March 26, 2021

Dr. Craig Scratchley
Dr. Shervin Jannesar
Dr. Andrew Rawicz
School of Engineering Science, Simon Fraser University
British Columbia, V5A 1S6

RE: ENSC 405W/440 Design Specifications for NovaBand

Dear Dr. Scratchley, Dr. Jannesar, and Dr. Rawicz,

Attached to this letter you will find the design specifications document for NovaBand, a programmatic resistance device intended for use in physiotherapy clinics for muscular rehabilitation. By working alongside practicing physiotherapists, our company aims to create an affordable, versatile device that facilitates an efficient recovery process for physiotherapy patients through the application of isokinetic exercise.

The design specifications document details NovaBand's functionality and justifies the design choices made. Our design choices are founded in engineering experience, research, and experimentation and were selected to meet the requirements outlined in our previously transmitted requirements specifications document.

Our team consists of five senior engineering students, each with a varied engineering background: Kevin Jerome, Arvin Amini, Nicolas Skinner, George Lertzman-Lepofsky, and Jordan Lei. For the last several months, we have been collaborating to create a truly exceptional product.

We thank you for taking the time to read this design specifications document. If you have any questions, please reach out to our Chief Communications Officer, George, at gmlertzm@sfu.ca.

Sincerely,

Jordan Lei
Chief Executive Officer
NovaBand Solutions

ENSC 405W: Company 6

Design Specifications: NovaBand

Jordan Lei (CEO)
Kevin Jerome (COO)
Arvin Amini (CTO)
Nicolas Skinner (CFO)
George Lertzman-Lepofsky (CCO)

Contact:
George Lertzman-Lepofsky
gmlertzm@sfu.ca

Version History

Version #	Implemented By	Revision Date	Approved By	Approval Date	Reason
1.0	Jordan Lei, Kevin Jerome, Arvin Amini, Nicolas Skinner, George Lertzman-Lepofsky	03/26/21	Jordan Lei	03/26/21	Initial Design Definition Draft

Approvals

Signature:		Date:	03/26/21
Print Name:	Jordan Lei		
Title:	Mr.		
Role:	Chief Executive Officer		

Signature:		Date:	
Print Name:			
Title:			
Role:			

Abstract

When used for physiotherapy, traditional resistance bands present several issues. First, they are unable to precisely vary resistive force as they are stretched. Second, the force produced is linearly related to the displacement of the band. These problems result in suboptimal exercise and rehabiliatory efficiency; there is a dramatic difference between the muscle-torque curve and the force applied by the band in the latter half of a given exercise. Existing physiotherapy machines attempt to address these weaknesses, but ultimately fail to do so for various economic and practical reasons. To cover these shortcomings, NovaBand Solutions offers a programmatic resistance device: NovaBand. NovaBand is an affordable, versatile device that works in concert with muscle characteristics to provide a custom-tailored isokinetic exercise for physiotherapy patients. Physiotherapists can precisely control the device via a mobile application while their patients physically interact with the device through carefully controlled exercises.

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Glossary

Term	Definition
Isokinetic	Exercises that keep the speed of movement constant throughout the exercise
UART	Universal Asynchronous Receiver-Transmitter
RPM	Rotations Per Minute
Back EMF	Counter Electro-Motive Force that is caused by a change in current in a material
PCB	Printed Circuit Board
BJT	Bipolar Junction Transistor
LED	Light Emitting Diode
IR LED	Infrared Light Emitting Diode

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1. Introduction

1.1 Background

NovaBand is a programmatic resistance device designed to aid physiotherapists and their patients undergoing muscular rehabilitation. NovaBand aims to be a direct replacement for traditional resistance bands. These resistance bands are only able to increase tension mid-exercise and exert force in a way that diverges from the typical joint-angle curve observed in common muscle groups [1] [2], potentially leading to slower patient rehabilitation times or further injury.

Existing physiotherapy machines attempt to solve these two issues by having the patient perform an *isokinetic* exercise, which is carried out at a constant velocity and has clear benefits for both strength building and muscular rehabilitation [3]. However, these machines are cumbersome and expensive and are therefore not used outside of research and specialized clinics [4]. In contrast, NovaBand aims to provide a portable, low-cost, and versatile medical device that makes isokinetic exercise accessible to patients in a way that was not previously possible. NovaBand is also very convenient for physiotherapists by eliminating the need for multiple sets of bands.

1.2 Scope

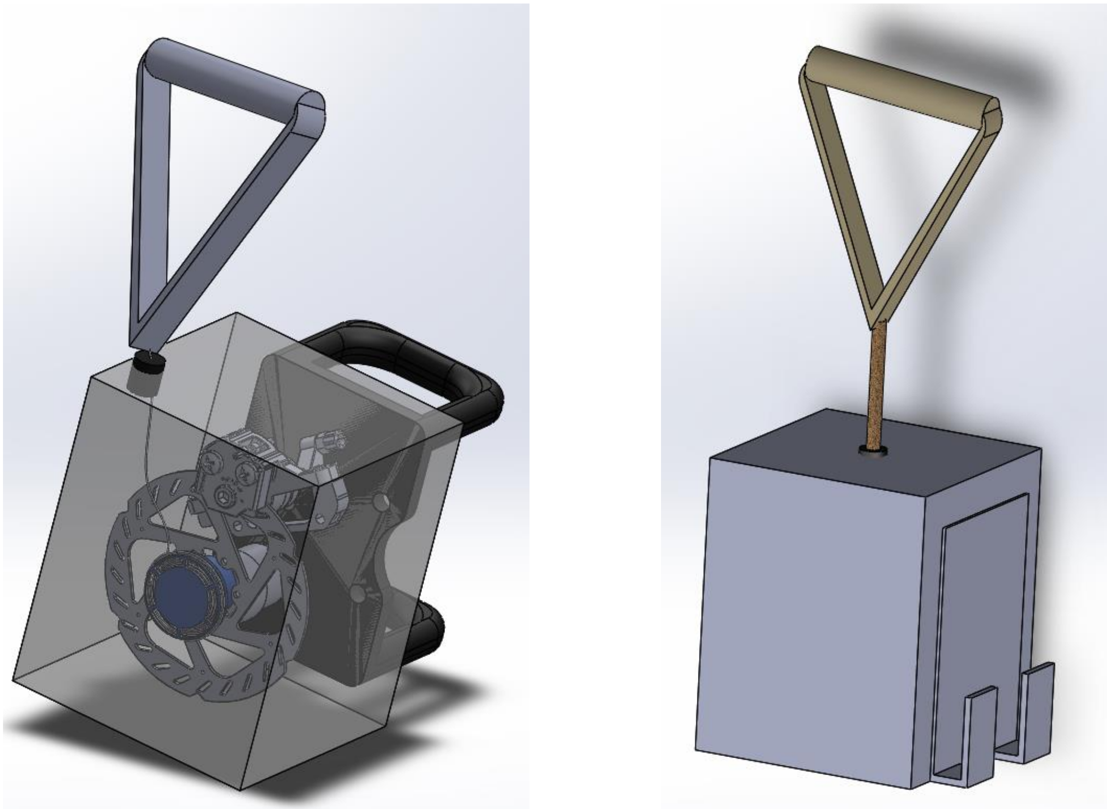
This document provides justification and appropriate background explanation for each of the major subsystems that constitute the proof-of-concept version of NovaBand, and, if known, later versions of the product.

Each design section illustrates the purpose of a particular device subsystem, lists relevant design specifications, and offers justification for the final design choice selected. Appendix A contains supporting test plans that ensure each design specification is achieved. Appendix B provides additional subsystem justification and outlines alternative design choices that were researched for each subsystem.

1.3 System Overview

NovaBand consists of two distinct elements: a physical *device* (herein referred to as “the device”) and a *mobile phone application* (herein referred to as “the app”) which provides a software user interface for the device. Most often, patients will interact with the device itself while a physiotherapist will primarily use the app. Fig. 1(a) shows a partial SolidWorks rendering of the device. Note that some device subsystems are not included in Fig. 1(a) for brevity and clarity. Fig. 1(a) is an alternative placement for the handle and pictures an experimental handle used for testing on the back of the system. Fig. 1(b) shows a Solidworks rendering of the device with an opaque housing. A mounting system is visible on the right side of the body of the device.

As introduced previously, NovaBand aims to provide patients with a truly isokinetic exercise. To achieve this, the device must be able to closely match the force exerted by a patient as they perform an exercise repetition. Patients interact with the device by exerting a pulling force on a handle connected to a rope that is precisely unspooled from the device. The device subsystem used to counteract the force applied by the patient is referred to as the “braking system” can be seen on the right-hand side of Fig. 2. As the patient pulls, a sophisticated control system instructs the internal braking system on the exact configurations needed to match this pulling force.



(a) (b)

Fig. 1. A older SolidWorks rendering of NovaBand’s rope and handle assembly, braking system, and mounting system encased inside a translucent housing. A newer rendering with an opaque housing and the mounting system visible.

Once the device has spooled out rope, a subsystem is required to reel the rope back in to prepare for the next exercise. This subsystem is referred to as the “retraction system” and is pictured on the left-hand side of Fig. 2.

To coordinate the braking and retraction subsystems, a microcontroller is used. The microcontroller, also shown in Fig. 2, communicates with each subsystem to provide configuration instructions. It also transmits and receives data to and from the app, respectively, via an electrically connected Bluetooth module. As shown in Fig. 1, these systems are contained in a box-like housing which serves to separate these systems from the external environment and protect the patient. However, one system exists *outside* of the housing: the “mounting system”. The mounting system, shown on the right of the housing in Fig. 1(b), secures the device to a surface to prevent excess movement while an exercise is being carried out by a patient. This subsystem is also shown on the right-hand side of Fig. 2.

Clear design challenges are present when holistically examining the product. For instance, the braking system must be precise enough that subtle changes in the patient's pulling force can be appropriately matched. Additionally, the retraction system must be slow to ensure safe retraction of spooled-out rope, but must also be fast enough to not impede the progress of the physiotherapy exercise. Moreover, the housing must be durable and lightweight while the mounting system needs to be secure and reliable for the safety of the patient. Lastly, the app-to-device communication must be responsive enough to transmit information used for updating the device configuration mid-exercise.

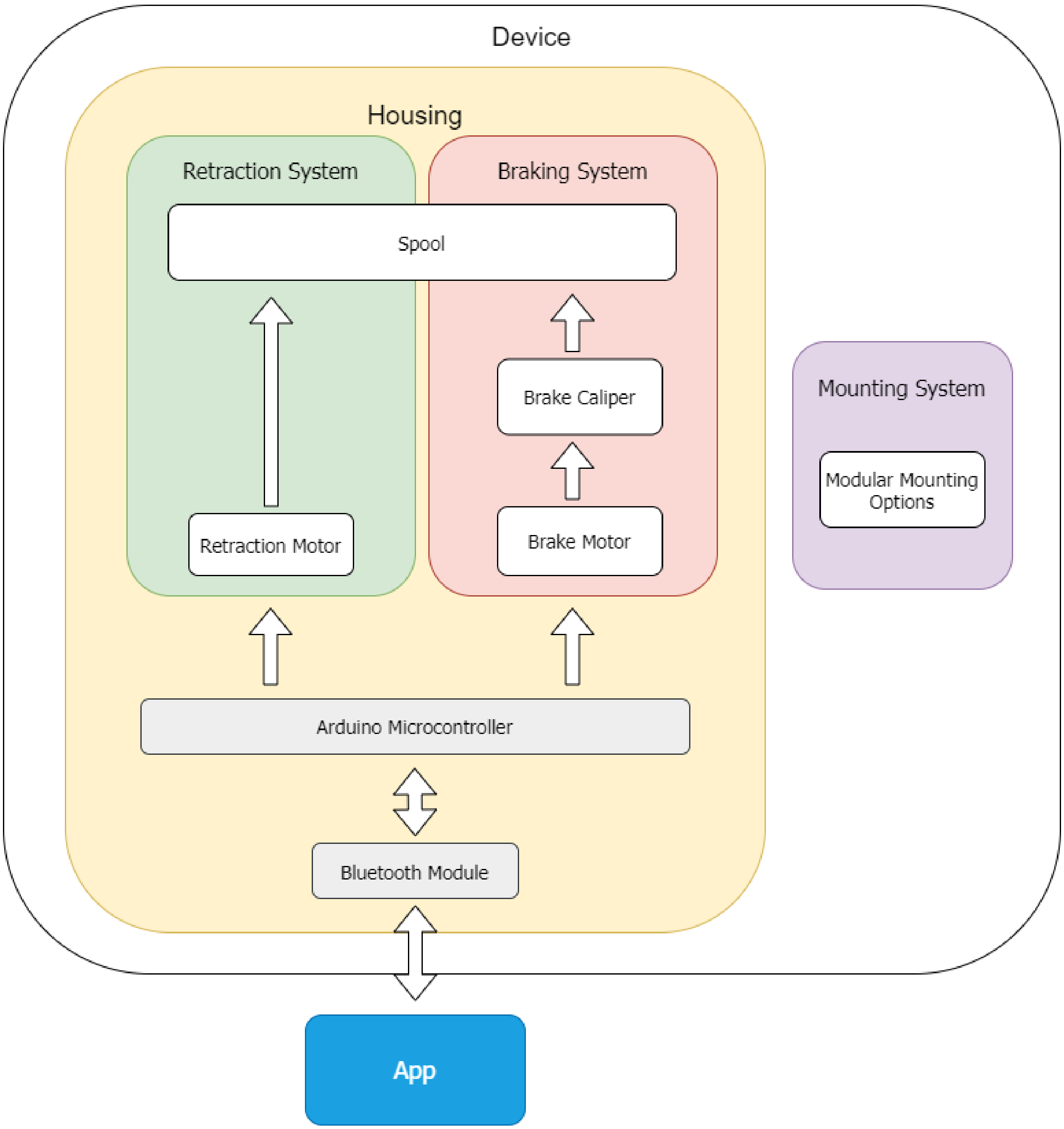


Fig. 2. A block diagram of NovaBand components and subsystems.

2. Mechanical

While NovaBand is controlled by the software and electronic subsystems, it is primarily a mechanical device: its mechanical subsystems perform the most important functions of the product. While there may not necessarily be clear division in mechanical components for the proof-of-concept device, they are sectioned-off here for clarity.

2.1 Braking System

The braking system is truly the core of NovaBand – it is the reason for all other mechanical, electronic, and software-based subsystems. The system also has very high interplay: it interacts directly with the Retraction System (Section 2.2), the Housing (Section 2.3), the Motor Driver (Section 3.2), the Control Systems (Section 3.3), and the rope spool.

In essence, the braking system applies a resistive force acting against any force applied that works to unspool the rope from the device as well as implementing inputted resistance curves. This braking force is required to be highly precise, accurate, and fidelitous: any dramatic deviation from the expected applied force causes a failure in NovaBand's primary purpose (isokinetic exercise), as well is potentially injurious to the patient. Furthermore, this force must be able to be engaged or disengaged rapidly in case of sudden changes in the velocity of the exercise – again to both maintain a constant velocity and prevent injury.

2.1.1 Braking Mechanism

Fig. 4 shows the normal operation of the braking system/rope/spool assembly. The force of exercise F_e is applied at a distance d_e from the central axis. An opposing braking force F_b is applied at a distance d_e. By design, the torques created by these opposing forces are equal and opposite: while there *will* be a constant velocity, the balanced torques mean there will be no acceleration.

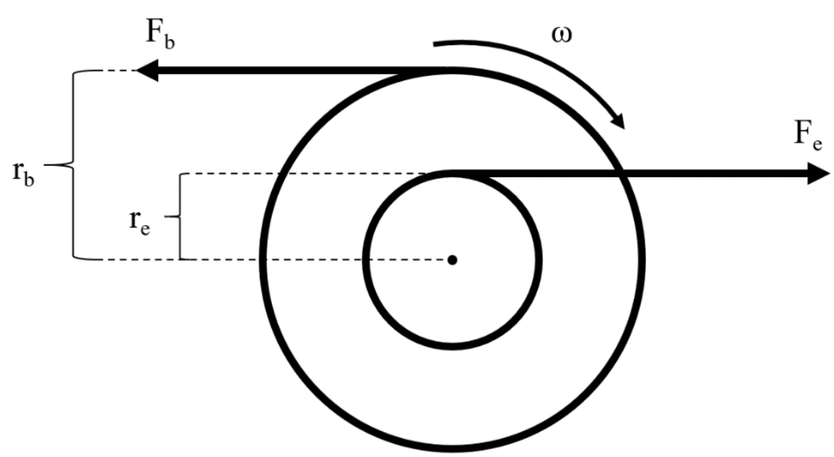


Fig. 3. Torque diagram of the braking system.

$$\sum \tau_i = 0 \;\longrightarrow\; F_b r_b = F_e r_e, \tag{1}$$

$$F_b = \frac{F_e r_e}{r_b}. \tag{2}$$

If we take the maximum F_e to be 140N (defined by **Req. 3.1.3**), the radius of the spool to be 5.0cm, and the radius of the disc to be 8cm, we have:

$$F_b = \frac{F_e r_e}{r_b} = \frac{140 \cdot 0.05}{0.08} = 87.5N. \tag{3}$$

This gives an upper bound on the required resistive force. This is related to the *applied* force F_a through the coefficient of friction of the braking surface, μ:

$$F_b = \mu F_a, \tag{4}$$

where F_a gives the true force required by the brake. If we consider the distance of an exercise d_e to be the hypotenuse of the triangle created by the arc of the exercise, we have

$$d_e = \sqrt{2a^2} = \sqrt{2}a, \tag{5}$$

where a is the length of limb performing the exercise. A length of rope d_e unspooled from the device will cause the spool itself to rotate s_b times, proportional to its radius:

$$s_b = \frac{d_e}{r_e}. \tag{6}$$

We can consider a to be the average length of a male forearm, approximately 25.40 cm [5]. The brake rotor must rotate the same amount, so we can relate the above braking force to work W as follows:

$$W = F \cdot d = F_b \frac{\sqrt{2}\,a}{r_e}(2\pi r_b) = (87.5)(7.18)(2\pi 0.08) = 316J. \tag{7}$$

This is an upper bound on the amount of energy output required by the braking system in a given exercise. Now,

$$P = \frac{W}{t}, \tag{8}$$

where P is the power output by the brake during an exercise. If we assume a reasonable exercise to take two seconds, we have:

$$P_b = \frac{316}{2} = 156W. \tag{9}$$

Again, this is an upper bound on the power output by the braking system but will provide an adequate target for design considerations. Realistically, the power involved in a standard exercise (and thus the heat input to the rotor) will be much less: most physiotherapeutic exercises are performed slowly and at low weight (the equivalent of F_b).

When selecting a braking mechanism, the following qualities were considered:

1) maximize holding strength;
2) maximize fidelity in instantaneous braking force;
3) minimize actuation time;
4) minimize diameter;
5) maximize durability;
6) minimize weight;
7) minimize cost.

For the proof-of-concept prototype, we have selected a cable-actuated hydraulic disc brake designed for use in bicycles: the RUJOI Bike Disc Brake Kit [6], Fig. 4.

Fig. 4. RUJOI Bike Disc Brake Kit cable-actuated hydraulic bicycle disc brake system [6].

A typical braking force to stop a bicycle with an 80kg rider using a 160mm rotor is approximately 1700N [7]. Assuming a coefficient of friction of 0.5, this means the brake itself needs to apply upwards of 3400N, from 100-150N applied to the handle by the rider [7]. Likewise, these systems must dissipate the high heat produced while bicycling. RUJOI brakes are designed to meet this high standard for braking force and heat dissipation, so it is safe to assume that the chosen braking system is more than robust-enough for the normal use of NovaBand – even using the upper-bound calculations above. This excess also gives NovaBand considerable freedom in the exact dimensions and materials of the rotor and the brake pads, which may dramatically affect the maximum braking forces.

Cable-actuated hydraulic disc brakes combine the best of traditional mechanical disc brakes and pure hydraulic disc brakes: they do not require NovaBand to design a specialized piston to compress the brake line and retain the better modulation and increased braking force of hydraulic brakes. Details about the performance and design of the braking system are given in TABLE I.

TABLE I

DESIGN SPECIFICATIONS FOR THE BRAKING SYSTEM

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 2.1.1 A	The RUJOI cable-actuated hydraulic disc brake shall apply a variable resistive braking force to a rotor attached to the rope spool.	**Req 3.3.5 A**
Des 2.1.2 A	The RUJOI braking system will take input from the Control System and the app to increase or decrease the applied braking force.	**Req 3.3.6 A**
Des 2.1.3 B	The RUJOI braking system shall be able to apply forces of at least 140N.	**Req 3.1.3 B**

2.1.2 Brake Pad Material

The RUJOI braking system can apply a much larger braking force than is likely needed in NovaBand. As well, testing has revealed that unmodified bike brakes are *unable* to reach the necessary level of fidelity in braking force. To address this, the brake pads will be modified to hold a piece of felt cloth to the rotor, rather than the stock sintered metal. Further testing has revealed that the modified felted brake pads give higher fidelity in the braking force. Furthermore, the cloth surface reduces (or eliminates) the noise produced while braking. Details about the performance and design of this component are given in TABLE II.

TABLE II

DESIGN SPECIFICATIONS FOR THE BRAKE PAD MATERIAL

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 2.1.4 A	The brake pad will be covered in felt to increase the fidelity of braking force.	**Req 3.1.1 A**
Des 2.1.5 B	The felted material of the brake pad will dampen any noise produced by the frictional braking to within 60dB.	**Req 3.3.8 B**

2.1.3 Brake Rotor

The primary design considerations for the brake rotor are weight, heat dissipation, size, and structural integrity. Standard bicycle brake rotors range from 140mm to 205mm, of which the smallest has been selected – to minimize weight and overall size of the device. When used on bicycles, larger rotors are valued for increased heat dissipation, but NovaBand operates these brakes at such low forces (3) and produces such little heat (9) relative to their normal application that heat dissipation should not be a concern, even with a smaller rotor. To compromise between weight, heat dissipation, structural integrity, and braking modulation, NovaBand will use a Jagwire 140mm hybrid aluminum-and-steel rotor [8]. This rotor gives substantial weight savings (25%) and thermal dissipation over 100% steel rotors, while maintaining the increased braking modulation and durability of a steel braking surface. Details about the performance and design of this component are given in TABLE III.

TABLE III
DESIGN SPECIFICATIONS FOR BRAKE ROTOR

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 2.1.6 A	The Jagwire brake rotor will provide adequate structural integrity to withstand the braking force applied during an exercise.	**Req 3.3.5 A**
Des 2.1.7 B	The Jagwire brake rotor will provide adequate heat dissipation.	**Req 3.3.7 B**

Fig. 5 shows a SolidWorks model of the interior of NovaBand, showing the third-party disc bike brake, the rotor, the rope/spool, and the retraction motor.

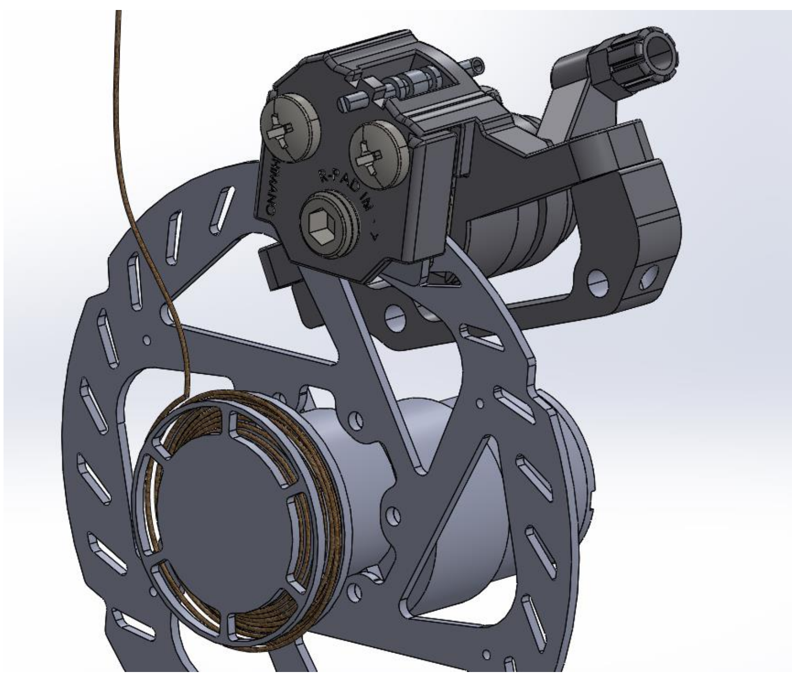


Fig. 5. SolidWorks model of braking system showing third-party bicycle disc brake and rope/spool assembly.

2.2 Retraction System

To successfully complete an exercise repetition, the rope spooled out during the first half of an exercise must be retracted back towards the device once the exercise is completed. Once fully retracted, the device state will be properly configured, allowing for another exercise repetition to begin. To be able to meet retraction time requirements while having enough power to retract the rope a 24V, a 178RPM DC motor was chosen. This motor will be attached to a spool inside the device and is activated when instructed by the microcontroller.

As the motor is connected to the spool directly, it is possible to calculate the estimated maximum speed of rope while retracting. Equation (10) shows the formula for calculating the speed of rope, *v*, given a spool of radius *r*:

$$v = r\omega. \tag{10}$$

To be able to use (10), the 178RPM rotational speed of the motor must be converted to rad/s speed. As shown in (11), the rotational speed of the motor is calculated to be 18.64rad/s:

$$1RPM = \frac{2\pi}{60} rad/s \rightarrow 178RPM = 18.64rad/s. \tag{11}$$

Using this rotational speed and (10), we can calculate the rope speed using (12):

$$v = 1.6cm * 18.64rad/s = 29.824cm/s. \tag{12}$$

The calculated rope speed in (12) is the maximum speed that the rope reaches while being retracted by the retraction motor. TABLE IV summarizes the design specifications for the retraction system and its related requirement specifications.

TABLE IV
DESIGN SPECIFICATIONS FOR THE RETRACTION SYSTEM

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 2.2.1 A	As soon as encoders detect an input force, a hardware interrupt will be activated that stops the retracting motor from winding the rope.	**Req 3.3.9 A**
Des 2.2.2 A	The retraction motor is hardware limited at 178RPM which equates to maximum of 0.3m/s rope speed.	**Req 3.3.10 A**
Des 2.2.3 A	As soon as encoders detect that there is no input force, a hardware interrupt will be activated that makes the retracting motor begin winding the rope.	**Req 3.3.11 B**
Des 2.2.4 A	At the 0.3m/s maximum rope speed based on Des 2.2.2 A the 0.9m rope of NovaBand will retract in three seconds.	**Req 3.3.12 B**

2.3 Housing

The housing encloses the physical parts of the NovaBand device. In general, the housing can be considered a single unit, or box, which encloses the mechanical and electronic components. The housing is designed to protect the user from the movement and potentially noxious temperatures of internal components, as well as the subsystems from potential damage from drops or external sources. TABLE V highlights the design specifications for the housing system.

TABLE V
DESIGN SPECIFICATIONS FOR THE HOUSING SYSTEM

Specification ID	Specification Description	Requirement Reference ID
Des 2.3.1 A	All of the electronic and mechanical components, except for the rope and handle, will be enclosed in the device. None of the internal components will be directly accessible.	**Req 3.3.15 B**

2.3.1 Layout and Subsystems

The layout is how the internal components are placed in the device. The positioning of the components needs to be optimized to balance the size of the device with the thermal output of each component.

TABLE VI highlights the design specifications for the layout and how it will be optimized for space and user feedback.

TABLE VI
DESIGN SPECIFICATIONS FOR THE LAYOUT

Specification ID	Specification Description	Requirement Reference ID
Des 2.3.2 A	The layout of internal components shall minimize the space used, without leading to thermal issues.	**Req 3.3.3 B** **Req 3.2.10 P**
Des 2.3.3 B	Components such as buttons and LEDs will be on the surface of the device to serve as input and feedback to the user.	**N/A**

The following subsystems will be included inside of the housing:

1) a tension system;
2) a retraction system;
3) the encoders and sensors;
4) and all other electronic components named in Section 3.

The following components will *not* be inside of the housing:

1) a smartphone;
2) the user interface to customize and control the internal components.

Some components, including but not limited to buttons/switches to turn the device on and off, will also be on the surface of the housing to give the user visual feedback on the state of the device (e.g. the device is on or paired over Bluetooth) and some means of control without a phone.

2.3.2 Structure

There will be two general elements to consider when looking at the design of the housing. One will be the interior structure which will hold together all the mechanical and electronic components. The other is the exterior structure which will be added to enclose the entire device.

TABLE VII highlights the design specifications for the internal and external structures and their interaction with other components of the device.

TABLE VII
DESIGN SPECIFICATIONS FOR THE STRUCTURE

Specification ID	Specification Description	Requirement Reference ID
Des 2.3.4 A	The internal and external structures should be reliably connected but easy to connect and disconnect when necessary for maintenance.	**N/A**
Des 2.3.5 A	The internal structure shall hold all the internal components reliably.	**Req 3.2.11 B**
Des 2.3.6 B	The external structure will be made from soft plastic to avoid hurting users or the device without significant additional forces applied.	**Req 3.2.4 B** **Req 3.3.14 B**

Internal Structure

The internal structure is designed to hold the internal components of the device, as well as maintain the layout should any external forces get applied. Each of the components will be mounted onto the internal structure. This structure should be rigid and resist any change in shape, which is why aluminum was chosen as the material.

External Structure

The external structure, or shell, has two primary functions: to protect the user from any motion, heat, or electricity in the internal components, and to protect the internal components from any external damage.

The shell will have no sharp corners or edges so that it will not easily hurt the user without excessive force.

2.3.3 Material

The materials for the internal structure must be rigid and strong while not being too heavy for a user to carry. Aluminum is a good choice under these restrictions. A metal also provides the benefit of acting as a heat sink to dissipate any unwanted heat generated in any of the subsystems.

The material of the external structure should be light and soft to keep it easy to carry, dampen any drops or forces onto the device, and not hurt the user under normal conditions. For these restrictions, plastic would be the ideal material.

TABLE VIII highlights the design specifications for the materials of both the internal and external structures.

TABLE VIII
DESIGN SPECIFICATIONS FOR THE MATERIALS

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 2.3.7 A	The internal structure shall be made from aluminum.	**N/A**
Des 2.3.8 B	The material of the external structure shall be made of soft plastic to shield the user from electrical and thermal damage and product the internal components.	**Req 3.2.12 P** **Req 3.3.13 A**
Des 2.3.9 B	The material of the external structure will not block Bluetooth signals.	**Req 3.4.2 B**

One of the overall goals is for the materials to be lightweight, to keep the device fairly portable.

For the external structure, NovaBand will use a soft plastic material. This will give the flexibility in the shape and design of the shell. Plastic will also not black any Bluetooth signals used for communication between the device and the app.

2.4 Mounting

As a multipurpose device, our device will need to be mounted in different locations and situations. The mounting system will be a modular mechanism, where different mounting systems can be mounted to the main device and swapped out with other systems. For proof-of-concept, a door mount will be used which is shown in Fig. 1.

TABLE IX highlights the design specifications for the mounting system which include the modular mounting system and how it is attached to the device in the beta product.

TABLE IX
DESIGN SPECIFICATIONS FOR THE MOUNTING SYSTEM

Specification ID	Specification Description	Requirement Reference ID
Des 2.4.1 A	The mounting system shall be attached to the housing.	**Req 3.1.2 B** **Req 3.3.17 A**
Des 2.4.2 B	The mounting system shall be modular to allow different mechanisms to be mounted in different environments.	**Req 3.3.19 P**
Des 2.4.3 B	The modular mounts shall be held firmly via a locking mechanism, with a release system.	**Req 3.2.8 B,** **Req 3.3.18 B**

One of the obstacles expressed by physiotherapists while using resistance bands was difficulty in finding places they can mount them for patients to do their exercises properly. As many environments are different, from homes to offices to clinics, a modular system is the best choice. Modularity gives us the possibility to design various mounts that will be better in certain situations. For the purpose of proof-of-concept prototype, a single mount design is being considered, which attaches to a door.

In beta, these mounts would have a locking mechanism which will give them a reliable connection and not slip out during use. When swapping the mount is desired, the user will be able to release the lock via a mechanical latch to attach a new mount.

2.5 Tension System

The tension system is a point of constant and direct contact with the patient. The core design parameters are safety, reliability, and comfort, while avoiding compromising the functionality of the device.

2.5.1 Rope

The primary design considerations for the rope are as follows:

1) minimize diameter;
2) maximize strength;
3) minimize stretch;
4) minimize cost;
5) maximize durability;
6) minimize weight.

To match these constraints, emma kites UHMWPE Braided Cord [9] – ultra-high molecular weight polyethylene has been selected. This product is marketed as having the “least stretch” (only 4.5% elongation at breaking weight) and is rated for a maximum load of 350lb (1556.88N, 158.7kg). Minimum stretch is a high priority, as any non-programmatic stretch during an exercise will cause a deviation from the intended torque-muscle curve. Typical maximum recommended working load-limit for ropes is 20% of the rope break-strength [10], so this rope comfortably exceeds the tension specified by **Req. 3.3.1 A** with a 2.22 times safety margin (or room for an increased maximum exercise force). As well, this high-tensile-strength material allows for a weight and size reduction compared to other materials, while maintaining high durability. Fig. 6 shows a spool of the selected braided cord.

$$350lb = 1556.88N \tag{13}$$

$$0.20 \cdot 1556.88N = 311.376N \tag{14}$$

$$\frac{311.376N}{140N} = 2.22 \tag{15}$$

Fig. 6. A 100’ spool of emma kites UHMWPE Braided Cord [9].

Details about the performance and design of this component are given in TABLE X.

TABLE X
DESIGN SPECIFICATIONS FOR THE ROPE

Specification ID	Specification Description	Requirement Reference ID
Des 2.5.1 A	The tension system will use emma kites UHMWPE Braided Cord, which is rated for maximum of 1556.88N.	**Req 3.3.1 A**
Des 2.5.2 B	The tension system will use emma kites UHMWPE Braided Cord, which is rated for 4.5% elongation at breaking.	**Req 3.3.2 A**
Des 2.5.3 B	The tension system will use emma kites UHMWPE Braided Cord, which is advertised as being highly abrasion resistant.	**Req 3.3.4 P**

2.5.2 Handle

The handle is the mechanism by which the user interacts with the main functionality of the device. The handle that has been selected can be viewed in Fig. 7. The KKTOCHVC Premium Exercise Handles are ideal in terms of grip and comfort during exercises.Fig. 7. Two KKTOCHVC Premium Exercise Handles .

Fig. 7. Two KKTOCHVC Premium Exercise Handles [9].

TABLE XI
DESIGN SPECIFICATIONS FOR THE HANDLE

Specification ID	Specification Description	Requirement Reference ID
Des 2.5.4 A	The handle is ideally sized and ergonomically shaped to comfortably fit the human hand.	**Req 3.3.3 B**
Des 2.5.5 B	The handle can be easily unclipped and swapped with other handles or mounts using the same mechanism.	**N/A**

The rope is attached to the loop on the handle. As the user pulls on the handle, they will unspool the rope and work directly against the braking system.

The handle will be a modular system. The user will be able to swap the handle out for other handles or mounts, which enables them to work out other muscle groups that are not able to hold the handle.

3. Electronics

Electronic processing components are required to coordinate NovaBand’s various subsystems. The electronic components act as a bridge between the mechanical and software systems.

3.1 Microcontroller

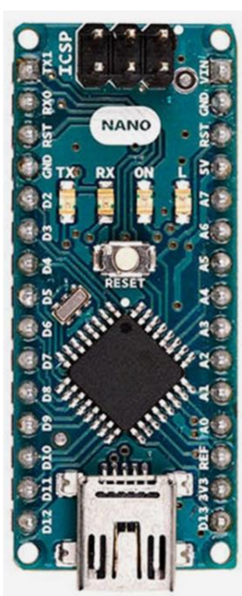
In essence, the microcontroller is the brains of the project that connects each piece of hardware together and allows them to communicate with the software. However, the Novaband microcontroller does not require any complex calculations to operate successfully.

NovaBand requires a microcontroller to send the proper signals to the drivers to control the motors. It must also communicate with the Bluetooth module using the UART protocol. TABLE XIITABLE IV shows the design specifications for the microcontroller and its related requirement specifications.

TABLE XII
DESIGN SPECIFICATIONS FOR THE MICROCONTROLLER

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 3.1.1 A	The microcontroller shall be able to communicate with the motor drivers.	**Req 3.4.2 B**
Des 3.1.2 A	The microcontroller shall support the UART communication protocol.	**N/A**
Des 3.1.3 A	The microcontroller shall be able to communicate with encoders.	**Req 3.4.2 B**
Des 3.1.4 B	The microcontroller shall be able to communicate with tension sensors.	**Req 3.4.2 B**
Des 3.1.5 B	The microcontroller shall support hardware interrupts.	**N/A**

The Arduino Nano is a simple microcontroller designed for use in small projects with no need for large amounts of processing power. The Arduino Nano and its relevant technical specifications can be seen in Fig. 8(a) and Fig. 8(b), respectively.



(a)

Microcontroller	ATmega328
Architecture	AVR
Operating Voltage	5 V
Flash Memory	32 KB of which 2 KB used by bootloader
SRAM	2 KB
Clock Speed	16 MHz
Analog IN Pins	8
EEPROM	1 KB
DC Current per I/O Pins	40 mA (I/O Pins)
Input Voltage	7-12 V
Digital I/O Pins	22 (6 of which are PWM)
PWM Output	6
Power Consumption	19 mA
PCB Size	18 x 45 mm
Weight	7 g
Product Code	A000005

(b)

Fig. 8. Arduino Nano and relevant technical specifications for the board [11].

3.2 Motor Driver

As the power output of the microcontroller alone is not enough to drive the motors, there is a need for motor drivers. A motor driver module is a H-bridge with back EMF protection that can translate the low-power digital output of the microcontroller into the high-power signal that is needed to drive a motor. TABLE XIIITABLE IV shows the design specifications for the motor driver.

TABLE XIII
DESIGN SPECIFICATIONS FOR THE MOTOR DRIVER

Specification ID	Specification Description	Requirement Reference ID
Des 3.2.1 A	The motor driver shall handle voltages up to 24V.	**N/A**
Des 3.2.2 A	The motor driver shall handle two motors independently.	**N/A**
Des 3.2.3 A	The motor driver shall handle current draws up to 2A.	**N/A**
Des 3.2.4 A	The motor driver shall handle communication with the microcontroller.	**Req 3.4.2 B**

The L298N is a common choice for a simple motor driver that can communicate easily with an Arduino. Additionally, this driver meets all the design requirements in Table XIII. Fig. 9 shows an example image of this driver that displays the back EMF protection diodes as well as the connectors needed along with relevant specifications.

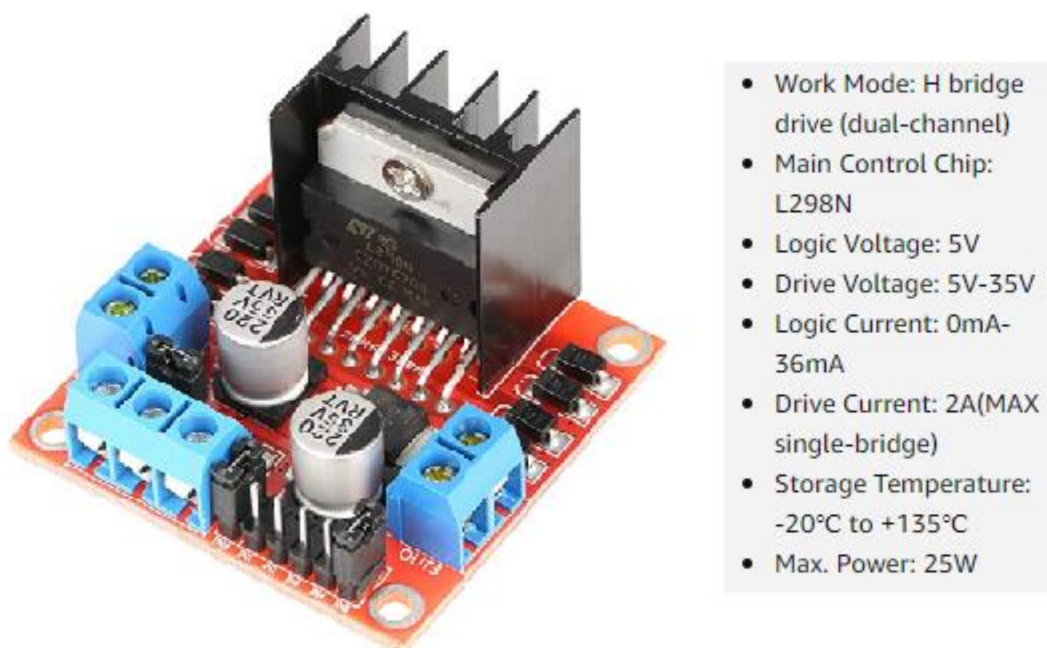


Fig. 9. L298N motor driver module with its manufacturer specifications [12].

3.3 Control Systems

The NovaBand device requires a proper control system to achieve precise management over rope tension and speed during an exercise. A few control mechanisms are available for use. For example, by using encoders, the rope speed can be measured in order to be maintained when preforming isokinetic exercises. In addition, NovaBand will have a current sense chip that is able to measure the amount of power consumed by each of the motors. Using the current sensors, the device is able to detect excessive force on the motors and prevent damage. TABLE XIVTABLE IV shows the design specifications for the control systems and its related requirements.

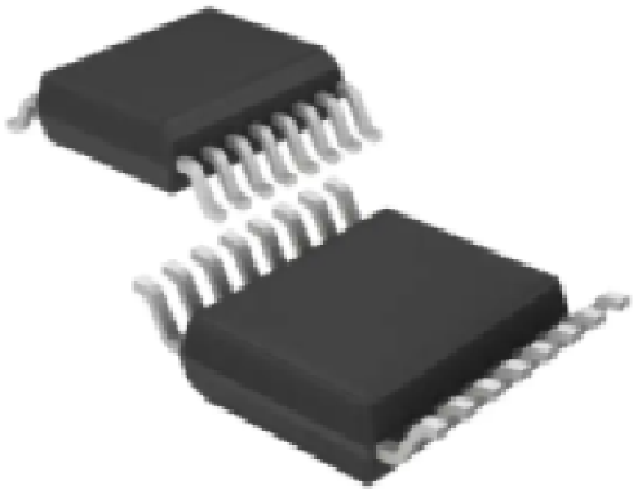
TABLE XIV
DESIGN SPECIFICATIONS FOR THE CONTROL SYSTEMS

Specification ID	Specification Description	Requirement Reference ID
Des 3.3.1 A	The encoder shall be attachable to a rotator.	**N/A**
Des 3.3.2 A	The encoder shall be able to communicate to the microcontroller.	**Req 3.4.2 B**
Des 3.3.3 B	The encoder shall detect the end of the rope.	**Req 3.3.6 A**
Des 3.3.4 B	The encoder shall detect the speed of the rope with high accuracy.	**Req 3.3.6 A**
Des 3.3.5 B	The current sensors shall be able to measure power consumption of the motors.	**N/A**
Des 3.3.6 B	The current sensors shall halt device operation before the motors are damaged.	**Req 3.3.6 A**

AMT102-V, shown in Fig. 10, is a great choice for the design specifications mentioned above. This encoder adapts to different shaft sizes from 2mm to 8mm. The resolution of the encoder can be changed from 50 to 1000 pulses per rotation depending on the settings.

Fig. 10. AMT102-V encoder with different shaft adapters [13].

As for the current sensor, it is possible to use a chip like the MLX91220, shown in Fig. 11. With this sensor, it is possible to measure the amount of current drawn by each motor and, given voltage, calculate the power draw of the motors.



Part Status	Active
For Measuring	AC/DC
Sensor Type	Hall Effect, Open Loop
Current - Sensing	25A
Output	Ratiometric, Voltage
Sensitivity	80mV/A
Frequency	DC ~ 300kHz
Linearity	±0.6%
Accuracy	-
Voltage - Supply	4.5V ~ 5.5V
Response Time	2µs
Current - Supply (Max)	21mA
Operating Temperature	-40°C ~ 125°C

Fig. 11. MLX91220 current sensor and its specifications [14].

3.4 Power Source

As managing battery charging and dissipation is a challenging task, the proof-of-concept will be powered using a lab power supply. By using a power supply, the power input to the device can be limited while still maintaining a reliable source of power. However, for the beta phase of the project, the device will be battery powered. During the beta phase, the device battery must last at least eight hours so it can be used at a physiotherapy center during a work day, according to the requirement specifications listed in TABLE XV.

This table also shows other design specifications for the power source. To clarify notation in this table, 1C rating means that if the current drawn from the battery is equal to the battery capacity, it will take the battery an hour to discharge. Likewise, 0.5C means that if the current drawn from the battery is half of its capacity it will take the battery two hours to discharge [15].

TABLE XV
DESIGN SPECIFICATIONS FOR THE POWER SOURCE

Specification ID	Specification Description	Requirement Reference ID
Des 3.4.1 A	The power supply shall be able to provide up to 2 amps.	**N/A**
Des 3.4.2 A	The power supply shall be able to provide up to 24 volts.	**N/A**
Des 3.4.3 B	The battery shall last at least eight hours on one charge so it doesn’t have to be charged during a workday assuming that the device is on during all that duration.	**Req 3.3.20 B**
Des 3.4.4 B	The batteries shall charge and discharge at currents higher than 0.15C for no longer than 10 seconds to avoid damage to the batteries.	**Req 3.3.20 B** **Req 3.3.21 B**

4. Software

All mechanical and electronic components of the product are controlled through software. Specifically, a mobile application communicating with a Bluetooth module attached to the device's microcontroller is the chosen method of control.

4.1 Physiotherapist-to-Device Interface

This section describes the design choices that relate to how a physiotherapist interacts with the NovaBand device and how the user input is captured and transmitted to the device.

4.1.1 Mobile Application

NovaBand is intended to be precisely controlled by a physiotherapist to optimize the rehabilitation routine of their patients. To meet this requirement, a physiotherapist needs an effective interface to dynamically configure the device state.

The leading interface candidate is a custom mobile app. Apps are commonplace nowadays, meaning that new apps can present an easier learning curve for a user than more traditional hardware-based controls due to the significant transfer of previously learned knowledge. Importantly, apps offer significant customizability with their ability to be altered via software updates. Lastly, mobile apps are inherently portable; physiotherapists are afforded the flexibility of operating the device from a comfortable distance.

TABLE XVI outlines the design specifications for the NovaBand mobile app. For the proof-of-concept, the app shall be able to configure the tension or speed of the exercise on the NovaBand device. Arguably, this is the most important feature to implement as all other configurations rely on a reliable mechanism for updating the device tension settings.

The beta stage of development and onward present unknown challenges. Beta stage specifications are shown in latter rows of TABLE XVI. It is expected that by the end of the beta stage, physiotherapists shall be able to change exercises, receive notifications, and manage patient-specific profiles. The exact implementation details of these features are not fully understood as of now, but early progress indicates that each feature is likely achievable using the current development technology. For instance, creating a simple list of preset exercises and allowing the physiotherapist to select one of them fulfills most of the functionality required to change exercises dynamically. Push notifications or on-screen textboxes can serve as general notification messages. Lastly, using a simple database on the physiotherapist's phone may be a sufficient means to save and retrieve multiple patient profiles.

TABLE XVI
DESIGN SPECIFICATIONS FOR MOBILE APP

Specification ID	Specification Description	Requirement Reference ID
Des 4.1.1 A	The app shall allow the user to change tension required for an exercise.	**Req 3.1.1 A** **Req 3.4.1 A**
Des 4.1.2 A	The app shall allow the user to change the type of exercise being performed.	**Req 3.1.1 A** **Req 3.4.1 A**
Des 4.1.3 A	The app shall allow the user to change speed for an exercise.	**Req 3.1.1 A** **Req 3.4.1 A**
Des 4.1.4 B	The app shall notify the user when an exercise is in progress.	**Req 3.4.1 A** **Req 3.4.2 B**
Des 4.1.5 B	The app shall allow users to switch profiles and access their saved exercises.	**N/A**

4.1.2 Data Transmission

For the mobile app to send data to the device, a data transmission protocol is required. An ideal protocol must be simple to use, low latency, consume minimal power, and have a medium-long communications range. It is noted that not all desired characteristics are explicitly listed in the product's requirements specifications document for various reasons. However, Bluetooth is one such protocol that has these characteristics.

The Bluetooth protocol operates by establishing device-to-device trust using a *pairing* process, which permits communication between bonded devices [16]. This pairing process can be completed quickly via a phone user interface and without knowledge of the internal workings of the protocol, fulfilling the requirement of the protocol being easy to use.

Continuing, TABLE XVII lists relevant technical specifications for *Bluetooth Low Energy*, a feature supported by Bluetooth version 4.0 and newer, which consumes considerably less energy than the previous ("classic") versions of Bluetooth [17]. Based on the latency, power, and range specifications listed in TABLE XVII, combined with the simplicity of pairing Bluetooth devices, Bluetooth 4.0 is the leading choice for the required data transmission protocol.

TABLE XVII
TECHNICAL SPECIFICATIONS FOR BLUETOOTH LOW ENERGY [18]

Technical Specification	Value for Bluetooth Low Energy
Range	Less than 100m
Over air data rate	Up to 2Mbit/s
Latency	6ms
Power Consumption	0.01W – 0.50W
Peak Current Consumption	Less than 15mA

In more detail, our mobile app will use the host phone's Bluetooth transmitter to send data that is needed to configure the device state. A Bluetooth receiver module connected to the device's circuitry will be listening for incoming data sent from the phone. Fig. 12 shows one such standalone Bluetooth module which can connect to microcontrollers via simple serial transmit and receive pins. Once received by the Bluetooth module, data will then be processed accordingly by the device's microcontroller unit.

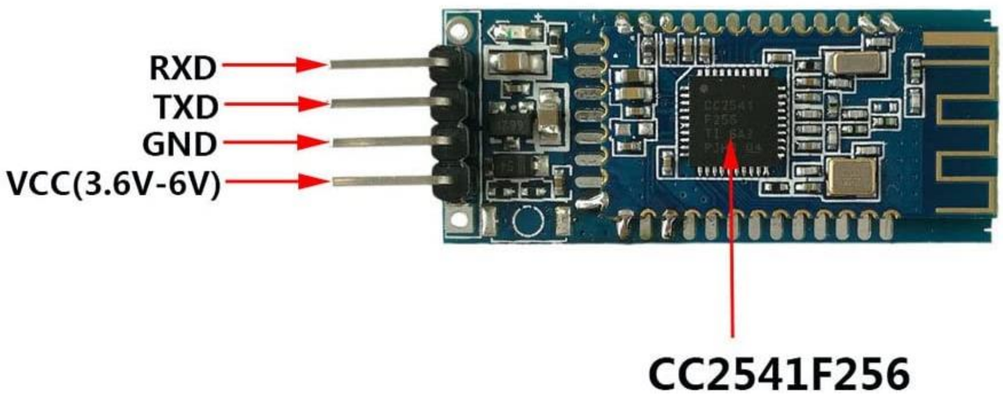


Fig. 12. DSD TECH HM-10 Bluetooth module pin diagram [19].

TABLE XVIII outlines the design specifications for the data transmission protocol for NovaBand. Specifications listed include the length of pairing time as well as an indicator for the user to visually check the pairing status of the device. Bluetooth 4.0 has been selected as the data transmission protocol for the reasons listed previously.

TABLE XVIII
DESIGN SPECIFICATIONS FOR DATA TRANSMISSION

Specification ID	**Specification Description**	**Requirement Reference ID**
Des 4.1.5 A	The app shall use Bluetooth 4.0 to connect to the device.	**Req 3.4.1 A**
Des 4.1.6 A	The Bluetooth connection shall remain paired with the device until the device or phone is powered off or the phone manually disconnects.	**IEEE 802.15.1**
Des 4.1.7 B	The device will have an LED indicator to indicate that it is paired with a phone.	**N/A**

5. Conclusion

NovaBand is a complex system made up of many different subsystems to achieve the purpose of providing an isokinetic and customizable exercises to patients at a low cost. The braking mechanism that is used to vary the tension is made up of a RUJOI Bike Disc Brake Kit with a prefabricated Jagwire rotor and modified cloth brake pads. The retraction system that retracts the rope and handle to allow the user to perform another exercise, is being performed by a 24V, 178RPM motor to ensure that the device can retract fast enough to avoid slowing the rehabilitation exercises. The housing of the device is made up of a relatively soft plastic to avoid injuring the user or causing damage to structures during use and storage. The internal structure is made from aluminum to keep the weight low while keeping the structure strong. The mounting system will be attached to the housing to allow the user to secure the device before performing an exercise. For beta development, the mounting system will be modular to allow for multiple options and increase the number of exercises that can be performed. The rope is a polyethylene braided cord with minimal stretch to ensure that the braking system is responsible for all sources of tension. The handle attached to the rope is a KKTOCHVC Premium Exercise Handle to allow for comfortable grip during exercises.

An Arduino Nano was selected as a microcontroller due to its small size, low cost, and ease of use. A L298N motor driver was used to control the motors from the microcontroller as it is standard and reliable. The control system is made up of a AMT102-V encoder and a MLX91220 sensor to inform the device how fast and how hard the user is pulling in their exercise. The device will be powered by a power supply for the proof-of-concept, while a transition to a portable battery is a necessity for the beta development.

Physiotherapists will use a mobile app to control settings and exercises for NovaBand and the mobile app will use Bluetooth to transmit those changes to the device.

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Appendix A – Supporting Test Plans

This appendix lists test plans which can be used to verify that all design specifications listed in the document are fulfilled.

A.1 Mechanical

Mechanical test plans correspond to the device's braking, retractions, housing, mounting, and tension systems.

A.1.1 Braking System

The following tests relate solely to the device's braking system:

Design Specification Tested	Test Procedure	Pass/Fail	Comments
Des 2.1.1 A	Perform five separate exercises over a wide range of different velocities. Verify that the velocity is constant regardless of force applied.	□ Pass □ Fail	
Des 2.1.2 A	Perform five separate exercises at while suddenly varying force throughout the exercise. Verify that the velocity is constant regardless of force applied.	□ Pass □ Fail	
Des 2.1.3 A	Perform five separate exercises over a small range of different velocities. Verify that the velocity is constant regardless of force applied.	□ Pass □ Fail	
Des 2.1.4 A	Perform five separate exercises under high tension. Verify that the device does not produce more than 60dB of noise.	□ Pass □ Fail	
Des 2.1.5 A	Inspect the shape and seating of the brake rotor, record notes. Perform 50 exercises under high tension and reinspect the rotor, ensuring that there are not differences.	□ Pass □ Fail	
Des 2.1.6 A	Measure the temperature of the brake pads and brake rotor, record these values. Perform 25 exercises	□ Pass □ Fail	

	at high tension, record the final temperature of the rotor. Ensure that the temperature does not exceed 52℃.		
Des 2.1.6 A	Perform one rep at high tension to verify function of the device. Perform 25 more exercises and then reperform a rep at high tension. Verify that the velocity is constant throughout the exercise.	□ Pass □ Fail	

A.1.2 Retraction System

The following tests relate to the device's retraction system:

Design Specification Tested	**Test Procedure**	**Pass/Fail**	**Comments**
Des 2.2.1 A	Perform an exercise and allow the system to retract. As it is retracting, pull on the rope and ensure it stops retracting.	□ Pass □ Fail	
Des 2.2.2 A **Des 2.2.3 A**	Perform an exercise and release the handle. Ensure that the handle begins to retract and does not retract faster than 0.3m/s.	□ Pass □ Fail	

A.1.3 Housing, Materials, and Layout

The following tests relate to the device's housing, materials, and layout:

Design Specification Tested	**Test Procedure**	**Pass/Fail**	**Comments**
Des 2.3.1 A	Physically inspect the device and attempt to open it at the seams. Ensure that none of the components can be accessed.	□ Pass □ Fail	
Des 2.3.8 B	Lift the device to one meter of elevation and drop it. Ensure the device did not sustain any significant damage.	□ Pass □ Fail	
Des 2.3.9 B	Change settings of an exercise. Ensure that the settings were changed.	□ Pass □ Fail	

A.1.4 Mounting System

The following tests relate to the device's mounting system:

Design Specification Tested	Test Procedure	Pass/Fail	Comments
Des 2.4.2 B	Detach the existing mounting system, attach a different module, and ensure that the module locks in place. Mount the device, perform an exercise, and ensure that the device is securely mounted	□ Pass □ Fail	

A.1.5 Tension System

The following tests relate to the device's tension system:

Design Specification Tested	Test Procedure	Pass/Fail	Comments
Des 2.5.1 A	Perform a maximum resistance exercise. Ensure that the rope does not break or strain.	□ Pass □ Fail	
Des 2.5.2 B	Stretch the rope manually. Measure the stretch and ensure it remains under 4.5%.	□ Pass □ Fail	
Des 2.5.3 B	Stretch the rope and rub it against an abrasive surface. Ensure the rope does not sustain any structural damage.	□ Pass □ Fail	

A.2 Electronics

The electronics test plans correspond to the device's force and distance sensors, as well as the encoders.

A.2.1 Microcontroller

The following tests relate to the device's microcontroller:

Design Specification Tested	Test Procedure	Pass/Fail	Comments
Des 3.1.1 A **Des 3.1.3 A**	Perform an exercise with a set speed. Perform an exercise with a	□ Pass □ Fail	

Des 3.1.4 B **Des 3.1.5 B**	set tension curve. Ensure that all functionality is correct.		

A.2.2 Motor Driver

The following tests relate to the device's motor driver:

Design Specification Tested	**Test Procedure**	**Pass/Fail**	**Comments**
Des 3.2.1 A **Des 3.2.2 A** **Des 3.2.3 A** **Des 3.2.4 A**	Perform an exercise. Ensure the device properly brakes and retracts.	□ Pass □ Fail	

A.2.3 Control Systems

Design Specification Tested	**Test Procedure**	**Pass/Fail**	**Comments**
Des 3.3.3 B	Pull the device as far as comfortably possible. Ensure that the device stops it before it reaches the end of the rope.	□ Pass □ Fail	
Des 3.3.4 B **Des 3.3.6 B**	Perform an exercise and at extreme speed. Ensure that the motors are not damaged.	□ Pass □ Fail	

A.2.4 Power Source

Design Specification Tested	**Test Procedure**	**Pass/Fail**	**Comments**
Des 3.4.1 A	Check the current using a multimeter over 10 seconds.	□ Pass □ Fail	
Des 3.4.2 A	Check the voltage using a multimeter over 10 seconds.	□ Pass □ Fail	
Des 3.4.3 B	Use the device with minimal power output and time it until it turns off.	□ Pass □ Fail	
Des 3.4.4 B	Check the rate of the charger while the battery is below 5% state-of-charge.	□ Pass □ Fail	

A.3 Software

The software test plans encompass all testing related to the mobile app used in the product.

A.3.1 Physiotherapist-to-Device Interface

The following tests relate to the mobile app:

Design Specification Tested	Test Procedure	Pass/Fail	Comments
Des 4.1.1 A	Use the app to change the tension in an exercise of your choice. Perform the exercise and ensure that the tension change succeeded.	□ Pass □ Fail	
Des 4.1.2 B	Use the app to change the exercise being performed. Perform the exercise and ensure that the type change succeeded.	□ Pass □ Fail	
Des 4.1.3 B	Use the app to change the speed at which an exercise being performed. Perform the exercise and ensure that the speed change succeeded.	□ Pass □ Fail	
Des 4.1.4 B	While performing an exercise, check the app and ensure that it displays that an exercise is in progress.	□ Pass □ Fail	
Des 4.1.5 B	Use the app to change profiles. Ensure that settings changed and match the profile that was selected.	□ Pass □ Fail	

Appendix B – Supporting Design Options

B.1 Mechanical

B.1.1 Braking System

B.1.1.1 Braking Mechanism

Mechanical Bicycle Disc Brake

The most common type of bicycle disc brake is mechanical – a lever arm pressed by the rider pulls on a steel cable attached to a clamp, which closes onto a metal disc, which is in turn attached to the wheel. Any commercially available disc brake would provide more than enough braking force [7], but might not necessarily have enough high-enough fidelity at the relatively low forces of this application. Mechanical brakes have the advantage of being actuated by a simple lever, which is inherently easy to actuate with the axle of a motor. Mechanical disc brakes are also usually much cheaper than other options, though the cheapest end of hydraulic brakes do come close. Product options for mechanical disc brakes are given in TABLE XIX.

TABLE XIX
PRODUCT OPTIONS FOR MECHANICAL DISC BRAKES

Product Name	**Description**	
RUJOI Bike Disc Brake Kit [6]	Price	$45.99
	Rotor Material	Stainless steel rotors
	Rotor Diameter	160mm
	Configuration	Front and rear
	Misc.	Includes handles and cable
WINOMO Pack of Disc Brake [20]	Price	$20.32
	Rotor Material	Aluminum
	Rotor Diameter	160mm
	Configuration	Front and rear
	Misc.	
2pcs Bike MTB Mechanical Disc Brake Kit [21]	Price	$28.93
	Rotor Material	Stainless steel
	Rotor Diameter	160mm
	Configuration	Front and rear brakes
	Misc.	

Hydraulic Bicycle Disc Brake

Hydraulic brakes operate by way of a closed line of hydraulic fluid connected on one end to a piston that is compressed by the handle and on the other to a pair of calipers. This closed hydraulic line provides a much more consistent and smooth modulation of the braking force (which is desirable), but would require a linear actuator or a complicated and custom mechanism to convert from rotary motion to rotational to actuate the line's piston. Luckily, there exists a hybrid: cable actuated hydraulic disc brakes. For NovaBand, these combine the best of mechanical and hydraulic disc brakes: they can be actuated with a simple motor axle and they have the modulation of hydraulic brakes.

For both hydraulic and mechanical disc brakes, the rotor is screwed onto the wheel of the bike itself. The rotors simply have a large hole in their centers, with six screw holes around the inner radius. The holes come in a few spacing standards (e.g. International Standard (IS), 51 mm). For all disc brakes (regardless of actuation mechanism or brand) it is necessary to print or otherwise construct an adaptor to mount the rotor to the spool and mount the caliper to a separate component.

In general, there are problems with frictional braking: friction produces heat and causes constant wear on the braking surface and rotor, necessitating maintenance over the product lifetime. Product options for hydraulic disc brakes are given in TABLE XX.

TABLE XX
PRODUCT OPTIONS FOR HYDRAULIC DISC BRAKES

Product Name	**Description**	
RUJOI Bike Disc Brake Kit – Line Pull Hydraulic Disc Brake Set [6]	Price	$57.99
	Rotor Material	Aluminum
	Rotor Diameter	160mm
	Configuration	Front and rear
	Misc.	Includes handles and hydraulic lines
1 Pair Bicycle Brake Fine Paint Aluminum Alloy Hydraulic Disc Brakes [22]	Price	$80.55
	Rotor Material	Rotor not included
	Rotor Diameter	Rotor not included
	Configuration	Front and rear
	Misc.	Includes handles and hydraulic lines
USDREAM Hydraulic Disc Brakes Mountain Bike Sets [23]	Price	$69.99
	Rotor Material	Rotor not included
	Rotor Diameter	Rotor not included
	Configuration	Front and rear
	Misc.	Includes handles and hydraulic lines
SHIMANO BR-UR300 DISC BRAKE [24]	Price	$37.99
	Rotor Material	Rotor not included
	Rotor Diameter	Rotor not included
	Configuration	Front only
	Misc.	Just the caliper, no other components

Magnetic Braking

Eddy current braking was considered early in the design process, because NovaBand is similar in principle to exercise bikes and rowing machines (which sometimes operate by this physical phenomenon). In essence, the relative motion of either a magnet over a piece of metal or a metallic disc in a constant magnetic field induces eddy currents in the free electrons in the conducting disc. In turn, these eddy currents induce magnetic poles. These poles resist entry into and exit from the applied magnetic – slowing down rotation in both cases. The force created is dependent on the magnitude of the magnetic field (which can be varied through the distance to the magnet to the disc or varying the strength of an electromagnet) and the magnitude of the relative velocity. This principle is illustrated in Fig. 13.

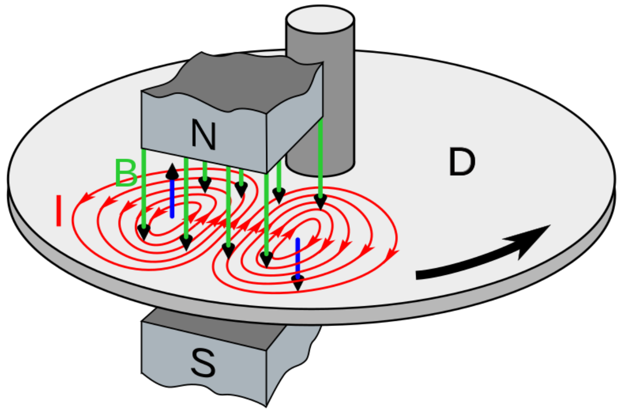


Fig. 13. Eddy currents induced by the passage of a metal disc through a permanent magnetic field [25].

The electromotive force (EMF) produced by the eddy currents is proportional to the speed of rotation, i.e. this system works very well for fast-moving discs (train wheels, rowing machines…) but is not appropriate for NovaBand: the disc will likely move rather slowly during a standard exercise. This could be addressed using a gearbox to step down the angular velocity from the rotor to the shaft. Regardless, there will be zero force when the disc is stationary. When braking using induced currents, the energy of rotation is dissipated almost purely as heat. Depending on the housing and how fast the disc ends up spinning (or other unforeseen factors), this could be an issue with prolonged use – even more so than with frictional braking.

If implemented, a magnetic system would entirely remove the need to replace worn brake-pads, which increase the necessary level of user-expertise and is an added recurring cost and annoyance.

Finally, electromagnetic braking combines the benefits of eddy current braking and frictional braking. This actuation method is distinct from the above because while the actuation is supplied by an electromagnet, the braking force is entirely frictional. This mechanism actuates *very* quickly and would give very fine control over the braking force, but would require extensive testing and development of custom mechanical components. It may be explored in later stages of product development (ENSC 440). These brakes can also be of power-off type, where power is only applied when *disengaging* the caliper.

B.1.1.2 Brake Pad Material

There are two common types of disc brake pads, both of which are used in mechanical and hydraulic disc brakes: sintered (metallic) and resin (organic). They vary in performance, cost, and durability. Sintered pads are more durable (especially in wet conditions, which is not relevant here) but typically cost much more. Resin pads are quieter (desired) and have a faster bite. They also produce less heat but perform worse once they are hot. In testing, it was found that unmodified bike brake pads have much to high friction to produce the necessary modulation of braking force, and other options (like felt) were explored. While PLA brake pads will not be nearly as strong or as durable as the metal pads, they are much lighter and easier to manufacture. Product options for brake pad materials are given in TABLE XXI and each was confirmed to fit the RUJOI brake system.

TABLE XXI
PRODUCT OPTIONS FOR BRAKE PAD MATERIALS

Part Name	Description	
4 Pairs Resin Bike Bicycle Disc Brake Pads [26]	Price	$33.34
	Pad Material	Resin
	Number Included	Four pairs
	Weight	80g
AHL 4pairs Bicycle Disc Brake Pads [27]	Price	$23.99
	Pad Material	Sintered metal
	Number Included	Four pairs
	Weight	50g
Custom 3D printed pad with custom surface material	Price	$0.18
	Pad Material	Felt
	Number Included	N/A
	Weight	6g

B.1.1.3 Brake Rotor

There are a number of different styles of bicycle disc brake rotors. Broadly, they work regardless of brake actuation type – there are international standards for the inner mounting radius and width. Among the styles, one can choose between aluminum, steel, hybrid aluminum-and-steel, and carbon. Carbon rotors can be eliminated as viable options because of cost. Other materials have tradeoffs, which are given in TABLE XXII.

TABLE XXII
BRAKE ROTOR MATERIAL PROPERTIES

Material	Properties
Steel	Lowest heat dissipation, highest weight, high modulation, high availability
Aluminum	Highest heat dissipation, lowest weight, low modulation, low availability
Hybrid	High heat dissipation, low weight, high modulation, high availability

Without an unreasonable increase in price, hybrid rotors combine the best of aluminum and steel. Product options for brake rotors are given in TABLE XXIII.

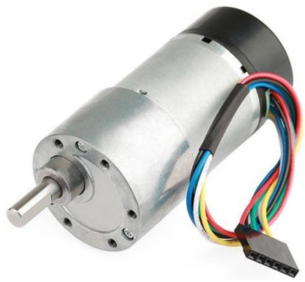
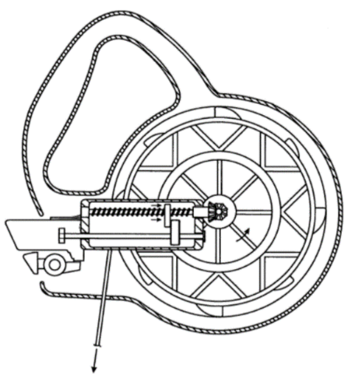
TABLE XXIII
PRODUCT OPTIONS FOR THE BRAKE ROTOR

Part Name	**Description**	
JAGWIRE LR1 PRO LIGHTWEIGH ROTOR [8]	Price	$64.99
	Material	Hybrid aluminum-and-steel
	Number Included	One
	Diameter	140mm
	Weight	80g
Corki Disc Brake Rotor [28]	Price	$44.99
	Material	Steel
	Number Included	Two
	Diameter	140mm
	Weight	100g

B.1.2 Retraction System

For the retraction system to be able to function, NovaBand must be able to retract the rope fully at safe speeds specified by **Req 3.3.12 B**. There are a few ways that this can be achieved. TABLE XXIV shows different choices for the retraction system.

TABLE XXIV
PRODUCT OPTIONS FOR RETRACTION SYSTEM

Part Name	**Description**
Direct drive DC motor [29] 	Easy to retract the rope with a simple signal from the microcontroller. It has built in encoder which helps with accurate retraction amount as well as helping with measuring the speed of the rope while unwinding. All of these features make this option better than other choices.
Dog leash spring mechanics [30] 	It is a more reliable mechanism for retracting rope as it is designed for that purpose only. The cons are not being able to retract the rope accurately back to the same spot, as well as not being able to control the speed of the retraction in a reliable way.
Manually design spring system	This mechanism is harder to implement but has the advantage of adding more control and customization.

B.1.3 Housing, Materials, and Layout

B.1.3.1 Structures

We have considered different structures for NovaBand. Optionally, the metal structure could be an exoskeleton, rather than being internal to the device. This would provide a simpler design and easier manufacturing. As well, this design would necessarily require a more complicated antenna structure, e.g. external banding akin to cellular phones. Using other materials could also be an option in this case, but would lead to either complication than the chosen design, or higher costs to use stronger materials. The metal exoskeleton would also be more difficult to shape into more portable and ergonomic structures, which would decrease portability.

B.1.3.2 Materials

Structurally we need materials fairly strong for our device. For the structure we have considered materials such as carbon fiber, steel, and other stronger plastics. With carbon fiber, we would have a strong and durable lightweight material, but the costs for carbon fiber parts is quite high, which would not allow us to reach our desired price point for the device. Steel is a strong metal which could work well for our purpose, but its weight is a very limiting factor when considering that our device is designed to be portable. Stronger plastics could be a good option, but we were worried about durability of the product, as well as the buildup of heat that it would lead to.

For external parts, we have considered stronger materials to avoid damage, such as aluminum, but decided against it due to the lack of dampening from its rigidity and the signal shielding for the Bluetooth signal, without heavy customizations.

B.1.4 Mounting

For mounting, we have considered non modular systems. This would save on time and costs as we could design a single mounting system which would likely be more reliable. The issue with this design, is that as a portable device, the different mounting possibilities varies greatly, and have options gives greater functionality to the user.

For the one mounting option we have decided on for the proof-of-concept, we have considered using suction cups and clips. Industrial grade suction cups would be a good lightweight option for a portable device, but as it will be moved around a lot, we were concerned about the reliability and consistency of the system. If a failure were to occur, it would be much greater of an issue than if the door mount failed. It would also require a very smooth service to mount which not all clinics or homes would have. Clips would also be a good lightweight solution, they are very simple and we would have less to design, but finding strong places to clip the device could be difficult, whereas most homes and clinics will have doors they can mount the device to.

B.1.5 Tension System

B.1.5.1 Rope

Generally, a cord is a collection of fibers no larger than $1/8^{th}$ of an inch, while a rope is a twisted or braided line of cord larger than $1/8^{th}$ of an inch. There are many types of rope and cord, but only a few are appropriate for use in NovaBand. Some characteristics of the common types of rope are given in TABLE XXV.

TABLE XXV
CHARACTERISTICS OF COMMON TYPES OF LINES [31]

Line Type	**Description**
Twine and string	Lightweight, made from cotton, manila, and polypropylene. Easy to tie, less durable.
Wire rope	Metal wire twisted into a plait, usually steel, can be nylon coated, virtually no stretch, "good for industrial and sports purposes".
Paracord	Lightweight nylon with an inner core, woven outer sheath. Abrasion resistant, general purpose.
Polyester rope	Synthetic, little to no stretch, durable, resistant to abrasion, general purpose.
Polypropylene rope	Lightweight, strong, stretchy, hard to tie.
Nylon rope	Synthetic fiber, very elastic, strong, durable, good for towing and tiedowns.
Sisal rope	Holds knots well, natural fibre, not durable.
Manila rope	Natural material, easy to tie, strong, durable, biodegradable.

As well, ordered from most to least stretch: nylon, polypropylene, polyester, Kevlar (aramid), wire [32]. From this information, research was limited to wire, paracord, Kevlar, and polyester ropes. Wire rope can be eliminated because it does not bend easily (for storage inside the device) and can break when fatigued. As well, paracord has too much stretch. Commercially available high-molecular weight polyethylene and aramid ropes were judged to be largely functionally identical, with some differences in pricing. Product options for the rope are given in TABLE XXVI.

TABLE XXVI
PRODUCT OPTIONS FOR THE ROPE

Part Name	Description	
No Stretch Rope [33]	Price	$64.85
	Material	Braided polyester
	Length	1000ft
	Break Strength	Unknown
	Stretch	Low
	Diameter	3.17mm
emma kites 100% Braided Kevlar String [34]	Price	$24.95
	Material	Kevlar
	Length	30m
	Break Strength	300lb
	Stretch	Very low
	Diameter	1.1mm
emma kites UHMWPE Braided Cord [35]	Price	$19.95
	Material	Ultra-high molecular weight polyester
	Length	31m
	Break Strength	350lb
	Stretch	Low
	Diameter	1.0mm

B.1.5.2 Handle

Other options explored for the handle were the uses of loops, clamps, and also the idea of a static nonmodular design. The loops would be the most general design which would allow for the most multipurpose use, but we believe this to be an inferior design for each of the cases it would be used in. Clamps would be a great option looking at workouts for the lower body, but much harder for conventional uses in the upper body compared the the handle with the grip for a hand. As each part of the body is quite different, we believe a modular system with various options to give the user the best option for any part of their body, while also requiring minimal design as standard clips could be used to swap out handles. TABLE XXVII outlines the potential design options for the handle.

TABLE XXVII
DESIGN OPTIONS FOR HANDLE

Part Name	Description
KKTOCHVC Premium Exercise Handle [36] 	This handle is already owned by a group member. The handle is easy to grab with either hand and perform all types of arm exercises.
Ankle Strap Handle [37] 	This handle is designed to be strapped around the ankle for leg exercises.

For proof-of-concept, one group member already owns the KKTOCHVC handle which has been selected. In beta stages, the ankle strap handle will be added as a modular option for the handle for ease of use and convienence in different types of exercises.

B.2 Electronics

The electronic components of the NovaBand are the intelligent parts of the device. These components are the bridge between the software and the hardware elements.

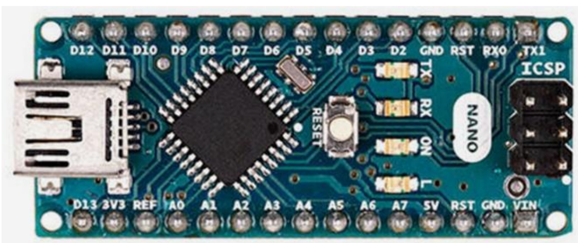
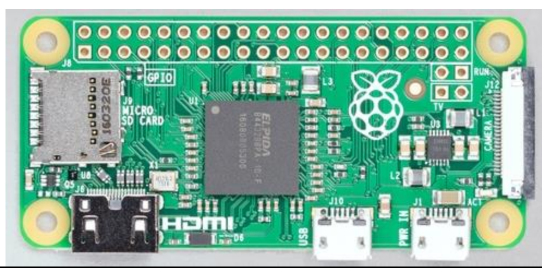
B.2.1 Microcontroller

The requirement for the microcontroller is highlighted in **Req 3.4.2 B**, stating that the firmware must communicate between all hardware components. As such, microcontrollers with increased cost due to higher CPU (central processing unit) power were eliminated from contention. Our chosen method of communication between the microcontroller and the mobile app is Bluetooth, therefore the microcontroller is required to be Bluetooth capable. The final considerations once those requirements were met came down to minimizing size and cost.

B.2.1.1 Microcontroller Options

TABLE XXVIII outlines the different options for microcontrollers that were considered in the research process for the NovaBand proof-of-concept. Both Arduino and Raspberry Pi families outside of the Nano and Zero respectively were considered as well, however, they were quickly eliminated due to size constraints and the lack of a need for a high-powered CPU.

TABLE XXVIII
DESIGN OPTIONS FOR MICROCONTROLLER

Design Option	**Technical Specifications**	
Arduino Nano [11] 	Operating Voltage	5V
	Clock Speed	16MHz
	DC Current per I/O Pins	40mA
	Input Voltage	7-12V
	Power Consumption	19mA
	PCB Size	18mm x 45mm
	Weight	7g
Raspberry Pi Zero [38] 	Operating Voltage	5V
	Clock Speed	1GHz
	DC Current per I/O Pins	40mA
	Input Voltage	5.1V
	Power Consumption	100mA (typical)
	PCB Size	30mm x 65mm
	Weight	9g
Printed Circuit Board (PCB)	All technical specifications vary depending on the board that is designed.	

The Arduino Nano is a simple microcontroller designed for use in small projects with no need for large amounts of processing power.

The Raspberry Pi Zero is an extremely low-cost board, with a relatively high-powered CPU for the size of the board. The Pi Zero is a standalone computer and functions as such, but also has general-purpose input/output, or GPIO, pins to allow for connections to multiple external devices which allows it to function as a microcontroller as well as a computer.

Finally, the last option considered was to use a custom printed circuit board. A printed circuit board, or PCB, has specific components soldered onto the board at the request of the purchaser. PCBs are very versatile and relatively inexpensive. However, to properly make use of the benefits of a PCB, one would need to know all the exact requirements in advance of fabricating and ordering the board.

B.2.1.2 Microcontroller Decision

For the NovaBand proof-of-concept, the Arduino Nano was selected as the microcontroller candidate. The Arduino Nano fulfills all the requirements needed (low speed CPU, GPIO, Bluetooth) all at a low cost while also fulfilling **Req 3.4.1 A**. The Raspberry Pi Zero could also have been selected, however, multiple team members already owned Arduino Nanos and the higher CPU power provided by the Raspberry Pi is unnecessary for this project. Finally, the PCB option is being heavily considered for the beta production of NovaBand. However, for proof-of-concept, the PCB would not allow us to experiment thoroughly and make changes, without needing to design and order an entirely new board. Once selections and features have been finalized, a PCB will allow us to streamline our microcontroller and possibly increase performance by eliminating unnecessary components that are present on the Arduino Nano.

B.2.2 Motor driver

There are many choices on how to drive a DC motor. Some of these choices involve custom designed circuits and some involve integrated chips that are able to perform the same task. It is possible to use a half bridge motor driver. In this method of driving a motor, the motor can only turn in one direction and there is no control on the motor in the other direction. As this method doesn’t give full control on the motor it won't be explored further. The other method of driving the motor is using an H-bridge motor driver. Fig. 14 shows the configuration for a H-bridge diagram.

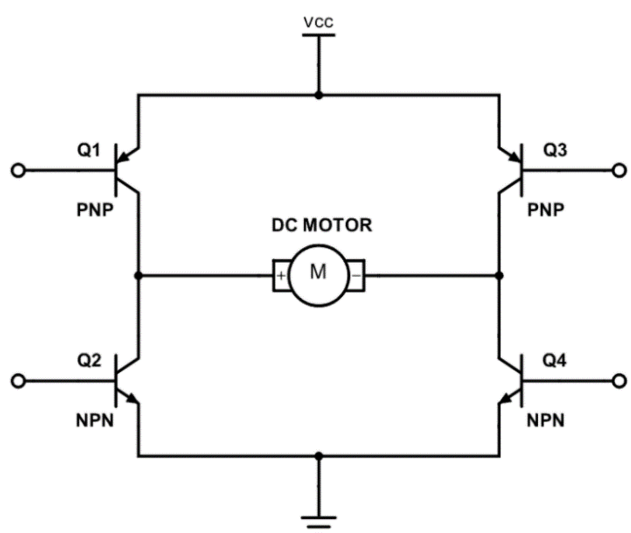
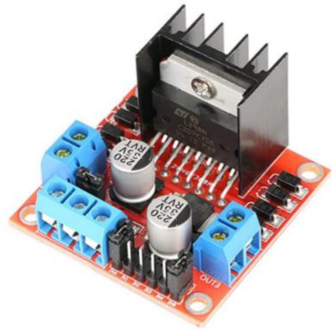
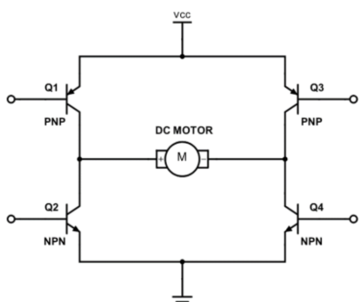


Fig. 14 Full bridge motor driver [39].

Based on this choice TABLE XXIX lists some of the options that was explored.

TABLE XXIX
DESIGN OPTIONS FOR MOTOR DRIVER

Part Name	**Description**
L298N motor driver module [12] 	This is the best option. The L298N motor driver module with the back EMF diodes all on the module. This driver is capable of meeting all design requirements mentioned in TABLE XIII. As well as that compared to the other options it is an easier implementation.
H-bridge motor driver using BJTs [39] 	This method is exactly same as the L298N driver mentioned. The internal circuitry in L298N is an H-bridge that specially designed and put in an integrated system. The main benefit of this method is being able to output more current and handle higher voltages. This can be an option for the beta version of NovaBand aad the L298N will be sufficient enough for the proof-of-concept.

B.2.3 Control systems

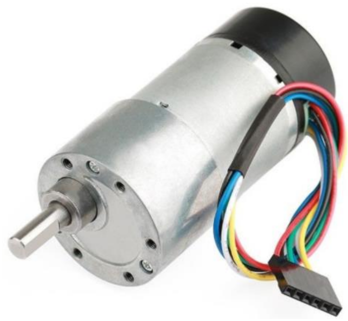
The control system has a few subsystems. The encoders will be measuring the speed of the rope while current sense chips are going to be used to measure the power consumption of the motors. The encoders will ensure that NovaBand is able to maintain the correct amount of tension during an exercise repetition. The current sense ship will be measuring the current going into each of the motors to prevent them from possible damage.

B.2.3.1 Encoder

The encoder as mentioned is used to measure the rope speed. There are many ways for an encoder to measure the speed of the rope. Some rely on linear actuation while some rely on rotational actuation. The linear actuations can directly measure the movement of the rope while the rotational encoders will need an extra mechanical part that translates linear motion of the rope to rotational motion. TABLE XXX lists a few encoder options that are viable for NovaBand.

TABLE XXX

DESIGN OPTIONS FOR ENCODER

Part Name	**Description**
AMT102-V encoder [13] 	Using this encoder, it is possible to measure the speed of the rope with higher accuracy. Using a mechanical mechanism that translates the linear movement of the rope to rotational speed this encoder will output the most accurate results compared to other option.
Direct drive DC motor built in encoder [29] 	The motor used in the retraction system has a built-in encoder. With this encoder it is possible to measure the rotational speed of the spool. In this way it is possible to measure the rope speed. However, this method won't be accurate as the rope will be at different parts of the spool and it's hard to measure the exact position.
Linear encoder using IR LED	By having lines with different colours on the rope with high contrast and using IR LEDs it is possible to make a linear encoder. This method is viable but in terms of manufacturing reliability and light condition in the environment the results might be affected

B.2.3.2 Current sense chip

To be able to keep the motors operating under safe rated speeds current sense chip will be needed. Using current sense chips it is possible to measure the current going to each motor. By knowing the current and the voltage of each motor it is possible to measure the power draw of the motor. This information can be used to prevent the motors from damaging as well as getting information about the amount of tension on the rope. TABLE XXXI lists a couple choices for the current sense chip. The other methods not mentioned in this table is either similar to these two options or more expensive.

TABLE XXXI

DESIGN OPTIONS FOR CURRENT SENSE CHIP

Part Name	Description
MLX91220 current sensor [14] 	Using an integrated chip like MLX91220 and a low resistance high accuracy resistor outputs the most accurate results as the current will be measured directly from the wires that are attached to each motor. This option is also cheaper than the other methods mentioned below
CR9321 current sensor [40] 	The other method is using current sensors that enclose the wiring that goes to each motor and measures the current using the magnetic field generated by the current. This method is much more expensive while less accurate and only good for really high current systems which is not needed for NovaBand.

B.2.4 Power source

There are multiple ways to power the device. As mentioned in the body a power supply will be used for the proof of concept while lithium-ion batteries are the chosen option. Pros and cons of each method is shown in TABLE XXXII. TABLE XXXII
DESIGN OPTIONS FOR

TABLE XXXII

DESIGN OPTIONS FOR POWER SOURCE

Part Name	Description
Lab power supply	This method is reliable and provides enough power for NovaBand to operate. The power supply provided from the engineering lab is able to provide up to 30V and 3 amps which is higher than the needs for the device.
Lithiom-ion battery cells	For beta, the source of power will be changed to batteries. Using batteries NovaBand can operate without being attached to power supply. This method is not used for the proof-of-concept as focusing on the other parts of the product was more important and operating lithion-ion batteries comes with its own risks which will require proper battery management circuit.

Directly powered from the wall using internal power supply	This method is not ideal as NovaBand has to be pluggd into the wall at all times to operate while being more danagarous. In addition, heavy AC and DC converters will need to be added.

B.3 Software

The software component of the product operates in a domain adjacent to the physical device. Broadly, the software works in tandem with the electrical and mechanical subsystems to configure the device state dynamically depending on the needs of a particular rehabilitation exercise.

B.3.1 Physiotherapist-to-Device Interface

The physiotherapist-to-device interface is a critical bridge between the product's software and hardware components. The physiotherapist must be able to easily and precisely control the device to provide the best rehabilitation work out for their patients.

B.3.1.1 Physiotherapist-to-Device Interface Options

For the physiotherapist-to-device interface, three options were considered: a mobile application, an on-device button interface, and a custom remote control. Each option needs to meet both **Req 3.1.1 A** and **Req 3.4.1 A,** which require that the device must be able to programmatically vary resistance and must respond to user input within one second, respectively.

A mobile application is a low-cost, highly customizable design option. The graphical user interface of an app, if well designed, creates an easy-to-use abstraction for controlling the device. If changes to the app are needed, they can be made available via software updates and quickly applied. Since an app functions on mobile phone software, the phone's hardware peripherals, including the communication components, can be utilized. However, some challenges arise due to differences in operating system specific features between Android and iOS. Additionally, data transmission latency and operating range depends on the data transmission protocol used, such as WiFi and Bluetooth.

Alternatively, an on-device button interface allows the NovaBand device to be completely stand-alone while still providing a way for physiotherapists to interact with the device. This approach comes with a couple of issues, however: lack of post-manufacturing customization, device fragility, additional production cost, and a potentially difficult learning curve for users. Button mappings that cover all possible configurations would be far too complex to operate or require additional clarifcation. Unfortunately, this approach also adds another point of failure to the overall design of the device; if the buttons stops working, the physiotherapist has no way to confgure the device.

The final option considered was a custom remote control. This option has many similarities to the on-device button interface in that it still suffers from a lack of post-manufacturing customization. Additionally, the complexity of the customization options would force the design to include many buttons which is both clumsy and unintuitive. It is also worth noting that the remote itself is susceptible to damage from being dropped and will be harder to replace than a mobile phone. Lastly, the remote also requires wireless data transmission, just as the mobile application does.

B.3.1.2 Physiotherapist-to-Device Decision

The device must be able to programmatically vary resistance according to **Req 3.1.1 A.** The option that best fulfills this requirement while leading to the fewest additional challenges is the mobile app. Both the built-in button interface and remote control options cost more than the app, will be more difficult to use, and cannot be easily changed after they are. In contrast, the app is free to develop, offers a familiar interface to users, and, most importantly, can be changed via software updates after the initial version is deployed.

Req 3.4.1 A notes that the device must respond to user input changes within one second. All design options considered are likely to impose a similar latency, but the app can choose from Bluetooth, Wi-Fi, and other protocols to communicate. Compared to the app, the other design options do not offer sufficient communication protocol alternatives which can guarantee meeting the latency requirements.

To summarize, **Req 3.1.1 A** and **Req 3.4.1 A** require the device to both have the ability to programmatically vary resistance and respond to input within one second. Three design options were considered: a mobile application, an on-device button interface, and a remote control. Among these options, a mobile application has been selected due to its low cost, ease of updating, and support for multiple data transmission protocols.

B.3.2 Data Transmission

As stated previously, the app will need a wireless protocol to communicate with the device. **Req 3.4.1 A** requires one second for data transmission and settings updates. As such, the data transmission needs to be performed in under one second and the protocol selected must meet that requirement.

B.3.2.1 Data Transmission Options

TABLE XXXIII outlines the different options for data transmission. There are multiple options that exist to wirelessly transmit data: Bluetooth, Wi-Fi, and Zigbee.

TABLE XXXIII
DESIGN OPTIONS FOR DATA TRANSMISSION

Design Option	Technical Specifications	
Bluetooth 4.0 and Bluetooth Low Energy [18]	Range	Less than 100m
	Over air data rate	Up to 3Mbit/s
	Latency	6 - 100ms
	Power Consumption	0.01W – 1W
	Frequency	2.4GHz
Wi-Fi [41]	Range	Up to 95m
	Over air data rate	Up to 600Mbit/s
	Latency	150ms
	Power Consumption	High
	Frequency	2.4-5GHz
Zigbee [42]	Range	75-100m
	Over air data rate	Up to 250Kbit/s
	Power Consumption	0.001-0.1W
	Frequency	2.4-5GHz

B.3.2.2 Data Transmission Decision

The final decision for data transmission was Bluetooth. All of the options listed in TABLE XXXIII are able to fulfill **Req 3.4.1 A,** as a result, the selection was made due to convenience for the user and ease of implementation. Both Bluetooth and Wi-Fi come built in on almost every smartphone in use, whereas Zigbee does not. As such, Zigbee was eliminated from contention. Between Bluetooth and Wi-Fi, the specifications are fairly similar, however, power consumption needs to be of slightly higher priority due to **Req 3.3.20 B**. Finally, Bluetooth is more commonly used to connect to external device in mobile apps, as a result, more documentation for programming exists and users are more familiar with using Bluetooth.