

Development of a Prototype of an Intelligent Knee Orthosis for Rehabilitation Support

Integrating Sensor Feedback and Control in an Early-stage Prototype for Rehabilitation Assistance

Degree project report in Electrical engineering

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Cover: An image of the intelligent prototype.

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Abstract

The report centers on the design and construction of a prototype of an intelligent knee orthosis that has 1-DOF and can support a user during knee rehabilitation and collects data during a set exercise. The research questions revolve around the construction and selection of components for the prototype, how to tailor assistance to the user during the exercise, factors for modularity and how the collected data can be prepared for usage in the medical field. Unlike previous research within the field focused on walking and gait patterns, this project centers on a specific rehabilitation exercise, the standing leg curl. The intelligent knee orthosis has one degree of freedom and provides adjusted assistance during the exercise.

The orthosis is modular, with adjustable Velcro straps and the links being designed to fit two individuals of varying sizes and lengths. The actuator and tactile sensors were chosen to fit the average human, with added buffers to fit a wider range of users. For safety, the orthosis was tested in two ways, passive and active, simulating varying support when the sensors were touched. The orthosis successfully performs the exercise and can collect data, which potentially can be a foundation for further development to enhance knee rehabilitation. Challenges that can be improved in further developments include changing the type of tactile sensor to get better readings and finding a less powerful actuator or stronger link material to ensure user safety.

Keywords: Orthosis, knee, rehabilitation, support, sensors, prototype, exoskeleton.

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Contents

1	Introduction	1
1.1	Background	1
1.2	Purpose	2
1.3	Limitations	2
1.4	Research Questions	3
2	Theory	5
2.1	Orthosis	5
2.2	Intelligent Orthosis	5
2.2.1	Links	6
2.2.2	Joint	6
2.2.3	Encoder	6
2.2.4	Actuator	7
2.2.5	Sensors	7
2.2.5.1	Tactile Sensors	7
2.2.5.2	Safety Sensor	8
2.2.6	Control Unit	8
2.2.7	Orthosis Model	9
2.2.7.1	Kinematic model	9
2.2.7.2	Dynamic model	11
3	Methods	13
3.1	Work Plan	13
3.2	Selection of components	14
3.2.1	Links	15
3.2.2	Actuator and Encoder	15
3.2.3	Tactile Sensors	17
3.2.4	Safety Sensor	18
3.2.5	Control Unit	19
3.3	CAD Modeling	21
3.4	3D-Printing	23
3.5	Hardware Architecture	25
3.6	Electrical Schematic for a Tactile Sensor	26
3.7	Testing of Components	28
3.8	Final Prototype	29
4	Experimental Validation & Results	31
4.1	Passive Test	31
4.2	Active Test	33
5	Discussion & Conclusion	35

5.1	Challenges	35
5.2	Further Developments of the Prototype	36
A	Appendix	I

1

Introduction

This chapter provides background of the project, describes the purpose, the project scope, including limitations, and specifies the research questions.

1.1 Background

Chronic knee pain and knee injuries are challenges that many face [1]. The standard recommendation for rehabilitation typically includes training and, in some cases, the use of a fixed orthosis supported by guidance of a physiotherapist. A common challenge for patients is to perform exercises correctly as well as judge the appropriate intensity on their own at home between visits. This challenge has driven the demand for systems that can offer help with these tasks and simultaneously provide feedback to improve training in between visits to the physiotherapist [2].

There is a need to create a portable, user-friendly appliance that helps both the user and the physiotherapist, while maintaining the quality of the physiotherapy and the rehabilitation process. The electrical engineering department of Chalmers University in collaboration with Sahlgrenska University Hospital are developing intelligent rehabilitation systems that offer support for patients, called the AURORA project [3]. One of the components in the AURORA project, particularly relevant to knee injuries, is the intelligent knee orthosis. There have been research done under AURORA as well as externally of elbow rehabilitation using intelligent orthosis [4], which has inspired the application of a similar approach in knee rehabilitation.

A comparison to other previous research was made of projects within mechanical orthoses for the knee. The main difference was that many other scientific articles focus on assistance during walks and gait patterns [5], [6], [7], [8], meaning the manner a person walks, some focus on the alignment of the knee [9] or doing specific movements for everyday tasks such as walking up the stairs [10], while this project focuses on assistance during a specific exercise.

1.2 Purpose



Figure 1.1: *The standing hamstring curl.*

The purpose of the project is to design and construct a prototype that can support a user during knee rehabilitation while collecting continuous data during a set exercise, namely the standing hamstring curl, as visualized in Figure 1.1.

1.3 Limitations

To specify the scope, the following limitations has been set for the project.

Firstly, the prototype is designed for a right leg and cannot be interchanged between the left and right legs. This is to facilitate the development of the prototype regarding safety measures such as physical breaks.

Secondly, the primary focus of this project is functionality. Portability is an issue that can be enhanced in future iterations.

Lastly, the size of the prototype will be tailored to accommodate two specific individuals, being the project developers. These individuals have the following specifications:

- Person 1:
 - Leg length: 106cm
 - Calf circumference: 28cm
 - Thigh circumference: 45cm
- Person 2:
 - Leg length: 85cm
 - Calf circumference: 28cm
 - Thigh circumference: 51cm

This decision was made in favor of prioritizing the functionality and accuracy of the prototype over the ability to accommodate a wider range of users with varying

heights and body weights, as the primary focus remains on creating a functional prototype.

1.4 Research Questions

During the project the following questions will be examined:

- How can the construction of the frame and selection of components for an intelligent knee orthosis ensure proper fit and functionality for the lower leg?
- How will the prototype offer tailored assistance during the exercise?
- What factors should be considered when designing modular features for an intelligent knee orthosis?
- How can the data measured and collected by the orthosis be used to improve physiotherapy and rehabilitation?

2

Theory

This chapter provides context and a technical background for each component of the intelligent knee orthosis.

2.1 Orthosis

An orthosis is an externally applied device designed to support the body, often described as an exoskeleton. In contrast, prosthetics are artificial devices intended to replace a missing body part [11]. The two devices may seem similar, but the main difference is that orthoses provide support and enhance the function of existing body parts whereas prosthetics replace lost body parts or limbs to restore function. In knee rehabilitation, these specific orthoses can also be called knee braces.

Orthoses have four body areas of classifications according to the International Organization for Standardization (ISO) [12]. There are orthoses for the lower extremities, for the upper extremities, for the trunk, and for the head. The intelligent knee prototype falls under the lower extremities section.

An important part during the development of the orthosis' frame was to implement physical stops at both end positions to provide more safety for the user, even though the prototype won't be worn by an actual patient in this stage. In order to define the maximum and minimum angle for the exoskeleton, literature was revised to find the range applicable for the target exercises to ensure comfortability, support, and safety. The recommended range of motion (ROM) for a knee is 130° [13], but the ROM was reduced to include a conservative motion with additional safety. The decided ROM became 125° .

2.2 Intelligent Orthosis

The intelligent orthosis includes a joint, links and electrical components such as an actuator and sensors, making it similar to a robot by being able to assist the user during the movement. This section will describe the different components that together creates the intelligent orthosis.

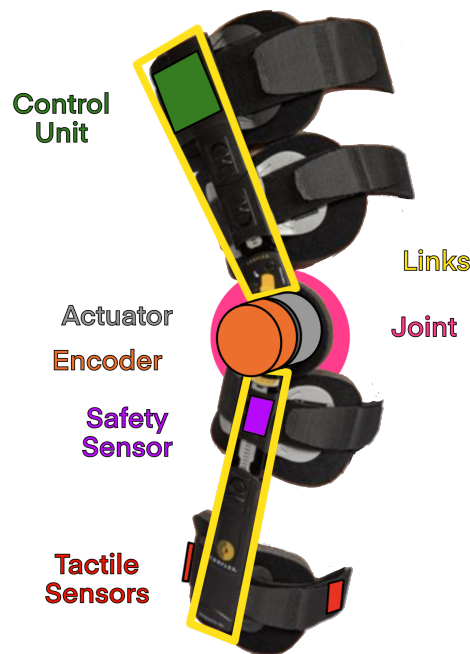


Figure 2.1: *A visual representation of the different components that together makes the intelligent orthosis.*

2.2.1 Links

The frame of the intelligent orthosis consists of two links, as shown in in Figure 2.1, which implies the two plastic parts of the frame that are fixed to the leg. One being the static link that will be attached to the thigh of the user, in this project also called the upper link. The other being the moving link that will be attached to the users calf and will move during the performed exercise, called the lower link in this project. These links provide structural support and also work as mounting points for the electrical components of the system. Additionally, the links are designed to be lightweight yet strong, avoiding unnecessary weight on the user’s leg while remaining sturdy.

2.2.2 Joint

The mechanical system that allows relative motion between links is called a joint. The intelligent orthosis consists of one joint outside of the knee, as depicted in Figure 2.1. One link is connected to the rigid part of the actuator and the other link is attached to the moving part of the actuator. The joint is a critical component since it enables movement in the knee.

2.2.3 Encoder

Encoders are used to measure the relative position of the links, ensure they stay within the set range of motion (ROM), and track the current speed and direction

of movement. For the intelligent knee orthosis, this feedback mechanism is implemented using an encoder, as shown in Figure 2.1.

2.2.4 Actuator

An actuator is a device that converts electrical energy into mechanical movement, essential for assisting the user wearing the orthosis. To enable the links to move and assist during exercise while supporting a lower leg weighing approximately 5 kg [14], an actuator must be integrated into the joint, as depicted in Figure 2.1

In selecting the appropriate actuator, brushless DC (BLDC) motors were favored due to their high efficiency and precise control capabilities. Unlike other electric motors, which convert electrical energy into mechanical energy [15], BLDC motors offer finely controlled torque and rotational speed, either with integrated or external encoders. A significant advantage of using a BLDC motor with a built-in encoder is its ability to provide accurate readings of position, speed, and direction, as the encoder is matched to the motor's characteristics by the manufacturer. Additionally, BLDC motors generate low electrical noise, enhancing the overall reliability of the electronic system, and their compact design is highly desirable for the project.

2.2.5 Sensors

Sensors have an important role in the intelligent knee orthosis since they provide different types of data from the movement during the exercise. This section will explain the background of the two different types of sensors that were used and their respective role in the prototype.

2.2.5.1 Tactile Sensors

To be able to measure the force, and through this force calculate the torque of the movement, some type of tactile sensor needs to be implemented into the design, as shown in Figure 2.1. These types of sensors are categorized based on their underlying technology and the specific type of tactile information they capture. There are many different types of tactile sensors such as Piezoelectric-, Optical-, Magnetic-, Thermal- and Resistive tactile sensors. Among the various types of sensors, resistive pressure sensors are distinguished by their flexibility, high sensitivity, and ease of integration with electronic systems [16].

The resistive pressure sensor decreases the resistance depending on how much force is applied. It does so through its two layers, where the top layer is pressure-sensitive and the bottom layer contains a conductive circuit. When pressure is applied to the active area, the pressure-sensitive layer bridges the disconnected circuit in the lower layer, converting pressure into resistance. As pressure increases, the output resistance decreases. The sensor is capable of measuring pressures within different ranges, detecting both static and dynamic pressure.

2.2.5.2 Safety Sensor

An additional safety measurement that needed to be incorporated into the design was some type of safety sensor, as depicted in Figure 2.1. This is needed to collect data to implement as a software stop that would stop the movement in that direction in case the actuator tries to move the links outside the set ROM. Therefore some type of sensor that can change state in case it detects that it is outside of the ROM was needed. There are many types of sensors that could be useful as a safety sensor, such as IR- (Infra Red) and mechanical switches. When researching these different types of sensors, IR-sensors became a good fit for the project due to their compact size, reliability, and easy integration into electronic systems [17].

The IR-sensor emits infrared light using an IR LED which means that when an obstacle is in front of the sensor, the IR light reflects off the object and is detected by an IR receiver. The sensor module processes the received signal and generates a digital output signal that changes state. Most IR-sensors have a built-in potentiometer to be able to adjust the sensitivity and detection range of the sensor.

2.2.6 Control Unit

To provide a "brain" for the intelligent orthosis, where the instructions and calculations are performed, it needs a control unit, as illustrated in Figure 2.1. This is where the communication between the components will occur, meaning it sends signals to components (output), and reads signals from a component (input).

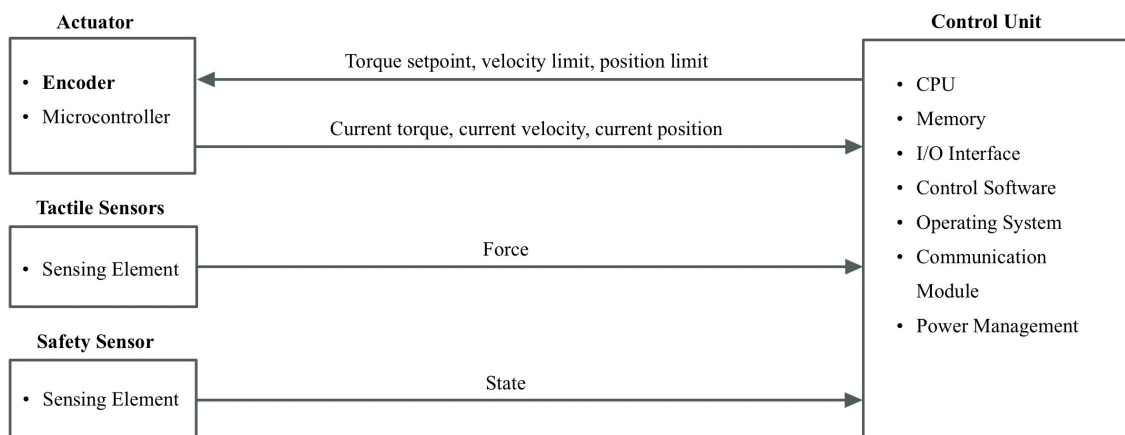


Figure 2.2: An overview of the control unit's inputs and outputs between the different components.

Figure 2.2 depicts a general overview of the in- and outputs between the different components and the control unit of the system. Where an arrow that points to the control unit is an input and an arrow from the control unit is an output.

The control system for an intelligent knee orthosis manages the interaction between the orthosis and the user by adjusting the assistance based on the tactile sensors' inputs. The sensors measure the force exerted by the calf when the user attempts

to lift their leg. This data is crucial for detecting the initiation of movement and adjusting the actuator's response. The built-in encoder in the actuator provides measurements of the actuator's position and speed, allowing for accurate control of the leg's movement.

The control system must process sensor data in real-time to provide immediate feedback to the actuator. For instance, if the pressure sensor detects that the user is initiating a leg lift, the control system should immediately activate the actuator to assist with the movement. The system should continuously monitor the pressure and encoder data to adjust the actuator's force and speed. To prevent over-extension or over-compression of the knee joint, the control system should include software stops to ensure that the actuator operates within a safe ROM.

When researching what type of control unit fits the project best, SBCs (Single Board Computers) stood out due to their high processing power, suitability for complex algorithms, and data processing [18]. Additionally, they often use standard protocols and interfaces to communicate with components, which facilitates the design of systems with various components. Some common examples of these connectivity options are General Purpose Input/Output (GPIO), Inter-Integrated Circuit (I²C), Universal Serial Bus (USB), Universal Asynchronous Receiver-Transmitter (UART) and High-Definition Multimedia Interface (HDMI).

2.2.7 Orthosis Model

To control the intelligent orthosis and estimate its behaviour mathematically, a model is required. The model for the project will have one joint with two links, and is a simplified model of the overview depicted in Figure 2.1, that visualizes the equation and the movement of the orthosis. Specifically, the model is based on a differential equation that captures the relationship between the applied forces and the movement of the links. This differential equation predicts how the orthosis will behave under different conditions, providing a foundation for further analysis and control.

2.2.7.1 Kinematic model

A kinematic model is a mathematical representation of the movement of a robot, focusing on position, velocity, acceleration, and degrees of freedom (DOF) [19].

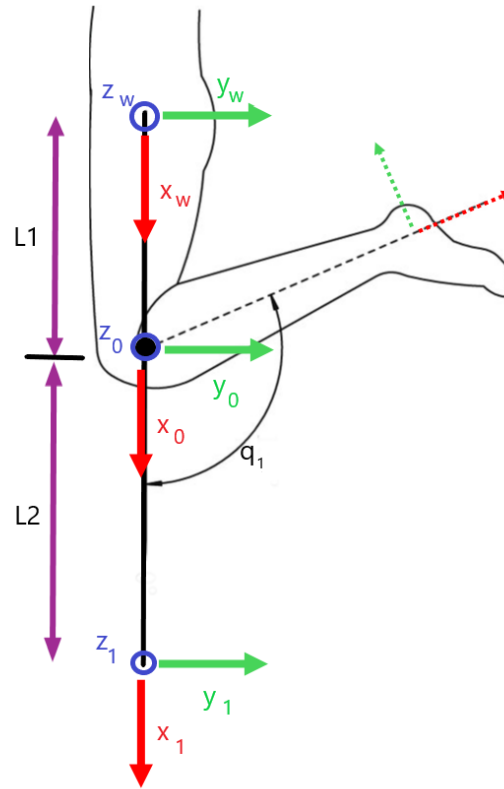


Figure 2.3: *Kinematic Model of the intelligent knee orthosis with 1-DOF.*

The kinematic model visualized in Figure 2.3, provides a mathematical representation and the relationship of the motion of the intelligent knee orthosis that serves as a mathematical framework for understanding and predicting the motion of the orthosis. The model is essential to accurately calculate and solve the kinematic equations, which is fundamental in determining the movement dynamics and the required torque at the joint. By using vector mathematics, the model calculates the relationship between the motion parameters and the forces involved, including the control of motion and the torque requirements. This information improves the device's performance, safety, and efficiency. Given that the system has one joint and allows one type of movement, in this instant a rotation in the z -axis, the system has 1-DOF. To clarify the notations shown in Figure 2.3 the following definitions are provided:

$L1$: Length of the thigh

$L2$: Length of the lower leg

x_w, y_w, z_w : World coordinate system axes

x_0, y_0, z_0 : Coordinate system at the origin of the thigh link

x_1, y_1, z_1 : Coordinate system at the origin of lower leg link

q_1 : Joint angle at the knee

This model defines the intelligent orthosis' workspace, positional capabilities, and constraints and is primarily used to describe the robot's kinematics, which helps

derive the Denavit–Hartenberg (DH) parameters [19]. These parameters are used to form homogeneous transformation matrices, which define the relationship between each successive joint and the previous one through a series of transformations around and along the model’s axes and joints. Using these transformation matrices, key variables such as torque and Jacobian matrices can be calculated. The Jacobian matrices, which relate the velocities of the joints to other points of interest within the system, are tools for analyzing the system’s velocity and understanding its dynamic behavior. For example, the matrices allows for calculations in how changes in joint angles affect the motion of different parts of the orthosis, which optimizes control.

2.2.7.2 Dynamic model

Dynamic models are mathematical representations that describe the relationship between motion and the forces that generate it. These models are crucial for understanding how internal and external forces influence the movement of objects within the system over time. In the context of the orthosis, the dynamic model specifically maps the actuator torques to the resulting motions, providing insight into how the system responds to different forces and enabling the precise control of movement. The intelligent knee orthosis moves in one plane, as visualized in Figure 2.3. Where the torque applied at the knee joint directly influences the movement and position of the orthosis [19]. By calculating the required torque, it is possible to ensure that the orthosis moves in a controlled and precise manner, mimicking the natural movement of the knee. This was calculated by using the equation of motion for the dynamic model of the intelligent orthosis:

$$\mathbf{M}(\mathbf{q})(\ddot{\mathbf{q}}) + \mathbf{C}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \tau \quad (2.1)$$

Where:

$$\begin{aligned} \mathbf{M}(\mathbf{q}) &\in \mathbb{R}^{n \times n} : \text{Inertia matrix} \\ \ddot{\mathbf{q}} &\in \mathbb{R}^{n \times 1} : \text{Joint accelerations} \\ \mathbf{C}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}) &\in \mathbb{R}^{n \times n} : \text{Coriolis and centrifugal forces} \\ \mathbf{G}(\mathbf{q}) &\in \mathbb{R}^{n \times 1} : \text{Gravitational forces} \\ \tau &\in \mathbb{R}^{n \times 1} : \text{Joint torques} \end{aligned}$$

where n is the number of degrees of freedom (DOF). In the case of the orthosis, $n = 1$.

The equation for the inertia matrix:

$$\mathbf{M}(\mathbf{q}) = \sum_{i=1}^n \left\{ m_i (\mathbf{J}_{\mathbf{v}_{cmi}}^0)^\top \mathbf{J}_{\mathbf{v}_{cmi}}^0 + (\mathbf{J}_{\boldsymbol{\omega}_{cmi}}^0)^\top \mathbf{R}_{cmi}^0 \mathbb{I}_{cmi} \mathbf{R}_{cmi}^{0\top} \mathbf{J}_{\boldsymbol{\omega}_{cmi}}^0 \right\} \quad (2.2)$$

The equation for the Coriolis and centripetal effects:

$$\mathbf{C}(\ddot{\mathbf{q}}, \dot{\mathbf{q}}) = \mathbf{C}_{kj} = \frac{1}{2} \sum_{i=1}^n \left\{ \frac{\partial M_{kj}}{\partial q_i} + \frac{\partial M_{ki}}{\partial q_j} - \frac{\partial M_{ij}}{\partial q_k} \right\} \dot{q}_i \quad (2.3)$$

The equation for the vector of gravitational torques:

$$\mathbf{G}(\mathbf{q}) = \mathbf{G}_k = \frac{\partial P}{\partial q_k}, \quad P = \sum_{i=1}^n m_i \mathbf{g}^{0\top} \mathbf{t}_{cm_i} \quad (2.4)$$

Where:

- $\mathbf{J}_{\mathbf{v}_{cm_i}}^0 \in \mathbb{R}^{m \times n}$: Jacobian of linear velocities
- $\mathbf{J}_{\mathbf{w}_{cm_i}}^0 \in \mathbb{R}^{p \times n}$: Jacobian of angular velocities
- $\mathbf{R}_{cm_i}^0 \in \mathbb{R}^{3 \times 1}$: center of mass matrix
- $\mathbb{I}_{cm_i} \in \mathbb{R}^{3 \times 3}$: Inertia Tensor
- $M_{ki} \ M_{kj} \ M_{ij}$: Scalar elements of the mass in matrix M
- $P \in \mathbb{R}$: Scalar Potential energy
- $\mathbf{t}_{cm_i} \in \mathbb{R}^{3 \times 1}$: position vector

The torque calculation is necessary in selecting the appropriate actuator, meaning that it needs to be strong enough to lift a lower leg.

3

Methods

This chapter describes the development process of the intelligent knee orthosis, including the work plan, component selection and specification, CAD design, 3D printing, assembly, and programming

3.1 Work Plan

The work plan was made through Chalmers GitLab where different milestones and tasks were created to specify what needs to be done within the set time frame.

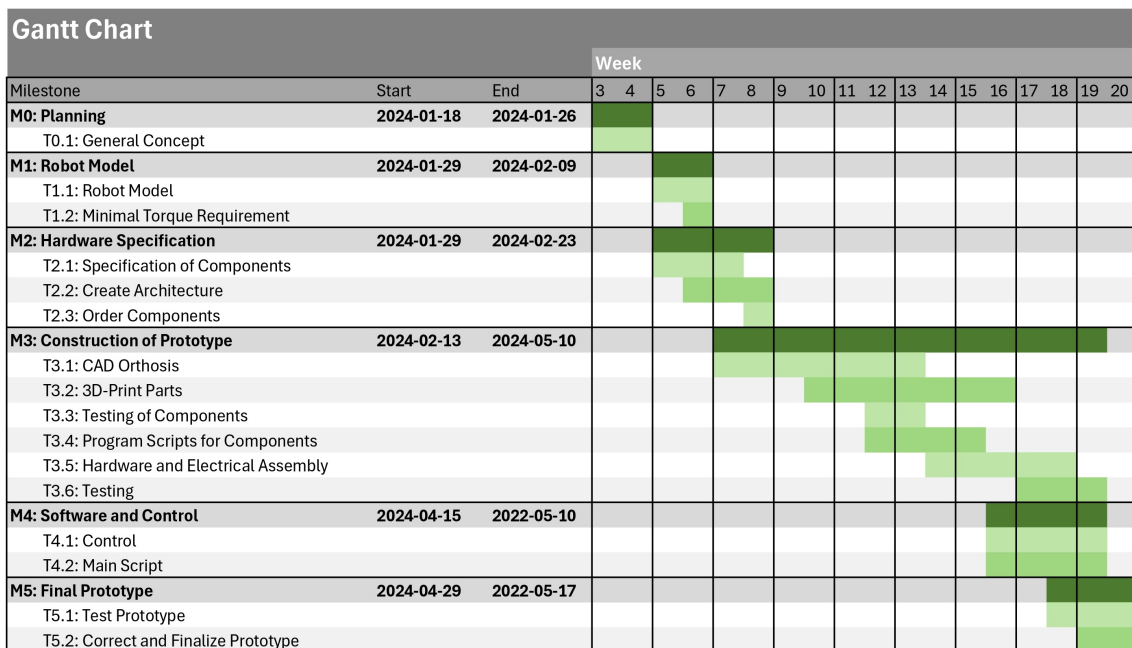


Figure 3.1: An overview of the work plan.

The Gantt chart shown in Figure 3.1, depicts the five milestones that were set for the project, as well as the set tasks respectively. As shown, the most time-consuming part of the project is milestone three, "Construction of Prototype", which includes the creation of the links, hardware assembly, basic programming, and testing for each component as well as a simple main script that combines all components in software.

3.2 Selection of components

When selecting the specific components for the intelligent knee orthosis, a list of requirements for each component and a sketch of the general concept was created.

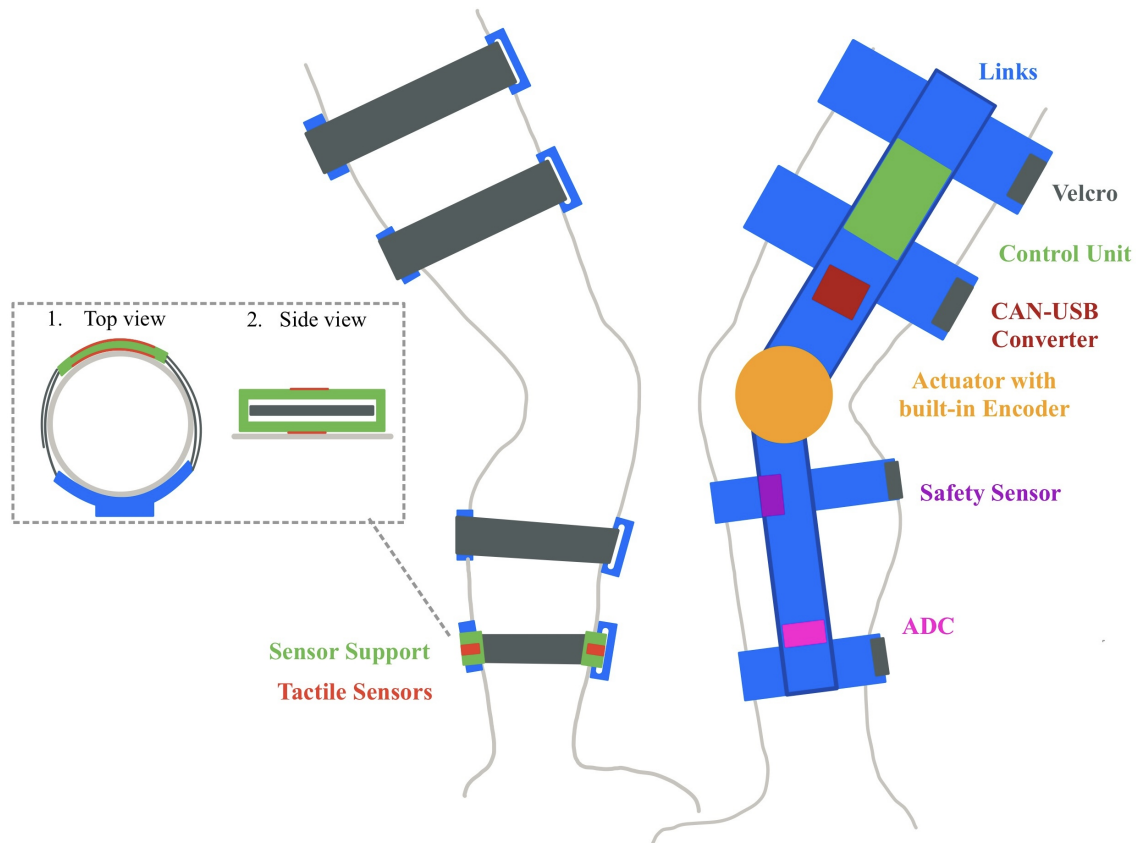


Figure 3.2: *An overview of the general concept with the specified placement of each component, including communication adaptors for two of the components and custom support for the tactile sensors.*

The sketch was used to specify the placement of each component including additional components for adapting the communication between components, as shown in Figure 3.2. The sketch also included a general idea of the design of the links, including a plan for fixtures for the components. Lastly a concept of a custom support around the Velcro for the tactile sensors was sketched, since the tactile sensors need a firm surface to be able to get a good reading.

3.2.1 Links



Figure 3.3: *The Contender Post-Op Knee Brace by Coreflex Global. An example of a standard knee orthosis [20].*

For the design and construction of the links, two options were presented. The first alternative was to build the prototype using an existing standard orthosis, e.g. the orthosis depicted in Figure 3.3 as a frame. The second alternative was to design custom links for the prototype. The second option was selected since it provides easier integration of components and allows for a more tailored fit. The development of these custom links was based on researching both the existing frame, meaning the knee brace in Figure 3.3, and Auxivo’s EduExo Maker, which is an exoskeleton designed for elbows [21].

3.2.2 Actuator and Encoder

There are many different types of encoders such as optical, magnetic, and capacitive encoders. Where optical encoders use light to detect position changes, magnetic encoders use magnetic fields and capacitive encoders use changes in capacitance. When researching the different types, magnetic encoders seemed to be the best fit for the project due to their durability, reliability and ease of integration with actuator systems [22].

As mentioned in Chapter 2, a type of actuator that fits the project well was a BLDC motor with a built-in encoder. However, the actuator also needs to fit some additional requirements that need to be specified. It must be lightweight and compact in size to not disturb the given exercise. Preferably, it should also be cylindrical and as flat as possible to reduce bulk and have a more ergonomic shape. This shape was considered especially since the actuator is going to be placed on the outside of the knee and needs to be comfortably integrated into the joint to move the links. After

3. Methods

measuring the two individuals, a decision was made about the maximum weight, shape, and size.

Since actuators differ in strength, there was a need to calculate the minimal torque based on the average weight and length of the lower leg. An additional buffer also needs to be accounted for, to ensure that the actuator is strong enough to lift the lower leg without any assistance from the user. An average lower leg weighs about 5kg [14], and measures about 50cm [23]. These values were used when calculating the minimal torque to use as an additional requirement in choosing a suitable actuator.

Equation 2.1 was used to calculate the value for minimum torque, at approximately 8.4Nm. The value was then multiplied with a safety factor of 1.2 [9], meaning it is designed to handle loads and stresses that are 20% higher than expected. The calculations resulted in the minimum torque of approximately 10Nm to lift a lower leg, which became an additional requirement for the actuator. To summarize, the following requirements were established:

- Type of actuator: BLDC motor with a built-in magnetic encoder
- Maximum weight: 1000g
- Shape: Cylindrical and flat
- Maximum size: 70x50mm
- Minimum torque: 10Nm

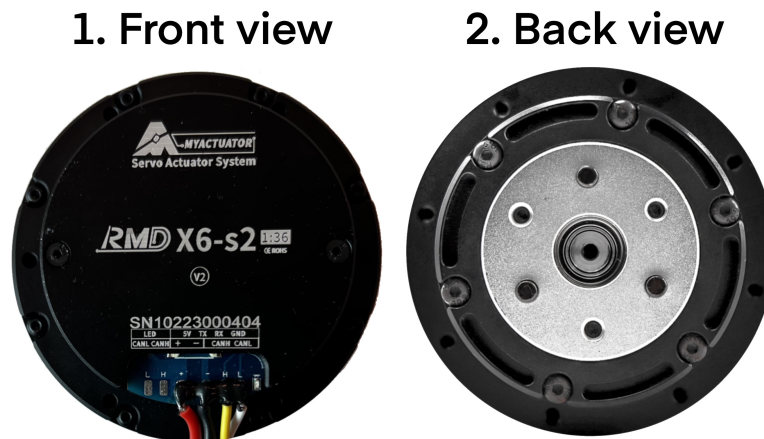


Figure 3.4: *Front- and back view of the RMD-X6 S2 1:36 actuator from My Actuator.*

An actuator that was the closest match to all requirements was the RMD-X6 S2 1:36 actuator from My Actuator, shown in Figure 3.4. It is a BLDC motor with a built-in 16-bit magnetic encoder, has a nominal torque of 18Nm, weighs 600g, is cylindrical,

and flat and measures 68x43.5mm. Additionally, it has a built-in micro-controller, torque sensor, temperature sensor and driver [24]. It meets the set requirements, and the additional specifications facilitated both the development of the software and the hardware assembly. The "1:36" describes the actuator's gear ratio, meaning that the input gear is significantly smaller compared to the output gear [25]. A 1:36 gear ratio means a significant reduction in speed and a corresponding increase in torque, suitable for applications requiring high torque at low speeds which is the case of the orthosis.

The chosen actuator can use either UART or CAN protocol to communicate different signaling. CAN was decided to be used since it is reliable, especially in electrically noisy environments, it is also robust and highly efficient. To provide the actuator with enough voltage and current, a 24-48V, 4A power supply was needed.

3.2.3 Tactile Sensors

Four tactile sensors needed to be incorporated into the design. Two to be placed on the inside of the frame, front and back, to measure the internal force, meaning the force generated by the user. The other two are placed on the outside in the same manner, to measure external force in preparation for further development. The purpose of incorporating these sensors was to enable a physiotherapist to provide a set torque or goal torque for the movement, which can later be used in the software to calculate the amount of assistance or resistance a user requires during rehabilitation.

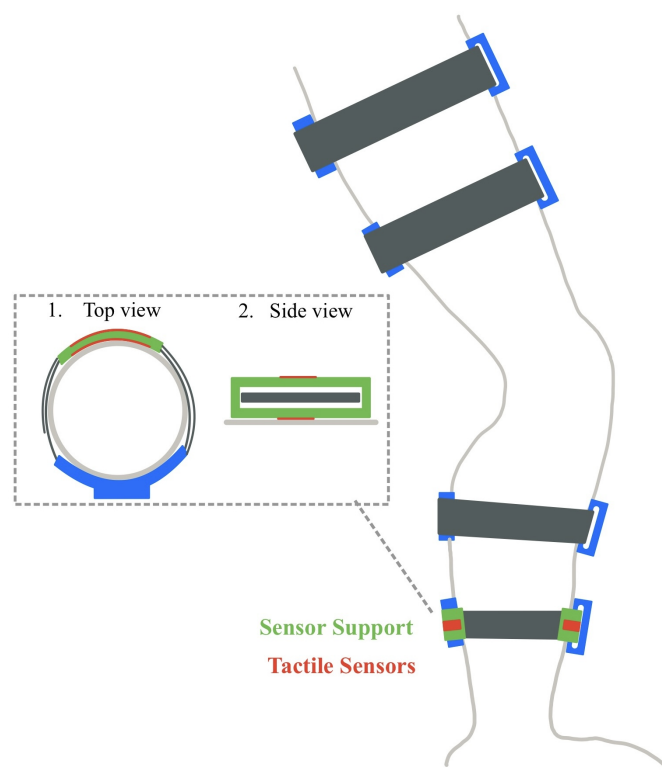


Figure 3.5: *General concept of the placement of the tactile sensors.*

Given that the sensors must fit a calf with a circumference of 28 cm and that the links, depicted in Figure 3.5, occupy approximately 12 cm of this circumference, the sensors need to be small, thin, and flexible to conform to and curve along the user's calf. Additionally, they need to have a high sensitivity to measure the applied force since the input from the user can vary depending on the user's strength. In a peer-reviewed article where they also used tactile sensors to measure the force exerted from the calf [8], the load range for the sensor ranged between 0 - 60N, and the highest measured force was 35.4 N which is approximately 3,6kg. With an added buffer of 1.2, the set requirement became 4.32kg. Therefore the following requirements were established:

- Maximum size: 50x70mm
- Maximum thickness: 10mm
- Flexibility: High
- Range of pressure: 50g-4320g



Figure 3.6: *RP-L-400 Thin Film Pressure Sensor from DF Robot.*

These requirements were met by the RP-L-400 Thin Film Pressure Sensor from DF Robot [26], depicted in Figure 3.6. It is flexible, 0.35mm in thickness, has a 20g to 10kg measuring range and is 15x400mm long, but can be cut to the length needed.

3.2.4 Safety Sensor

Since the task of the safety sensor is to always verify that the links are within the specified ROM, the placement of the sensor is important. The chosen placement is on top of the moving link, as depicted in Figure 3.2, close to the static link to get an accurate reading. Because of the choice to use an IR sensor, the links were printed in black filament, and optical safety stops at the end positions of the ROM were made using white tape. This was done for the sensor to easily differentiate between the two, to ensure that the moving link is within the ROM.

The specific safety sensor chosen was the IR Obstacle Avoidance Sensor Module by SunFounder[27], as seen in Figure 3.7. The reasoning behind the choice was that it is

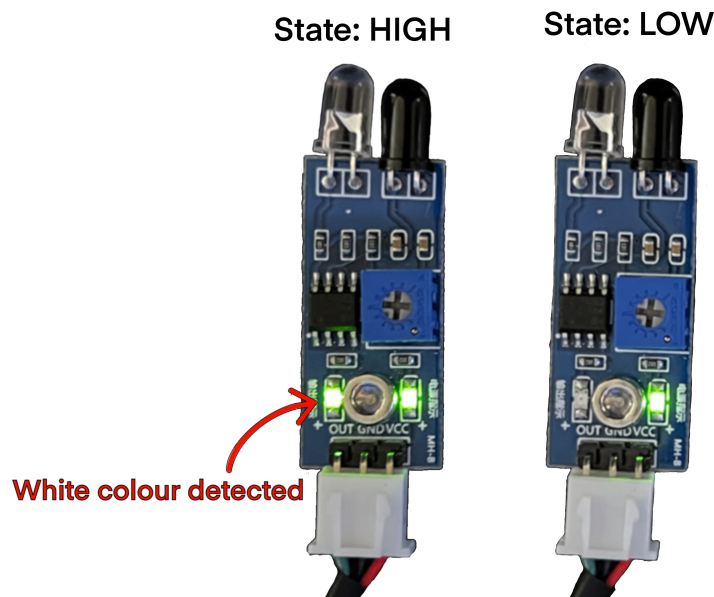


Figure 3.7: *IR Obstacle Avoidance Sensor Module by SunFounder.*

simple, measures 20x40x8mm and also has a LED on its top to show when the sensor is detecting an object and changes state to HIGH, shown by the red arrow in Figure 3.7. This facilitated the process of adjusting the potentiometer during testing to have the correct sensitivity and observe that the sensor can verify the correct ROM. It also gives a visual confirmation of the sensor detection of the optical stops while the orthosis is performing the movement. The sensor's visibility range is between 2cm and 40cm, with a detection angle of 35° [27] and was therefore placed 4cm from the optical stops that were designed to be visible within the sensor's detection angle.

3.2.5 Control Unit

When deciding which type of Single Board Computer (SBC) to use after choosing the other components, the main requirement for the SBC became as follows:

- Includes Central Processing Unit (CPU).
 - Executes instructions and performs computations for various tasks.
- Supports I²C protocol.
 - Used to simplify communication between the Raspberry Pi and devices such as Analog to Digital Converters (ADCs) for the sensors.
- Minimum of 3 USB ports.
 - Used for various peripherals such as keyboards, mice, and CAN-USB Converters.
- Minimum 1 HDMI port.
 - Used to connect to a screen or monitor for display output.
- Includes GPIO pins.
 - Used for connecting various components, such as the safety sensor.

Raspberry Pi, specifically the Raspberry Pi 5, as seen in Figure 3.8 was a good fit

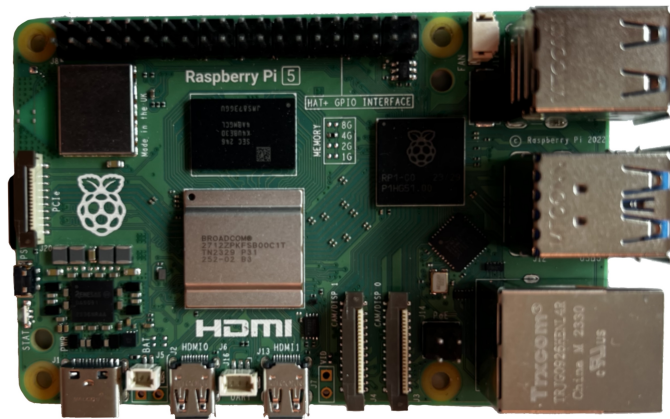


Figure 3.8: *Raspberry Pi 5.*

since it supports advanced software. This was due to the fact that it supports advanced software capabilities, multitasking, and easy integration with other software tools[28]. It has 8GB RAM, a CPU and several choices for connectivity such as four USB ports, built-in WiFi, HDMI and GPIO ports that support various types of in- and output such as I²C [29]. Additionally, it has high processing power and is suitable for complex algorithms and data processing. Power delivery is supported via a USB-C port for 5V/5A DC.

When all components had been chosen, the communication between components and the Control Unit needed to be checked to see if any conversion units were needed:

- Actuator communication protocol: CAN
- Tactile sensor: Analog voltage output
- Safety sensor: Digital output

When revising the communication from the list, it was clear that the information between the actuator, tactile sensors and control unit needs to be converted. The safety sensor could be directly applied to the GPIO ports on the Raspberry Pi. To convert the tactile sensors' analog signal into a digital signal that the Control Unit can read through its GPIO ports, an Analog to Digital Converter (ADC) was needed. This is due to that analog signals can be continuous and change when the voltage changes, here meaning when force is applied to the pressure sensors, while digital signals work with binary signals meaning they have two states, either 1 (HIGH) or 0 (LOW) [30]. The ADC takes periodic samples of the continuous analog signal at a specific rate, where the value that represents this analog voltage depends on the resolution of the ADC.

The chosen ADC was ADS1015 from Sparkfun. This ADC has four analog inputs, 12-bits (meaning the resolution is 4095, or $2^{12}-1$) and uses I²C protocol for communication [31]. This ADC was selected since it has four analog inputs, which makes it able to read data from all four sensors simultaneously. Additionally, it provides high-resolution readings and since it uses I²C protocol for communication it will

easily be integrated with the control unit. The ADC is also compatible with the input voltage range of the chosen sensors, which is crucial for accurate readings.

To convert CAN bus messages into something that the control unit can read, such as USB, a converter was needed. Therefore a CAN to USB converter was added to the concept. The chosen converter was USB2CAN from Innomaker because it is bidirectional, "plug and play", small in size, and reliable.

3.3 CAD Modeling

The links were designed in Computer-Aided Design (CAD) through the software application Autodesk Fusion 360. The design was based on the sketch seen in Figure 3.2, which also was the premise for implementing fixtures to the design to attach the components.

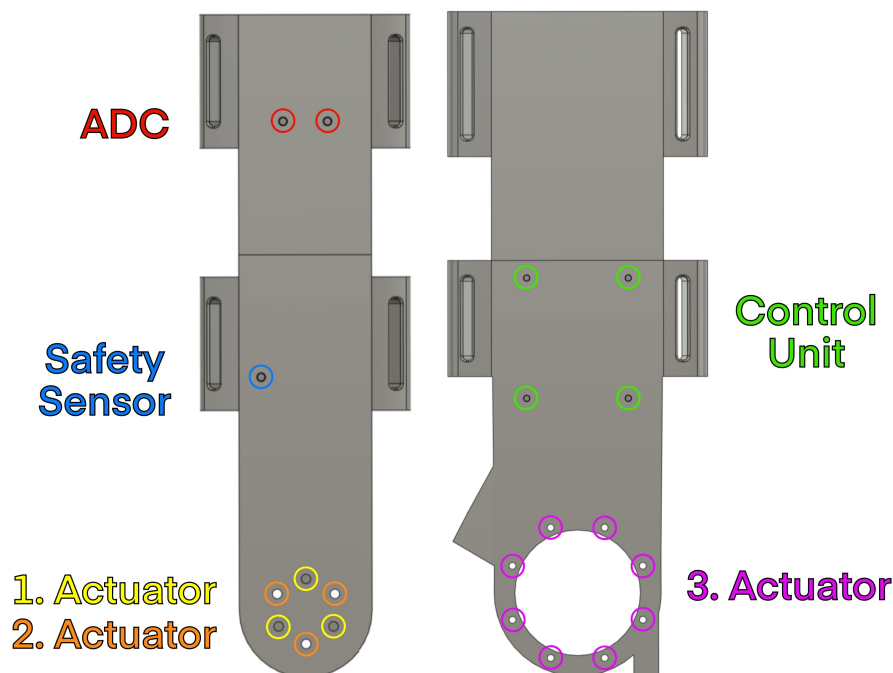


Figure 3.9: *CAD model of the links including fixtures.*

In Figure 3.9, the different holes are color-coded to indicate what fixture corresponds to what component. The red, blue and green circles in the figure highlight holes designed for heat-set threaded inserts. These holes do not go through the links. The purple circles are screw holes for the stator, meaning the static part of the actuator, and the orange are screw holes for the rotor, meaning the moving part of the actuator. The yellow circles in the figure highlights the actuators metal pieces sat on the moving part, seen in Figure 3.4. All fixtures were designed with a tolerance of +0.3mm, which was found through testing for a perfect fit.

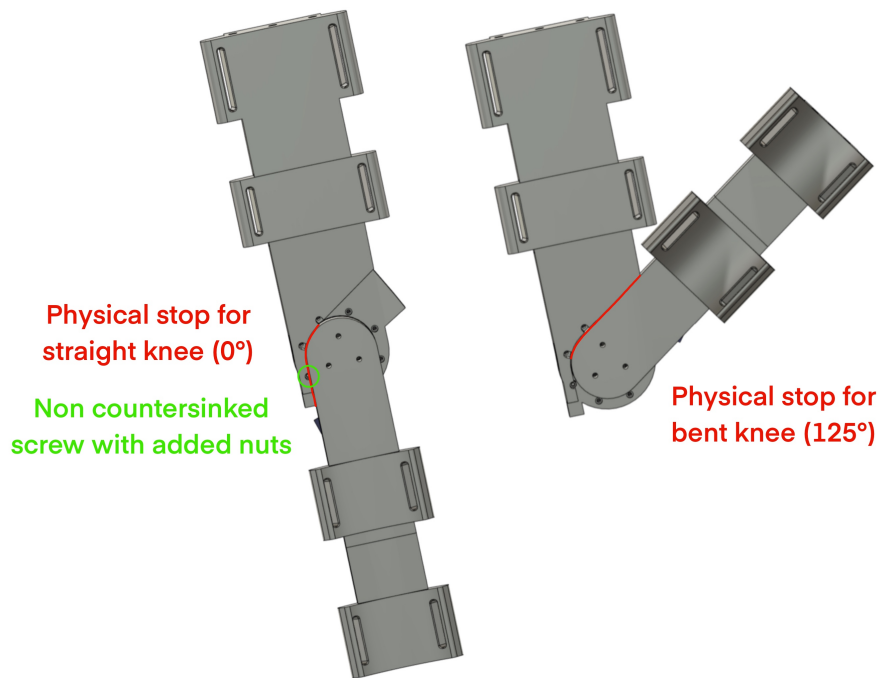


Figure 3.10: *The physical stops implemented into the upper link at both endpoints of the ROM.*

Two physical breaks were implemented into the design of the upper link, shown by the red markings in Figure 3.10. They were positioned at each end of the ROM to physically stop the moving link. In the straight position at 0° there was also designed a fit for a non-countersunk screw with three added nuts, marked with a green circle, that was screwed into the actuator to provide extra strength to the physical stop.

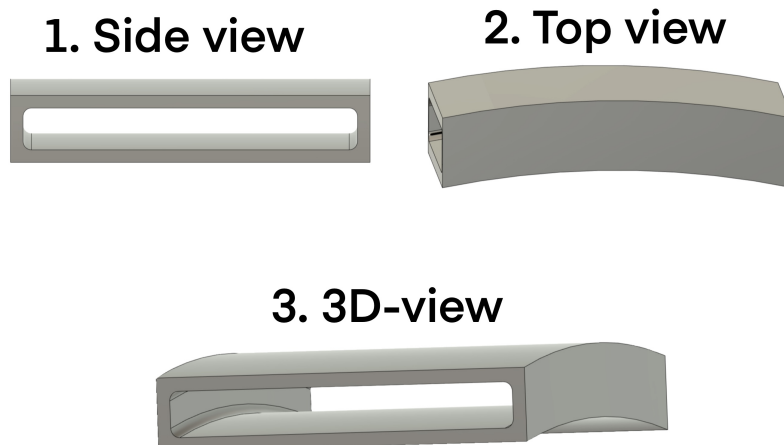


Figure 3.11: *Side-, top- and 3D-view of the sensor supports.*

Two sensor supports were designed, as seen in Figure 3.11. These supports are curved and hollow rectangles that were designed to fit the Velcro straps through its hole, providing a rigid surface to attach the sensors. This design helps ensure more accurate sensor readings. The supports are curved to follow the contour of the leg,

yet small enough to fit correctly on the front and back. Each sensor support can hold two pressure sensors, one on the inner side and one on the outer side.

The different parts were created in separated files and then assembled together with all components including screws etc in a new file where the movement was simulated. This helped with ensuring that all components, screws and links fit correctly and can perform the movement before 3D-printing.

3.4 3D-Printing

To facilitate the development process and easily make adjustments, the links and sensors supports were 3D-printed. The selected material became PETG (Polyethylene Terephthalate Glycol), due to its durability, formability and resistance factors. The color black was chosen to make it easier for the safety sensor to distinguish between the link and the optical stop.

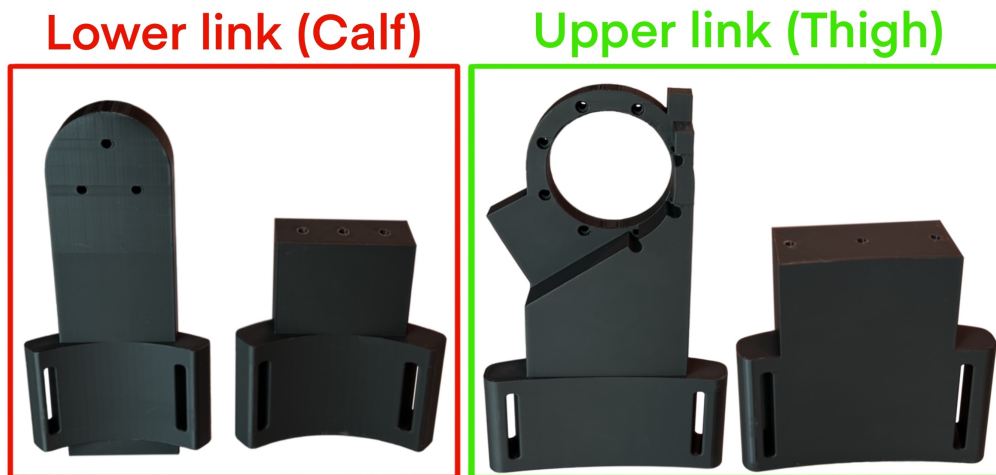


Figure 3.12: *The 3D-printed links.*

Both links were too big to be printed as whole pieces, hence each link was designed as two pieces, as shown in Figure 3.12, and afterward attached to each other with heat-set threaded inserts.



Figure 3.13: *The 3D-printed sensor supports attached to the Velcro, including tactile sensors.*

The sensor supports, shown in Figure 3.13, were attached to the Velcro with a tight fit to make sure that the tactile sensors do not move to provide a better reading.

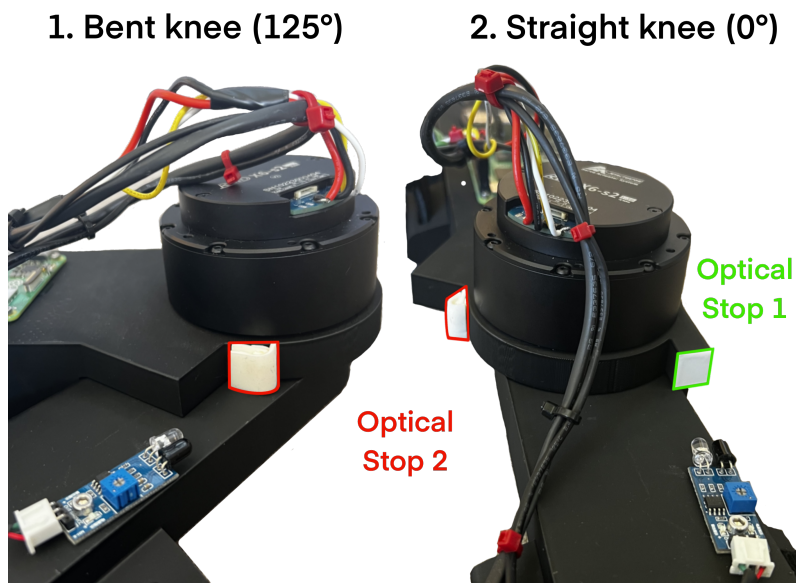


Figure 3.14: *The sensors placement and the optical stops at the two end points of the ROM.*

The red and green markings in Figure 3.14 show the optical stops that were designed at the end-points of the ROM.

3.5 Hardware Architecture

The hardware architecture shows how all components are connected in the system. It works similarly to a blueprint for the system and makes the assembling of the system easier, as well as facilitates troubleshooting.

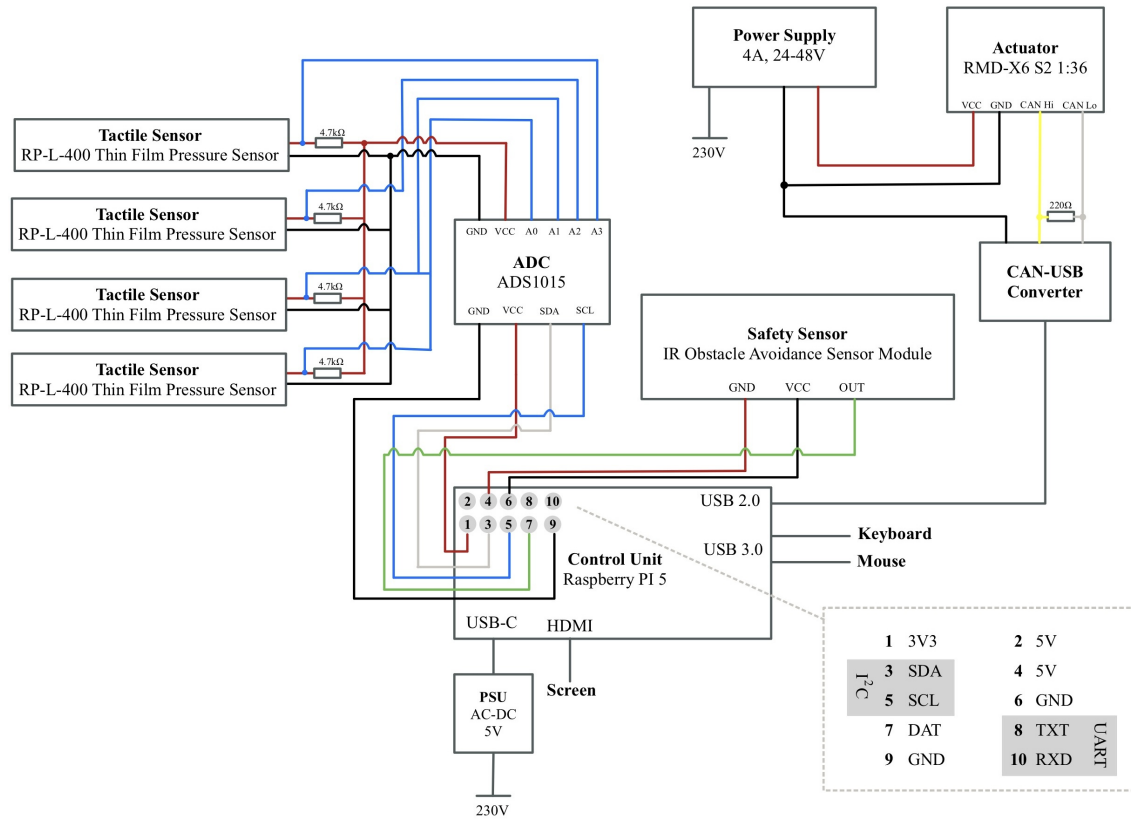


Figure 3.15: *The hardware architecture of the system.*

As seen in Figure 3.15 the colors of the cables are the same as they are used on the prototype, to verify that the assembly was done correctly. The GPIO pinout header, as displayed in the traced, grey box in Figure 3.15, shows the used pins for the project. Several of them have predefined purposes, except for GPIO 4 (pin 7) which we assigned for DATA input from the safety sensor to the controller. The Raspberry supplies power to the sensors but not the actuator as it needs higher voltages.

3.6 Electrical Schematic for a Tactile Sensor

Electrical schematics are detailed diagrams that represent the physical connections and layout of an electrical circuit. It depicts the circuit's functions and is a guide for assembling and troubleshooting the system.

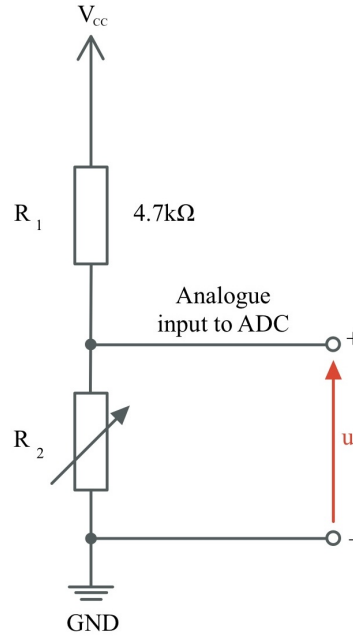


Figure 3.16: *The electrical schematic of a tactile sensor.*

Since the tactile sensors have two purposes, collecting data regarding force from the user and also are used to calculate the torque based on the read force for the system, an electric schematic of the component was needed, as seen in Figure 3.16, where:

- u : Output voltage, to the ADC
- V_{cc} : Input voltage
- R_1 : Known resistor of $4.7k\Omega$
- R_2 : Variable resistor, meaning the tactile sensor

For gain 1 the internal voltage of the ADC ranges between 0 to 4.096V. There are 2048 ($=2^{11}$) counts due to the ADC being 11 bits at 1 gain, so to calculate a value of V/count shown in equation 3.1.

$$k = \frac{4.096}{2^{11}} = \frac{4.096}{2048} = 0,002 \left(\frac{V}{count} \right) \quad (3.1)$$

The ADC has the count 1652 when untouched, due to the input voltage being 3.3V with the calculated k. This was verified in testing the component, as well as calculated through equation 3.2.

$$u = k \cdot ADC_{count} = 0.002 \cdot 1652 \approx 3.3V \quad (3.2)$$

When this has been established it's possible to calculate the tactile sensors' resistance, R_2 , as a function of varying output voltage, shown in equation 3.4 through the voltage divider formula seen in equation 3.3.

$$u = V_{cc} \cdot \frac{R_2}{R_1 + R_2} \quad (3.3)$$

$$R_2 = \frac{R_1 \cdot u}{V_{cc} - u} = f(u) \quad (3.4)$$

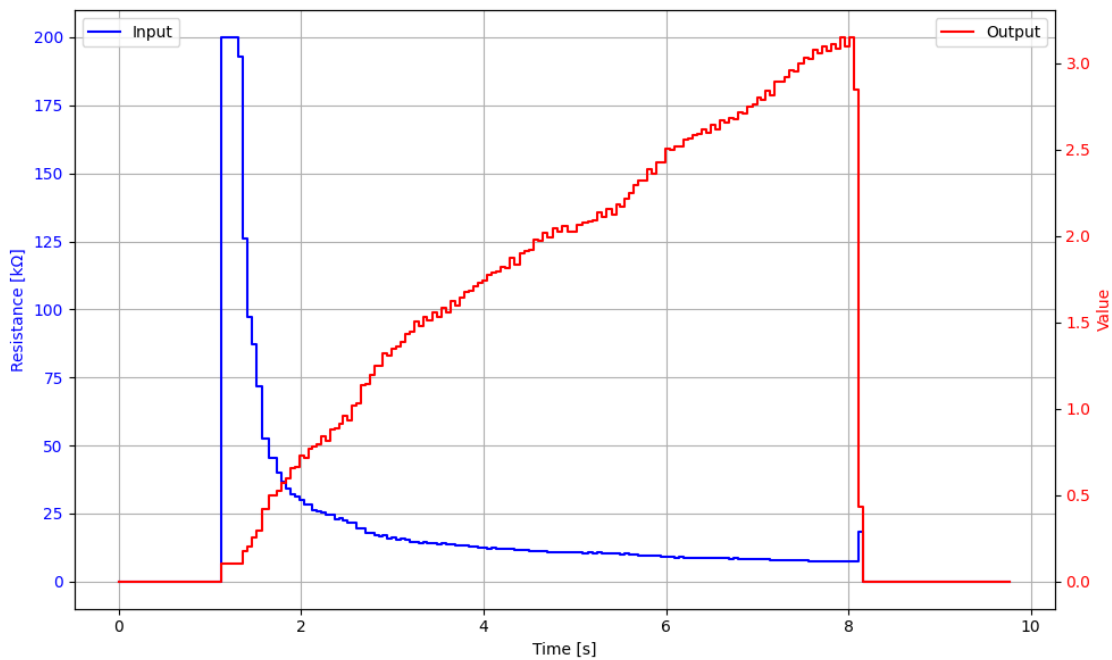


Figure 3.17: *The tactile sensors input values during linearly applied force and the output calculated to use as data output in the system.*

As shown in Figure 3.17 the resistance of the sensor, shown by the blue graph, is an exponentially decreasing graph although a linear force was applied. This became a challenge, due to the sensor being sensitive to small forces but having a problem in reading high forces. This means that when the resistance is below $30k\Omega$ it barely reads a difference in force even though linearly increasing pressure was applied. This had to be solved to get a system where the force applied is linear to the output value, meaning that small forces give a low value and high forces give an equally high value. This was done by putting a scale underneath the tactile

sensor, putting different amounts of weight on the scale, calculating the force applied through equation 3.5 and saving the corresponding value of resistance. These values were then put into a plot and using a standard exponential equation, as seen in equation 3.6, the notations a , b , and c could be calculated through fitting the graph to the data points. The linear function could then be derived by using the natural logarithm on both sides of the equation, and the output became linear to the force applied, shown by the red graph in Figure 3.17.

$$F = m \cdot a = m \cdot g = m \cdot 9.82 \quad (3.5)$$

$$f(F) = ae^{bF} + c \quad (3.6)$$

3.7 Testing of Components

To simplify the system's troubleshooting, as well as to understand how each component works on its own, some separate testing and simple scripts of the components were made.

The touch sensors were initially tested with a multi-meter one by one to verify that they could sense changes in force applied. Then a simple script was created, where the ADC counts were displayed and decreased in value when touched. The output showed 1652 counts when untouched with a dropping rate of counts when touched as expected from the calculations made in equation 3.2.

The safety sensor was tested through a simple script. It was visible both through the LED of the sensor and in printed outputs, showing that the white and black colours could be detected respectively. After testing, the sensor was attached to the links, and its potentiometer was adjusted to the correct range.

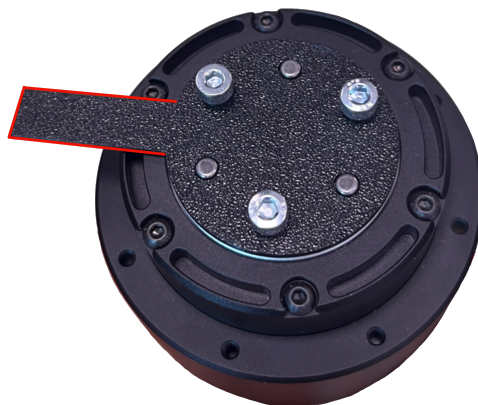


Figure 3.18: *The actuator with a 3D-printed test part to use during calibration and testing.*

The actuator was initially tested using the test environment provided by the manufacturer. A test part including a protruding lever, marked with red in Figure 3.18,

was created to show directional speed and position visually to verify the script's inputs. When the initial testing was made, a simple script was created using libraries made for the actuator found at GitHub by 2b-t [32]. This facilitated the process since libraries for many functions were prepared and could later also be implemented in the main script.

3.8 Final Prototype

Once communication between the components was established and the scripts and basic functions of each component were verified, the final prototype was assembled.



Figure 3.19: *The final prototype of the Intelligent Knee Orthosis.*

Once assembled the final prototype seen in Figure 3.19 was ready for experimental testing.

4

Experimental Validation & Results

The experimental validation was done through two tests, active and passive, due to the prototype not being allowed to be worn by a user with the actuator powered on. The two tests were conducted to simulate how the support varies with different levels of applied force from the user.

4.1 Passive Test

The passive test consists of collecting the data input from the tactile sensors with the actuator unable to assist the movement. The user is wearing the prototype but performs the movement with no added assistance since the actuator is not active. The purpose is to collect data from the tactile sensors during the movement to provide insights into measured force, position, velocity, and torque, as well as see that the safety sensor still verifies that the movement is within the ROM.

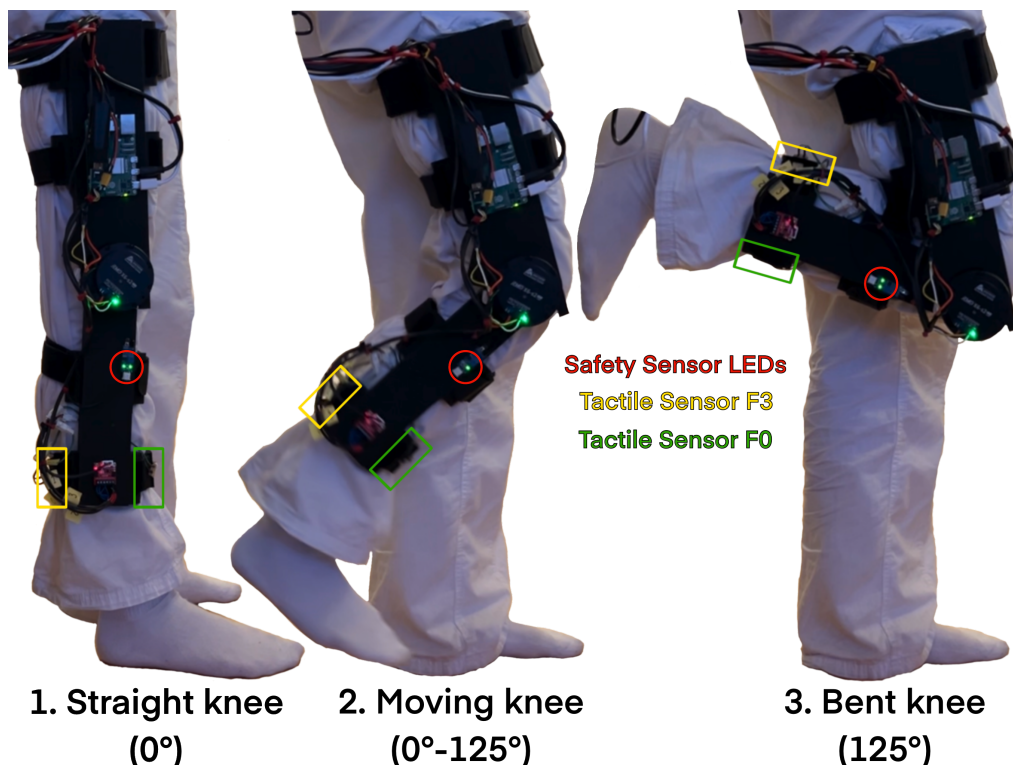


Figure 4.1: Visual of the passive test.

The tactile sensors F0 and F3, marked with green and yellow in Figure 4.1, are placed on the inside of the prototype, and strapped on tight to the leg to get accurate readings. As shown in Figure 4.1, the safety sensor still reads the ROM correctly, although it cannot stop the movement through software due to the actuator not being able to assist the movement.

4. Experimental Validation & Results

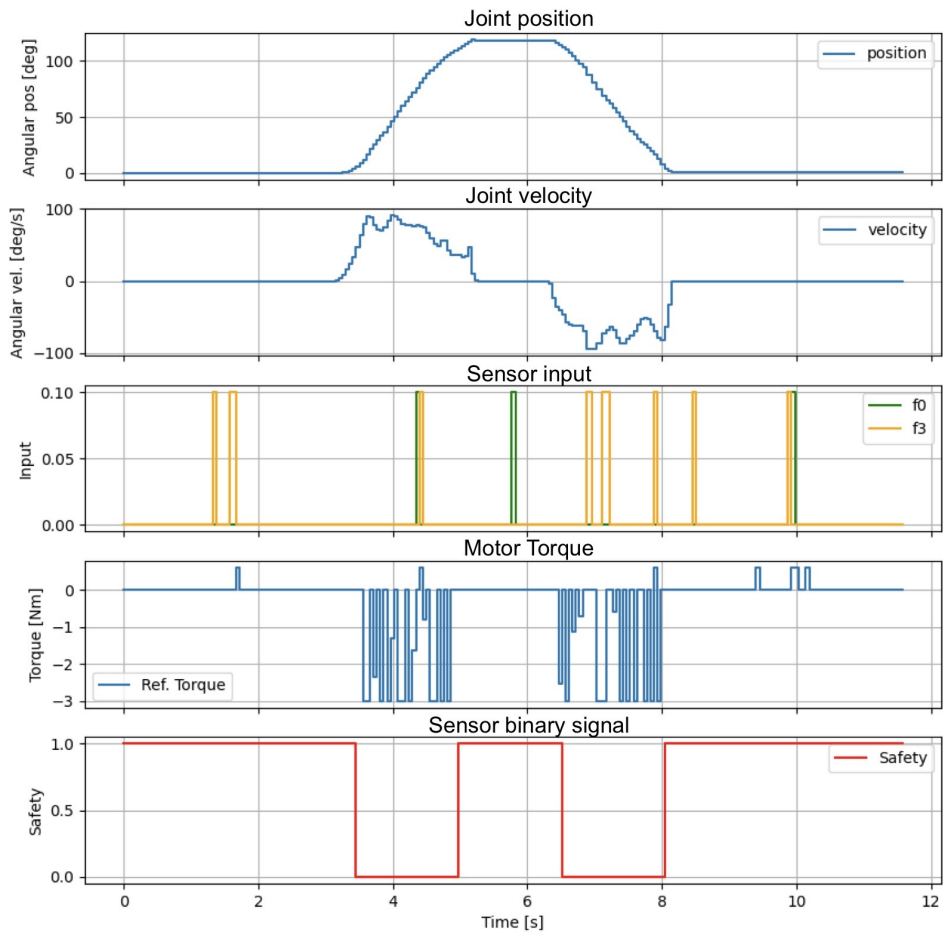


Figure 4.2: *Plots with data from the passive test.*

The graphs shown in Figure 4.2 describe the collected data from the tactile sensors and safety sensor during the movement. Note the graph of inputs from the sensors F0 and F3, depicted in yellow and green, occasionally behaves irregularly due to the sensors not being able to get completely accurate readings for parallel loads.

4.2 Active Test

The active test is used to show the movement of the prototype when different forces are applied to the tactile sensors. This means that when higher force is applied, the actuator moves the lower link with a higher torque, and respectively for a smaller amount of forces applied.

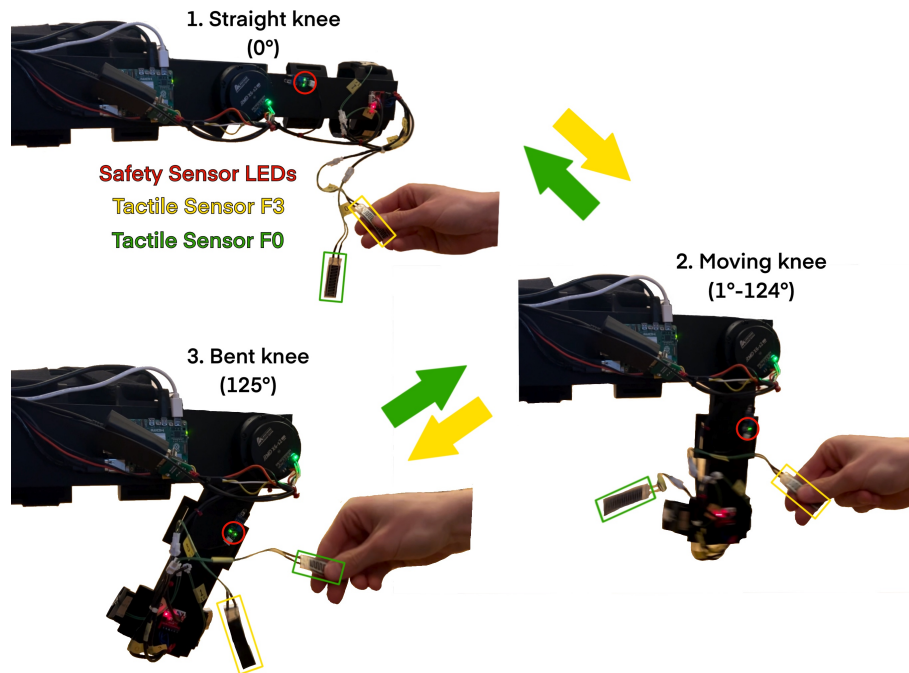


Figure 4.3: *Visual of the active test.*

As shown in Figure 4.3, when the tactile sensor F3, highlighted with yellow, is pressed, the links move from an extended position towards a bent position, and stay within the ROM. This is highlighted by the red circle around the LEDs from the safety sensor where two LEDs means that an optical stop is detected and one LED indicated that the optical stop is not detected and the link are within the set ROM. This means that when sensor F3 is pressed and the prototype reaches 125°, the safety sensor sends an input to the actuator to stop the movement in that direction. Sensor F0, marked by green, works the same way, but in the other direction and can not move below 0°.

4. Experimental Validation & Results

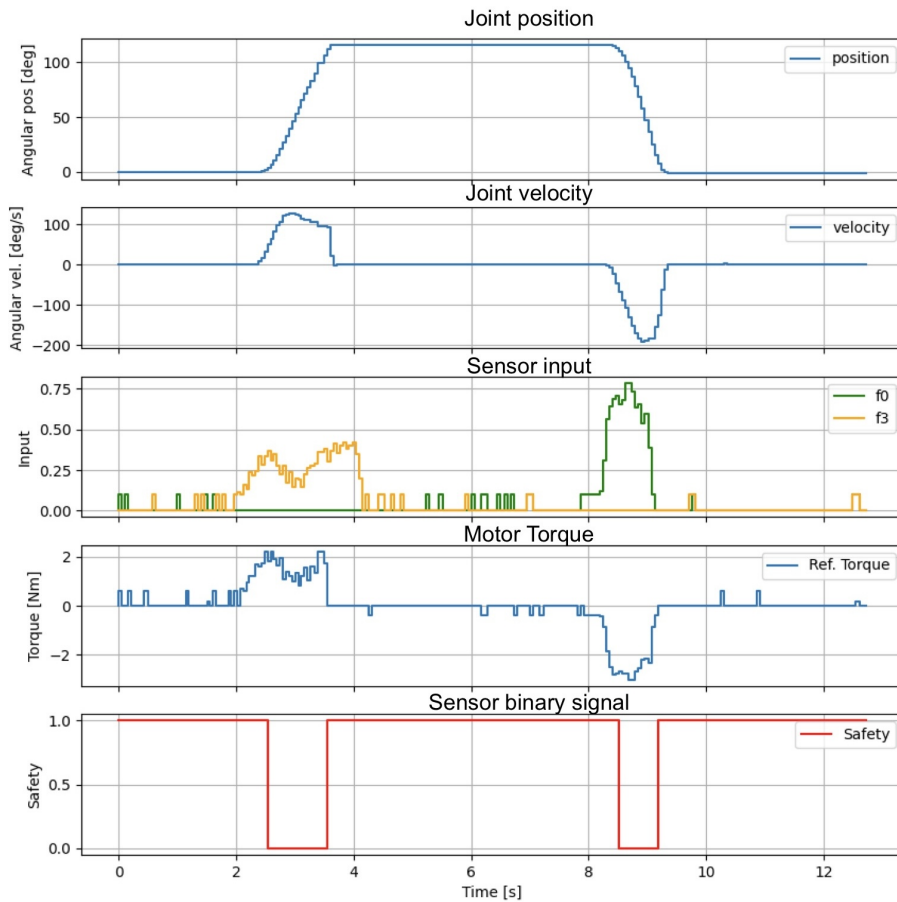


Figure 4.4: *Plots with data from the active test.*

The collected data depicted in Figure 4.4, shows the movement through angular position, angular velocity, and torque, based on the inputs from the tactile sensors. The safety graph shows when the end of the ROM is detected by the safety sensor, A value of 1 on the graph means optical stop is detected, while a value of 0 means it is not.

5

Discussion & Conclusion

The final prototype, seen in Figure 3.19, measures the position, velocity of the joint, and the torque of the actuator. It also measures the applied force on the tactile sensors and the binary state of the safety sensors. The prototype can assist movement based on the amount of force applied to the tactile sensors. The links move within the set ROM during normal forces applied to the tactile sensors. This is due to the optical stops detected by the safety sensor and the software that adjusts the torque when approaching the end points of the set ROM. The set ROM can easily be changed to fit a wider range of users through moving the white tape that is the optical stops and adjusting the set end point limits in the software.

5.1 Challenges

The most difficult challenge has been to constraint the joint motion to the defined ROM due to the high torque of the actuator. Since only the minimal requirement of the torque was calculated, the challenge of controlling an actuator with abilities to apply such a high torque wasn't taken into consideration.



Figure 5.1: *The result of aggressive testing of the actuator and physical stops during development.*

The actuator moves as expected when normal forces are applied to the tactile sensors, but during experimental testing of more aggressive forces applied, to see if the physical stops could actually stop the actuator, the actuator broke the physical stop at 0° , bent the screw attached to the stator and upper link by scraping the lower link attached to the rotor, as seen in Figure 5.1. This problem resulted in the need for 3D-printing new parts and include a safety range that decreased the torque when approaching the end points of the ROM.

Another challenge throughout the project was the sensitivity issue of the tactile sensors, as shown in Figure 4.2, which verifies the challenge visualized in Figure 3.17, in getting a correct reading of high forces applied through the tactile sensors. It was also noted that the sensors have different sensitivity individually, which had to be adjusted in software.

5.2 Further Developments of the Prototype

Further research and development of the prototype should include the usage of the external tactile sensors for physiotherapists to be able to set a goal torque and thereby the prototype can adjust its assistance accordingly with additional implementation to the existing software. Meaning that if a patient should move by a certain amount of force, but is too weak to perform the movement, the actuator supplies the remaining amount of support to help the user. Additionally, resistance instead of assistance can be implemented, meaning that when the patient becomes stronger and needs a challenge instead of support, the prototype can provide the correct resistance input by the physiotherapist's set torque goal.

The collected data from the tactile sensors can be implemented in an easy-to-use interface for both patient and physiotherapist to review how the rehabilitation has gone between visits. The tactile sensors can also be changed into another type of sensor, to get a better reading and a more linear relationship between applied force and resistance. If further developments include the chosen tactile sensors, some type of material that can distribute the parallel loads in a different way for more accurate readings could be applied on its top.

Another improvement could be to either find a weaker actuator or implement an even more reliable control of the actuator through software for a safer solution that could possibly be worn by a patient. Another solution could be to make the links and safety stops in a sturdier material to ensure that the actuator cannot physically move outside of the set ROM, although it could make the prototype heavier.

Lastly, to make the prototype portable, some type of portable power supply for the control unit and actuator should be considered, for instance, implemented in a backpack or some other type of portable way.

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A

Appendix

Access our complete code repository on GitHub via the following link.

<https://github.com/janinaudiljak/intelligent-knee>

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