Design of an active orthosis for improved rehabilitation of stroke patients

Providing movement support based on myoelectric pattern recognition

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Abstract

To regain mobility in an affected limb after a stroke it is important to be consistent with rehabilitation exercises. The purpose of this project was to create an active orthosis for the elbow joint. The intended use of the orthosis is to help stroke patients during rehabilitation and to enable the possibility to use the orthosis at home without the assistance of a physiotherapist or other help. The active orthosis that was developed in the project is a further development of a passive orthosis developed at the Center for Bionics and Pain Research (CBPR) in Gothenburg.

To make the orthosis active a servo motor was added to the elbow joint. To control the orthosis EMG-signals were collected from the participants bicep brachii and tricep brachii. The EMG-signals were thereafter interpreted by a machine learning algorithm in the open source program BioPatRec. The machine learning algorithm constructed a movement classifier based on data from a training set. The program thereafter sent a motor command with the intended direction to an Arduino. Lastly the Arduino sent a pulse width modulation (PWM) signal to the motor to move it a predetermined amount of degrees.

Two different ways to obtain the data for the training set were designed. An evaluation test was performed to evaluate the methods. Seven participants made flexion and extension movements from endpoint to endpoint in the range of motion. The two training methods were considered to be equally good. It was possible to control the orthosis in both directions but it was easier to do the flexion movement than the extension movement. The participants did not feel that the orthosis movements were scary but they experienced a delay in the movement.

With the end product it is possible to test the concept of an active orthosis but much development is still needed for it to be a rehabilitation tool for stroke patients.

Preface

This report was written as a master thesis to finalize the two authors' education at the Biomedical engineering program at Lund Technical University (LTH) in Lund. The report was written during the spring term of the year 2022.

The master thesis project was conducted at the Center for Bionics and Pain Research (CBPR), in Gothenburg. We would like to thank the CBPR group for the opportunity to write our thesis with them and for all the inputs on our project.

During our project a lot of people have helped us and given us advice. We would like to thank Ingrid Svensson at the Department of Biomedical Engineering at LTH for the input on our calculations regarding biomechanics. We would also like to thank the staff at the university facility X-lab who have been very helpful with our 3D-printing projects.

Lastly we would like to extend our gratitude to our two supervisors, Morten B. Kristoffersen from CBPR and Christian Antfolk from the Department of Biomedical Engineering at LTH. Their input, advice and commitment to our project have been very valuable.

Contents

1 Introduction

1.1 Stroke

Stroke is a collective name of the symptoms that occur when parts of the brain are damaged due to lack of oxygen. This can for example be caused by a blood clot or if a blood vessel inside the brain breaks [1]. Stroke can lead to both physical and cognitive disabilities depending on which part of the brain that is damaged. Examples of disabilities that can occur after a stroke are concentration difficulties, aphasia and hemiparesis, which is weakness in one side of the body [2]. Another side effect of stroke is that it can lead to spasticity, which can make the muscles stiff and it can also lead to uncontrollable movements [3]. Stroke is the third leading cause of death internationally and the biggest cause of invalidity [4].

1.1.1 Conventional stroke rehabilitation

Different types of rehabilitation exercise methods can be done to help the body regain the lost motor skills. This can be done due to the brain's neuroplasticity which is its natural ability to relearn old skills and rebuild neural pathways to healthy areas in the brain. Practice of a lost skill is the basis of stroke rehabilitation since it encourages the brain to build new neural pathways. If the patient still has some mobility in the limb, the best way to practice is to perform arm rehabilitation exercises. If the patient has no mobility in the limb, neural pathways can still be rebuilt by passive exercises. A passive exercise can be performed with the help of a physiotherapist that moves the limb or the patient can move the affected limb with a non-affected arm [5].

Two other methods of stroke rehabilitation are mental practice and mirror therapy. During mental practice the patient visualises the movement of the affected limb. With mirror therapy a mirror is placed on the center of the patience's body. Thereafter the patient moves the non-affected limb while looking in the mirror. This tricks the brain to believe that the affected limb is moving, which encourages new neural pathways [5].

Rehabilitation of stroke is very individual, where both the timeline and the outcome varies. The one thing that all stroke rehabilitation have in common is that it is important with consistency and repetitive practice to see results [5].

1.1.2 Experimental stroke rehabilitation

Unconventional and experimental rehabilitation methods have also been explored in addition to the more conventional ones. The research group Center for Bionics and Pain Research (CBPR) is one of many that are trying to develop these methods further. One of these methods are the use of virtual reality (VR) or augmented virtual reality (AVR). By measuring the electromyography (EMG) signals (muscle signals) of the arm in real time they can control a virtual arm on a computer screen that mimics the intended movement. AVR is used by also recording and showing the patient on the screen and applying the virtual arm onto the patient. This is a good way to give a visual feedback to the patient and it also encourages the patient to continue the rehabilitation process as well as helps promote neuroplasticity [5].

Further on another experimental method is something called serious gaming and this is something that CBPR has investigated as well. Likewise as when using VR and AVR the EMG-signals are recorded in real time to interpret the intended movement. In the project myoelectric pattern recognition is used in order to drive different serious games. Instead of only repeating a flexion and extension movement a patient can be occupied playing a game which makes the rehabilitation process more fun to do and helps promote neuroplasticity [5]. For example the arm can be used to play the game Breakout where flexion of the arm moves the platform to the left and extension of the arm moves the platform to the right.

The project in this report is a new part of this project that has the focus on helping patients that have minimal function to be able to move again. The idea is to apply some sort of motor to an orthosis to help assist the arm in the intended movement simultaniously as playing a game. Since stroke patients have compromised mobility they can normally not finish a complete flexion and extension movement of the arm. By assisting them in the intended movement they can complete the movements and the visual feedback would be a great way to encourage the patient to continue the rehabilitation.

It also helps promote neuroplasticity [5]. In spite of the positive effects of this treatment it is important to consider the risks that comes with using an active orthosis. When applying a motor to an orthosis it is important that its range of motion does not extend that of the person's arm. Stroke patients' range can be very limited due to cramps and stiffness so it is important not to try to exceed these limits [3].

The active orthosis can be run by different activation methods and one is by detecting muscle signals. The orthosis can be run by using force-myography (FMG) which detects when muscles are activated with the help of a force sensor. No further prossessing is needed and when a FMG signal is detected the whole movement is executed [6]. The orthosis can also be run by placing electrodes on the arm and measuring EMG-signals. This is what the group CBPR are working with and they record the muscles activity in real time. In comparison to FMG the muscles signals are processed in order to recognize the intended movement and can thereby be more precise. It can move more accurately according to the intended arm movement and does not simply execute the whole movement at once [7]. Some studies instead use the opposite arm (the healthy arm) for the muscle recordings to establish a mirrored control [8]. This is based on the method mirror therapy which is mentioned in section 1.1.1.

Another thing that is important to take into consideration when designing an active orthosis for rehabilitation purposes is to consider the risk of slacking from the patient [9]. The human body always strives to be as energy efficient as possible which could lead to patients slacking during rehabilitation if an assistive device is used. If an arm orthosis is designed to assist with the power needed to complete an arm movement the arm will likely eventually take advantage of this assistance and provide as little power as needed [9]. This would then prevent the arm from rehabilitating properly.

1.2 The orthosis

During 2021 a project was done by two students who designed an orthosis for the upper limb that was intended to help stroke patients during their rehabilitation process [10] [11]. The orthosis was intended to support and guide the movement of the upper limb of the patient. Electrodes were also placed on the arm in order to record the EMG-signals that were generated. These were in real time interpreted with the use of algorithms in a program called BioPatRec [12] where the intended movement was calculated. These movements were simultaneously used in combination with VR, AVR or serious gaming.

The orthosis was designed with two joints that were situated at the elbow and the wrist [10] [11], see figure 1. The range of motion around the joints could be adjusted and it was possible to lock them in one position to constrain the upper arm, lower arm and hand all together or separately. This could be done by using the yellow mechanical stops which can be seen in figure 1.The orthosis was constructed in a way that prevents compensatory movements (movements in unwanted directions) from happening and was only enabling the flexion-extension movement of the elbow and the wrist. A belt was also added to provide support and to help with restraining the unwanted movements [10] [11].

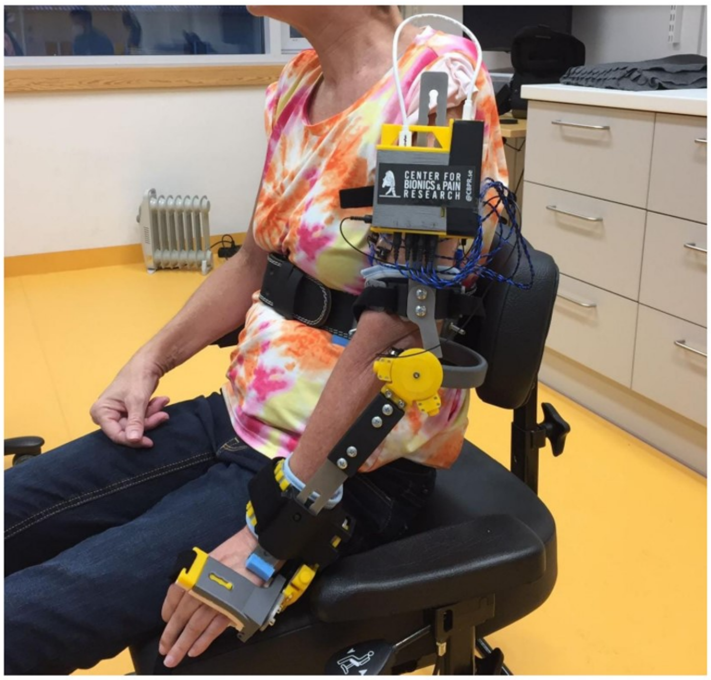

Figure 1: Picture of the original orthosis with attached EMG-measuring tool [10] [11].

When developing the orthosis several requirements were determined beforehand. These stated that the orthosis should enable and help with the flexion and extension movements of the elbow and wrist. Compensatory movements that arise during the exercises should also be restrained so that only the flexion and extension movements are present. The different parts of the orthosis must be able to be adjusted in size to account for the fact that people have different lengths of their upper and lower arms. The orthosis should also be able to be worn for 2-3 hours due to the time it takes to finish rehabilitation exercises and how frequently they are performed. It should also cover a maximum of 40% of the arm to enable the placement of electrodes on the skin when measuring the EMG-signals. The cost of producing the orthosis should not exceed the limit of 200 euros because it is intended to be available to a wide variety of people. Moreover the weight of the orthosis should be less than 1kg in order to assure that the weight is not too heavy for the stroke patient and will affect the rehabilitation. The lifespan of the product was set to a minimum of 2 years and it should also be able to attach to and remove from the arm only with the use of one hand due to the fact that one arm has an impairment. This would enable the possibility to use it at home without assistance from a physiotherapist [10] [11].

1.3 EMG-measurements

When controlling active orthoses and other motor controlled devices it is common to use EMG-signals. It is “one of the most robust and accurate interfaces for controlling robotic devices” as the article written by Liu et al.(2017) states [13]. The article also states that it is an important part of therapy that is robot-aided. EMG stands for Electromyography, as previously mentioned, and it involves the measuring of the electric activity that originates from the muscles when they contract [14]. The contraction and relaxation of muscles are controlled by the nervous system and the signals that originate from them are also dependent on the type of muscle used. Depending on the physiological and anatomical properties of the muscle the signal can differ a bit. It is also affected by the type of electrodes chosen to measure the signals. Surface EMG (sEMG) places electrodes on the skin and this results in the signals having to travel through different tissues before being recorded. This will add noise to the recorded signals. It will simultaneously enable the possibility to record the activity from several motor units which can lead to different signals interfering with each other [14]. To make the signal as good as possible the electrodes should be placed on the middle of the belly of the muscle [15]. Because the different factors affect the outcome of the recorded signals it is important to recalibrate the recognition algorithm between each patient as well as before each recording session [7]. Using an invasive EMG measurement (iEMG) would minimize the noise and disturbance of the signals but it would also enable risks that come with operating on the patient [15].

A common way to place surface electrodes is in a bipolar configuration, this means that two electrodes are placed on the belly of each muscle about one to two centimeters apart. A reference electrode is placed on electrically neutral tissue, which commonly is where the surface of the skin is close to a bone. The advantage of this method instead of monopolar configuration where only one electrode is used per muscle, is that with two signals per muscle it is possible to suppress noise that both inputs have in common and the differences between the inputs can be amplified [16].

An sEMG measurement system (ADS_BP4) was created at the research center CBPR, that includes components for a signal acquisition system called ADS_BP4, see figure 2 [17]. It has wires that are to be connected to electrodes placed on the skin and it also has its own wifi which enables the recordings to be sent to a computer, in real time [17]. The ADS_BP4 is placed onto the orthosis as can be seen in figure 1.

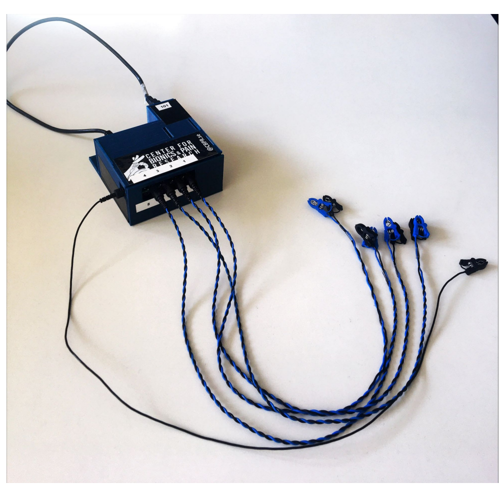

Figure 2: Picture of the EMG-measuring tool.

1.4 Machine learning

BioPatRec is an open source program that can be used for real time control of prosthetic devices. In this project the program will be adjusted for real time control of an active orthosis. In order to achieve this control BioPatRec facilitates machine learning algorithms to perform pattern recognition on collected EMG-signals. Most pattern recognition algorithms need the signals to be categorized with the help of features. In this paper the four most common features in prosthetic control have been used. These are: mean absolute value, zero crossing, slope sign changes, and waveform length [7].

After the features have been extracted, pattern recognition can take place. For offline pattern recognition the data is divided into three sets used for training, validation and testing. The data in the training and validation sets are used to train a classifier. To evaluate the classifier the data from the testing set is used. This is sorted automatically by BioPatRec after the user has chosen what pattern recognition algorithm that will be used. In this paper linear discriminant analysis is going to be used. This algorithm is commonly used in prosthetic control due to its speed, accuracy and simplicity. Once the classifier is trained it can be used for pattern recognition on new data in real time [7].

Another way to control a prosthetic device or an active orthosis through EMG-signals is via "direct control". With direct control electrodes are placed on two separate muscles. Each muscle is associated to one motor direction. If the amplitude of the EMG signal from one muscle is higher than a threshold value the motor turns in the assigned direction. This method works well when only one degree of freedom is required [18]. However it will not be used in this project because the end goal for the product in this project is to facilitate movement in multiple degrees of freedom.

1.5 Project purpose and limitations

1.5.1 Project purpose

The purpose of this project is to create an active orthosis based on an existing prototype made by Schuurbiers and Joosen [10] [11]. The intended use of the orthosis is to help stroke patients during rehabilitation and to enable the possibility to use this orthosis at home without the assistance of a physiotherapist or other help. The orthosis is supposed to help guide the movement of the arm and by making it active it will help to visualize the intended movement that the patient is trying to achieve. This will help enhance mobility in the arm and to promote the neuroplasticity of the brain. The quote "If I can't do it once, why do it a hundred times?" from a post stroke patient is a good example of how important visualization of the intended movement can be [19].

The idea is to add motors that will be able to rotate the elbow- and wrist joint. The motors will be programmed to respond to EMG-signals that are recorded and interpreted in real time from the patient. The EMG-signals will be interpreted by the program BioPatRec that was used in the project that created the orthosis [10] [11] [12]. The output from the program will be connected to the motors and through a programmed algorithm they will respond with movements in real time.

Conclusions were drawn that what needed to be done in this project was to find motors that would be a good fit for the flexion and extension of the elbow and wrist, how to control the motors, how to achieve the power transmission and how to attach all the parts needed to the orthosis.

1.5.2 Limitations

The project is limited to the flexion and extension movement of the elbow and the range of motion of the active orthosis should be no less than that of the original prototype. It will primarily work for patients that have close to no mobility in the upper limb which means that no consideration for "assist when needed" is required. The orthosis should move in accordance with the intended movement of the arm, which is to be measured with EMG-signals.

If time permits it the wrist joint will be made active as well. The orthosis will also be better adjusted for people with some mobility. This will be done by adding "assist when needed" functionality to account for slacking. Lastly it would also be preferable to perform tests of the orthosis on people with full mobility as well as stroke patients.

2 Method

2.1 Method disposition

Before writing this thesis the project had to be divided into different sections due to the large number of different topics that needed to be investigated. The three main sections were “Motor selection”, “Attachment” and “Programming the motor” which can be seen in figure 3. In addition to these sections the method chapter starts with a literature review after which the criteria for the orthosis are set. Safety measures are further on also mentioned at the end of the chapter. After this the chapter ends with a description of the different evaluation tests that were performed.

In the first section the power transmission is discussed and the torque needed from the motor is investigated as well as compared with previous studies. Thereafter different motor types are mentioned after which electric motors are investigated further. Then a selection is made and the chosen motor is described. The section ends with a description of the choice of battery.

The next section starts by discussing different attachment methods after which one is chosen. Variants of this type of attachment are discussed and several designs are proposed before a choice is made. After this discussions are made of how to go forward with executing the changes needed on the orthosis to attach the motor and associated parts. This includes new designs of both plastic and metal elements as well as the circuitry of the motor and associated parts.

In the third section the choice of hardware and communication choices between the motor and the program BioPatRec are discussed. After this different ways of adjusting and calibrating the rotational range of the motor are described. A connection test between the Arduino and the BioPatRec program is then explained. Further on it is also discussed how to perform a real time rehabilitation session with the orthosis. After this it is explained how the collection of data for the training algorithm is performed in order for the program to recognise the arm movements. It is also discussed how to change these training sessions.

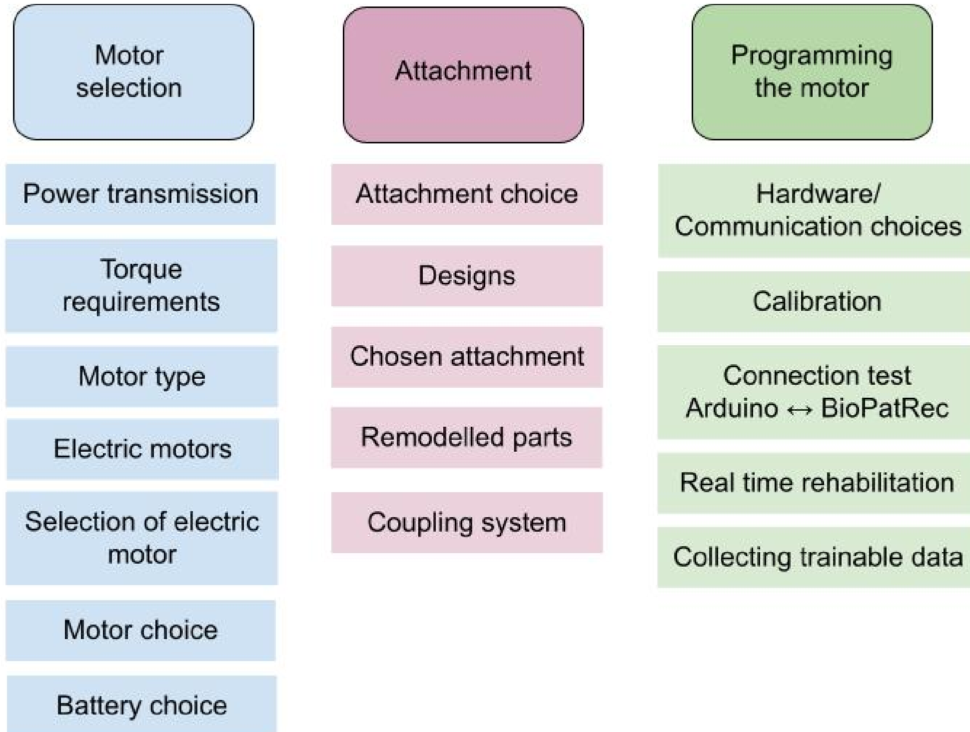

Figure 3: The figure shows the disposition of the method section regarding the three main parts "Motor selection", "Attachment" and "Programming the motor".

2.2 Literature review

The project was initiated by doing a literature review to find out what previously has been done in similar areas. Search word combinations that were used were firstly "orthosis + stroke" and "exoskeleton + stroke" after which several words were combined to the longer sentences "hardware system + orthosis + upper limb" and "orthosis|orthoses|exoskeleton + emg|electromyography + arm|upper limb + stroke|hemiparesis". The searches were performed at the search engines Google Scholar and Pubmed.

After doing some research a conclusion was drawn that there were few articles that suited the project perfectly. A lot has been done regarding exoskeletons and active orthoses but often in a bigger scale with motors that weigh several kilos. Articles were also found regarding orthoses that were EMG-driven but instead made for a hand or a leg. What could be done was to locate only the interesting and well suited parts of different articles and combine them.

The articles from the literature review are used in many of the subsections in the method section of this rapport. They are used as a basis for the decisions about what method of power transmission, attachment, motor type and microcontroller that would be most suitable for this project.

2.3 Criteria

Before developing the orthosis several criteria were determined. Firstly the requirements stated in the previous project made by Schuurbiers and Joosen [10] [11] were looked over and only the ones that were relevant for this project were chosen and sometimes adapted to fit the project. After this new criteria were also set that focused on the movement of the orthosis and how added parts should and should not affect it. Lastly several requirements were set regarding the choice of battery and motor. The requirements can be seen below.

- The orthosis should enable and help with the flexion and extension movements of the elbow (and wrist).
- The orthosis should not move when the arm is resting.
- The range of motion of the elbow motor should be above 150 degrees to enable full movement of the elbow joint [20].
- It should be possible to adjust the range of motion of the orthosis to correspond to the range of motion of each patient. Safety measures should be made to ensure this.
- New parts that are added should not prevent the ability to adjust different parts of the orthosis, to account for the fact that people have different lengths of their upper and lower arms.
- The orthosis should cover a maximum of 40% of the arm to enable the placement of electrodes on the skin when measuring the EMG-signals.
- The new parts that are added to the orthosis should not weigh more than 1kg in order to assure that the weight is not too heavy for the stroke patient and will affect the rehabilitation.
- The new parts should not worsen the processes of attaching and removing the orthosis to and from the arm.
- The number of parts needed to make the orthosis active should be kept to a minimum to avoid risks that come with having a lot of different connections.
- Batteries needed should enable the orthosis to be used for a minimum of 2 hours due to the time it takes to finish rehabilitation exercises.
- The motor(s) and batteries should not be able to reach a too high temperature due to the fact that they will be situated close to the arm.
- The motor(s), batteries and additional new parts should be small enough to be able to place securely on the orthosis.
- The motor(s) should weigh less than 1kg in order to assure that the weight is not too heavy for the stroke patient and will affect the rehabilitation.
- The motor(s) should have high enough torque to handle the flexion and extension movements of the elbow (and wrist).
- The motor(s) should be able to move slowly enough to enable the patient to rehabilitate at a normal pace. The speed should be able to go from 1 up to 10 seconds per 90 degrees.

2.4 Motor selection

2.4.1 Power transmission

To enable movement of an orthosis there has to be a method of power transmission between an actuator and the orthosis. The data in this section was obtained during the literature review. Two common ways of power transmission in active upper limb exoskeletons are gear driven and cable driven power transmission which can be seen in figure 4 [21].

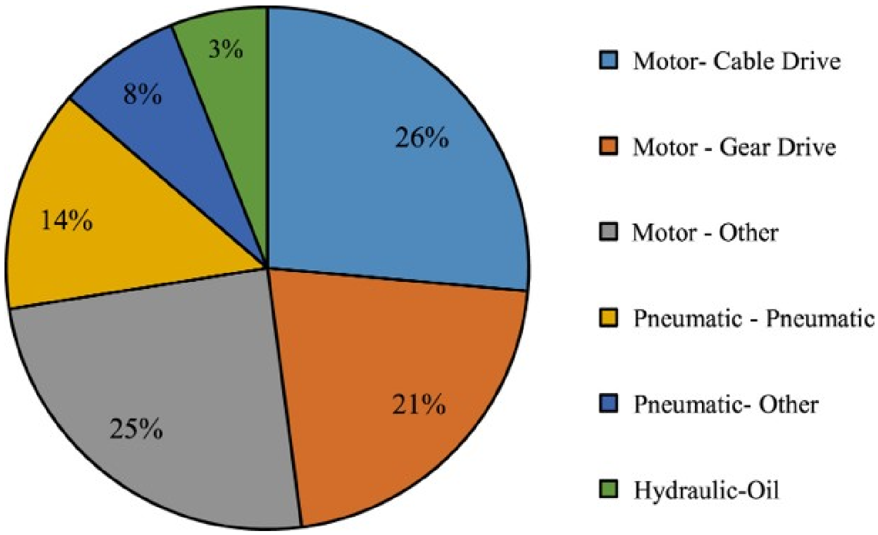

Figure 4: The figure presents different methods of power transmission in an active orthosis and how common they are [21].

With a gear driven transmission the actuator is commonly placed close to the joint [21]. An example of this is demonstrated in figure 5.

Figure 5: The figure presents an example of a gear driven orthosis [22].

In an orthosis with cable driven power transmission, cables are used to pull the limbs in the desired direction. An example of this is demonstrated in figure 6.

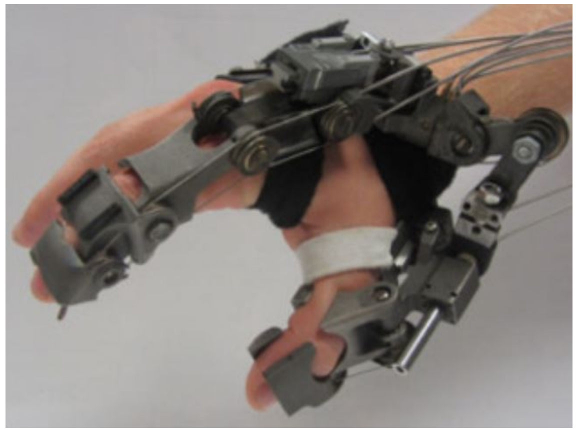

Figure 6: The figure presents an example of a cable driven orthosis [23].

A perk of having a cable driven system is that the actuators do not have to be on the limb and add weight to the orthosis and therefore less torque is required. The cons of this system is that a cable can only pull, not push, and therefore two actuators per degree of freedom is needed [24]. Another disadvantage is that position fluctuations can occur due to slack of the cables [8].

An article by Rzyman et al. argues that an orthosis should be built to mimic the human anatomy as closely as possible. This can be done by the direct matching of joint centers that may occur with gear driven power of transmission [25]. The main problem with a gear driven system is to achieve high enough torque because each actuator is going to add weight to the orthosis [24]. This was seen as a minor problem in this project because the orthosis is only going to have two active joints. Therefore it was decided to go forward with a gear driven method of power transmission.

2.4.2 Torque requirements

2.4.2.1 Motor torque in similar project

To get an estimate of how much torque was required for the project a comparison with similar projects was made. In table 1 motor torque of four different elbow orthoses is presented. The torque ranges from 7-16 Nm.

The torque needed depends on the weight of the orthosis and the intended use of it. For example if the user is intended to facilitate the movement or if the orthosis should be strong enough to lift additional weight, the torque needed differs. The required torque is therefore highly individual and the torques presented in table 1 was set as a guideline.

Table 1: The table presents the motor torque and the intended usage for four different elbow orthoses.

Motor torque (Nm)	Limb	Intended usage	Ref
7	Elbow	For stroke patients in everyday living. Lifts weights up to 1 kg.	[26]
7.35	Elbow	Stroke rehabilitation.	[27]
16	Elbow	Rehabilitation. Lifts weights up to 4 kg.	[28]
11.8	Elbow	Stroke rehabilitation. Lifts weights up to 1 kg.	[29]

2.4.2.2 Torque calculation

Depending on the design and intended usage of the orthosis different requirements are made on the actuators ability to produce torque. One way to estimate the required torque is to calculate the torque needed due to force of gravity and angular acceleration.

The torque needed due to the force of gravity is calculated by equation 1. The calculation is based on the angular position where gravity has the biggest impact, namely when the arm is positioned at 90 degrees. To get an estimate of where the arms center of mass is positioned a table of anthropometric data where the radius of gyration for different body parts are used [30].

$$T_g = m * g * L \tag{1}$$

where

m is the mass of the arm or orthosis,

g is the gravitational constant 9.81,

L is the length to the center of mass.

The torque due to angular acceleration is calculated by multiplying the rotational inertia with the angular acceleration, see equation 2. The rotational inertia consists of the motor inertia and the load inertia. The motor inertia is stated by the manufacturer in the motor data sheet. In general the motor inertia should be no less than 20-25 % of the load inertia to obtain stability in the system [31]. In this simplified calculation the motor inertia is neglected. The load inertia is calculated by equation 3.

$$T_a = I * \alpha \tag{2}$$

$$I_{load} = k^2 * m \tag{3}$$

where

I is the rotational inertia,

α is the angular acceleration,

k is the radius of gyration.

To minimise the torque the angular acceleration needs to be as small as possible, which in turn means that the velocity curve should have a linear appearance with its peak at the halfway point. The velocity curve will therefore be formed as a triangle, see figure 7. The area under the curve represents the distance the orthosis needs to move during time t. If an estimate of the mean velocity is done it is possible to extract the max velocity from the equation 4. Since acceleration is the slope of the curve it can be calculated by equation 5 [32].

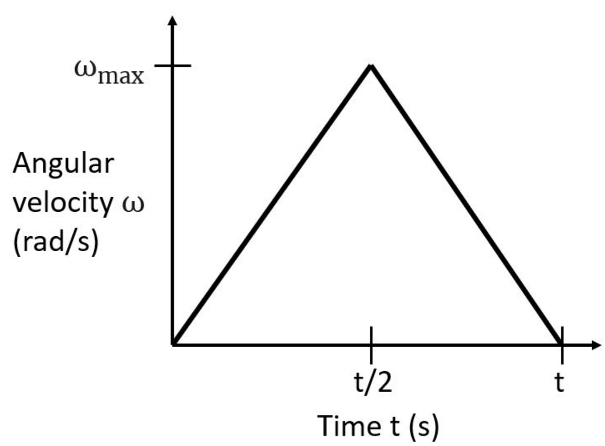

Figure 7: The figure presents the ideal velocity versus time curve.

$$D = \frac{1}{2} * t * \omega_{max} \longrightarrow \omega_{max} = \frac{D}{\frac{1}{2} * t} \tag{4}$$

where

D is the radians the orthosis moves during time t,

t is the time it takes to move the orthosis D radians.

$$\alpha = \frac{|change\ in\ y|}{change\ in\ x} = \frac{\omega_{max}}{\frac{t}{2}} \tag{5}$$

2.4.2.3 Calculate motor torque at different speeds

Motor specifications often state the no-load-speed and the stall torque of the motor. The stall torque is the highest torque that the motor can produce which coincides with when the rotational speed is zero. There is a linear relationship between the no load speed and the stall torque, which can be seen in figure 8. This means that with an increasing torque the rotational speed of the motor will decrease. To calculate the output torque at a specific speed equation 6 can be used. The variable ωmax should be in the unit revolutions per minute (rpm) [32].

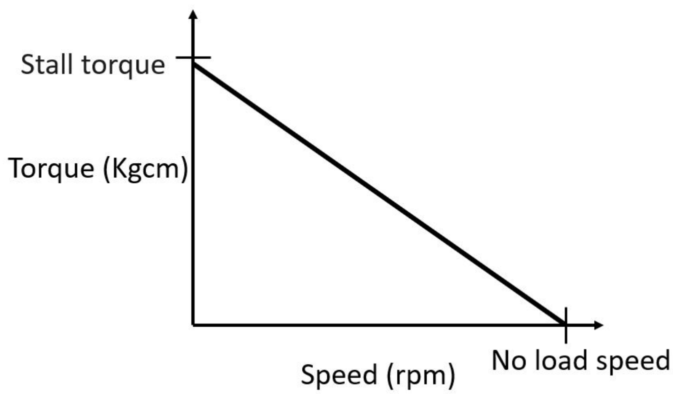

Figure 8: The figure presents the relationship between the no-load-speed and the stall-torque.

$$T = \frac{-stall\ torque}{no\ load\ speed} * \omega_{maxrpm} + stall\ torque \quad (6)$$

2.4.2.4 Torque calculation at elbow joint

A calculation was made to get an estimate of what torque that was required for the motor at the elbow joint. The data that was used to calculate the required torque is presented in table 2. Anthropometric data of an average man were used to calculate the torque. In the book "Introduction to biomedical engineering" a table of anthropometric data is presented for different body parts [30]. The segment "forearm + hand" is defined as the length between the elbow axis and the ulnar styloid, and therefore this length was used in the calculations below.

The part of the orthosis that is located on the lower arm was weighed and 0.52 kg was noted. The weight of the wrist motor was estimated to be 0.35 kg. The torque increases with higher angular acceleration, therefore the highest speed (1 sec/ 90 degree) from the project specification was used in the torque calculations.

Table 2: The table presents data required to calculate the torque at the elbow joint.

Description	Abbreviation	Data	Ref
Weight of average man	m_{man}	87.1 (kg)	[33]
Segment weight/ Body weight for forearm and hand	p_{arm}	0.022 (%)	[30]
Length elbow axis/ulnar styloid	l_{arm}	0.284 (m)	[34]
Center of mass/ Segment length for forearm and hand measured from the proximal part of the segment	$procMc_{arm}$	0.682 (%)	[30]
Radius of gyration/ Segment length for forearm and hand measured from the proximal part of the segment	p_{rg}	0.827 (%)	[30]
Mass of orthosis	$m_{orthosis}$	0.52 (kg)	-
Mass of wrist motor	m_{wmotor}	0.35 (kg)	-
Length to center of mass for wrist motor	l_{arm}	Length elbow axis/ ulnar styloid	-
Time it takes to move arm 90 degrees	$time_{90}$	1 sec/ 90 degree	-

Equation number 1-5 from section 2.4.2.2 where used in the following calculations. The inertia was calculated for both the arm and for the wrist motor separately in equation 8 and 9.

$$T_g = g * ((m_{man} * p_{arm}) + m_{orthosis}) * (procMc_{arm} * l_{arm}) + g * m_{wmotor} * mc_{wmotor} = 9.81 * (87.1 * 0.022 + 0.52) * (0.682 * 0.284) + 9.81 * 0.35 * 0.284 = 5.6098 Nm \tag{7}$$

$$I_{arm} = k^2 * ((m_{man} * p_{arm}) + m_{orthosis}) = (p_{rg} * l_{arm})^2 * ((m_{man} * p_{arm}) + m_{orthosis}) = (0.827 * 0.284)^2 * (87.1 * 0.022 + 0.52) = 0.1344 kgm^2 \tag{8}$$

$$I_{wmotor} = m_{wmotor} * l_{arm}^2 = 0.35 * 0.284^2 = 0.0282 kgm^2 \tag{9}$$

$$I_{total} = I_{arm} + I_{wmotor} = 0.1344 + 0.0282 = 0.1626 kgm^2 \tag{10}$$

$$\omega_{max} = \frac{\frac{\pi}{2}}{\frac{1}{2} * time_{90}} = \frac{\frac{\pi}{2}}{\frac{1}{2} * 1} = 3.1415 rad/s \tag{11}$$

$$\alpha = \frac{\omega_{max}}{\frac{time_{90}}{2}} = \frac{3.1415}{\frac{1}{2}} = 6.2831 rad/s^2 \tag{12}$$

$$T_a = I_{total} * \alpha = 0.1626 * 6.2831 = 1.0218 Nm \tag{13}$$

$$T_{total} = T_g + T_a = 5.6098 + 1.0218 = 6.6316Nm = 67.5311Kgcm \quad (14)$$

The resulting torque was estimated to 6.6 Nm. To have a safety margin it was decided to use 8Nm as a lower limit for the torque requirements of the elbow motor in this project.

2.4.3 Motor type

The first step of choosing a motor for the orthosis was to decide what type of motor that would be used. This was done by looking at the articles in the literature review. There are different kinds of actuators, for example electric, pneumatic and hydraulic motors. A study made by Gopura et al. that compared different hardware systems of active upper-limb exoskeletons concluded that electric actuators are by far the most common followed by pneumatic actuators which can be seen in figure 9. Pneumatic actuators have a higher power to weight ratio than electric motors but it was decided to focus on electric motors because they are easier to control and smaller in size [21].

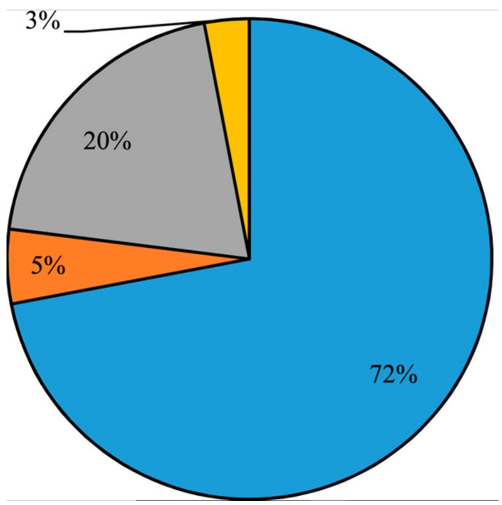

Figure 9: The figure present how common different motor types are according to a study by Gopura et al. Blue: Electric motor, Grey: Pneumatic motor, Orange: Hydraulic motor, Yellow: Other [21].

2.4.4 Electric motors

There are four different types of electric motors that are commonly used in active orthoses: DC brushless, DC brushed, stepper and servo motor. A DC brushed motor consists of coils that are connected to a commutator that is located inside a magnetic field. The coils rotate when a current is applied through the wires of the coils which leads to a force that enables the movement. A DC brushless motor consists of a rotor with a permanent magnet that is surrendered by coils. The movement is achieved by shifting the polarity of the current in the coils [35].

Stepper motors are set up similarly as a DC brushless motor with a rotator in the middle that is surrounded by coils. It includes a control board that sends electrical pulses that allow the motor to rotate in precise angular steps. A servo motor consists of a DC motor that is connected to gears. The gears decrease the speed and increase the torque in comparison to the original DC motor.

A servo motor also includes a positional sensor which allows a user to rotate the motor to a specific location via a microcontroller [35]. The pros and cons of each type of motor are presented in table 3.

Table 3: The table presents pros and cons of the motor types: DC brushed, DC brushless, Stepper and Servo motor [35] [36].

	Pros	**Cons**
DC Brushed motor	• High torque • Easy to control • Have previously been used a lot in active orthoses	• Maximum torque at specific parts of rotation • Cannot keep track of position by itself • Very loud (both parts rubbing together and sparks) • Easily worn out, need to replace brushes • Becomes very hot
DC Brushless motor	• High torque • Little noise • Constant max torque • High endurance	• Cannot keep track of position by itself • Can be hard to control and some need to be controlled by a special regulator
Stepper motor	• Max torque at low speed • High holding torque • Good tracking of position and speed • Easy to control with micro controllers • Easier to control than a DC or servo • Cheap	• Often needs a driver IC in addition to a micro controller to achieve a high enough torque • Can skip steps at high loads and speeds • Respond time is slower than a DC • Loud • Becomes very hot (Draws maximum power at all times)
Servo motor	• High torque • Higher torque at higher speeds • Good control of position • Cheap motors are available • Lightweight motors exists • Often recommended for robotic arms	• Can be limited in range of motion • Is constantly trying to adjust the position which can result in twitching movements

2.4.5 Selection of electric motor

The next step was to decide what kind of electric motor that would be suitable for the project. This was done by considering the pros and cons presented in section 2.4.4. Since the motor was going to be placed on the orthosis near the arm it was important that the temperature of the motor stayed within an acceptable range. This was the main reason why DC brushed motors were discarded, but also because they get very loud and require some maintenance. Stepper motors were also discarded because they can get very hot.

The two kinds that were left were DC brushless and servo motors. These motors are very similar. A servomotor is a complete package that includes a DC brushed or brushless motor and components that keep track of the position. They also often have components that increase the torque. With a DC brushless motor these parts have to be added separately. DC motors are therefore easier to customise but it can also be difficult to find compatible parts.

To find a suitable motor the articles in the literature review were evaluated based on the motor type and both DC brushless and servo motors were kept as possible candidates. None of the motors from the articles were deemed suitable for the project. Some were too heavy, some did not produce a high enough torque and some required a too high of a voltage. Many of the articles also only specified the type of motor and not the model which was not sufficient information in order to find the motor.

The next step to find a suitable motor was to search the internet. To get a working solution from a DC brushless motor the motor has to be matched with a gearbox and a control board. It was decided that this would be too time consuming for this project and thereafter the focus was set on servomotors. The internet search for servo motors resulted in the four different options presented in table 4.

Table 4: The table presents four different servo motors and their specifications.

Nr	Motor	No load speed (rpm)	Stall torque (kgcm)	Weight (g)	Voltage (V)	Rotation range (°)	Ref
1	Power HD WH-80KG 8.4V	353	80	186	8.4	125	[37]
2	RMD-X6 S2	70	18 (nominal)	600	48	>180	[38]
3	K-power HB150T	62.5	155	330	12	120	[39]
4	SG20-50 Series Servo Gearbox	14	169.9	196	6.0 - 7.4	504	[40]

A comparison between the different motors were made which resulted in that motor 1-3 in table 4 were ruled out. This is because the range of motion on the first and third motor is lower than the specified range of 150 degrees in the criteria set in section 2.3. Further on the second motor is the heaviest and needs a high voltage which is why it was discarded. It was decided to go forward with motor number four, the SG20-50 Series Servo Gearbox motor that is from the company Servocity. The primary reason why this motor was choosen is because it can produce a high stall torque.

2.4.6 SG20-50 Series Servo Gearbox

The servocity SG20-50 series servo gearbox motor is a servo motor with a built-in gearbox. It uses an encoder to keep track of the position. Because the motor is multi-turn the position feedback is relative rather absolute.

The motor is available in five different models where the torque and speed differ. The second strongest motor was chosen because it had a good balance between speed and torque [40]. Equation 6 was used for five different speeds to get an estimation of how high torque this motor would produce at different speed levels. The results for the Servocity SG20-50 motor can be seen in table 5. With the speed 5 seconds per 90 degree and slower it produces enough torque to be over the lower limit of 8Nm.

Table 5: The table presents the output torque at different speeds for the Servocity SG20-50 motor.

Motor	**Stall-Torque (Nm)**	**Output torque at 3 sec/90deg (Nm)**	**Output torque at 4 sec/90deg (Nm)**	**Output torque at 5 sec/90deg (Nm)**	**Output torque at 6 sec/90deg (Nm)**	**Output torque at 7 sec/90deg (Nm)**
SG20-50	16.7	5.0	7.9	9.7	10.8	11.7

The motor has a rotational range of 504 degrees which widely exceeds the movement of the elbow joint. The rotational range of the motor was meant to be adjusted to 180 degrees with a purchased servo programmer. The result from using the programmer where varying and unreliable in this project. This led to the servo programmer being discarded. The range of motion was instead set in the calibration program that will be discussed in section 2.6.2. Safety measurements were also set regarding the range of motion which is discussed in section 2.7.

2.4.7 Battery choice

When choosing the battery for the servo motor several things had to be taken into consideration. As stated in the criteria section in the report it should be as small as possible, not get too hot when used and should preferably last for at least two hours. To be suitable with the chosen motor it should provide a voltage between 6.0V – 7.4V and to investigate how long the battery would last with the chosen motor a simple calculation had to be made, see equation 15.

$$t = \frac{C}{I} \tag{15}$$

Here t is the battery time in the unit hours (h), C is the capacity specified in ampere hours (Ah), which is specified on the battery, and I is the current needed from the motor specified in ampere (A) [41]. The battery that was chosen had the capacity 3500mAh and the stall current of the servo motor was 2700mA (which is the current drawn at stall torque). The battery time would, with this battery, result in 1.3 hours if stall torque was required the whole session, see equation 16.

$$t = \frac{3500mAh}{2700mA} = 1,30h \tag{16}$$

Due to the fact that the motor does not work at stall torque at all times the calculated battery time will only be theoretical and is longer in reality. The no load current for the motor is 250mA which would give a battery time of 14 hours, see equation 17.

$$t = \frac{3500mAh}{250mA} = 14h \tag{17}$$

When performing evaluation tests with the orthosis the battery time was tested in real life, see section 2.8. As can be read in the section several tests were performed and they took around 1.5 hours to finish. This concludes that the battery should last for at least 1.5 hours during real rehabilitation sessions and might last longer due to the fact that the battery will not be working at stall current at all times. The battery was also relatively small with the dimension 70x19x36mm.

Conclusions are drawn that the battery should be sufficient enough for this project due to the fact that 1.5 hours are long enough to properly assess the performance of the orthosis' movements. Batteries with higher capacity are available on the market but the size of the chosen one was determined to be small enough to outweigh the advantages with the other ones that were found. But to ensure that the battery will last the whole session it should be recharged after each finished session.

2.5 Attachment

In the literature review it was found that there are many ways to attach a motor to an orthosis. The first decision that had to be made was if the motor was to be placed on, near or away from the joint [42]. Because of the choice of a gear driven power transmission and a not too heavy servo motor was desired, it was possible to place it near or on the joint. The closer the joint the motor is the less gears and other parts are needed which in turn leads to less energy loss [42]. It also more accurately represents the real anatomical movement of the arm, as previously stated, so a decision was made to place it as close as possible [25].

According to an article written by Desplenter et al. (2020) [42] positioning the motor near the joint is the most common way to place a DC motor for an elbow joint. In this article servo motors are included in the DC category. DC motors are usually heavy and therefore often placed further away depending on the consequences its weight will have on the job [42]. Since one of the criteria for the orthosis was that the motor should be small and lightweight this enabled the possibility to also place the motor on the joint if needed [42]. To minimize the effect the motor would have on the torque needed, it was decided to attach it to the upper part of the orthosis that is not included in the flexion-extension movement of the elbow.

An early idea that was discussed was to remove the mechanical stop on the joint of the orthosis to be able to attach the motor directly to the metal parts, see figure 1. But it was decided that the safety function that the mechanical stop had, and its possibility to constrain different parts, were too important to exclude. One downside to this was that the range of motion of the orthosis was limited to 120 degrees of motion. This is less than the normal 150 degrees of motion of the human arm [20]. Many different options were discussed regarding how to attach the motor and the ideas that were tested are presented in this chapter. A common feature among all the designs was that the motor was partly attached to the upper part of the orthosis.

2.5.1 Design 1

One idea was that the gears of the servo motor would be positioned above the joint while a mount arm would be attached to the gears as well as to the lower part of the orthosis. This would position the gears above the mechanical stop, without any disturbance of its movement, which would make it possible to maintain its function. A mountarm, metal U-channel and associated screws and nuts would be used and the U-channel would enable the possibility to attach the servo motor to the orthosis properly. A sketch was made to visualize the intended attachment of the different parts as can be seen in figure 10.

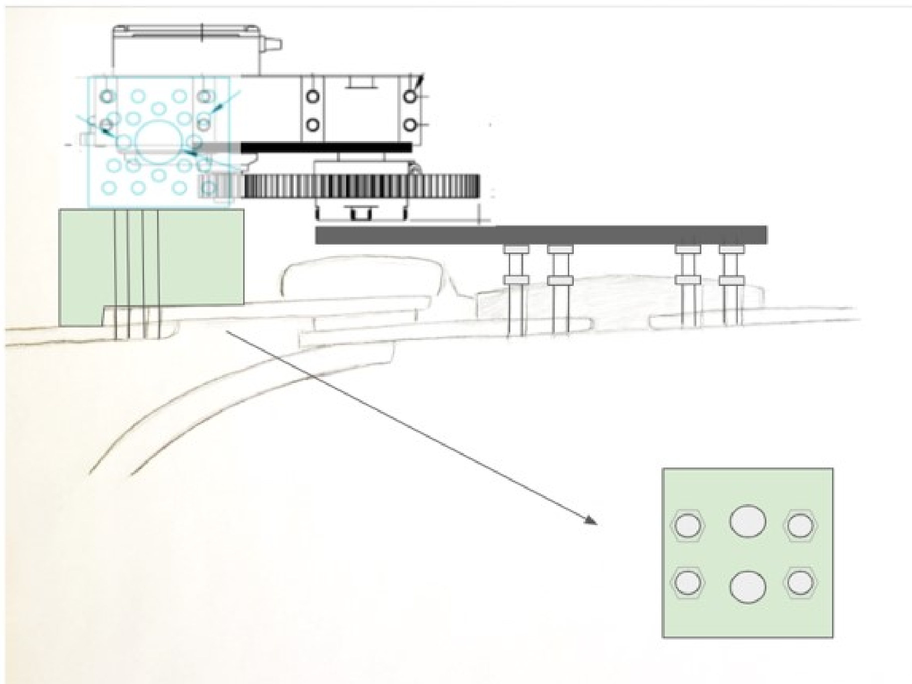

Figure 10: Sketch of the first design that shows how to attach the motor to the orthosis [40] [43].

In the sketch it was visualized that a plastic part (green) would be attached to two already existing screws on the orthosis that had been replaced with longer ones. On top of this plastic piece a metal U-channel (blue) would be attached with the help of four screws and nuts which was visualized in the right lower part of the figure. The plan would be to attach the servo motor to this U-channel and let it float above the mechanical stop. The size of the plastic part (green) would help with the height difference. A mount arm (black) would be attached to the gears of the servo motor and also to four screws on the lower part of the orthosis. The four screws of the original orthosis would be replaced with longer ones to account for the height difference and the structure would be tightened and secured with the help of four nuts. If the structure on the lower part of the orthosis would not be stable enough an idea would be to raise the level by replacing the existing plastic piece on the orthosis with a larger one here as well. Other projects with lightweight orthoses have constructed them in a similar way where the motor is positioned near the joint which validates this approach [26] [44].

2.5.2 Design 2

A second approach would be to attach the motor directly to the metal parts of the orthosis. This is visualized in figure 11. To attach the motor the mechanical stop would have to be moved to the inside of the orthosis. Since the metal bar on the upper part of the orthosis had a ball bearing that the mechanical stop was attached to, it would also be moved closer to the inside of the orthosis. This would instead place the metal bar of the lower part of the orthosis on the outside of the orthosis and thereby enable the placement of a motor on its surface. Notice differences between figure 11 and 10. The mechanical stop would be remodeled in the CAD-program Solidworks to enable the placement on the inside of the orthosis. This design would keep the good aspect of the mechanical stop and also enable more torque of the motor since it could be attached directly onto the joint. The first idea of attaching the motor to a U-channel, that would be attached to a plastic piece on the orthosis, would be kept the same but with the use of a smaller piece, see figure 10.

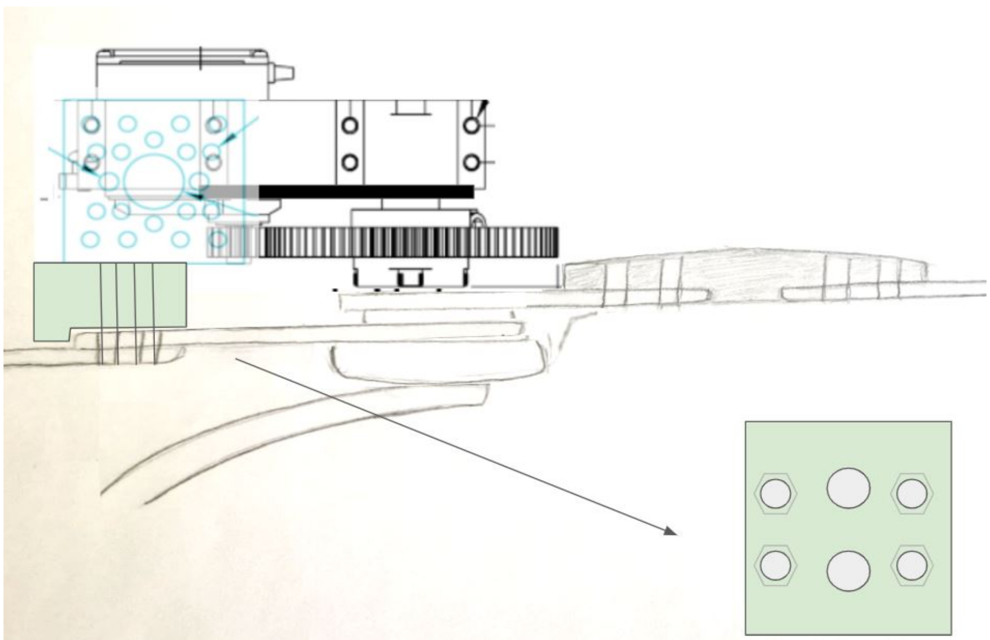

Figure 11: Sketch of the second design that shows how to attach the motor to the orthosis [40] [43].

2.5.3 Chosen attachment

The calculations that were made to estimate the torque needed from a motor to move the orthosis was based on the fact that the motor would be attached directly onto the joint. After making the first design it was concluded that the calculations could not be applicable for this mounting solution. This was because of the mount arm that would be attached between the motor and orthosis. The torque needed to move the orthosis would with this design be higher than the estimated torque. After consultation with the research group, it was concluded that with the first design it was probable that the torque needed would be too high for the chosen servo motor to handle. Therefore it was decided to move on with a second design. The second design required more redesigning of the orthosis but it was still the superior choice in the end because it required less torque from the motor because it could be attached directly onto the joint. A mountarm, metal U-channel and associated screws and nuts was located and purchased online [43].

2.5.4 Remodeled parts

2.5.4.1 Motor attachment

The second design required, as previously mentioned in the above chapter, that the mechanical stop would be moved to the inside of the joint of the orthosis. See differences between figure 1 and the figures 12 and 13 for a comparison between the previous and new model. This freed the surface of the metal piece as can be seen in figure 12 which made it possible to attach the motor directly to the joint.

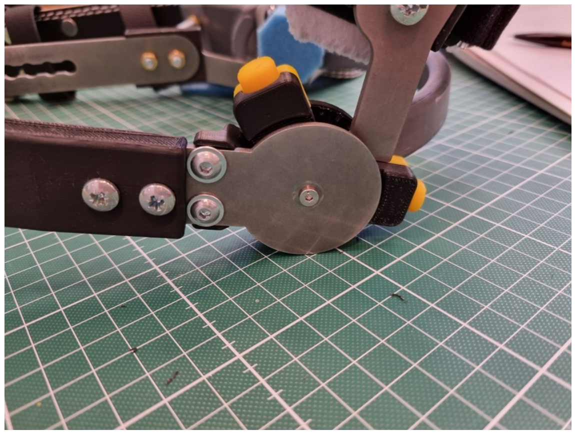

Figure 12: Picture of the orthosis that shows the surface where the motor is to be placed.

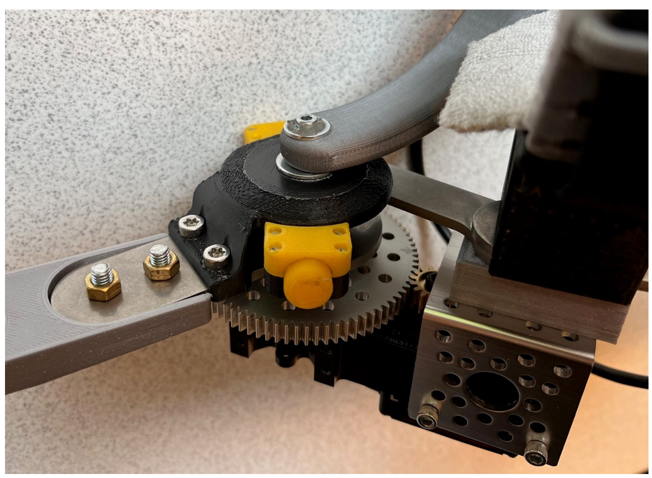

Figure 13: Picture of the inside of the orthosis that shows the new placement of the mechanical stop.

To attach the motor to the metal surface, four holes had to be made. To assure that the design had been correctly made regarding this attachment, a plastic version of the metal piece, that included the four holes, was 3D printed and tested. After assuring that the design worked, holes were made on the real metal piece. The mechanical stop had to be remodeled because of the ball bearing that it was attached to. The ball bearing had two sides that were of different size (both regarding height and width), see figure 14. Due to this the mechanical stop had to change the height of its covering cap as well as change the height of one of the pins. To be able to attach the stop and motor to opposite sides of the metal bar the screws and nuts attaching the mechanical stop had to be changed. In the previous design the screws entered from below the stop which can be seen in figure 12. Since the motor had to be attached to the metal surface before the mechanical stop the screws could only be entered from the opposite direction than before, see figure 13. Since the old screws were too big for this, new ones were located with corresponding nuts.

Figure 14: Picture that shows the ball bearing on the orthosis.

As explained when discussing the first design, a plastic piece had to be made to attach the U-channel to the orthosis and account for the height differences, see figure 10. The plastic piece can be seen in figure 15 where it is mounted to the orthosis. It was attached in the same way as it was explained in the first design section.

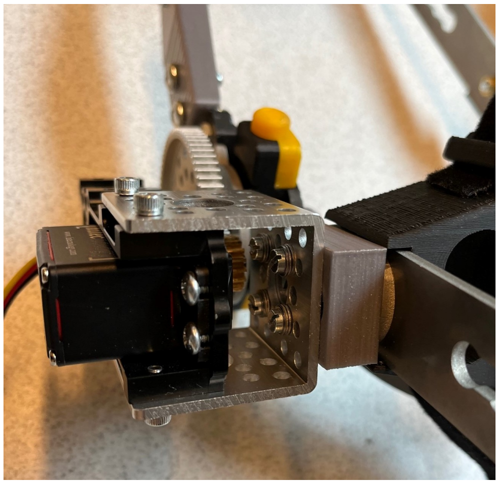

Figure 15: Picture that shows the placement of the plastic piece (grey) that the motor is attached to through the U-channel.

Four screws and corresponding nuts were located and the holes in the plastic piece were adjusted according to these so that the nuts would be lowered down into the piece, see figure 16. The two remaining holes in the piece were also adjusted so that the corresponding screws would be lowered down into the piece as well, see figure 16.

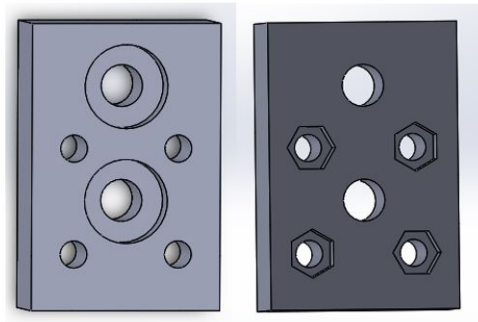

Figure 16: Figure that shows the placement of the screw holes in the plastic piece.

2.5.4.2 Microcontroller attachment

As will be described later in the report in section 2.6.1 a microcontroller was chosen to control the motor. The type of microcontroller that was chosen was an Arduino nano which was placed on a small breadboard that also included an attachment place for the battery as well as an on and off switch. The total dimension of the circuitry was 47x51x16mm. Due to the small size of the microcontroller circuitry it was decided that it would be beneficial to place this inside the ADS_BP4 along with the other microchips it contains. This would eliminate the risk of loose wires getting caught in the orthosis and the need for extended cables. To enable this the ADS_BP4 had to be remodeled in Solidworks. Firstly the height of the box had to be raised. After this a hole had to be made to enable the attachment of the USB cable to the Arduino. This is visible at the upper left wall in the left image in figure 17 and the right image in figure 18. Two holes also had to be made to the lid of the box to enable the attachment of the motor and to reach the on and off switch. This is the two holes to the left in the right image in figure 17. It can also be seen on the left image in figure 18.

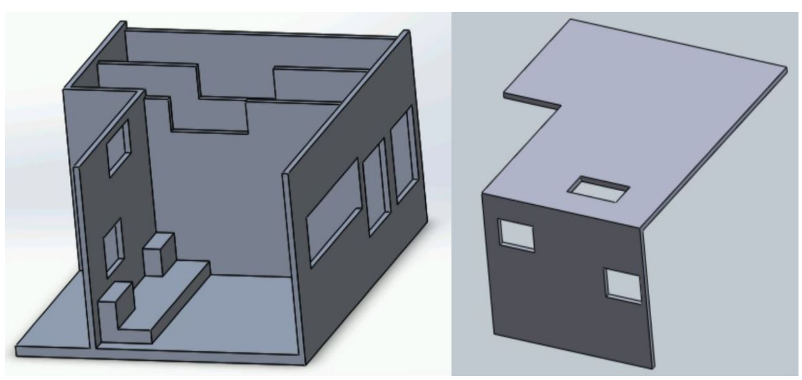

Figure 17: CAD images of the new ADS_BP4.

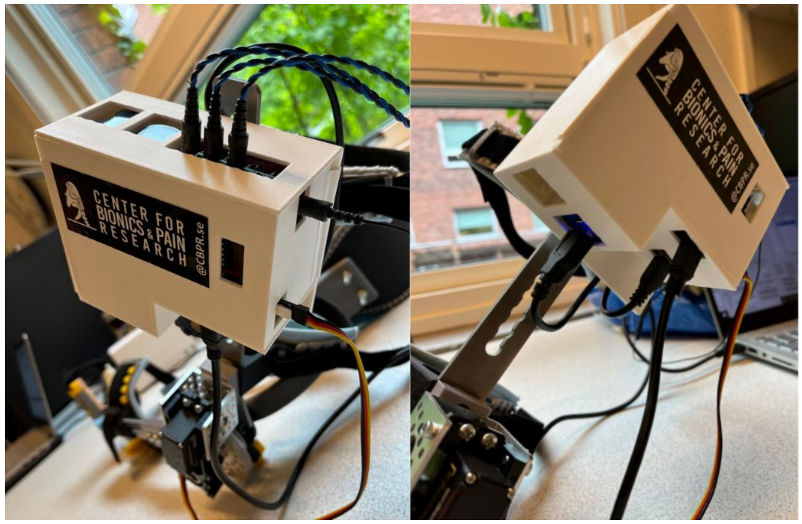

Figure 18: Pictures of the new ADS_BP4 attached to the orthosis.

2.5.4.3 Battery attachment

When discussing how to attach the battery it was concluded that it would be most beneficial to place it inside the ADS_BP4. This would eliminate the risk of loose wires getting caught in the orthosis and the need for extended cables. The ADS_BP4 that was used already had a compartment for a battery that powered its system. This compartment was determined to be a good solution for the placement of the new battery as well since the battery was small and had the dimensions 70x19x36mm. A second similar compartment was added next to the previous one by remodeling the ADS_BP4 in Solidworks, see left image in figure 17. Holes were also added to the walls on the two battery compartments to enable the battery wires to reach the Arduino and its attachment to the breadboard in the nearby compartment, see left image in figure 17. In addition to this, holes were added to each side of the two compartments to enable air to cool down the batteries, see right wall in the left image of figure 17. This is also visible in the two images in figure 18.

2.5.5 Coupling system

The coupling system is shown in figure 19 and visualizes how the wire circuits have been made between the components. The servo motor is connected to the battery via the power lead (red) and ground lead (black) and it is connected to a signal port at the Arduino via the signal lead (yellow). The Arduino is connected to the computer and BioPatRec through the serial port (USB). It is through this connection the Arduino is powered and also where it is grounded. The Arduino also shares the same ground lead of the battery as the servo. The connection between the battery and the servo can be disconnected through an on and off switch that is attached to the power lead.

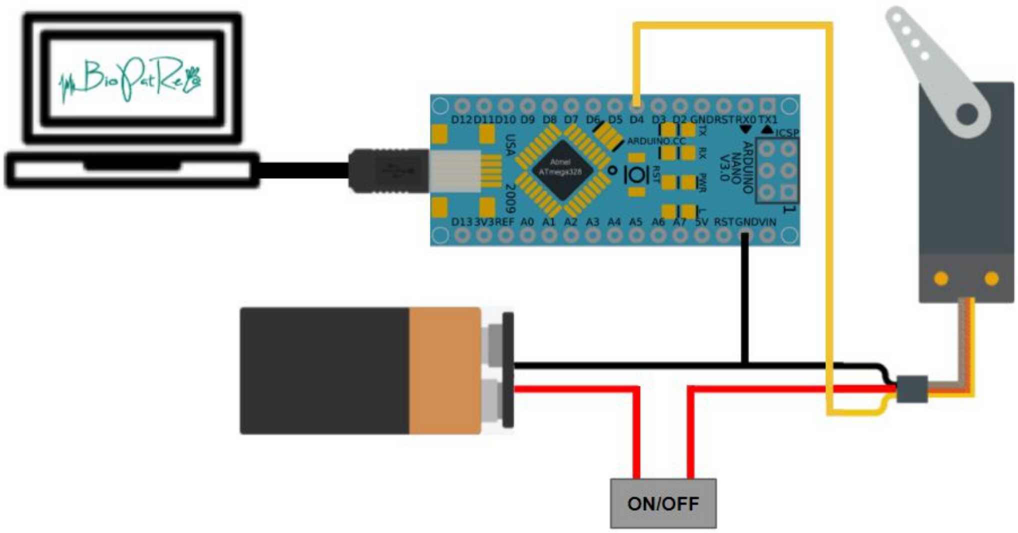

Figure 19: Figure that shows the wire connections between the different components that are to be placed on the orthosis [45] [46].

The Arduino is attached to a breadboard and the different leads were soldered to its corresponding places, see figure 20. The battery was attached to the board through an attachment piece (green) that the battery wires were screwed into. The motor was attached through a different attachment piece (white) that also was soldered into the board. The on and off switch (black) was attached to the breadboard as well.

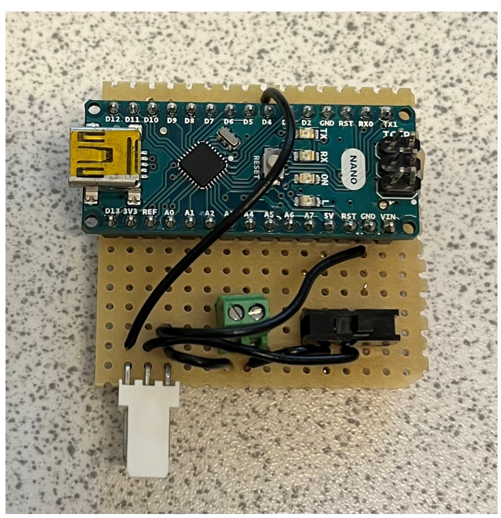

Figure 20: Figure that shows the wire connections between the different components on the breadboard.

2.6 Programming the motor

2.6.1 Hardware/Communication choices

When deciding which motor to choose it was also important to investigate what kind of communication choices they had. During the literature review it was found that a common way to control motors is to use microcontrollers that communicate by generating PWM (Pulse Width Modulation) signals. A PWM signal is created by sending succeeding pulses that come from altering a continuous digital signal [47]. It was decided that an Arduino board would be a suitable choice since it is easy to handle and there is a lot of open source code to find inspiration from [48]. It was also considered to be precise enough so that it would not compromise with the sensitivity or functionality of the ending result [48]. Since the chosen servo gearbox has an encoder included that keeps track of the relative position of the rotator, the positioning of the orthosis can be programmed with the Arduino without the need of any extra parts. This in turn minimized the risks that come with having a lot of different connections.

After deciding on using an Arduino board the connection to the Matlab program BioPatRec had to be established. This was determined to be done by using a serial port communication between the computer and the Arduino board. To gather the EMG-signals electrodes were placed on the biceps brachii and triceps brachii muscles as these are the main muscles used in elbow extension and flexion, as previously mentioned [49]. The electrodes were placed in a bipolar configuration and a reference electrode was placed on the electrically neutral tissue of the elbow joint (on the elbow bone).

The myoelectric signals is transferred to the EMG measurement system ADS_BP4 through wires that are connected to electrodes. The recordings are thereafter converted from analog to digital and transferred to BioPatRec via a local wifi created by the ADS_BP4. BioPatRec sends and receives a control index to and from the Arduino as well as the ADS_BP4 to ensure that a connection have been established. An overview of how the different devices communicate with each other can be seen in figure 21.

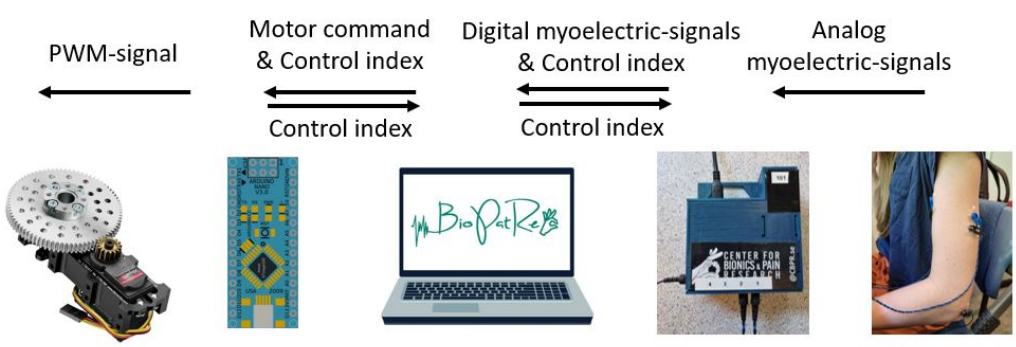

Figure 21: The picture presents how the different devices in the orthosis communicate with each other [40] [46].

2.6.2 Calibration

The SG20-50 Servomotor from Servocity is a multi-turn motor that uses an encoder to keep track of position. Because the motor is multi-turn the position feedback is relative rather absolute, as previously mentioned. This means that the motor only knows how far it moves relative to its starting point, not its absolute position. The motor sets a new coordinate system every time it is rebooted [40].

To get a functional motor for this project it was vital that the system knows what range of motion that is allowed for each patient. This was solved by doing a calibration before each use. A calibration interface was set up in BioPatRec and can be seen in figure 22. The user presses the “Big adjustment” and “Small adjustment” buttons to get to the desired endpoint location for both the flexion and extension movement of the elbow and sets the endpoints by pressing the “Set endpoint” button. The user can thereafter test the range of motion of the orthosis by using the “Sweep up” and “Sweep down” buttons. The “Close” button is used to close the calibration mode and proceed with the rest of the program.

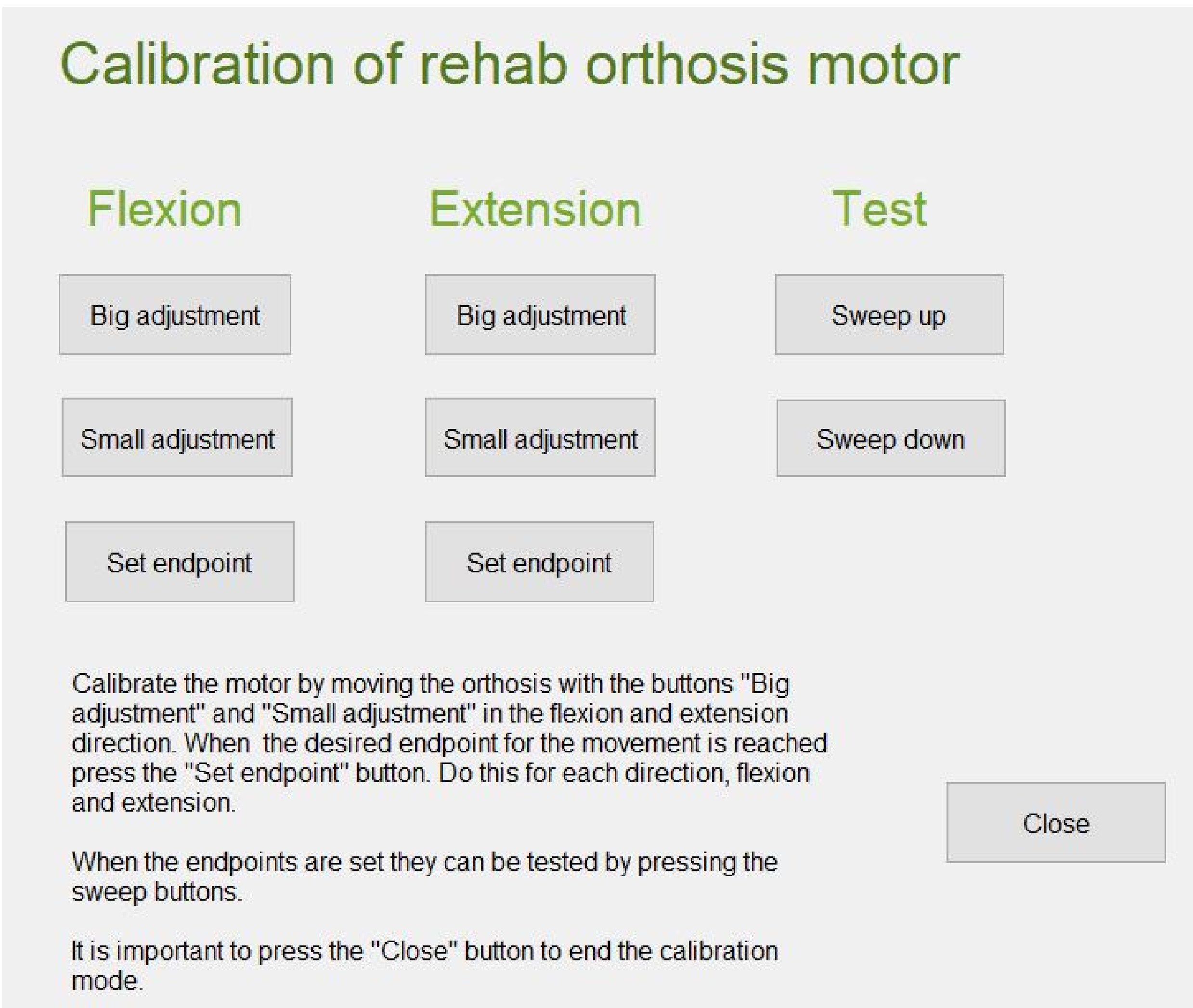

Figure 22: The figure presents the calibration interface.

The Arduino has two modes, calibration mode and drive mode where drive mode is standard. When the user starts a new calibration a command is sent by BioPatRec to the Arduino via the serial port connection to go into the calibration mode.

Each time the user presses a button in calibration mode a command is sent from BioPatRec to the Arduino. The "Big adjustment", "Small adjustment", "Sweep up" and ""Sweep down" button sends a motor command from the Arduino to the motor to move the motor a predetermined amount of degrees. The "Set endpoint" buttons saves the location of the endpoints in the Arduino EEPROM memory. This memory can keep its values when the Arduino board is turned off and rebooted [50]. This means that as long as the motor is powered (and thereby has the same coordinate system) it is possible to reconnect and restart the Arduino and also restart BioPatRec without needing to recalibrate the motor, as long as the same range of motion is required. When the "Close" button is pushed a command is sent from BioPatRec to the Arduino to go back to drive mode and to close the calibration interface.

2.6.3 Connection test between Arduino and BioPatRec

BioPatRec has a built-in function to connect to other devices via either serial port connection or via wifi. In this project a serial port connection was used to connect BioPatRec with the Arduino. BioPatRec is set up to send an index to the connected device and relies on that the connected device sends back that index to ensure that a connection is established. If the index is not received in BioPatRec the program will fail even if the index was received correctly in the connected device.

In BioPatRec there is a test program that tests if the connection between the devices has been successful. A script was made in the Arduino that receives data from the serial port and sends it back. With this script it was proven that a connection was established. This script was later on incorporated in the main Arduino script to ensure connection between the devices.

2.6.4 Real time rehabilitation

To use the active orthosis the user first needs to calibrate the motor to define the endpoints of the range of motion, as previously mentioned. The second thing the user needs to do in preparation of a rehabilitation session is a training session. This is done to achieve data for the machine learning algorithm to train on so that the intended movement can be identified. How the training session is performed is discussed in section 2.6.5.

Thereafter the rehabilitation session can begin. The user can perform one of three movements: flexion and extension of the elbow and rest. The machine learning algorithm in BioPatRec collects the data from EMG-signals and decides which movement the user is intending to perform every 50 millisecond. If the intended movement was rest, then no command is sent to the Arduino and the orthosis remains in the same position. If the intended movement was flexion or extension of the elbow a motor command is sent from BioPatRec to the Arduino through the serial port connection.

A motor command consists of an array of five elements: a header, motor type, index, direction and position/speed. In the active orthosis only element three and four are used. The index is used to ensure that there is a connection between BioPatRec and the Arduino, as mentioned in section

2.6.3. The direction element is either a one or a zero depending on if a flexion or an extension of the elbow have occurred.

As mentioned before the Arduino has two modes where drive mode is standard. When a motor command is received the code will examine the array to see which direction of movement that is required and move the motor and thereby also the orthosis the minimum amount possible in that direction. Thereafter the Arduino will wait for a new motor command.

2.6.5 Collecting trainable data

Before a real time session can begin a training session needs to be performed, as previously mentioned. The purpose of this session is to collect data that can be used by the machine learning algorithm to learn how to categorize different movements. This needs to be redone each time new electrodes are placed on the patient. The training session can be done in different ways.

To train the algorithm in this project the first method that was tried was CBPR's standard method. Five electrodes were placed on the user's upper arm. Two on the bicep, two on the tricep and one reference electrode on the elbow. Both movements, full flexion and extension of the elbow was performed three times each with a period of rest between each set. The result of the training session was evaluated by letting the user control the motor's movements by flexing and extending the arm via the real time settings in BioPatRec. The motor moved very accurately in regards to the user's intended movements when the user was near the endpoints of the extension and flexion movements. The algorithm did not recognize what was happening in all of the positions between full flexion and extension, which meant that no motor command was sent and the motor remained still. This was a problem because the algorithm needs to recognize what movement is intended when the arm is situated at all of the possible positions in its range of motion for the user to be able to control the orthosis.

To overcome this problem the training method was adjusted. The user performed flexion and extension in several points (locations) of the range of motion. At each point the user contracted the corresponding muscles for three seconds followed by a three seconds period of rest. Several attempts were made where the number of points varied between three and eight. A trainer provided some resistance for the user to move against at each location. This method resulted in the algorithm being better at recognizing which motion was performed. The algorithm seemed to get better when the number of points increased, so it was decided to use eight points for this training method. The disadvantage of this method was that the location of the different points were decided by the trainer. This meant that the points were not consistent between different training sets and that provided resistance could vary between different locations and sets.

To improve the training further it was decided that the user should wear the orthosis during the training session. This meant that the trainer could decide the number of points and the spacing between them by moving the motor and thereby also the orthosis. The resistance against the user's movement was provided by the orthosis. This made the training more consistent between different training sets. With these changes the algorithm became better at predicting which movements were made. The algorithm was best at correctly predicting flexion. It sometimes confused "rest" with extension and the hardest thing for the algorithm to correctly categorize was when an extension movement was performed when the arm was located at around 90 degrees.

When an investigation of the training was performed it became clear that the spacing between the different points changed during the range of motion even though the position command to the motor contains the same number of degrees. When the arm was close to 90 degrees the jump between different points became bigger than when the arm was close to 180 degrees. This was thought to be caused by gravity and resulted in that less training of the algorithm was made in the area around 90 degrees. To counteract this the training protocol changed so that the spacing between each jump were more even. This was done by taking smaller steps around 90 degrees than around 180 degrees. This resulted in the algorithm getting a little better at correctly predicting the intended movement but the biggest problem was still at predicting the extended movement correctly around 90 degrees.

As previously mentioned the electrodes should be placed on the belly of the muscle to get the best result. One problem with this is that a muscle moves under the skin during a flexion and extension movement of the arm but the electrodes remain in the same location on the skin. Depending on the user's anatomy it can also be hard to locate the belly of the tricep muscle. To increase the likelihood of getting a good reading of the EMG-signals for the extension movement it was decided to use four electrodes on the tricep brachii.

With these alterations the algorithm got better at predicting the intended movement but it could still misjudge what movement was intended to be performed. This resulted in the motor sometimes switching between rotation directions which could feel jerky to the user.

For the second training method it was thought to copy the movement that is done during a typical rehabilitation session. The speed of the motor was adjusted with delays so that a sweeping motion from endpoint to endpoint took about three seconds. The training consisted of doing the flexion movement from endpoint to endpoint three times and was then repeated for extension movement of the elbow as well. Between each set a rest of three seconds was conducted. During this test the electrodes were placed in the same way as in method one. With this type of training the algorithm was good at correctly predicting flexion of the elbow. Moreover the algorithm had worse results at correctly predicting extension of the elbow, especially when the arm was located around 90 degrees.

When the training is done there is one last thing that can be done to increase the smoothness of the motion and that is to add an algorithm that post-processes the output from the machine learning algorithm. BioPatRec has a built-in function called "Majority vote" that can be used for this purpose. In default mode the algorithm takes the three latest movements and returns the one in majority and this is the movement that is sent to the Arduino through a motor command. The number of movements that are used in each majority vote can be set by the user. The advantage of the "Majority vote" algorithm is that the movement gets smoother because outliers get cancelled out by the majority. The disadvantage of the algorithm is that it delays the response between the EMG-signals and the motor output. The delay is proportional to the number of data the algorithm is based on. By trial and error it was found that a data set consisting of five movements resulted in a good balance between a smooth movement of the orthosis and an acceptable delay time [7].

To evaluate the two training methods, from here on now called "eight point" training and "sweep" training a test was designed. This was also used to evaluate the active orthosis and is described in detail in section 2.8.

2.7 Safety measures

Several safety measures were made to the orthosis in order to ensure the safety of the user. The joints of the orthosis are able to bend in degrees unnatural to the human body which had to be prevented. It was important to ensure that the risk of breaking a patient's arm was zero. The first safety measure was the mechanical stop that is to be set during the startup of the rehabilitation session to ensure that it is properly set to the mobility of the arm. To further limit the orthosis to not go beyond the mechanical stops, endpoints are also set during the startup when calibrating the motor. Other safety measures are to simply turn off the servo motor by switching the on and off button that is attached to the battery or by removing the Arduino cable from the computer.

2.8 Evaluation test

To evaluate the finished orthosis a test was constructed. The test was performed by seven able-bodied participants aged between 20 and 30 years old. The test group consisted of three men and four women and the test took about one and a half hour to perform. Before the test could begin electrodes were placed on the participant's upper left arm. Two on the bicep brachii, four on the tricep brachii and one reference electrode on the elbow bone. The orthosis was then placed on the participants left arm and the motor was calibrated after the users endpoints of the range of motion. The mechanical stop were also adjusted.

The test consisted of two parts, one where the training was done with the eighth point method and one where the training was done with the sweep method. Which method the participant started with was altered between the participants to reduce the risk of the method order influencing the results.

Both of the training methods required that the motor could be controlled during the session which was not possible in the original BioPatRec training program. To make this possible two computers were used. The first computer used the BioPatRec training program and collected the EMG-signals through the ADS_BP4. The second computer was used to control the motor movements and was therefore connected to the Arduino. This computer ran an extended version of the calibration program, where the functions needed for the two training methods were added.

2.8.1 Eight point

As discussed in 2.6.5, the spacing between two points could differ depending on where they were located on the range of motion. Therefore the eight point training method started with a calibration of the jump length between each point so eight points were distributed over the range of motion and that they were spaced visually even. Thereafter the recording of the EMG-signals started. The participant started with the arm at around 180 degrees and flexed for three seconds, followed by a three second period of rest. During the rest period the orthosis moved to the next point. The above procedure was then repeated for each point.

The resulting EMG-signal was evaluated based on if there was a clear difference between the periods of flexion and rest, and if it was not the test was repeated. Thereafter the procedure was repeated for the extension movement where the arm started at the opposite endpoint (around 90 degrees) instead.

2.8.2 Sweep

The second training method was performed as discussed in section 2.6.5. First the speed of the motor was adjusted with delays so that the sweeping motion from endpoint to endpoint took around three seconds. The time of the delays changed between the users. Thereafter the recording of the EMG started and the user performed a flexion movement simultaneously as the motor moved the orthosis from the lowest endpoint to the highest. This was followed by a three second period of rest where the orthosis moved back to the starting point. The flexion movement was repeated three times. The resulting EMG signal was evaluated in the same way as in the eighth point method and thereafter the procedure was repeated for the extension movement where the arm started at the opposite endpoint (the highest).

2.8.3 Real time

After each of the training methods a real time test was performed. The majority vote function with a data set of five was used. Before the test started the participant got to try the real time function more freely in order to get used to how the orthosis felt.

Thereafter the evaluating test began. The participant performed three flexion movements from endpoint to endpoint and three extension movements. For each movement a time limit of 10 seconds was set. Each movement was evaluated separately by the authors of the thesis according to the following criteria. The authors also noted if anything out of the ordinary happened.

Evaluation criteria:

1. Smooth movement and reached the goal position.
2. Jerky movement and reached the goal position.
3. Stuck in the beginning but reached the goal position.
4. Stuck in the beginning and jerky movement but reached the goal position.
5. Jerky movement and did not reach the goal position.
6. Did not move.

2.8.4 Survey

After the test the participant filled in the following survey. The "training" and "real time" survey was filled in twice, one time for each training method.

Table 6: The table presents the survey questions that was answered after the evaluation test.

Question	**Answer option**
Training	
Did the orthosis movements feel scary, acceptable or unscary?	scary - acceptable - unscary
Other thoughts	
Real time	
Did the orthosis movements feel scary, acceptable or unscary?	scary - acceptable - unscary
On a scale of 1-5 how smooth did the movement feel when the orthosis went in the intended direction?	1=bad, 5=good
On a scale of 1-5, do you think the orthosis moved along with your intended flexion movement?	1=bad, 5=good
On a scale of 1-5, do you think the orthosis moved along with your intended extension movement?	1=bad, 5=good
Did you experience a delay in the flexion movement?	Yes/No
Did you experience a delay in the extension movement?	Yes/No
Other thoughts	
Comparison	
Which of the two training sets did you think was the easiest to perform?	Sweep / 8 points
Which of the two training sets did you prefer?	Sweep / 8 points
Which of the two real time test sets did you think was the best?	Sweep / 8 points
Overall, which of the two methods did you prefer?	Sweep / 8 points
Other thoughts	

3 Result

3.1 The product

The resulting product of the project was an active orthosis that was created based on a previous prototype. This means that the main purpose of the project has been met. Other goals were to make an orthosis that enabled the same flexion and extension movement, as well as range of motion, as the previous orthosis prototype. It was also to move according to the intended movement of the arm in real time. These goals were met and the quality of the movement of the orthosis due to different EMG-training methods can be seen in section 3.2.1. The goal was to make an active orthosis for the elbow and also enable the movement of the wrist if time permitted. The elbow movement has been added but the wrist movement still has to be implemented.

Another goal was that the orthosis should primarily work for patients that have close to no mobility. This criteria is concluded to have been met as well and the orthosis should also work for patients with some mobility due to the fact that the orthosis stops when the arm is resting and waits for further muscle activity. This is what is concluded from the results but tests have to be performed on stroke patients to secure that the criteria is met. In spite of it working for people with some mobility of the arm the goal to further adjust the orthosis for these patients have not been fully met. Assist when needed have not been implemented and more account must be taken for the occurrence of slacking. One last goal that would be executed if time permitted was to perform tests on people with full mobility as well as stroke patients. This goal has not fully been reached since no stroke patients have tested the product but tests have been performed on a couple of students with full mobility, see 3.2.1.

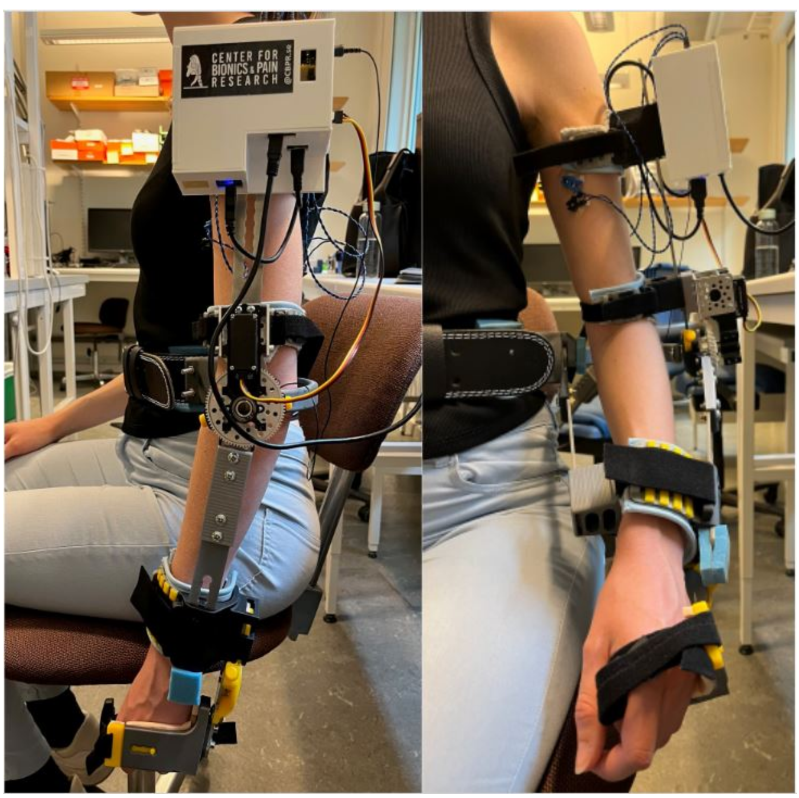

Figure 23: Pictures of the finished active orthosis.

Criteria were set at the beginning of the project, see section 2.3, and all of them were met or partially met. The orthosis is as previously mentioned successfully enabling the flexion and extension movement of the elbow but not the wrist. It is also programmed not to move when the arm is resting and how well this is executed is described more in detail in section 3.2.1. Further on the range of motion of the motor is at 504 degrees which is above the demanded 150. The range of motion of the orthosis can also be adjusted to fit the range of motion of the patient and several safety measures are available to assure this such as mechanical stops, calibrated endpoints, an on and off switch of the motor and pulling out the Arduino cable.

Moreover the ability to adjust the orthosis to fit different arm lengths have not been compromised since the added parts have been placed on parts of the orthosis that would not affect this. These places are on and near the joint and inside the ADS_BP4. When placing the new parts it was also taken into consideration the criteria that said not to cover more than 40% of the arm and the one that said not to make the process of attaching the orthosis more difficult. Electrodes were placed before the orthosis was attached but there was never any problems with reaching the electrodes after the attachment. In other words the orthosis never covered the electrodes. The criteria that stated that the new parts that are added to the orthosis should not weight more than 1kg was also met since the new parts combined weighs around 340g.

Furthermore the number of parts needed to make the orthosis active was kept to a minimum by choosing a servo gearbox with included DC motor, encoder and gears as well as choosing an Arduino connected to the battery and motor through a small breadboard. The criteria that said that the battery time should be at least 2 hours were not met since no tests ensured that it would work for that long. But the battery could last for at least 1.5 hours which was considered to be good enough to be used in this prototype of the orthosis. Further on, both the chosen motor and battery were small enough to be securely placed on the orthosis and neither of them got notably hot during the tests that were performed.

The motor criteria that said that the motor should weigh less than 1kg was met since the motor weighs 196g. The motor also had a high enough torque to assist the arm with its intended movements. Lastly the criteria that the motor should move at a speed appropriate during rehabilitation was not fully met. The speed of the motor has been adjusted to move slower or faster during the training method Sweep but no testing of speed changes has been made in real time.

3.2 Test results

3.2.1 Result of evaluation test

The result from the evaluation test is presented in this section. In figure 24 the results from the eight point method test are presented. The result from the sweep method test is presented in figure 25. During the tests it became clear that flexion of the arm was easier than extension of the arm for the participants. The hardest part of the extension movement was when the arm was at the top of the range of motion. Which training method that the participants started with altered and it was noted that the participants seemed to get slightly better results at the last test.

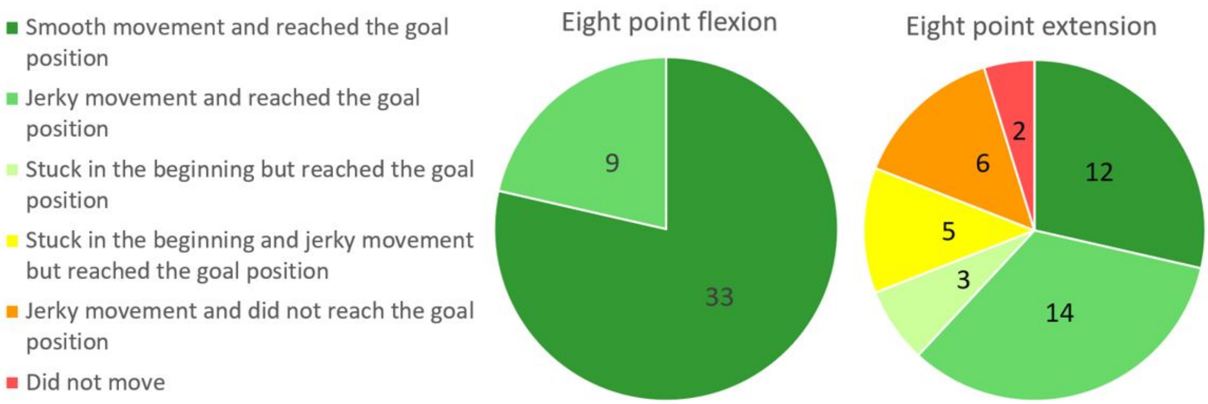

Figure 24: The figure present the result from the evaluation test of the eight point method regarding both flexion and extension of the elbow joint.

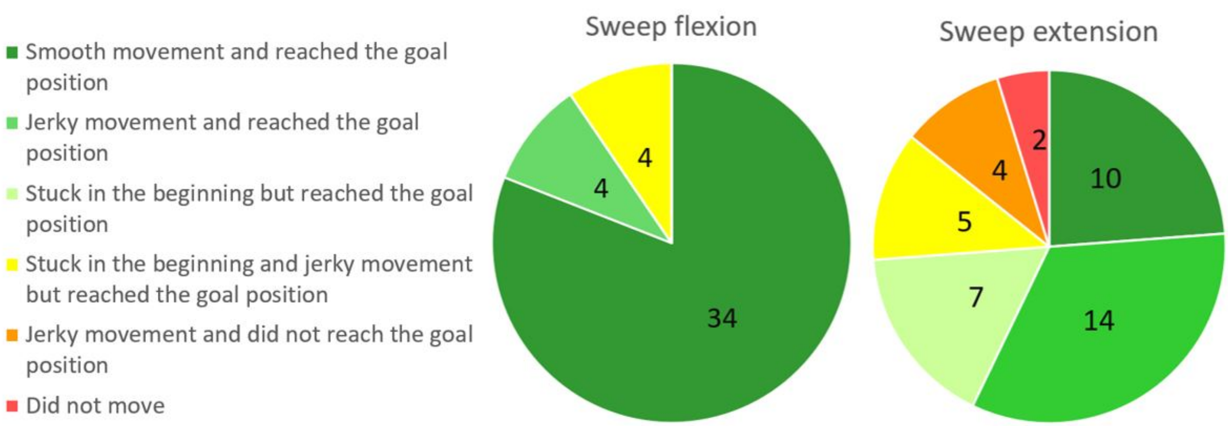

Figure 25: The figure present the result from the evaluation test of the sweep method regarding both flexion and extension of the elbow joint.

3.2.2 Result of survey

The results from the survey are presented in this section. Figure 26 presents the participants opinions regarding if the orthosis movement felt scary, acceptable or unscary in both the training session and in the real time sessions. One comment that came from multiple participants was that it would be nice with a longer period of rest between each period of flexion/extension during the training sessions. The purpose of this would be to have time to fully relax the arm. Figure 27 presents the users opinion on the smoothness of the orthosis movement and if the orthosis moved along the users intended direction. These opinions were rated on a scale of one to five, where one equals bad and five equals good. The survey also included two questions regarding if the user experienced a delay in the flexion and the extension movement. The result of these questions are presented in figure 28.

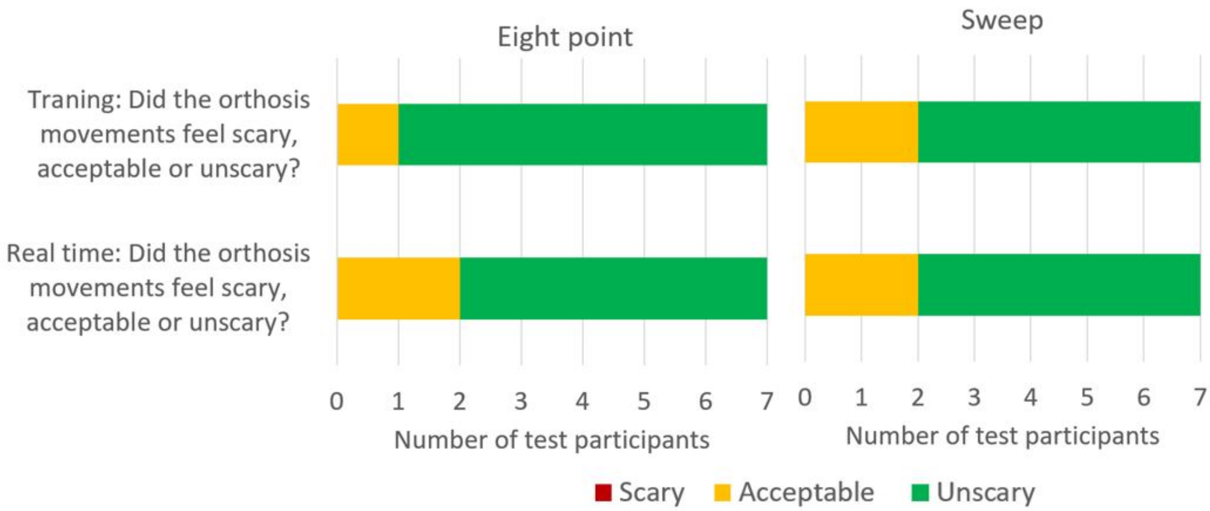

Figure 26: The figure presents the participants survey answers regarding if the orthosis movement felt scary, acceptable or unscary.

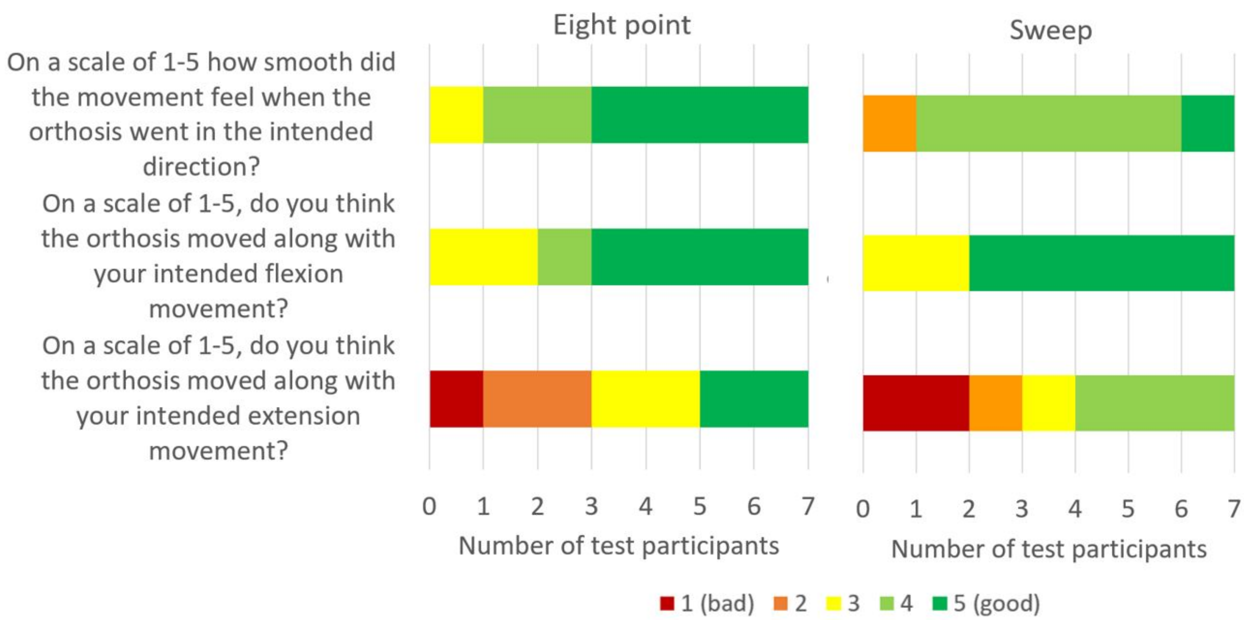

Figure 27: The figure presents the participants survey answers regarding the smoothness of the orthosis movement and if the orthosis moved along with the intended direction.

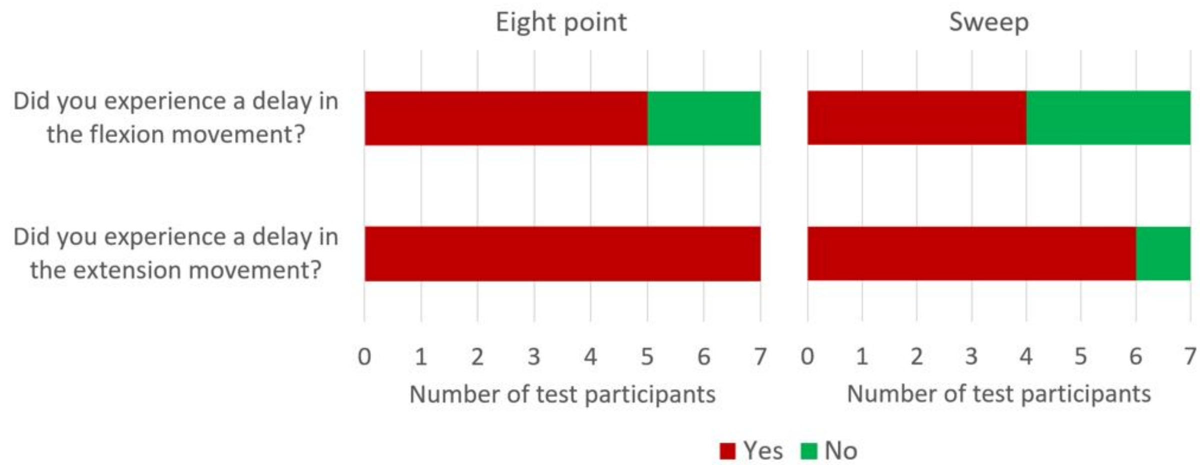

Figure 28: The figure presents the participants survey answers regarding if they experienced a delay in the orthosis movement.

The last part of the survey contained comparative questions about the two training methods "Eight Point" and "Sweep". The results of these questions are presented in figure 29. It should be noted that some participants preferred the same training method for both training and the real time sessions and other participants preferred one method for training and one for real time.

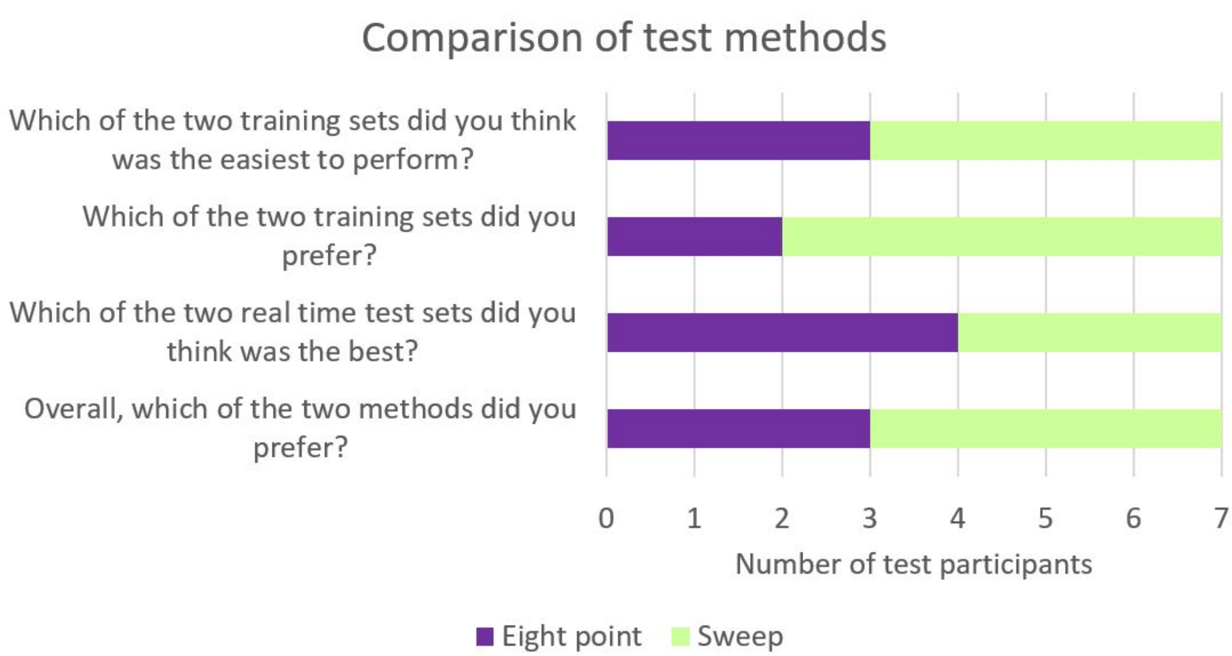

Figure 29: The figure presents the participants survey answers regarding the comparative questions of the two training methods.

4 Discussion

4.1 Goals and criterias

The results of the finished product shows that all the primary goals were fulfilled and almost all of the criteria were met. The resulting active orthosis works as it is intended to and has a lot of potential to improve further. It can move in the same range of motion as the previous prototype regarding the elbow movement. The orthosis also moves according to the EMG-signals and how well that movement is depends on several factors that will be discussed later in this section. The orthosis should also met the goal that it would primarily work for patients with close to no mobility since it is programmed to move when EMG-signals are found, and stop when they are not. Further testing on test subjects have to be made to make a proper statistical evaluation of this and of what EMG-training method is the best to choose, but the amount that was performed gave a good approximation of the result.

The motor moves 504 degrees which is above the demanded 150 which is both a good and bad thing. The orthosis can move the entire desired range of motion but the risk of moving beyond it exists. Since the motor inhibits an encoder that only has a relative position, a miscalibration or a reboot of the motor can lead to the orthosis trying to move beyond the allowed range of motion. Several safety measures exist to prevent this from happening but to totally eliminate the risk a potentiometer could be added in a future version of the orthosis. A potentiometer would have definite positioning instead of relative and the motor would thereby be in no need of an endpoint calibration. The current safety measures are considered to be very effective but some of them, including the on and off switch and pulling of the Arduino cable, rely on the participants to react fast. The on and off switch was also designed with a small hole in the ADS_BP4 which in further prototypes can be made bigger to make the access even easier. Further on it was a challenge to program the motor to move only in the intended range. The servo programmer that was bought did not function as it was intended which meant that a new approach had to be taken. The calibration program was a safe approach that enabled a secure way to carefully set the desired endpoints of the orthosis. This turned out to be of great use further on as well since it is easily adjusted to fit each patient's own range of motion and easily can be changed during a session.

Moreover another criteria that was met was that the orthosis ability to be adjusted to account for different arm lengths were not to be compromised. During the tests that were performed it was on the other hand concluded that it still was hard to adjust the orthosis to arms that were very long or very thin. The belt was also too small to fit all of the test subjects. These factors might have had an unknown effect on the results. In a new prototype the orthosis could be made more adjustable and a bigger belt can be attached instead. Further on the attachment of the orthosis was not affected in the new prototype but it was still a hard task to perform. The original idea was to be able to attach it with only one hand and this is still something that can be further developed in future prototypes. The fact that the motor is locked in a position when the real time tests are not activated could mean that the orthosis would be in a difficult position when a patient is trying to attach it. This problem is bypassed by activating the calibration program before attaching the orthosis and setting it to a desired position.

The requirement that the orthosis did not cover more than 40% of the arm was successfully met as the added parts did not cover more of the patients arm. It was easy to reach and attach the wires to each electrode on each of the test subjects after the orthosis was attached. After weighing the new parts of the orthosis it was also concluded that they weighed around 340g, which gave a total added weight below the requirement. When choosing a motor, how to control it, choosing a battery and attachment method, one of the priorities was to find lightweight options. What contributed the most to the weight gain was the motor which was to be expected. It was on the other hand a small weight gain since it is hard to find motors with the same torque as the chosen one that also has the same small weight and size since they often weigh closer to half a kilo or more. Since a servo gearbox was chosen there was no need for extra added parts such as encoders and gears that would increase the weight and size even more. The fact that the added parts were kept to a minimum helped with this as well. It was then concluded that the chosen parts and design was one of the most lightweight prototype options that could be made. Because the motor was a complete servo gearbox it was on the other hand less flexible for changes. In spite of this it was concluded that this was a good approach to be able to create a complete prototype within the project's time frame and test the whole concept. The choice of using an Arduino was also a good way to ensure that the whole project would be finished within the time frame since it is very easy to handle and a lot of open source information is available.

The criteria that said that the battery should last more than 2 hours were not met but the resulting battery time of 1.5 hours was deemed good enough to get an approximation of the function of the product. The battery could be used during a whole test session of a participant which indicates that the same battery can be used in further studies as well. Before using the battery for longer sessions it should be tested more closely how fast these rehabilitation tests drain the battery. It should also be tested how much the battery time differs if people with different weight of the arm is tested. The battery chosen was also small and lightweight enough to be placed safely inside the ADS_BP4. This both enabled a good design and prevention of cables getting caught since all of them were enclosed inside the ADS_BP4. If a new battery should be found for a future prototype, a similar attachment could be made but with some adjustments to the battery compartment. Holes had been made to ensure airflow to both of the batteries in the ADS_BP4-box but none of them got notably hot during any of the tests. This indicates that a slightly hotter battery could be chosen in a future orthosis if needed.

The chosen motor was also a motor type that usually does not get very hot which was desired since the motor is situated very close to the arm in the finished prototype. The arm inside of the orthosis is at no risk of touching the servo but since the motor is attached to a metal plate (see figure 13) that is situated at reaching distance to the arm, there would be a risk of transferring heat to that plate. This was avoided when choosing the servo gearbox. Further on, calculations had been made in the beginning of the project that estimated the needed torque from the motor to handle the flexion and extension movements of the arm and these were concluded to have been executed correctly. The motor functioned as estimated and was strong enough to perform the arm movements when power was supplied. Before the battery was found a different power supply was used where the voltage was adjusted and a maximum current allowed was set. This power supply did not work as well as the battery since it allowed the voltage to spike when the torque was too great. This led to the orthosis to jump a step, in the direction of the torque applied from the arm, after which it jumped back to correct its position. This problem was solved when the battery was applied, which had a constant voltage.

4.2 Evaluation tests result

By studying the results from the evaluation test in figure 24 and 25, it is clear that the flexion movement was easier to perform than the extension movement regarding both the training methods. That the results from the extension movement is worse than from the flexion movement depends largely on the fact the participants had difficulties to produce an extension movement at the top of the range of motion (when the arm was positioned around 90 degrees). It was easier for the participants to perform this movement the closer they were to the bottom of the range of motion. That the algorithm had a hard time identifying an extension movement close to 90 degrees can be explained by a few different causes. Firstly, at around 90 degrees it was harder to relax the bicep muscle, which meant that the algorithm got inputs from both the bicep and the tricep muscle. This could explain why the algorithm thought that a flexion movement was happening, which in turn led to a jumpy behavior of the orthosis.

At 90 degrees it was also harder to tension the tricep muscle than at around 180 degrees. This could be seen on the EMG-signals that were presented during the training session. The signals from an extension movement had a smaller amplitude when the arm was positioned close to 90 degrees than when the arm was positioned at 180 degrees. The smaller amplitude could cause the algorithm to confuse the movement with rest, which in turn could explain why the orthosis sometimes got stuck in this position.

That the algorithm had a harder time correctly categorizing the extension movement at a position close to 90 degrees was a known issue before the evaluation test. The participants were therefore encouraged to press a little harder at the top positions of the range of motion. The purpose of this was to get a higher amplitude of the EMG-signals to get a bigger difference between the rest and extension movement. As can be seen in the test results this alteration did not remove the problem the algorithm had with correctly categorizing the extension movement, but it was thought that it at least made it easier for the algorithm to do so. More tests are needed to be able to say if this alteration improves the test protocol or not. One negative thing with this protocol is that if more force is needed to produce a movement, it feels less natural and intuitive for the user.

Another thing that comes to mind when studying the results in figure 24 and 25 is that both training methods seem to give equally good results. Which training method that was tested first was altered between the participants. But there seemed to be a trend that the participants got slightly better results at the last test. This could be explained by the fact that the participants were more used to the orthosis movement. This effect could be minimized if the participant first had a test session before the actual evaluation test began.

In the training sets it is vital that the participant can tension the correct muscle. In the real time session the participant needs to mimic the tension they performed in the training session as close as possible so that the algorithm can correctly categorize the movement. Therefore a second possible explanation for why the two test methods got equal results could be that the different tests suit different people in regards to how easy they found it to correctly relax and tension the correct muscles.

One thing that had a great impact on the EMG-signals and therefore also the algorithm's possibility to correctly categorize the movements was the electrode placement. The electrodes should be placed on the belly on the muscle to get a good signal. One source of error during the evaluation test is that the authors of this paper had no previous experience of placing electrodes which meant that the electrodes probably were not in the ideal positions one the muscles. It was especially hard to localize the tricep muscle which is not as visual as the bicep muscle. To improve the test protocol it would be good if a person with more experience in this area placed the electrodes. Another way to improve the protocol is to experiment with the size of the electrodes and the number of electrodes used on the tricep to ensure that a good signal is received more easily. This is especially important in regards to the end goal of this product, which is that a patient should be able to use it in a home environment. This means that the patients would need to be able to place the electrodes on themselves or with help from a family member.

The results from this evaluation is based on movements from able bodied participants. The participants could therefore move their arms with varying force and had a full range of motion in the elbow joint. A typical stroke patient has less range of motion and strength in the arm, so it would therefore be interesting to do the same evaluation test of the orthosis with stroke patients to see if the results differ from the test on able bodied persons.

In this project the evaluation of the orthosis movement was made separately by the two authors of this paper. The two evaluations of each movement were most commonly the same, but differed in occasional cases. With this method of evaluation the result depends on how the person interprets the evaluation criteria, which can differ from person to person. To remove this problem a new evaluation test would have to be constructed that is based on data instead of visual interpretation. The perks of a visual interpretation test is that it is faster to construct, which in this case was important due to the time limit of the project. Another way to improve the test protocol is to let two independent persons with no personal interest in the result evaluate the orthosis movement to decrease the risk of biased results.

4.3 Survey results

After the training sets and the real time sessions, the participants answered a question regarding if the orthosis movement felt, scary acceptable or unscary. The result of this question can be seen in figure 26. The results were very promising because most of the participants thought that the movement felt unscary and no one thought it was scary. It should be noted that the test group consisted of students aged between 20-30 years old and is therefore not representative for the typical stroke patient. This question is therefore still relevant to ask and reevaluate if the orthosis is tested on stroke patients in the future.

In figure 27 it can be seen that the participants thought that the orthosis moved smoothly when the orthosis moved in the intended direction. Most of the participants rated the smoothness to a four or a five on a scale of one to five, regarding both training methods. This is a good indicator that the motor is able to do its job of producing a smooth movement as long as the direction command is steady.

The participants were also asked to grade how well the orthosis moved in the intended flexion and extension direction. In figure 27 it can be seen that the flexion movement went better than the extension movement and that there were no major differences between the two training methods. This result agrees well with the result of the evaluation test discussed in section 4.2.

In figure 28 it can be seen that most of the participants experienced a delay in both the flexion and the extension movement during the tests of both training methods. This can be explained by a number of reasons. The majority vote function is responsible for some of the delay because it looks at the five latest outputs from the machine learning algorithm and returns the movement that is in majority. The perks of this function were considered to outweigh the disadvantage of a delay because it results in a smoother movement of the orthosis. The delay can also originate from that the participant needed to tension the muscles in the right way for the algorithm to recognize the movement.

After the two tests were finished the participants answered comparative questions. The answers can be seen in figure 29. In the questions regarding what training method they found easiest to perform, what real time test they thought were best and what method they preferred overall there were no major majority for either method. This seems reasonable and could be expected due to the fact that no method has stood out as better than the other during the evaluation test. The question regarding which method the participants preferred during the training session is interesting because it has a more clear majority for the sweep method. Some participants commented that they liked the sweep training method more because it was faster.

All of the participants in this study were acquainted with the authors of this paper. This has to be considered when studying the result of the survey, because there is a risk that the results are influenced by the participants' will to please the authors. To remove this risk the participants should have no previous relation with the authors. This was not possible in this test due to the time limit of the project.

4.4 Future work

There are a lot of possibilities for future work with the active orthosis. Firstly the movement of the wrist should be implemented into the active orthosis as well. A similar approach as for the elbow could perhaps be taken for the wrist as well. Then the mechanical stops would be moved to the inside of the orthosis to enable a motor to be attached on the outside. For the wrist movement a smaller and more lightweight motor should be chosen to not add too much weight to the elbow movement. Since the wrist movement is horizontal it does not take the gravitation into account and a much weaker motor could be chosen for this joint.

As previously mentioned the chosen battery did not for sure last for 2 hours. Since the battery calculations at stall torque suggested a battery time at 1.3 hours one suggestion is to change to a new battery with a higher capacity. Further on it would be a good idea to replace the two batteries, that power the ADS_BP4 as well as the motor, with a single battery that can provide power for both causes.

The prototype was tested on seven students which as previously mentioned is not enough to make any great statistical evaluations. After a larger number of tests have been performed on people with normal mobility it can be decided which training method is to be preferred. After this is concluded tests can then be performed on stroke patients to evaluate the prototype further.

One of the criteria that was not met was the one that stated that the speed of the orthosis should be able to be adjusted to range between 1-10 seconds per 90 degrees. This is executed during the sweep training method where the speed is adjusted for each patient so that one sweep motion takes 3 seconds. The speed changes were not implemented into the real time tests of the orthosis so this needs to be done in order to ensure that the programming for this feature works properly. It is possible that the same programming works for the real time tests as well but there are some risks of delays and stack ups.

Another thing that can be implemented in future prototypes is the assist when needed functionality. At the moment the orthosis is focused on people with close to no mobility and moves when EMG-signals are notable and stops when the arm is resting. If assist when needed is implemented that would mean that the orthosis could assess the torque needed to do the intended movement, the torque the arm is able to manage on its own as well as supply just enough assist to help the arm perform the entire movement. It is important that the orthosis does not help the arm too much in order to minimize the risk of slacking. With the current motor choice this functionality is not possible. One way to further develop this functionality is to manually choose the parts to make a servo motor. One important part to add would be a potentiometer and the reasons for this are the same as described in section 4.1. A torque sensor would also be needed and a way to measure the speed of the orthosis.

The previous prototype that the active orthosis was based on had a range of motion of 120 degrees. The normal range of an arm is at 150 degrees which means that the whole movement of the arm is not able to be rehabilitated for all patients. In future prototypes this range can be extended to be closer to the range of an arm with full mobility.

Moreover the previous orthosis was made with parts that made it possible to assemble it with some variation each time. This was a problem in this project since the attachment design of the motor was based on precise measurements. If the orthosis was assembled in a different way than it was when the measurements were made some problems could occur when attaching the motor. These problems included difficulties with matching screws to their holes and screws loosening over time. In future prototypes this could be prevented by reshaping parts to not be able to be attached in different ways.

To use the program BioPatRec with our prototype several adjustments had to be made. Details had to be added regarding the motor and expected movements of the arm and some debugging of the program also had to be made in order to make it compatible with the orthosis. The changes made the program work as intended but some minor inconveniences still remains that needs to be looked over in future projects. The inconveniences are for example the need of rebooting the program after making a recording or by accidentally pressing the wrong button.

In future projects the training and testing methods of the orthosis can be developed further. The training methods needs, as previously mentioned, to be investigated further and more training methods than sweep and 8-point can be tested. The different methods could also be combined. A suggestion that also came from several of the participants was to elongate the time of the rest between the exercise movements during a test. This would give them more time to relax properly and prepare mentally for the next flexion or extension movement.

4.5 Ethics

During the project a big consideration has been taken to account for the safety of the patients that the product is intended for. The orthosis should not be able to harm the arm by moving it beyond the range possible or burn it if it comes in contact with a hot motor or battery. Before tests were performed on people with normal mobility these safety factors were secured by numerous tests and when choosing a battery and motor the ones that became too hot were discarded.

If the orthosis is to be used for independent rehabilitation at home it is important to make sure that this is done for the right reasons. It is important that this rehabilitation method is equally good or better than conventional rehabilitation methods. The cost reduce that comes with sending patients home should not outweigh the quality of the patient care.

With home rehabilitation more of the responsibility of the rehabilitation process is laid on the patient instead of on health practitioners. Therefore it is important that the patients are provided with good instructions and that they feel comfortable with the course of treatment. They should not feel abandoned in their care.

5 Conclusion

The project resulted in an active orthosis for the elbow joint. The orthosis can be controlled by measuring EMG-signals which are processed with a machine learning algorithm that performs myoelectric pattern recognition. A servo motor was used to facilitate the movement of the orthosis and it was controlled with an Arduino board. The orthosis can be used to move the arm in the intended flexion or extension movement. The orthosis worked as it is intended to for all of the participants in the evaluation test but the smoothness of the movement varied between each subject. The resulting active orthosis has a lot of potential to improve further and more tests need to be performed before it can be used in rehabilitation sessions with stroke patients.

6 Work contributions

This project has been carried out as a close cooperation between the two authors. During the initialization state the literature review and most of the information search was done. This was performed separately by the two authors after which what was found was thoroughly discussed. The practical part consisting of remodelling and attaching new parts to the orthosis was performed together. The writing of the rapport was done by first thoroughly discussing the structure of the rapport. The writing occurred separately but with recurrent reconciliations with each other.

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