MOBILITATE

October 19, 2015

Dr. Andrew Rawicz
School of Engineering Science
Simon Fraser University
Burnaby, BC V5A 1S6

RE: ENSC 440 Functional Specifications – R2000 Rehabilitative Exoskeleton

Dear Dr. Rawicz,

The attached document contains the functional specifications for our R2000 exoskeleton. The R2000 is designed to assist the user in performing a simple stretching exercise, which is to raise and lower the calf and foot while sitting, in order to help rehabilitate weakened leg muscles. The user selects using a controller, which then commands the exoskeleton to assist the user in performing that exercise.

Functional specifications will be viewed from the perspective of the entire R2000 system, followed by specific requirements of the controller unit, and finally the exoskeleton itself. These sections will address any physical, technical, safety, and environmental requirements applicable to the R2000. Each section will focus on the major proof-of-concept prototype requirements in order for the R2000 to operate; however, functional specifications for a final product are also given.

Mobilitate is comprised of four Simon Fraser University Engineering Science students: Jialiang Ou, Lucia Zhang, Ryan Villanueva, and Chantal Osterman. If you have any questions or concerns, please feel free to contact us at chantalo@sfu.ca

Sincerely,

Chantal Osterman
CEO

MOBILITATE

Functional Specifications for the R2000 Rehabilitative Exoskeleton

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Executive Summary

Every year, millions of Canadians suffer from leg injuries, often targeting the ACL located in the knee. However, research has shown that the majority of these injuries can be rehabilitated to near pre-injury condition without the need for surgery, as shown in Figure 1. Yet many Canadians forego this alternative and instead wait for surgery, which is often the result of the inconvenience of starting a rehabilitative leg program.

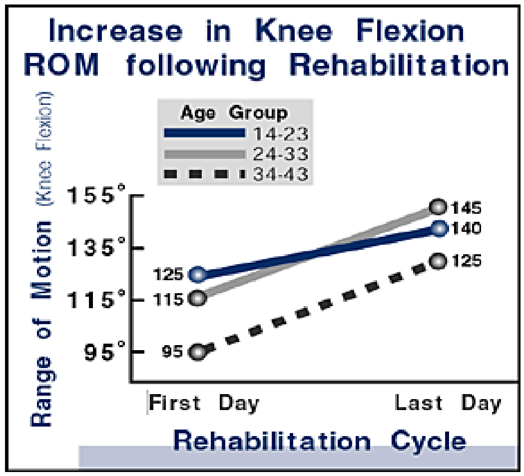

Figure 1: Knee Rehabilitation Time in Terms of Range of Motion [1]

Mobilitate aims to assist users into a recovering leg program. With the R2000 exoskeleton, patients can perform a safe exercise that will stimulate recovery of leg injuries. With its portable and sleek design, users will also be able to enjoy the convenience of exercising in their own home.

The R2000 consists of a convenient controller with an LCD display will allow users to select certain stretching routines, the number of repetitions needed, and regulate the amount of assistance needed from the exoskeleton. In turn, the controller outputs the user's selection to the exoskeleton, providing the proper exercise and number of repetitions, while providing increasing assistive force when feedback circuitry suggests to the controller that leg strength is lacking. Upon finishing their routine or with low power, the exoskeleton should return to a proper position to allow the user to remove the exoskeleton.

This document addresses the functional requirements for the R2000, which looks at the overall system requirements, then the subsystem requirements for the controller and the exoskeleton. Attention to proof-of-concept and a final product is given.

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Glossary

ACL	Anterior cruciate ligament
Arduino	Microcontroller unit
C2C	Cradle-to-cradle design, representing how the manufacturing, production, and disposal of the device satisfy the environment, economy, and equity of workers
Controller	Refers to the Arduino located on the exoskeleton
CO_2	Carbon dioxide
ISO/IEC	International Organization for Standardization (ISO) by the International Electrotechnical Commission (IEC)
LCD	Liquid crystal display: electronic visual display
Stepper Motor	An electric motor that allows rotational movement with good precision
UI Unit	Arduino microcontroller, Wi-Fi/Bluetooth shield, and its accompanying input pad and LCD
PAM	Pneumatic artificial muscle
Shield	Various attachable circuitry for the Arduino microcontroller unit

1. Introduction

Mobilitate's R2000 is an attachable exoskeleton to aid in leg rehabilitation. The product can be used in conjunction with some pre-purchased compression braces or as a stand-alone. By simply inputting parameters, such as degree of extension and number of repetitions, the R2000 will provide the power and assistance required for the user to reach their rehabilitative goals. The R2000 is designed for home usage, so it will be implemented with an intuitive interface and a less clunky design than many competitor's products.

1.1 Scope

The functional specification outlines the requirements that must be met for Mobilitate's R2000. The requirements fully describe the proof-of-concept device, as well as many features of the production device. The document will be the basis for all future work on the R2000, and will be traceable in future design documents.

1.2 Intended Audience

The functional specification is written for all members of Mobilitate. Each team member will refer to the functional specifications throughout all phases of development to ensure all goals are met. In the design phase and implementation phases, the document will be referenced to guarantee consistency and that all standards are met. During testing, engineers will refer to the specifications to compare the intended functionality and achieved functionality.

1.3 Classification

Throughout this document, each function will be accompanied by:

[Rn-p] [A functional requirement]

Where n is the functional requirement number, and p is the secondary classification and is assigned to one of three values:

- I Applies only to proof-of-concept system.
- II Applies to both proof-of-concept system and final product.
- III Applies only to final product.

2. Overall System Requirements

The general requirements applicable to the entire system are presented in this section.

2.1 System Overview

A simplified diagram of the R2000 system is shown below in Figure 2

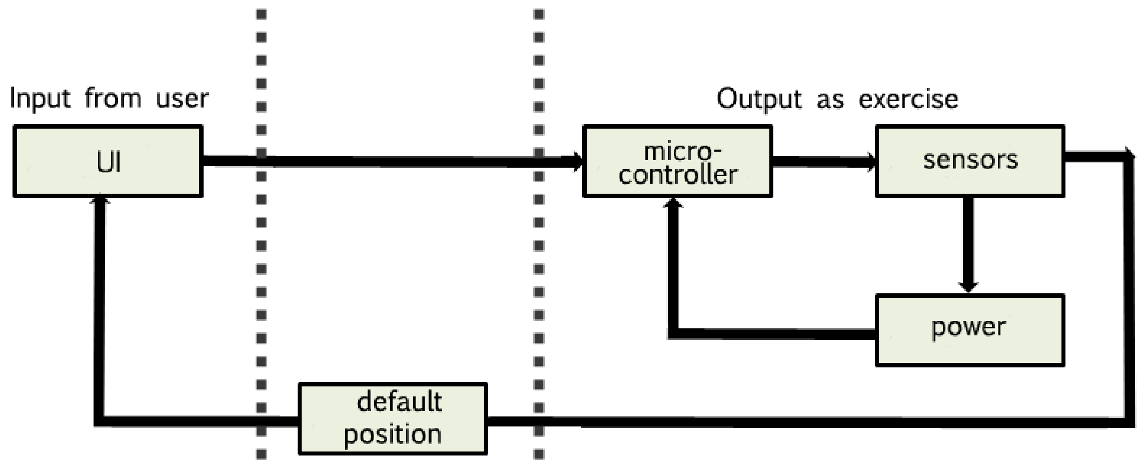

Figure 2: High-level system diagram

The user will first wear their prescribed knee brace if owned. Then they will attach the R2000 through a system of straps as shown in Figure 3, including securing the muscle sensor leads to their skin according to the criteria shown in Table 2 of Section 4.1.1.

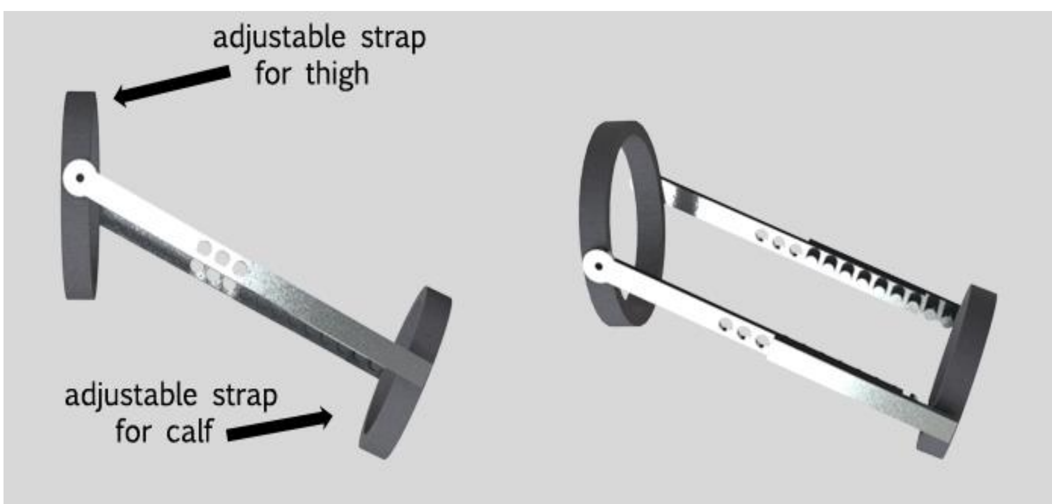

Figure 3: Rough design of exoskeleton, showing adjustable straps and the adjustable connection between them

The length of the bars along the sides of the legs can easily be manipulated by securing the bolts into different holes, also shown in Figure 3.

After attachment is complete, the user will turn the system on via the UI unit and begin inputting exercise parameters. One parameter is the degree of inclination, depicted in Figure 4. Other parameters include number of repetitions and number of sets. For example, three sets of 10 repetitions means 10 repetitions will be made, followed by a break for the user to relax. The method of repetitions and sets will be further explained in Section 3.1.

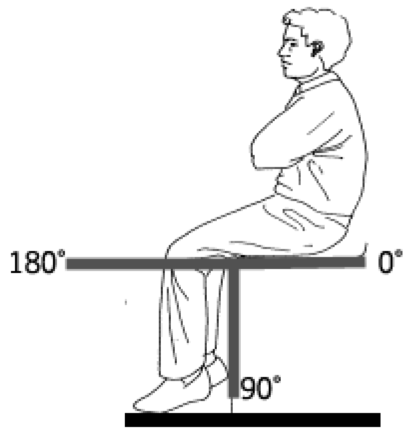

Figure 4: Legend for input angles as measured when the user is sitting [2]

The proper usage of the R2000 dictates that the user will be seated comfortably, with enough room in front and to the side for full leg extension. If the user cannot balance confidently on one leg, then the user must refrain from standing and performing exercises with the R2000.

The average height of Canadians is 174cm for males and 160cm for females [3]. However, most Mobilitate members stand at a maximum of 170cm, so proof-of-concept will be delivered using this maximum. 170cm and 160cm were also used in calculations in Section 4.2. The average weight is also reported to be approximately 80kg [4]. However, due to time and financial constraints, the proof-of-concept prototype of the R2000 may only accommodate users up to 73kg. This is primarily due to the fact that stepper motors that provide a torque over 63kg-cm are quite heavy and expensive.

An estimation of torque required to rotate the knee uses Equation (1) and data from Table 1. The calculation was done roughly, assuming that the mass of the calf is concentrated in the middle of the calf, and the mass of the foot concentrated approximately a quarter of the calf length past the ankle, using Equation (3).

$$\tau = \mathbf{F\,x\,r} \tag{1}$$

Table 1: Segmental mass of an average person's lower body [5] [6]

Segment	% Mass	Average Length (cm)
Thigh	9.46	$Thigh\ Length = \frac{Height - 65.53}{2.32}$ (2)
Calf	4.20	$Calf\ Length = \frac{Height - 81.93}{2.42}$ (3)
Foot	1.35	$Foot\ Length = \frac{Calf\ Length}{4}$ (4)

Using the knee as the place of origin, the torque required to counteract the force of gravity on the calf and foot for a 170cm, 73kg person (maximum) is approximately 10N*m.

2.2 General Requirements

[R1-II] The R2000 will have an emergency stop switch functional at all times, as a switch will avoid unintentional emergency activation.

[R2-II] The system will return to a default position when the exercise is complete or when the emergency stop switch is activated.

[R3-I] The user should weigh no more than 73kg.

[R4-III] The user should weigh no more than 95kg.

[R5-I] The user's height should be between 157-170cm, in accordance to results using equation (1) with values from Table 1.

[R6-III] The user's height should be between 157-182cm, in accordance to results using equation (1) with values from Table 1.

2.3 Physical Requirements

[R7-II] The weight of the system will not burden the user. More details can be found in sections 2.3 and 3.3.

2.4 Electrical Requirements

[R8-II] All electrical components, with the exception of the muscle sensors, will be enclosed to ensure safety and avoid tampering.

2.5 Usability Requirements

[R9-II] The product will function safely assuming the user is seated properly.

[R10-II] The user should read the user manual to familiarize himself with the functions of the R2000 before operating it.

2.6 Safety Requirements

[R11-II] The product will not injure the user, and will only perform regulated exercises aimed to help recovery.

2.7 Sustainability Requirements

[R12-II] The R2000 does not need to be manufactured custom for each person, but is rather adjustable and accommodates users that are described under 2.1. This cuts down materials and labour required.

[R13-II] A short-term user could rent the exoskeleton from hospital, decreasing overall ecological cost.

[R14-II] The material used for the exoskeleton should be recyclable and acquired through environmentally friendly means, as per the ecology requirement of C2C design.

[R15-III] If mass-produced, all employees must earn a living wage and face no discrimination, as per the equity requirement of C2C design.

[R16-III] If mass-produced, some health care funding put towards immediate surgery for knee injuries can be put towards something else. This will turn over a profit, as per the economy requirement of C2C design.

2.8 Environmental Requirements

[R17-II] The exoskeleton will be fully functioning indoor within a temperature range of 0°C to 35°C.

[R18-II] The noise of the exoskeleton when it is functioning should be less than 90dB.

2.9 Reliability Requirements

[R19-III] Production models should be shock-tolerant to up to 99 N.

3. User Interface Requirements

3.1 System Overview

The user interface unit, hereby referred to as the UI unit, is the connection between user and exoskeleton structure. On one end it controls and regulates the power source, on the other end it provides user interface for patients to select different predefined exercise mode and input several parameters, including angles to reach, repetition times and etc. It also receives the signal from muscle sensors or motors, gives data feedback and indication to users.

The user first enter the main menu, where they enter the angle depicted in Figure 4, number of repetitions, and number of sets if they so desire. If no set number is inputted, the system will automatically assume one. The UI unit will then send this information to the controller on the exoskeleton, and the exercises will begin. During the exercise, the following information will be available for the user to review via LCD screen:

- Current duration of exercise
- Current number of reps completed
- Current number of sets completed
- Angle of extension chosen

At the end of the exercise, the UI will return to the main menu. Figure 5 below is the flowchart of the interface.

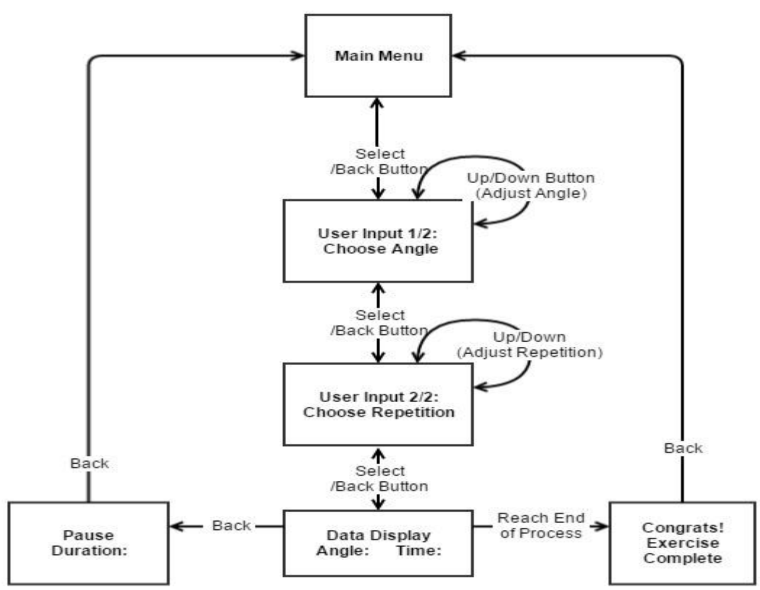

Figure 5: UI Flow Chart

Figure 6 presents a conceptual illustration of the UI unit:

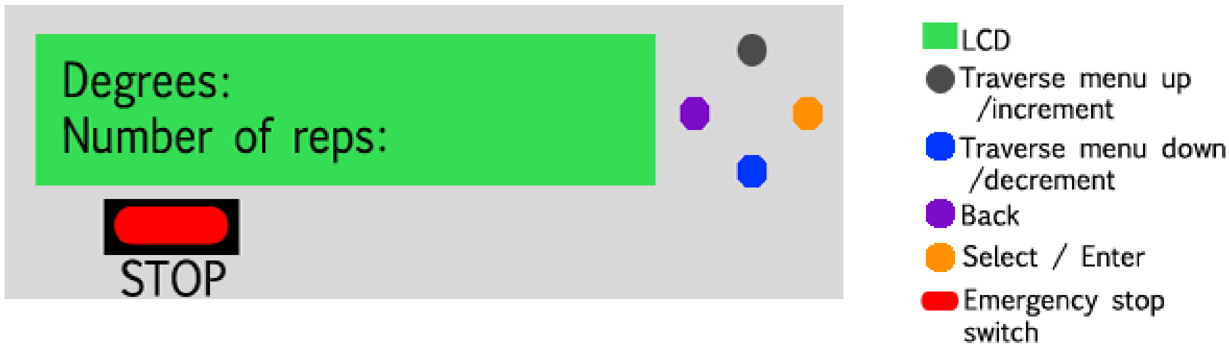

Figure 6: Conceptual User Interface Unit

3.2 General Requirements

[R20-II] The UI unit will receive input from the user through buttons and switches.

[R21-II] The UI unit will send the input from the user to the controller on the exoskeleton.

[R22-III] Users can adjust backlight of LCD screen.

[R23-III] Progress from the previous few sessions will be available so the user can see their improvement.

3.3 Physical Requirements

[R24-II] Controller shall be reachable for user whenever in exercise or at rest.

[R25-II] If wired, the controller wire will be no more than 50cm and will not hinder the user's movements or become tangled with the rest of the product.

[R26-II] The controller will be easily accessible at all times.

[R27-II] The controller will not be exceed dimensions of 12cm x 10cm x 5cm.

3.4 Electrical Requirements

[R28-II] The controller shall run under 5V based on Arduino board limit.

[R29-II] The controller shall be grounded.

3.5 Usability Requirements

[R30-II] The user will use the controller to select various customizations including, but not limited to, exercise type and method for the angle presented in Figure 4.

[R31-II] An LED on the controller will indicate when the power supply is 10%.

[R32-II] Information will be displayed to the user via LCD including, but not limited to, repetitions left, exercise duration, and exercise options.

[R33-II] If the R2000 malfunctions in any way, an error message will be printed to the screen and, after a short delay, the system will return to its default position.

[R34-II] UI is user-friendly.

[R35-II] Confirmation of parameters before the exercises begins will be required, with the parameters displayed on the LCD.

[R36-II] An error message will be displayed on the LCD, along with a red LED, in cases of error.

3.6 Safety Requirements

[R37-II] The UI unit will have an emergency stop switch to stop all operations and return the exoskeleton to the default position when safe.

3.7 Sustainability Requirements

[R38-II] Arduino board and LCD screen can be reused.

[R39-II] The material for controller's shell shall contains no hazardous materials and can be reused.

3.8 Environmental Requirements

[R40-II] Controller shall function within a temperature range of -20°C to 70°C.

4. Exoskeleton Requirements

The exoskeleton consists of both software and hardware components. Requirements for both are listed below.

4.1 System Overview

4.1.1 Hardware

The hardware portion of the R2000 consists of the following:

- Attachable, adjustable straps around the hip, thigh, and calf
- Rigid, length-adjustable bars between the straps to transmit power and motion
- A power supply mounted around the waist
- A component to cause movement (eg. stepper motors, PAMs)
- Sensors for detecting muscle tensing and displacement

A rough sketch of the main part of the exoskeleton is presented in two views in Figure 3. As a main power source has not been chosen yet, the design is general for either application. Another connection similar to the pin-in-hole connection in Figure 3 will be attached to the thigh strap and another strap around the hip.

There are two purposes for the connection between the hip and thigh:

1. The source of power, either battery-powered or CO_2, will be mounted around the hip and transmitted along this path to the knee, and
2. the upper thigh should be kept stationary while the knee is bending and extending.

A motor or other component that generates movement will be mounted between the two straps shown in Figure 3, and allow for movement in the knee region. The range of movement is shown above in Figure 4.The displacement sensor will be placed on the lower strap, around the calf, as this is the part of the leg that will move most during exercise.

All lengths used in the requirements below were determined by taking the measurements of all group members and creating a range around them. To determine the weight of the exoskeleton, the worst case actuator, in this case two stepper motors was taken to be 6kg. Adding in the UI and the power source brings this total to 7kg. An approximate 3kg in lightweight materials for the exoskeleton structure rounds this number to 10kg maximum for the exoskeleton.

4.1.2 Software

An Arduino will be used to regulate and monitor all hardware components. It serves two main functions:

1. The Arduino will receive signals from the muscle and displacement sensors, and
2. using this data, regulate the power supply to allow exercise to occur.

4.2 General Requirements

[R41-I] The exoskeleton will accommodate exercises ranging from 90° to 180° as shown In Figure 4.

[R42-III] The exoskeleton will accommodate exercises ranging from 0° to 180° as shown In Figure 4.

[R43-II] The attachment straps around the thigh will be adjustable within a range of 30cm to 55cm.

[R44-II] The attachment straps around the calf will be adjustable within a range of 23cm to 48cm.

[R45-II] The connection between the hip and the centre of the knee will be adjustable within a range of 45cm to 53cm.

[R46-II] The connection between the centre of the knee and the bottom adjustment strap will be adjustable within a range of 16cm to 19cm.

[R47-II] If pneumatics is used, the air pressure provided to the PAMs should be approximately 50 psi [7].

[R48-II] If motors are used, they must weigh no more than 6kg each.

4.3 Physical Requirements

[R49-II] The power supply must be portable.

[R50-II] The placement of all components, for example motors or air muscles, will not inhibit the user's movements.

[R51-I] The weight of the exoskeleton around the knee should not exceed 8kg.

[R52-I] The weight of the exoskeleton around the hip should not exceed 10kg.

4.4 Electrical Requirements

[R53-II] The draw on any power source should be sufficiently below the maximum that the source can provide to avoid overheating and overdrawing.

[R54-II] Wires from the hip to the knee should be gathered together and encased to not interfere with the user's movements or environment.

[R55-II] The displacement sensor will only be used within a range of 4cm to 30cm.

[R56-II] The motor drivers will provide between 12-24 volts of at least 1A, as these are the minimum requirements for most motors.

4.5 Mechanical Requirements

[R57-III] The structure of the exoskeleton should be compact.

[R58-II] The depth of the adjustable bars must be no more than 3cm for the user's comfort.

[R59-II] The width of the bar must be at least 3cm wide to avoid strength degradation due to drilling holes, but be less than 6cm wide to ensure the user's comfort.

[R60-I] The mechanical components, such as gears, may be made of either plastic or metal, depending on time constraints.

[R61-III] The mechanical components, such as gears, will be made of metal to provide more strength and reliability.

4.6 Usability Requirements

[R62-II] The user manual for attaching and removing the exoskeleton will be easy to understand.

[R63-II] The process of attaching and removing the exoskeleton will be simple.

4.7 Safety Requirements

[R64-II] The outer shell of the exoskeleton should be insulated material.

[R65-II] The system should be able to detect any failure for both mechanically and electrically.

[R66-II] The displacement sensor must be able to detect the displacement of the motion, e.g. for leg extension, with attaching the sensor to the middle of shank (length of the shank=L), if the exoskeleton moves beyond the a vertical displacement of L/2, then the sensor should be able to detect it and report to the controller when exceeding critical values.

[R67-II] The exoskeleton should give a warning when the power source is at 10%.

[R68-II] The exoskeleton should be able to return to the default position before the system shuts down.

[R69-II] The user must first consult with their doctor to ensure each exercise is appropriate for their injury.

[R70-II] If stepper motors are used, they will not exceed 70°C to avoid wire isolation and rotor-magnetization degradation [8].

4.8 Sustainability Requirements

[R71-II] If batteries are used, they should be rechargeable.

4.9 Environmental Requirements

[R72-II] The exoskeleton should be used indoor.

[R73-II] The exoskeleton should be fully functioned within the temperature range: 0℃~ 35℃.

4.10 Reliability Requirements

[R74-II] The portable power supply should be able to run for 3 days when exoskeleton remains on.

[R75-II] The portable power supply should be able to run for 0.5 hours per day for 3 days when it is fully functioning.

4.11 Engineering Standards

[R76-II] The outer shell of the exoskeleton conforms to ISO/IEC TR 29138-1 5.5.1.6 people with physical disabilities. [9]

[R77-III] The system shall conform Medical Devices SOR/98-282 regulation. [10]

5. Conclusion

This functional specifications document has laid out our requirements for the R2000 rehabilitative exoskeleton needed for proof-of-concept, final product, and requirements needed for both. To summarize, the general system requirements for the proof-of-concept would be:

- To rehabilitate users between 157cm to 170cm
- To rehabilitate users no more than 73kg
- To generate a maximum of 10N*m of torque to lift from the knee to foot
- To safely rehabilitate and not injure users
- To implement an emergency stop switch when a user feels the need to do so

Specifically, the UI should:

- Allow users to input their exercise, repetitions, and knee angle
- Output user's choices to the exoskeleton

Whereas the exoskeleton should:

- Adjustable for users between 157cm to 170cm
- Be able to lift a user's shank from 90° to 180°
- Weigh no more than 10kg

It would be these functional specifications which our R2000 is mainly based on and which we would like to achieve and build by December.

6. REFERENCES

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