{\tau_{motor}}{r_{spool}} \tag{C.8}$$

This gives an operational force of 180 N, and a maximum momentary force of 530 N

Following the same equations for the other configurations, the cable tensions can be seen in the table below:

	Cable tension (N)
l_{90}	73.58
l_{10}	147.33
l_0	441.45

As it can be seen, the cable tension is 441.45 N when the arm is fully extended, which the motor can overcome momentarily, and even at 10°, the force needed to flex the arm is within the operational range of the motor, and this falls as the elbow moves towards 90°.

The problem with the elbow torque being 2.21 Nm is that the motor may burn out, since it is continuously using more torque than it is rated for in continuous use.

This may be compensated for with the use of the user's muscles, which may compensate for the difference in torques.

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