Athletic Recovery Device (ARD)

Amanda Ashmen, Ryan Bosanko, & Herschel Norwitz

ECE-498: Capstone Design Project

Advisor: Professor Takashi Buma, Phd

November 22, 2020

Acknowledgements

Thanks to Professor Takashi Buma for guiding us through this project and being our advisor. Your insight really helped us develop our ideas and stay on track.

Thanks to the Union College training room, in particular Cheryl Rockwood and Jill Crary for taking the time to cooperate with us and answer all of our questions about treatment and product requirements for a recovery device.

Thanks to Gene Davison for acquiring and ordering our needed parts and supplying use with needed components that had not arrived yet.

Thanks to Mark Hooker for corresponding with us on the specification of copper plates and for providing a plate for initial testing.

Table of Contents:

List of Figures

List of Tables

Introduction

Despite many injury prevention programs, acute injuries such as ankle sprains, muscle sprains, and broken bones are inevitable. Risk of injury, associated with competing in a sport at a high level, is a threat that all athletes fear and many come to face. Union College offers 24 varsity sports teams, and like many other colleges across the country, the recovery process can be intense and complicated for many acute injuries.. To combat these injuries, cold therapy is frequently used in conjunction with the R.I.C.E. method: Rest, Ice, Compression, and Elevation. If an athlete sustains an injury, they will typically make an appointment to see the athletic trainer, complete their rehabilitation exercises, then sit on a training bench and ice the injured area for ten to twenty minutes.

In the Union College training room, plastic ice bags are used for cold therapy treatment. These recyclable bags are typically applied to the body and strapped on with additional wrap to secure them in place. As shown in the picture below, these bags are even used at the highest level (Fig. 1).

Figure 1: Single-use Ice Bags

After speaking with the head athletic trainer at Union College, we learned that these bags are used because they are easy to set up, inexpensive to use, and sanitary since each bag is only used once [1]. Unfortunately, this single-use characteristic means that hundreds of these bags are used per week, which is unsustainable. While there are reusable gel ice packs on the market, the surface temperature for these products can become too cold or not cold enough for ideal cold therapy treatment. Chemical based ice packs must also be refrozen between uses. Other products which are able to hold a temperature for an extended period of time, such as liquid-based cold therapy machines, do not provide temperature regulation that could be useful for personalization to the athlete or body part. While some products do have the ability to control temperature and apply compression, this comes at a steep cost and makes operation and sanitization cumbersome.

For this project, we will be working with Union College's athletic training room to design a device that will address the drawbacks of the current cold therapy methods being utilized. This product aims to be sanitary and environmentally-friendly. In order to address the needs of the training room, which deals with many athletes each day, this product will need to have a user-interface that does not require professional supervision and will be able to handle consecutive athletes during the busiest times of the day. While this product might not replace all of the single-use ice bags that student-athletes get after practices, this could be a more sustainable and reliable method of cold therapy. We propose that an electronically powered ice pack with the ability to control the temperature and duration of the treatment for consecutive uses would be a valuable and sustainable asset to the Union College training room.

This report aims to provide a comprehensive and exhaustive account of the process by which we attempt to solve this problem thus far. We will first go into detail about background work that served as inspiration for pursuing this project. This includes motivation for choosing this topic and other devices that have been made to address a similar need. From here we will move on to constraints the device needs to fill including needs specified by the trainer. This will be followed by discussions of various methods of addressing and applying our ideas to make a working system. After detailing alternative design ideas, we will go into detail about how we applied the design process to make important decisions about our project. We detail tests we ran, the motivation behind them, and the results of these tests and their implications for the overall project. Lastly we intend to give a layout of what we expect our times table to be going forward in order to fully develop and test our project.

Background

Through various medical studies relating to the effectiveness of different systems for athletes, we see a variety of different approaches to recovery devices. A popular method is to implement cold therapy, which cools the injury to decrease blood flow to an injured area. Athletes use cold therapy to enhance their performance by increasing the speed of recovery by reducing DOMS (delayed onset muscular soreness), which can occur following high-intensity training and competition [2]. After an athlete sustains an injury, it has been shown that the combination of compression and continuous cryotherapy is an effective method for healing by decreasing inflammation [3]. There are a combination of factors that influence the effectiveness of this process, such as: temperature of the applied surface, duration of treatment, degree of conformity to the surface of the skin, and to the shape of the body part. We will explain in detail the requirements we chose to model our design after in our design requirements section. To determine what goals were realistic and attainable, we did extensive research on products that already have been industrially developed and marketed to audiences seeking cold therapy treatment alternatives to recyclable ice bags.

Currently on the market, most products use one of two different methods of cooling for cold therapy products: chemical packs or systems that pump cold water to an insulated sleeve. Chemical packs are typically filled with a soft gel material and are put in the freezer for a few hours before being applied to the injured area. As previously stated, these devices can either be above or below the desired temperature, rendering them less effective. Additionally, they must be refrozen, so they are not useful in Union College's training room environment which must treat consecutive athletes. The same negative characteristics apply to the PowerPlay device (Fig. 2), which is a machine that holds a gel pack and allows the user to simultaneously provide compression to the injured area [4].

Figure 2: PowerPlay Device

Liquid circulation systems, on the other hand, can be used consecutively over a span of hours. Some of these products are very expensive, and others lack the ability to provide the user with specific temperature control. One example of a liquid circulation product is the GameReady system; this product works by circulating cold air through tubes connected to the compression sleeve [5]. Not only is this system messy and cumbersome to use, as stated by the Union College head athletic trainer, but it is also very expensive; these devices can cost from two to three thousand dollars. A more portable and less expensive device on the market is the Breg Polar Care Kodiak Cold Therapy Units, shown in Figure 3 below, which does not provide the option to control the specific temperature [6]. Different individuals, different injuries, and different body parts all require different temperature profiles for optimal recovery. As such, there are inherent advantages to any system that can provide temperature regulation.

Figure 3: Breg Polar Care Kodiak Cold Therapy Unit

One device that was able to provide temperature control is the ThermalZone Thermal Therapy system, shown in Figure 4 [7]. This is a wall pluggable device that uses cold water in order to create cooling. It can regulate set temperatures between 34 and 125 degrees Fahrenheit. This device looked to be the closest to what we were thinking of what we wanted our device to be like because it is well sized, appears fairly easy to use, is reasonably priced and can provide good temperature control. Similar to the Breg Polar Care Kodiak Cold Therapy Unit, it used pumping cold water through a tube to an insulated sleeve as its method to apply cold treatment. While this unit has the ability to control its temperature, it comes at a higher cost than most cold therapy units, and users who purchased the device from Amazon.com complained that this device was too loud, leaked water, and did not maintain temperatures within the cold range settings.

Figure 4: ThermaZone Thermal Therapy System

Another common cooling method is refrigeration. The main goal of refrigeration is the removal of heat from the system and prevention of heat from entering a system. Common refrigerators prevent heat from entering by being made of insulating materials. In order to remove heat, refrigerators apply a similar method of cooling as the human body. As the body gets hot, it produces the liquid sweat. As sweat evaporates and turns into vapor, heat is removed and the body is cooled. In order to mimic this behavior, fridges pump in liquid chemicals that can very easily evaporate. As it flows throughout the system, it absorbs the heat, evaporates, and turns into gas. This gas is brought out of the system where the excess heat is siphoned off by discharge lines. As shown in Figure 5, the vapor is passed through a compressor where it is returned to its liquid form before it is pumped back in and the process repeats [8]. This is the most common method used today to induce cooling in a non-medical environment.

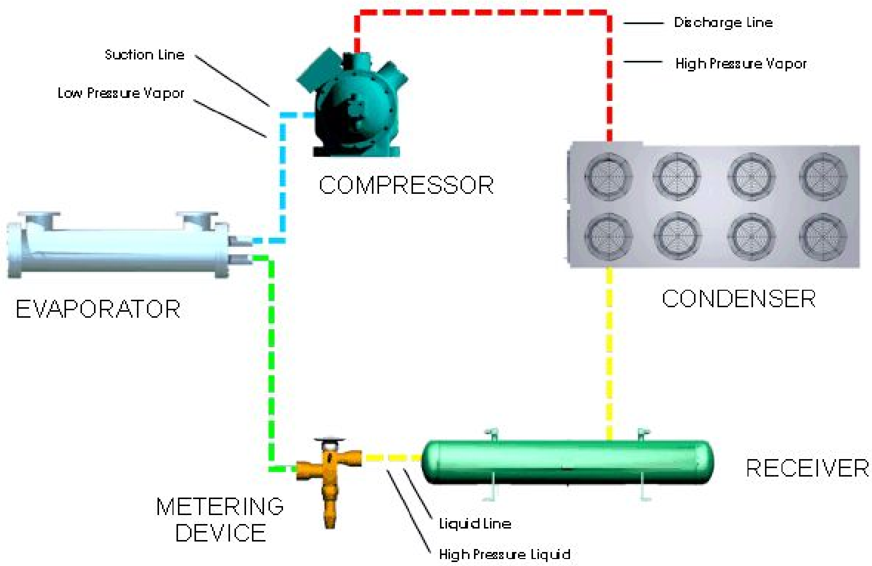

Figure 5: Basic Refrigeration System

An alternate form of cooling that is found in many systems is the use of thermoelectric modules, which often use the Peltier Effect, which tells us that under certain circumstances, an applied current can directly cause a temperature gradient [9][10]. As displayed in the diagram in Figure 6, this can only occur when the current is applied through the transition, or “junction”, between two different conductive materials [9][10]. Each material can be given its own “Peltier coefficient”, which represents how much thermal current a given electrical current carries in different metals [10]. Here, thermal current can be thought of as a sort of potential energy carried by electric currents, not in their magnetic fields, but caused by the electrons interacting with their material. When this coefficient varies at a junction, the energy entering the junction no longer is equal to the energy leaving the junction, so the excess energy is dissipated as heat, or absorbed in a cooling effect [10]. Whether absorption or dissipation occurs at the junction relies on both the direction of electric current and on which Peltier coefficient of the materials is larger. Of course, the energy for this must come from somewhere, so the other junction for this operation will either dissipate the absorbed energy as heat, or absorb energy itself to power the junction's heat dissipation. This means that however much energy is being produced by the first junction, that much heat is absorbed by the other junction. A medical recovery device is a viable application for thermoelectric cooling, which needs to be regulated for long periods of time.

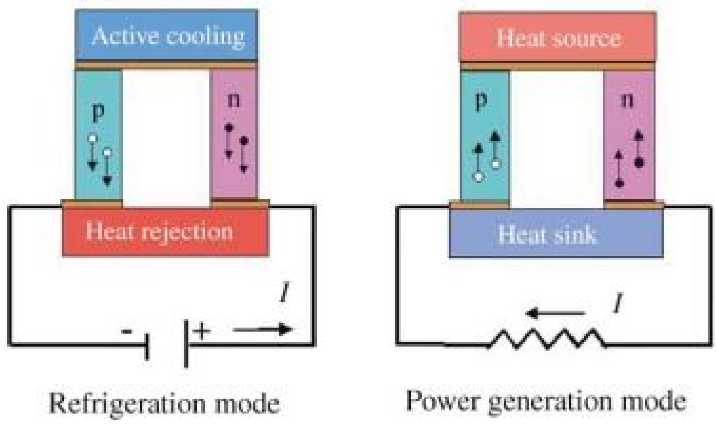

Figure 6: Peltier Thermoelectric Couple

In order to get a better understanding of how to drive Peltier units, we found previous works on Peltier-controlled heating/cooling systems. For example, we found a design project report that created a small Peltier controlled device using an atmega-1248 microcontroller and Peltier unit with a heatsink; the device had a digital graphical user interface powered using MATLAB [11]. We also found work done by an Iranian team who made a Peltier system based on warming what was essentially a bag of water. The team used a simple bag of water with a single Peltier and heat exchanger on top of the bag of water, which they called an "ice pack" [12]. An image of their system is shown below (Fig. 7).

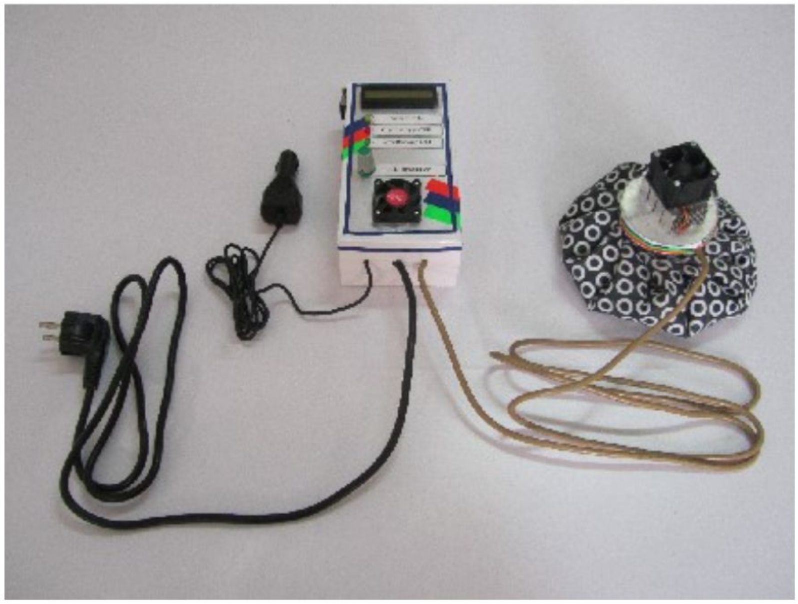

Figure 7: Peltier Cooling Device

The main components here are their control system in the center and their ice bag, shown to the right. The team was able to keep the water at 3-5ºC consistently and only took around 15 minutes to cool down the water to the desired temperature [12]. Because the Peltier was on top of the "ice pack", with the heat sink and fan included and kept relatively small, we took this as further evidence that it may be possible to keep the Peltiers cool using reasonably sized heat sinks while still delivering the required power.

This is not the only research that exists detailing the use of Peltier coolers for cryotherapy. A team from The University of Texas at Austin was also able to demonstrate the viability of Peltier units for more explicitly medical cooling applications [13]. The team constructed a device with two Peltier coolers and used it to perform cryotherapy on nine healthy subjects [13]. Their device in operation is shown below in Figure 8.

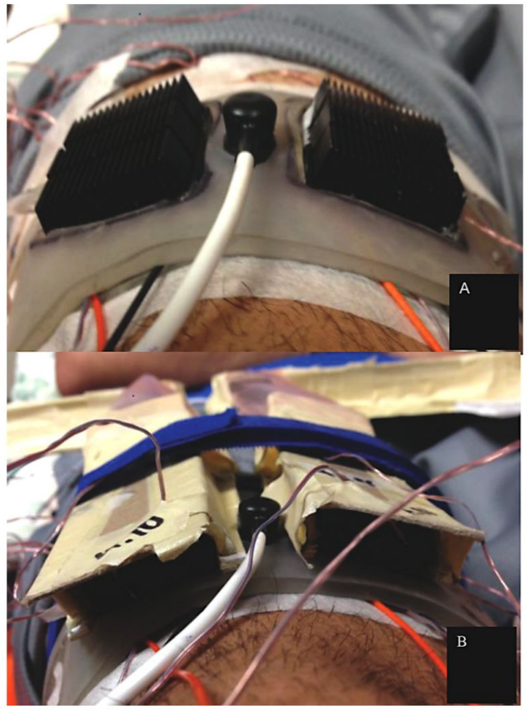

Figure 8: Operational Peltier System

In the upper photo (A), the two Peltiers with heat sinks are shown flanking a blood perfusion probe. The bottom photo (B) shows the system with air circulation to help the heat sinks. As is evident, this device was far from a commercial product and was intended for injuries in a medical context [13]. They were able to show, however, that the device was able to cool the skin by 6^{o}C and largely control blood perfusion around the affected area [13]. With such a small temperature change on the surface of the skin, they were able to reduce blood perfusion by 60% [13]. Their device was also able to provide heating, which they used to increase blood perfusion by 200%, with an upwards increase of 6^{o}C on the temperature of the skin[13]. A graph of their results is shown below in Figure 9, with blood perfusion in the upper graph and the skin temperature in the lower graph [13].

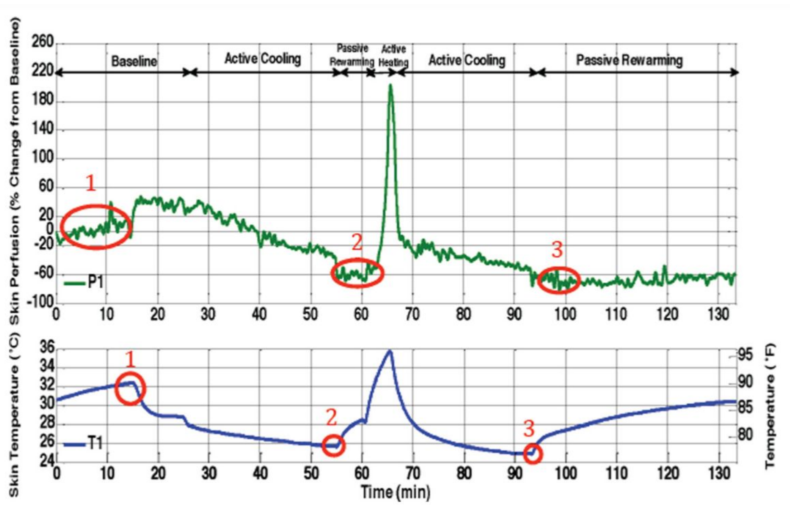

Figure 9: Blood Perfusion and Temperature

They ran their system for about two hours, mostly performing cooling but with a brief warming period in the middle [13]. While the need we are trying to address aims to operate for a shorter treatment period (less than thirty minutes), it is good to have an understanding of what a longer time interval would look like. Overall, their system does a fantastic job of proving the viability of using Peltier coolers to help with recovery from injuries. Such a system can have very precise temperature regulation while staying relatively small and light.

Design Requirements

Before we could start thinking about different ways to approach the problem we aimed to address, we first had to get a solid understanding of what the requirements of the device were. In order to figure this out, we needed to have in depth communication with the trainer to see what they were looking for in an athletic recovery device. They laid out several requirements relating to performance and safety. From these specifications we developed several of our own more specific requirements for how we would operate the system, what safety features were needed to account for this, and what the overall cost and final appearance should be.

Performance:

The trainer specified that the device would need to maintain temperatures between 4 and 10 degrees Celsius at the point of contact between the gel pack and the skin [14]. Our team decided that to best achieve this, our system should maintain a measured temperature to within 2ºC of the desired temperature at the point of contact on the surface of the skin. While they did not specify exactly how fast it needed to reach those temperatures during the initial start-up period, they stated that faster is better and anything more than 5 minutes would likely be impractical for use in the busy training room environment. As for overall duration, the training room is typically open for treatment during the week during the hours of 9-12pm and 1-4pm. That is, for two different three hour periods during the day, athletes can come in for their appointments with athletic trainers to do rehabilitory or recovery activities. After communicating with the athletic trainers to get a rough estimate of how many athletes they treat each day, we were told that an average of 40 athletes use an ice bag at a training bench each day during the fall term, and about 20 athletes each day for each of the winter and spring terms [1]. This defines the requirement that the athletic recovery device be able to operate for a three hour period with only a few short, approximately 5-10 minute, breaks in between athletes. During this break, the device will have to be cleaned and sanitized.

Physical Parameters:

We then decided to determine the shape, size, and form that would be ideal for the training room environment. The head trainer of Union College told us that smaller is better for these devices. Though no specified dimensions were given, we aim to have the device fit within at most a 2 cubic foot volume to let it sit comfortably underneath the training bench. In order for this device to be practical, it needed to cover an area greater than 180 degrees around the area being treated, ideally wrapping around the body part at or near 360 degrees. For instance, for knee injuries, the device would have to actively cool an area stretching at least halfway around the knee. Furthermore, the cooling applied on the injured area needed to be fairly uniform throughout. This further implies that the device itself should be malleable and flexible enough to conform to the surface of the skin and to the appendage being treated.

Interface:

As for the process of using the device, it would ideally not require excessive supervision or direction to use, given that qualified athletic trainers can sometimes be heavily outnumbered by injured athletes requiring treatment. Since treatment temperatures vary per athlete, injury, and body part, there is no "one size fits all" treatment temperature/duration combination. The training room communicated that a few preset modes, such as 5 ^{o}C for 15 minutes or 8 ^{o}C for 20 minutes, would be convenient. To address unique treatment cases, a custom mode setting to adjust temperature or duration, which would be password locked, would be a useful function. Ideally, after multiple uses, an athlete could be given basic instruction to inform them of the treatment specifications they needed, and they would be able to input their setting for their treatment and subsequent appointments, without the need of supervision from the trainer. If the device adds more complication for the trainer who needs to set-up the device for each student then it would no longer be practical. We discussed the needs regarding the interface for the device. Given that cold therapy is a routine and low-risk procedure, the trainer specified that there would not be a need for a database or data collection system to store the treatment periods of the device per athlete [1]. Additionally, they stated it would be most convenient to have the controls of the system be directly operable from the device itself, rather than being on an external computer or phone application elsewhere[1].

Safety:

Another important area that the trainer provided specifications for was safety. One key reason that ice bags are used is because they are one-use, and thus do not need to be cleaned, nor do they pose a no risk of transmitting diseases. The trainer made it clear that whatever replaces the ice packs must be very easy to clean, to ensure that the device is sanitary between uses [1]. This means that the material must be made of something that is not damaged by cleaning fluids. Furthermore, the device must have safety features to prevent any harm to the user that may come from some sharp or moving component, or electrical system.

Power:

In order to get an idea of how much power our system would need in order to function, we performed some basic calculations. Regardless of the method we eventually choose to deliver this power, the power will still need to be provided. We first need to know the area that our system will need to cool. In order to be able to provide cooling to injuries of moderate size, we decided our device needed to be able to cool an area of at least 400 cm^2. For context, a typical circumference of the human leg 7cm above the knee is 26cm [15]. Assuming 360 degree cooling, that would mean our device would be capable of cooling about 15cm of the leg with an average circumference of 26cm.

With an area, we can now calculate how much cooling power our system must provide. We know from previous work that the thermal conductivity of various layers near the surface of human skin are as follows:

	Thickness, mm	Thermal conductivity, W/(m K)
Epidermis	0.1	0.235
Papillary dermis	0.55	0.445
Reticular dermis	0.55	0.445
Fat	2.0	0.185
Muscle	6.8	0.51

Table 1: Properties of Skin Surface[4]

If we assume this small region can be approximated by a rectangular prism, with our device on top providing cooling power at 10ºC, and the body below at 37ºC, we know the temperature difference across the region and we know the area of the region. We calculate the thermal resistivity as follows:

$$R_{Th} = (x_1/\lambda_1 \ + x_2/\lambda_2 + x_3/\lambda_3 + x_4/\lambda_4 + x_5/\lambda_5)1/A =$$

$$(\frac{0.0001m}{0.235W/(mK)} + \frac{0.00055m}{0.445W/(mK)} + \frac{0.00055m}{0.445W/(mK)} + \frac{.002m}{0.185W/(mK)} + \frac{0.0068m}{0.51W/(mK)})(\frac{1}{0.04m^2}) =$$

$$0.676^oK/W$$

Where R_T is the thermal resistance, x_i is the thickness of the layer in meters, λ_i is the thermal conductivity of each layer in watts per meter kelvin, and A is our area in square meters. We then can divide the temperature gradient by this thermal resistance to get the minimum cooling power required to power our device:

$$P \ = \frac{\Delta T}{R_{Th}} = \frac{27^oK}{.676^oK/W} = 40.0W$$

Here, P is the power in watts ΔT is the temperature difference in kelvin, and R_{Th} is the thermal resistance in degrees kelvin per watt.

Economic:

In order to ensure that our device meets the specifications set out by the trainer and to ensure the product we create is viable, our team came up with additional design requirements. Firstly, we decided on a cost to aim for. During the 2018-2019 academic year at Union College, the training room recorded that at least 3088 ice bags were used for treatment. Note that this does not account for instances where an athlete used two ice bags in a single treatment session, nor does it include ice bags used on-the-go after practices. Cramer ice bag rolls, as used in the training room, are sold in rolls of 750 for approximately one hundred dollars. If the training room purchases five of these 750 count rolls a year, to make this a financially valuable investment within three years, the product would need to cost less than $1500. We will keep in mind that the prototype will be more expensive than a design ready for manufacture. We also wanted to emphasise the importance of our device being self contained. A lot of products currently on the market require ice to be provided in order to function properly. In order to eliminate this burden from the training room, our device will not require other devices like ice machines to function.

Requirements Summary:

In order to make our product fit the needs that the training room requires, we will combine the functionality of athletic recovery devices currently on the market, while reducing the price by eliminating ability to perform the compression. We will focus on creating a product that can last for hours during the training rooms 4-hour treatment periods. It will have the ability to be set to a certain temperature or duration based on the specific athlete or body part. Additionally, it will be sanitary and easy to use so it does not compromise the benefits of the current method. Communication with the customer confirmed the need for this type of device; a preference for a touch screen display over buttons or a phone app was indicated.

Design Alternatives

In order to make our product fit the needs that the training room requires, we had to combine the functionality of athletic recovery devices currently on the market, while keeping the price low. We will focus on creating a product that can last for hours during the training room's 4-hour treatment periods. It will have the ability to be set to a certain temperature curve or duration based on the specific athlete or body part. Additionally, it will be sanitary and easy to use so it does not compromise the benefits of the current method. Communication with the customer confirmed the need for this type of device; a preference for a touch screen display over buttons or a phone app was indicated. To begin our design process, we first had to brainstorm various methods that could be used in order to achieve our main objectives. This means we had to consider different methods of cooling, how to control all those cooling systems, and how to power all of them. Our three major functions were broken down into the following: temperature control, user interface, and power system. Temperature regulation focuses on the method of cooling, adjusting temperature, and how to drive the cooling system. The user interface looks at how to control and monitor the system, as well as how to interact with users. The power system's main objective is to provide power to the other two systems such that their needs are met while not affecting the other systems. It also looks at how to connect everything together physically.

Thermal Regulation:

The role of the temperature regulation system is simple and self evident. It must take the control signal from the user interface and use it to provide the desired temperature to the surface of the skin. There were many approaches to doing this but all of them must at least be able to accomplish the goal shown in the Figure 10 below:

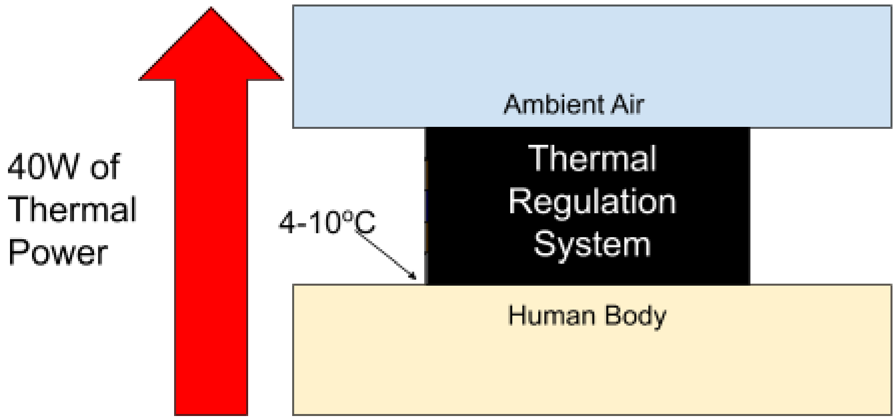

Figure 10: Thermal Regulation Goal

There are many different broad approaches to accomplishing this goal but we mainly considered three. These were air cooling, water cooling, and direct electric cooling. The idea for air cooling derived from the concept of air conditioning. Specifically, if it was possible to decrease the temperature in one's home with an air conditioner something similar could be done for applying cold treatment; this could allow for fast temperature regulation. The only device that we found that used entirely air cooling for medical purposes was the Zimmer Cryo 6 [16]. This device pumps cold air through a tube and can provide precision cold treatment to reach temperatures of -30 degrees Celsius. While this was an effective icing device, its price was between 6 and 7 thousand dollars. Furthermore, the temperature is way too cold for our purposes, it is massive, requires training to use, and it is meant for treating a very small precise spot rather than an overall area or appendage.

Figure 11: Cryo 6 [16]

Unfortunately there were too many drawbacks for us to realistically consider an air cooling system. These include cost, size, and implementation constraints. Specifically, making a reliable air conditioner relies heavily on fluid dynamics which none of us have experience in. At the same time we can not buy one because any that could meet the requirements that we need are way too big and expensive.

Water cooling showed slightly more promise for the following reasons. The main advantage of water cooling is its ability to keep the electronics of the device far from the treatment area. The idea is you cool down the water in the case of your device and then circulate the cooled water in watertight tubes which filter through a cuff and cool the skin. One such cuff which implements a liquid cooling system is shown below (Fig. 12):

Figure 12: Water Cooling Cuff [7]

This cuff is sold with a separate cooling device which has tube outputs which connect to the cuff. A design like this allows for the cuff to be relatively lightweight and simple, and comes with a controlling device that allows for temperature control. Some existing products are also reasonably priced, costing hundreds, not thousands, of dollars. The Thermalzone system that goes with the cuff shown above is $550, for instance. However, the existing products would not be able to meet all of the training room's desires for a product. The temperature regulation that exists lacks quick and easy presets which follow a temperature curve optimal for healing. The device also requires the user to add water for the product to work. The use of water also leads to the potential for the system to leak, which can be messy and hard to repair. Using water also increases the time the system needs in order to get to the desired temperature. One system diagram we considered is shown below in Figure 13:

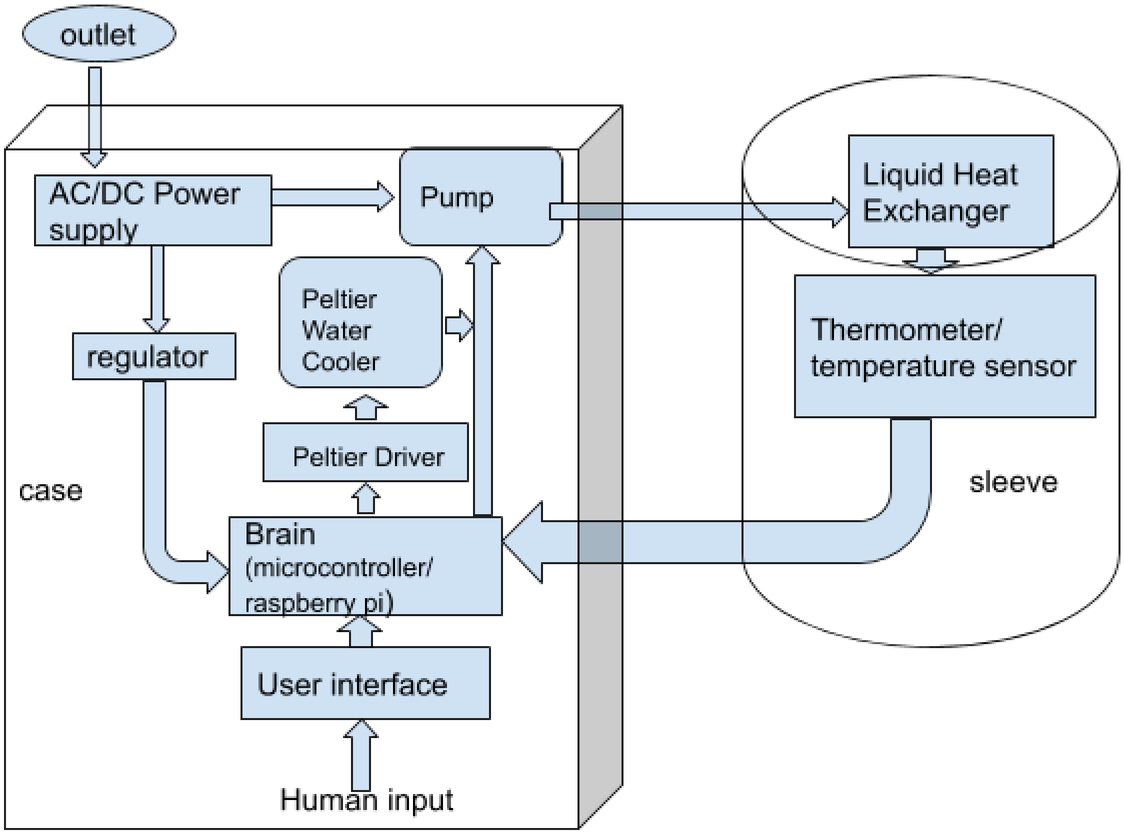

Figure 13: Water Cooling Approach

The last approach we considered was direct electric cooling, in which thermoelectric modules would be applied to the surface of the cooling cuff. Of the three approaches we considered, this was the only one where we were unable to find a commercial product which used it. There were, however, many studies which showed the feasibility of the method using peltier coolers[12][13]. There was also a pre-commercial product, the Recoverx [17]. The main disadvantage of this method is its requirement that the peltier coolers be close to the surface of the skin. This means that both the peltier coolers and the heat sinks would have to be located in the cooling cuff, which increases its weight and bulkiness. However, this comes with key advantages to offset this drawback. Firstly, the system does not use any water to operate. All it needs is a wall outlet and the system does the rest--very few systems on the market can say the same. Another advantage of the system is its simplicity. Every method has to cool things down, but air and water based methods also have to transport the cooled fluid to the area that needs to be cooled. The elimination of this step makes the implementation easier. This method can also provide temperature regulation, be easy to clean, and run for long stretches of time. For these reasons, we choose this general approach to providing cooling.

With this decision made, there were a lot of smaller alternate designs that we considered. A very important question was how to drive the peltier coolers. There are many chips that already exist that are designed specifically to drive peltier coolers. We were also capable of building our own simpler driving device. Buying a device to drive the peltier units comes with many advantages. Firstly, buying a system allows us to have access to something many times more complicated than anything we could hope to build. This complexity can give the chip things like thermal shutdown capabilities, fine-tuning control options, and enhanced efficiency compared to a system we might build. It also could come with application notes, which detail recommended ways to design peltier systems around the chip, and which could help us make design decisions. We researched some options for possible TEC, or thermoelectric cooler, drivers.

The first option we considered was the chip used by the Texas Instruments application report on driving peltier units, the TSP54200 [18]. However, this driver was designed for driving LEDs and would require a lot of alteration to make it applicable to our project [19]. On the expensive side, we were able to find a 28V 15A peltier driver with many customizable features [20]. However, these units were over $300 each and would require powerful and expensive peltier units, and we assessed that the cost would not be worth it. It was also apparent that buying one of these would require a great deal of correspondence with the manufacturer, which was undesirable. The MAX 1969 peltier driver occupies a middle ground between these two extremes [21]. They are around $20 each, capable of providing up to 30W of power each and include detailed application notes. Their main downside is they are only capable of using low voltages below 6V. It became clear that if we were going to buy a TEC driver, it would be the MAX 1969. The application notes that our design would have been based on had we used this chip are shown below (Fig. 14):

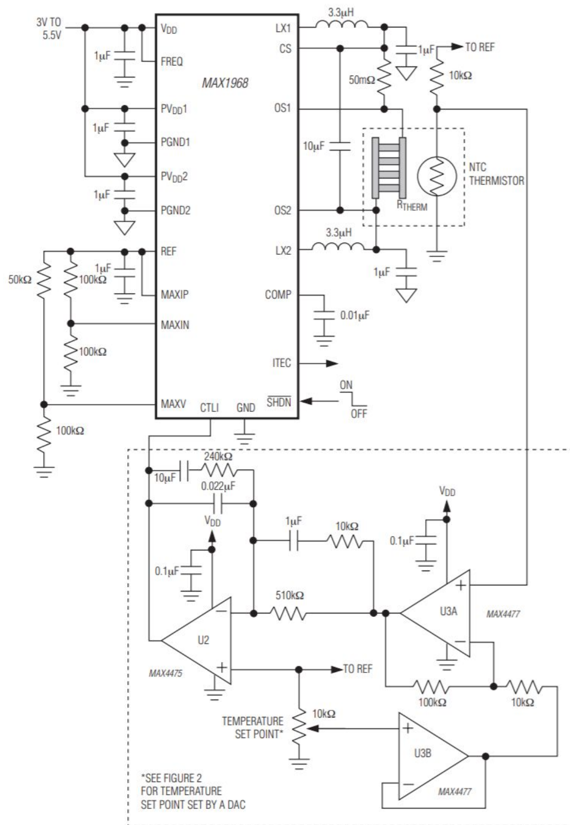

Figure 14: Alternate Design Application Notes

However, as mentioned before, driving the peltiers with a prebuilt chip comes with many downsides, and we were eager to have alternatives. For this reason, we also considered possible ways to build our own peltier drivers, which proved to be feasible. In the end, we did decide to build our own peltier driver, for a number of reasons. The biggest of these was the difficulty of building around a chip like the ones we had been looking at. The package these chips come in was simply not very conducive to small scale soldering. Trying to obtain the chip pre-soldered to all the relevant components would also be expensive and require correspondence with a company to achieve, which, again, is undesirable. The complexity of this chip, which earlier was an advantage, can also be a downside. The larger and more complex the chip, the more difficult it is to connect and the harder the system as a whole is to build. There is also the possibility that the complexity could reduce our understanding of the minutiae of our system, which would make troubleshooting and testing more difficult than they would otherwise be. For these reasons, we decided to forego the benefits of buying a TEC driver and build one ourselves, which we detail further in the design section.

User Interface:

In order to control the various components of the product, some kind of programmable device would need to be used to serve as the brain of the machine. Therefore, research was done to choose the type of processor needed, given the specifications required. We considered the pros and cons of each option, most heavily considering an Arduino Uno Wifi or a Raspberry Pi 4. The machine would need to complete multiple processes simultaneously, such as read an input temperature from a thermistor, output a signal to the temperature control unit, and power the controls of the interface. It would also need to not consume an excessive amount of power, be available at a reasonable price, and be able to handle the commands needed to be executed. First, when considering the power consumption of each device, a Raspberry Pi can consume up to 3A, while an Arduino can consume up to 500mA [22]. Though the Arduino draws significantly less current, it would not be unreasonable to supply the Raspberry Pi with 3A if needed. Therefore, either could be used. Next, we found that both fell within a price range of less than $100, which we felt was reasonable, and were compatible with various accessories such as displays and chips.

The most important requirement was the device's ability to complete the required tasks such as reading signals and writing output signals while maintaining a functional user interface. The Raspberry Pi is characterized as a mini-computer with its own operating system that can execute complex tasks simultaneously, while the Arduino is a microcontroller that can complete simple tasks one at a time [23]. Given the complexity of our intended system, the Raspberry Pi is the clear choice for the brain of the athletic recovery device since it will have to monitor and control multiple systems simultaneously.

There were a few different directions we could go in terms of designing a physical user interface. For example, we could develop a web site that the Raspberry Pi could connect to via the internet, or we could create a graphical user interface (GUI) program to be executed. Specifically, the technical work behind a website and a GUI would involve a combination of the HTML/CSS and Python programming languages, respectively. First, we considered the main characteristics of web design: accessibility from different devices and navigation tools. The nature of the internet lends itself to being available on all sorts of hosts, such as laptops, phones, and touch screen tablets. In the training room environment, it was communicated by the trainer that controlling the machine from an external device would not be convenient or useful [1]. Additionally, designing for a web page would not have an advantage in this situation given that the controls would only be accessed by the recovery device itself. A characteristic of web design is that it allows the user to be in control of their navigation; since the only application that the user needs will be the interface itself, there is no need for the user to have this ability to engage with external pages [24]. To understand not just why the web page wouldn't be ideal, but why a GUI would be, we must consider the qualities of a GUI. There are a multitude of frameworks that support GUI development for the Raspberry Pi. For example, guizero library, Kyvi Python, Electron, and Tkinter. The ideal specifications for a GUI framework compatible with a Raspberry Pi would be available in Python, offer many different widget options, and have a reasonable learning curve. To summarize the disadvantages of each framework, guizero has a limited options to cater to beginner designers, Kyvi Python requires previous knowledge of layout design, Electron uses an extensive amount of Node.js dependencies, and Tkinter appears outdated [25]. Even if the design is outdated, the effectiveness of the overall user experience that we have in mind would not be impaired, therefore Tkinter would be ideal. Overall, since there are no inherent advantages to web design, and the Tkinter framework would fit the requirements for a GUI developed on the Raspberry Pi, that is the option we decided on.

Power System:

There were two ways to go about the power system: design and build our own or purchase a premade one. If we were to construct our own, we would have needed to consider how to make our output either AC or DC based on what the loads demanded, look at how to step up or down the voltage, and how to regulate and isolate the systems. The different components that would need to be considered in a DC power supply connected to a wall outlet can be seen in Figure 15 below.

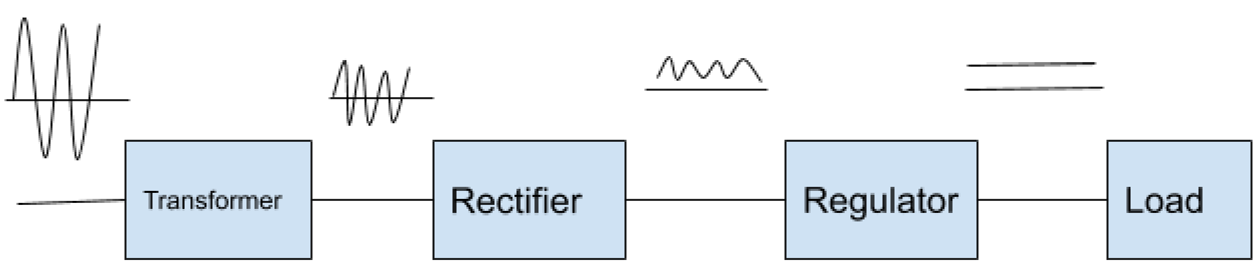

Figure 15: DC Power Supply Subsystem

The benefit to constructing such a system is that it could be more specifically designed to meet the needs of our intended system. The disadvantage of designing such a system would be that it would be very complex to build and it most certainly would not have all the built in safety features that a purchased one would include. The biggest disadvantage of purchasing a power supply would be its cost. In our situation, we expect to be dealing with a human patient and are expected to need roughly 40W, which could imply drawing many amps. Therefore, to ensure the safety of both the system and the user, the most reasonable choice is to spend the extra money on a pre-made power supply. The next difficulty from here is deciding which power supply to choose.

When it came to connecting various physical components together, there were various options available. There was screwing them together, clipping them together, or using some adhesive to stick them together. Since the system overall needs to be connected together such that thermal energy is transferred efficiently. At the same time, these would provide the most secure and firm connection between components. On the other hand, thermal adhesives would make it easy to apply, and depending on the adhesive, it may be strong enough to firmly hold the components together. In order to use screws and clips other pieces of equipment, such as a drip press, may be needed. Since this device will be resting on a stationary individual and not be used during vigorous motion, we decided to go with some form of thermal adhesive since it would be easier to apply, cheaper, lighter and could provide similar levels of thermal conductivity.

Design

Our final design involves the integration of three broad subsystems, whose structured block diagram can be seen in Figure 16 below.

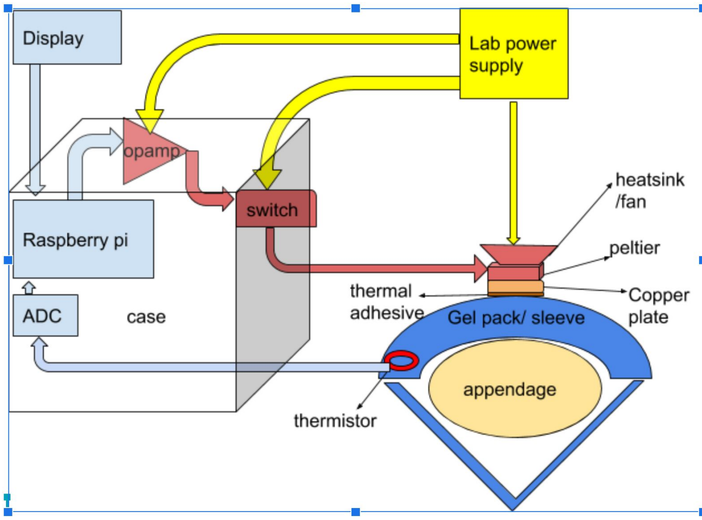

Figure 16: General Block Diagram

The three key subsystems for our design are arranged according to the following color scheme: red for components relating to thermal regulation, light blue for the user interface, and yellow for the power supply system. From here, we went into deeper detail about how each system was designed. Throughout the process we revisited our specifications to ensure we were meeting our requirements.

Thermal Regulation

The implementation of the thermal regulation system can begin with the overall motivation for the system. Mainly, the system must induce at least 40W of continuous heat transfer away from the human body, maintaining a temperature of at most 10ºC at the contact point with the skin. We decided to do this using a modular system to make testing and building the device easier and the device more effective. The device will ultimately consist of five identical modules each controlled by the single mini-computer and powered by the single power supply. The advantages of a modular system are manyfold.

One concern brought up early in our design process was the difficulty of ensuring the heat transfer away from the body occurs uniformly throughout the area being cooled. After all, peltier units themselves are relatively small in area, and could never cover the entire surface being cooled in the final design. This means that areas not directly underneath the peltier units will not be cooled as effectively as those directly underneath them. Having many separate peltier units mitigates this issue somewhat, compared to having one or few peltier units. The modular system also simplifies building and testing tremendously. Instead of having to build the entire system in order to begin testing, we can build a single module and perform tests on it and be confident the results will be applicable to our final design. In order to further mitigate the uneven heat transfer, we plan to have a 2”x1/8”x4” copper plate between the peltier and gel pack to help smooth out the heat transfer. A simplified diagram of the heat transfer is shown below (Fig. 17):

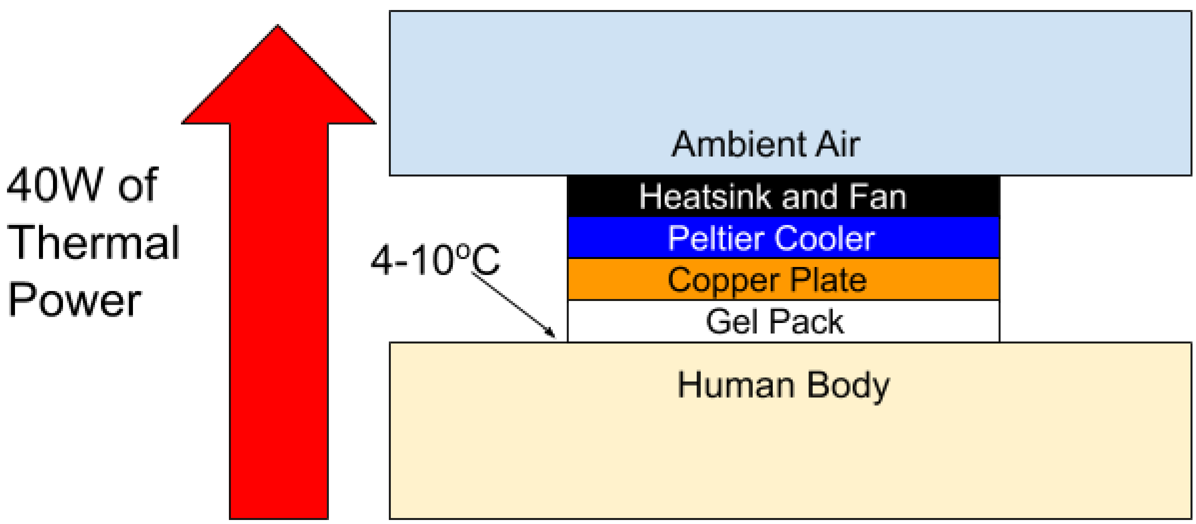

Figure 17: Thermal Transfer System

Peltier Coolers:

We can now look in some detail at the design of a single one of our modules, aware that five of them will be built in the winter term. We will begin with the choice of peltier unit, as this will largely determine the driving method used later on. As mentioned before, to ensure the heat transfer away from the body is as even as possible, there is a desire to employ a large number of peltier coolers. The two main options we considered were the TEC-30-38-71 and the TEC1-04905. The main difference between the units is that the TEC-30-38-71 is a slightly more powerful unit, requiring higher voltages of up to 8V to operate, compared to the lower operating voltages of the TEC1-04905 of up to 6V [26][27]. Another difference between them is the smaller unit is slightly more efficient. Though the units were similar, we chose the TEC1-04905 because of the preference for more, less powerful peltier units and the greater efficiency of the smaller units. Because the TEC requires voltages of above 5V and there will almost inevitably be some voltage drop across the driver, we also decided to go with a 12V power supply to make sure there will be enough voltage to run the peltiers at their rated conditions. With that decided, we could finally turn to the design of the peltier driver itself.

Peltier Driver:

One fundamental thing to understand is that peltier coolers are current driven systems. That is, their effectiveness is directly related to the current passing through them. It then made a lot of sense to drive the peltiers with an adjustable current source, to give the most flexible and direct control over the peltier units. The planned circuit diagram for this adjustable current source is shown in the Figure 18 below:

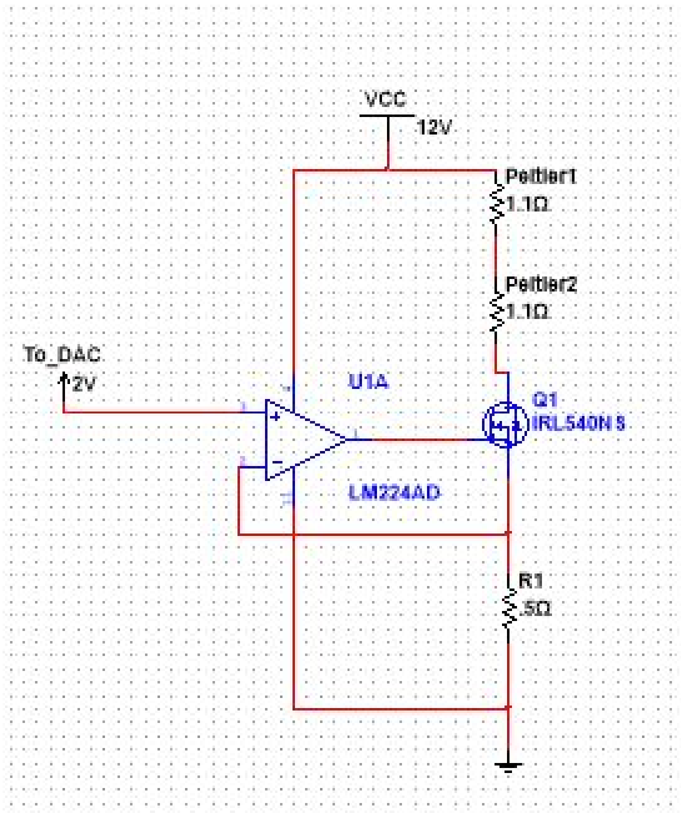

Figure 18: Adjustable Current Source

From this diagram, some implementational details become clear. Firstly, the control input comes from a digital to analog converter which will give an output voltage between 0V and 2.5V. This will set the current source to provide between 0A and 5A. Here, the peltier units are modeled as resistors. This is a slight simplification, as the effective resistance of the peltier units changes slightly both with ambient temperature and the temperature gradient across them. However, this change is small and the system still works reasonably well even in the worse case. We chose to use a power MOSFET for the design, the IRL520NPbF, which can handle up to 10A and has a low $R_{DS,ON}$ of below 0.3Ω even at high currents. Because we chose to use a MOSFET, the op-amp we chose had no current requirements and we were able to just use one from one of Professor Buma's labs. Finally, it is important to note that we chose to have two of our small peltiers wired to each current source in series. This lets us further spread out the peltiers without increasing the number of current sources needed, which will save money and building time.

Temperature Sensor:

The next important feature to design was the thermistor temperature sensor. Luckily, the design we settled on was very similar to one from one of Professor Buma's ECE 386 labs, so we were able to borrow some of his components. The design uses only an instrumentation amplifier, a thermistor, and various resistors. The planned circuit diagram is shown below (Fig. 19):

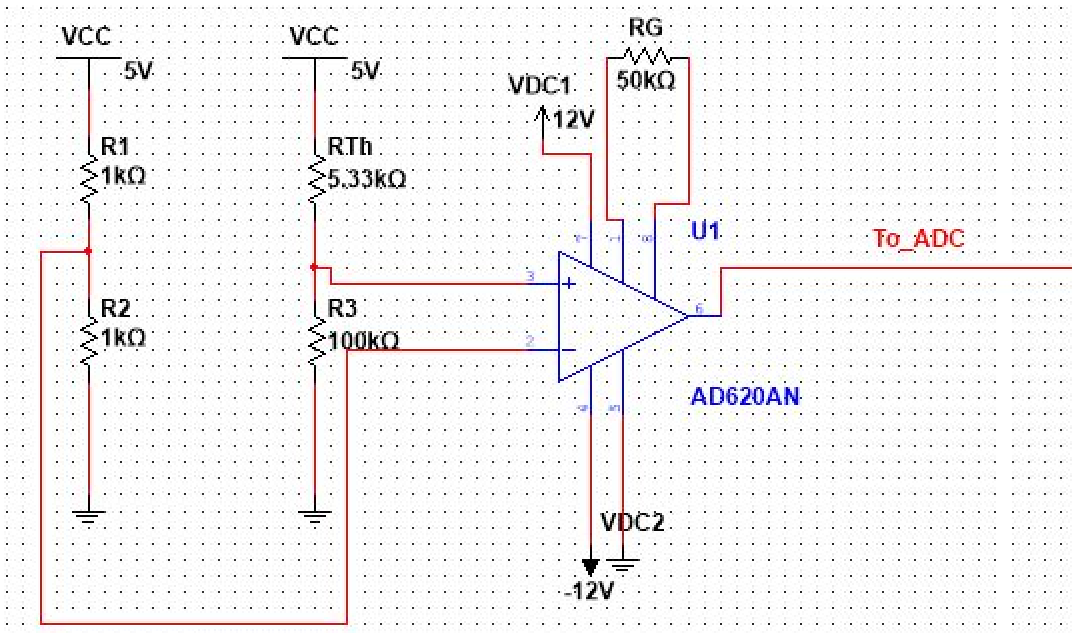

Figure 19: Temperature Measurement System

One important thing to mention is that the Raspberry Pi cannot handle analog voltages directly, so the output signal must be routed through an analog to digital converter before being read. Each module in our final design will have one thermistor temperature sensor. We wanted each thermistor to be able to measure temperatures ranging from -20°C to 40°C. According to the thermistor's datasheet, this corresponds to thermistor resistances(R_T) of 96.36kΩ and 5.33kΩ respectively [28]. Since we wanted the output of the temperature sensor to be a value between

0V and 5V, we designed the voltage divider for the non-inverting input to vary from around 2.5V to around 5V, set the inverting input to 2.5V with a voltage divider, and set the gain to 2 with a gain resistor of 50kΩ.

Heat Sinks:

One last consideration is which heat sink to use. It is critically important that the hot side of the peltier coolers remain reasonably close to the ambient temperature. The greater the temperature difference across the peltier coolers, the less power they can provide. Keeping in mind that the peltiers will likely operate at around 40% efficiency, the heat sink of each peltier will need to dissipate 10W of power [26]. Given this, we chose the HSF-55-33-B-F, which includes a fan and has a thermal conductivity of 0.6 ^{o}C/W [29]. This means that at full power, these units can keep the hot side of the peltiers less than 6^{o}C above the ambient temperature. A diagram of the system surrounding a single peltier unit is shown below (Fig. 20). Recall that the final product will include 5 modules, each with 2 peltier coolers, two heatsinks, and one temperature sensor.

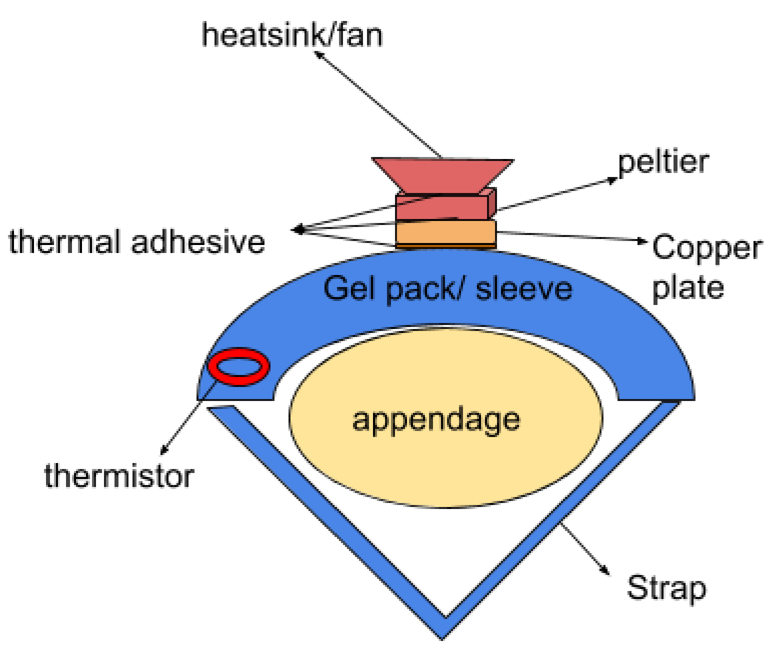

Figure 20: Thermal Regulation System

User Interface:

Input Signal

The user interface for this project involves the implementation and integration of both software and hardware components. The external inputs to the system include a signal based on the temperature on the surface of the sleeve and the output of the user interface system converts the input signal to drive the thermoelectric cooling module. A more detailed block diagram of how the input from the thermistor is processed, which will be elaborated on in the coming passages, is shown in Figure 21 below.

Figure 21: Thermistor Signal Processing

In order to better understand how the signals of the thermistor would interact with the input to the Raspberry Pi, research was done to learn how these devices communicate. First, we learned about the specifications of the NTC Thermistor we were supplied with, which we will use to take measurements on the exterior surface of the gel pack. An NTC (Negative Temperature Coefficient) Thermistor will exhibit a resistance that decreases as temperature increases and will be known with an accuracy of 0.5 degrees C over temperatures ranging from 0 to 50 degrees Celsius. This output signal as a resistance value will be converted to a temperature using the Steinhart-Hart equation. As shown in the Raspberry Pi 4 documentation, the general-purpose input/output pins (GPIO) are digital (3.3V high and 0V low) [30]. Therefore, we will need to do analog to digital signal conversion. Since the Raspberry Pi does not have hardware to do this conversion built in, an external ADC will be used, specifically the chip

MCP3008 [31]. For the software needed to convert this signal, Python code for Serial Peripheral Interface (SPI) will need to be implemented on the Raspberry Pi to read external analog devices.

Physical Interface

Once the Raspberry Pi kit and the touchscreen were delivered in the latter half of the term, we connected the two so that the Raspberry Pi now had its own physical monitor in the form of a 7 inch touch screen. Next, we tried to begin to download software packages on the Raspberry Pi through the Linux terminal. First, we had to download a virtual keyboard, since we didn't have access to one. After difficulties with SSH-ing into the Raspberry Pi, we instead chose to copy the commands onto a txt file which I downloaded on a USB. Since Union's residential WiFi requires the device to be registered for use, we found the MAC (Media Access Control) Address to utilize the MyResnetLegacy connection. Using the commands, `sudo apt update; sudo apt upgrade; sudo apt install matchbox-keyboard`, we were able to successfully enable a virtual keyboard. Next, we enabled the SPI and I2C Interface setting in the Raspberry Pi Configuration menu. From here, we will download the software necessary to communicate with the MCP3008 so that we can obtain an analog signal from the thermistor.

Reading Analog Signal from ADC

As shown in the document "Analog Inputs for Raspberry Pi Using the MCP3008", the packages for pip3, adafruit-blinka, and mcp3008 must be installed [1]. Then, a Python script is used to read the analog value, convert it to a range, and print the new output to the Pi. Using the wget command, followed by the url containing the python code, the script is saved to the Raspberry Pi and can be accessed using the following command `sudo python3 ./Analog_Inputs_for_Raspberry_Pi_Using_the_MCP3008.py`. Next, we implemented the hardware component for reading an analog input from a trimpot using the MCP3008; this circuit is shown in Figure 22.

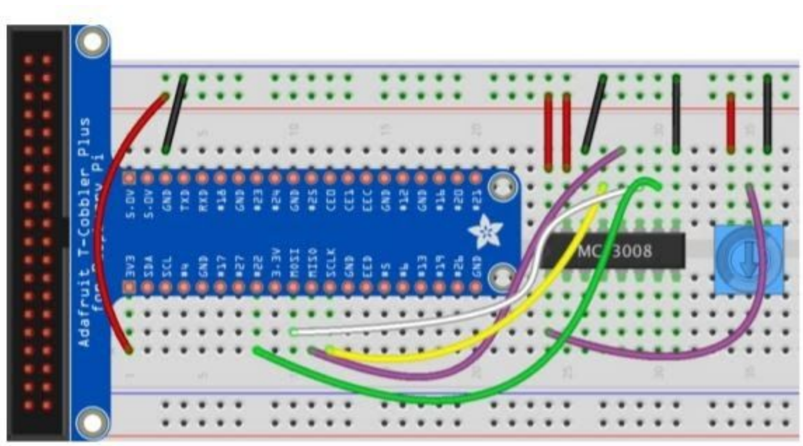

Figure 22: Circuit for Reading Analog Input from Trimpot using ADC

After running the Python code from the source above with the trimpot circuit, we were able to read the signal and print to the Raspberry Pi terminal (Figs. 23 and 24).

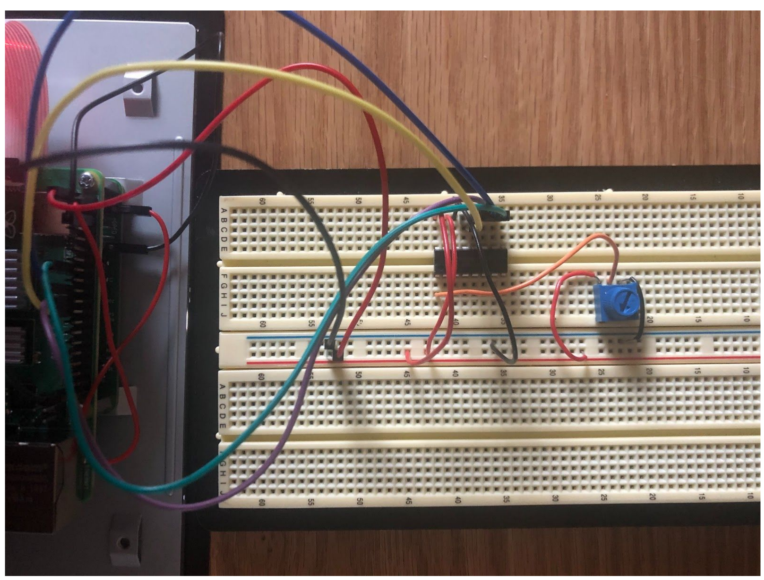

Figure 23 Implementation of ADC Circuit

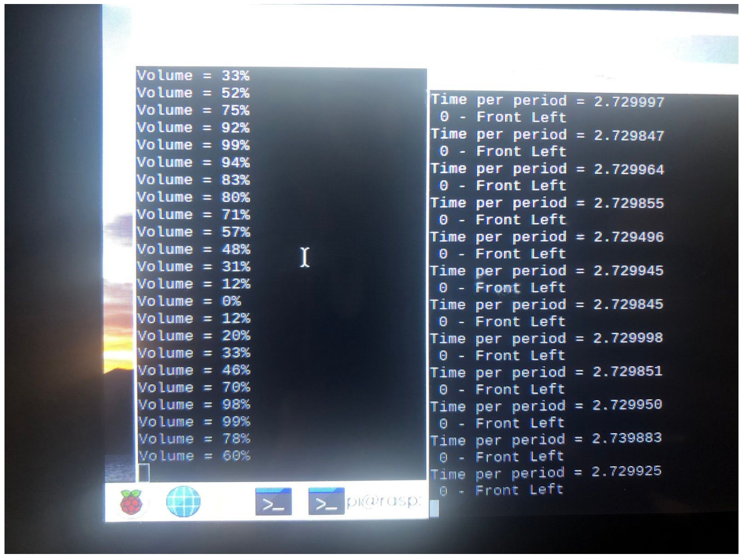

Figure 24: Terminal Output of Trimpot Signal

Obtaining Temperature Value

Next, we began to configure the signals to the Raspberry Pi from the value of the thermistor. Using the datasheet for the Vishay 103 NTC Thermistor, we found three temperature (°C) to resistance (kΩ) points to plug into a systems of equations solver for the three coefficients (x, y, and z) of the Steinhart-Hart equation: $T = [x + y\ln(1000R) + z\ln(1000R)^3]^{-1} - 273.15$ (Fig. 25).

$$\left\{x + 9.21034\,y + 781.31658\,z = \frac{1}{298.15},\; x + 11.47585\,y + 1511.3122\,z = \frac{1}{253.15},\; x + 7.82004\,y + 478.21874\,z = \frac{1}{333.15}\right\}$$

Result:

$$\{x + 9.21034\,y + 781.317\,z = 0.00335402,\; x + 11.4759\,y + 1511.31\,z = 0.00395023,\; x + 7.82004\,y + 478.219\,z = 0.00300165\}$$

Solution:

$$x \approx 0.00113414, \quad y \approx 0.000233106, \quad z \approx 9.32975 \times 10^{-8}$$

Figure 25: Solving Coefficients of Steinhart-Hart Equation

We then designed a circuit, shown above in Figure 19, that would let us read the thermistor resistance and output an amplified voltage to the analog to digital converter (ADC). Using this voltage, we would convert to the internal resistance of the thermistor, in order to find the temperature from the equation above. In order to know how to convert the output voltage from the temperature sensor into a resistance, R_T, we analyze the circuit shown in Figure 19. We know that the output voltage is the difference between the non-inverting and inverting inputs multiplied by the gain, which is two:

$$V_{OUT} = 2[\frac{100k\Omega}{R_T+100k\Omega}(5V) - 2.5V]$$

Then, we can simply solve for R_T:

$$R_T = \frac{5V(2)(100k\Omega)}{V_{OUT}+2.5V} - 100k\Omega$$

Note that despite the output bit length of the signal, the ADC will convert the value to 16 bits, which yields a range of 0 to 65535. The ADC has eight output channels, and the output can be either a raw voltage (chan0.voltage) or a scaled 16 bit value (chan0.value). By obtaining a voltage from the amplifier circuit connected to the output of the thermistor and reading that from the ADC output to the Raspberry Pi, we were able to successfully interpret temperature values from the NTC Thermistor.

Output Signal

Depending on the value of the temperature from the input signal, code will be developed in the upcoming term to determine the value of the output signal from the Raspberry Pi, which will be used to control the thermoelectric circuit. As explained earlier in the "Thermal Regulation" section, the method we will use to drive the peltier system is a continuous current method, which would require an analog input, but provide greater flexibility and increase the efficiency of the peltiers. Since we wish to use a MOSFET for a variable current source to the peltiers, we need a 0 to 5V analog signal. Since the output of the Raspberry Pi is digital and we need a 0 to 5V analog signal (which will be the input to Fig. 23), we will need a digital to analog converter (DAC) with I2C configuration [32][33]; this hardware will be implemented next term.

To clarify, there are different types of software that would allow for serial communication between the converters and the Raspberry Pi, predominantly SPI (Serial Peripheral Interface) and I2C (Inter-Integrated Circuit). Half-duplex is the term for one way communication at a time between devices, rather than full-duplex, which can go both ways simultaneously. For our device, the communication will only need to go in one direction, therefore half-duplex (I2C uses) will suffice (SPI uses full-duplex). When communicating with more than two devices, SPI can get complicated due to the need for individual chip select (CS) lines. I2C, on the other hand, can handle many devices at the same time without wiring difficulties. Given that the chip for the ADC supports SPI and the chip for DAC supports I2C, we will use SPI for the software for the input signal and I2C for the software for the output signal.

Graphical User Interface

For the interface, the user must be able to communicate with the device in an effective and safe manner; Figure 26 below shows a draft of the physical user interface for controlling the device.

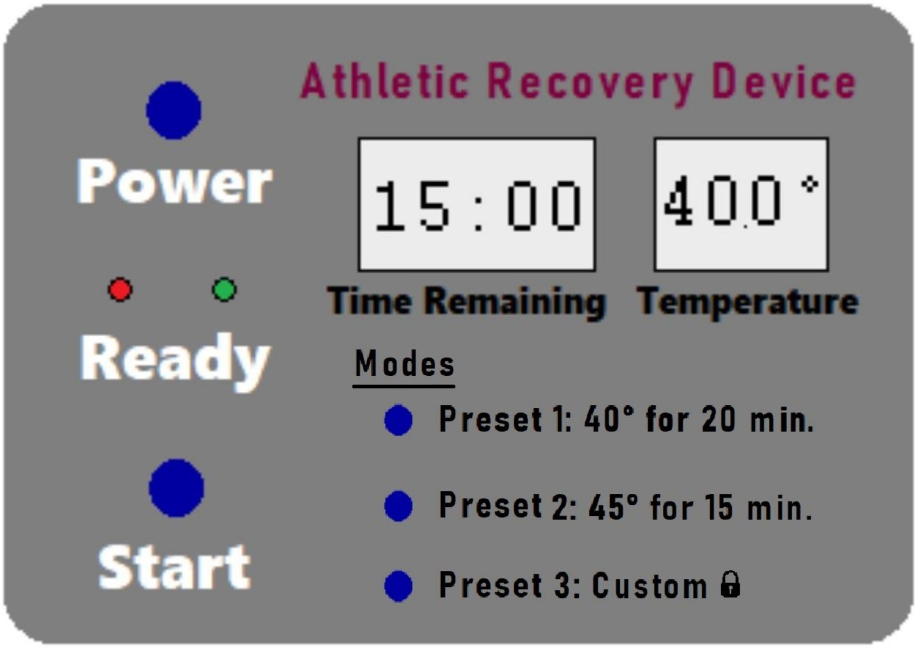

Figure 26: User Interface Appearance

For the physical command board shown above, which will be implemented with a touchscreen display, there will be an on/off button, a red light to indicate that the cooling system is not ready, a green light that will turn on when the system is ready, a treatment start button, a display for the current temperature, and a display for the time left in the treatment period. Below each of the displays will be two preset treatment options, the third option will be a passcode locked customizable preset. For the user to be able to control the device through the touchscreen display, a python script using Tkinter framework will be developed.

Power System

Power Supply

In order to choose the appropriate power supply it was essential that the load requirements be clearly specified. For the thermal regulation we are expecting to use 10 peltier units. The peltiers that have been selected, while current driven, require a DC voltage. At maximum they are expected to run at 5V and 5A. We intend to lay them out as shown in Figure 27, where there are 5 parallel sets of two peltiers in series, with each set connected to a current source. The internal resistance of the current source and peltiers in series is expected to consume roughly 2 volts.

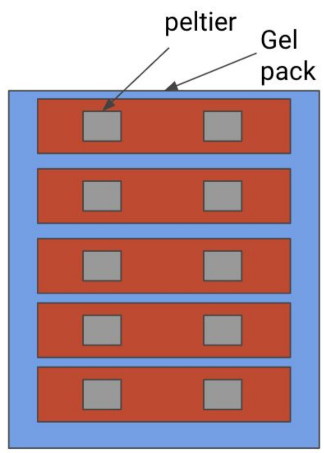

Figure 27: Peltier Layout

Since each set of peltiers is expected to draw a max of 5A and there are 5 sets we are expecting a maximum current draw of 25A. At the same time, since each one consumes 5V and we expect 2V to be consumed by internal resistance, the overall voltage going into each set needs to be 12 volts. Furthermore, the heat sink fans that have been selected need 12VDC in order to work. Thus the overall thermal load requirements are 12 and 25Amps. This means that a power supply we selected needed to have at least a 50A current rating, and output 12VDC. As for the Userinterface, the Raspberry Pi 4 that has been selected needs a 5 volts DC and a minimum of 3amps in order to operate.

Power Distribution and Connection

Since both the thermal and user interface load requirements differ significantly, and deal with such large values, it is essential that both are properly isolated from one another. This means that the power supply we selected needs to have multiple channels in order to properly isolate the two systems. Furthermore, since the Raspberry Pi required a lower voltage, a voltage regulator that could step down the voltage and handle the required amount of current also needed to be selected. Our load requirements for our power supply include a 12VDC power supply that had multiple channels and had a current rating greater than or equal to 50A.

In the end we selected the SE-600-12 power supply, as seen in Figure 27, since it met all our load specifications. This is a 12VDC power supply, with three channels, and 50A current rating. Furthermore, this power supply has a built-in fan making it so we do not need to worry about cooling it [34]. Regarding a voltage regulator for the Raspberry Pi, we chose the Drok 5A USB voltage regulator. This regulator can step 12V down to 5V and can provide between 3 and 6A. In addition, it has a built in USB port which makes it capable of easily connecting to the Raspberry Pi [35].

Figure 28: SE-600-12 Power Supply

Since we are dealing with such high current draws, we needed to determine which wires we were going to use to connect the components. To do this we referenced this source [36], which lists out the current rating for different wire gauges. Unlike selecting a power supply that has a current rating double the expected maximum current draw, as the current rating of a wire gets bigger so does the actual wire itself. Larger wires get cumbersome when trying to wire a circuit and figure out if pin holes are too small for a given wire. This means that when selecting a wire, one should be just a little bit over the expected current. By looking at this site and knowing that we expect the maximum current to be 5A, we can determine that 20AWG is the ideal choice since it has a current rating of 6A and is still fairly small and able to fit into our breadboards [36]. This would also work for connecting the power supply to the voltage regulator. At the same time since the selected power supply only has three channels and we will need to power five sets of peltiers we needed to get a cord that had five conductors so that one channel could neatly be able to power five sets. In addition, each wire for the power supply pelter connection needed to be of a higher rating. There are two reasons for this. Firstly, they need to have higher current ratings to account for the current drawn by the heat sink fans. Secondly, it is a good idea to have a higher current rating for the wire between the system and power supply, to deal with any large transients or inrushes that could occur. For this reason we are choosing to go with an 18AWG-5 conductor wire [37]. This is the next level above the 20AWG which is already going slightly above what is expected to be drawn.

In order to connect everything together, we settle on using some sort of adhesive. The two options we could have gone with were some paste or double sided thermal tape. We decided to look into tape since it would be less messy and easier to apply. The most important feature we were looking for was the smallest thermal coefficient and ability to hold the system togher. As a result, we selected LLPT double sided Thermal Conductive tape, shown in Figure 29, since it had the smallest thermal coefficient we could find for tape [38].

Figure 29: LLPT Double Sided Thermal Tape [38]

While double sided copper tape may have had a smaller thermal coefficient, the price was too high to consider it. While there were initial concerns about whether the tape would be strong enough, preliminary tests quickly resolved all concerns.

Container and Sleeve:

For the container we needed to choose a case that could hold all the expected electronics including the power supply, Raspberry Pi 4, and the peltier drives. In addition, it needed to be made of a material that was insulating and durable. In the end, we selected the junction box seen in Figure 29 below because we believed it would be of the right size, and allow for easy wiring access [39]. That being said, we still need to figure out how we will cut out space in the container to place the fans to cool other electronics in the case and the touchscreen to allow for convenient user access.

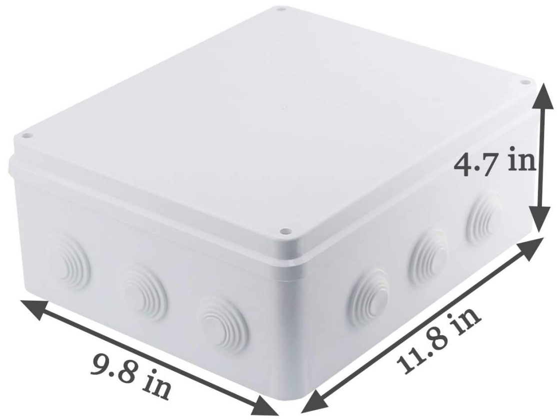

Figure 30: Case For Electronics

Regarding the pack, we decided it would be best to choose a multi-compartmental gel pack. The reason for this is that it could both work with the sets of peltiers we are planning on making and could serve as a good way to prototype one system and then scale it up. In addition, based on the models we choose, we could get one that straps onto the user. The current gel pack we are using can be seen below in Figure 31 [40].

Figure 31: Current Gel Pack Sleeve [40]

Preliminary Testing

Interface Development:

Before we could begin our tests, progress was made developing the code to collect thermistor data and to designing the interface. First, a simple Tkinter program was created to test the ability to press a button on the Raspberry Pi screen to turn on an LED Light. Next, we decided to implement changes to the program that interprets the temperature from the thermistor. Using matplotlib, we were able to obtain graphs for the temperature vs the time for the length that the program was set to run. For each thermistor reading, the value of the temperature in degrees Fahrenheit and time in seconds from the start of the program is stored and exported to a .csv (comma-separated values) file. This data, along with all of the Python files, can be found on our personal seniorcapstone gitlab [41].

Current Source Testing:

We began our preliminary testing when our initially ordered components all arrived, with the exception of the peltier units. We were also able to get access to the 12V 18A power supply from Tech House for testing purposes seen in Figure 32. We began to build our test circuit, and came up with numerous tests to perform once we had the peltiers.

Figure 32: Tech House Power Supply

To begin, we set up the current source and took measurements to see if it operated as intended. We were able to successfully construct and test the current source at lower currents to protect the breadboard we used. The results for this test can be seen in Figure 33 below.

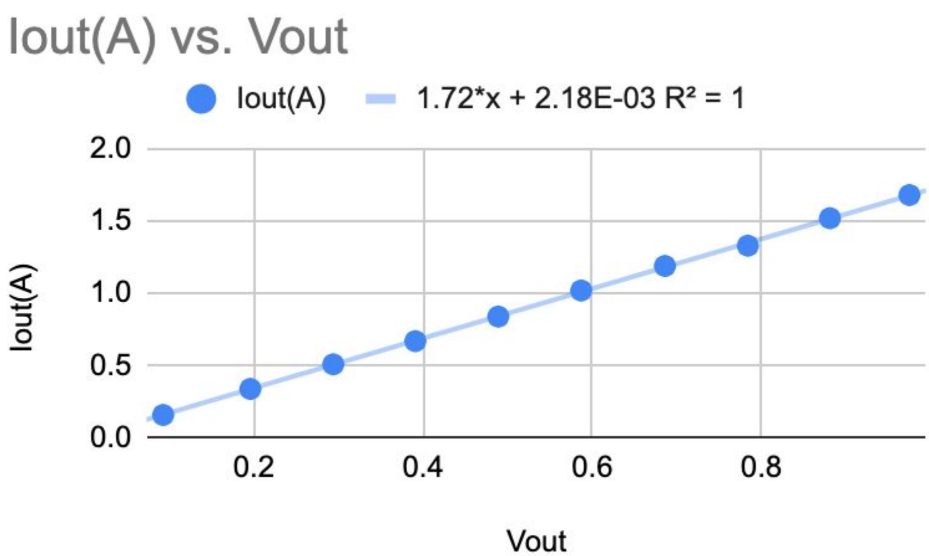

Figure 33: Output Current Versus Output Voltage

Here, the input voltage is the voltage that will come from the DAC in our final design. For this test, we used a potentiometer to achieve the same effect. The output voltage is the voltage across the resistors.

One issue we had with our current source was our inability to directly measure the resistance of the supposedly 1Ω resistors we bought for it. We built the circuit with two of the resistors in parallel between the MOSFET and ground, but when we tried to measure their resistance with our multimeter, it became clear that the ohmeter couldn't get accurate measurements at resistances that low. Luckily, from our tests of the current source, we were able to calculate the effective resistance of the two resistors in parallel. To do so, we simply took the inverse of the slope of the line of best fit of the graph shown in Figure 32. We calculated their resistance to be 0.58Ω, which is acceptable for our design, as long as we factor this value into our control program. When the peltiers had still yet to arrive, we acquired different peltiers from Gene Davison. We then tested to see if our circuit would work when a peltier and heat sink were implemented. As a result of these tests, we found our system was able to drive and control the peltier at reduced currents.

Thermal Tape Testing:

During this time, we also tested the double sided thermal tape to see if it had the durability and strength to hold everything together. Luckily, the tape proved to be exceptionally strong when bonding metal surfaces together. Unfortunately, the tape was so strong that we were unable to remove the peltier from the heat sink after it had bonded. This means that unlike screws and bolts that can be removed and adjusted, during construction we will need to be extremely careful, precise, and deliberate about applying the thermal tape.

Peltier Testing:

Once our peltier units arrived, we only had one heat sink left that was not powerfully bonded to a peltier unit because of the exceptionally strong thermal tape. To avoid repeating this, we decided that, for testing purposes, we would physically press the heat sink we had into the peltiers and the gel pack. For this test, we pressed the heat sink into two peltiers. For our final design, we intend for each peltier to have its own heat sink. However, because of the reduced currents we ran these tests at, and the reduced power consumption of the peltiers, one heat sink would be more than sufficient for our test. We were able to perform 4 separate tests in our first testing session. The general setup can be seen in Figure 34 below.

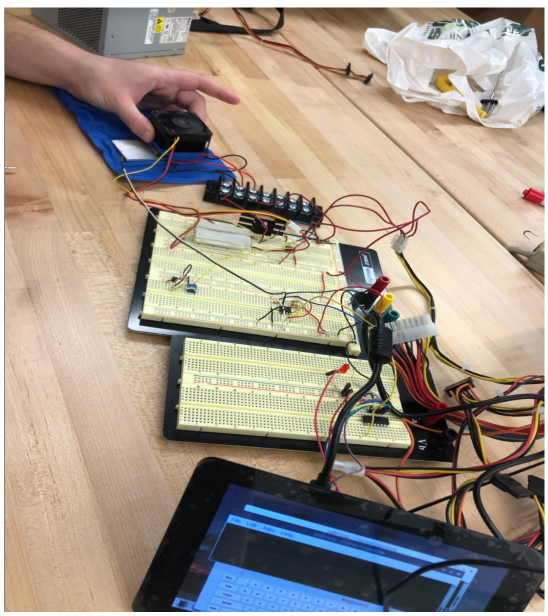

Figure 34: General Setup For Testing

The thermistor was placed in various locations, which we will state for each individual test, and the unit was pressed down on to create good thermal contact. We ran the peltiers with 1.5A flowing through them, or about 30% the maximum in our final design. We were able to read plots of temperature into the Raspberry Pi.

In the first test, we placed the thermistor between the peltier and the gel pack. The purpose of this test was to see the loaded response of the peltier unit itself. We were satisfied with how this test turned out, the peltier was able to get rather cold very quickly (Fig. 35).

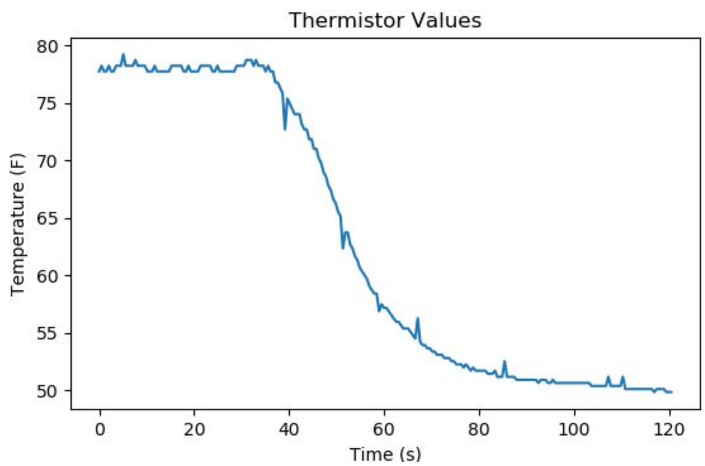

Figure 35: Test 1. Thermistor Directly Under Peltier For 2 Minutes

For the next test, we placed the thermistor between the gel pack and the table, directly underneath the peltier. We were pleasantly surprised that we saw temperatures of around 50^{o}F, or 10^{o}C by the end of six minutes, which is on the upper end of what we are aiming for in our final design (Fig. 36).

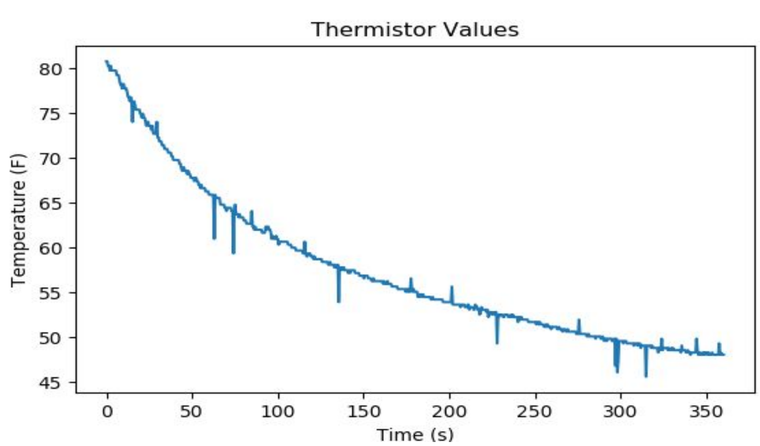

Figure 36: Test 2. Thermistor Between Table and Gel Pack - Directly Under Peltier For 6 Minutes

Encouraged, in our third test we decided to test our system on a live subject. Luckily, we had one lying around, and soon Herschel was hooked up to our device.

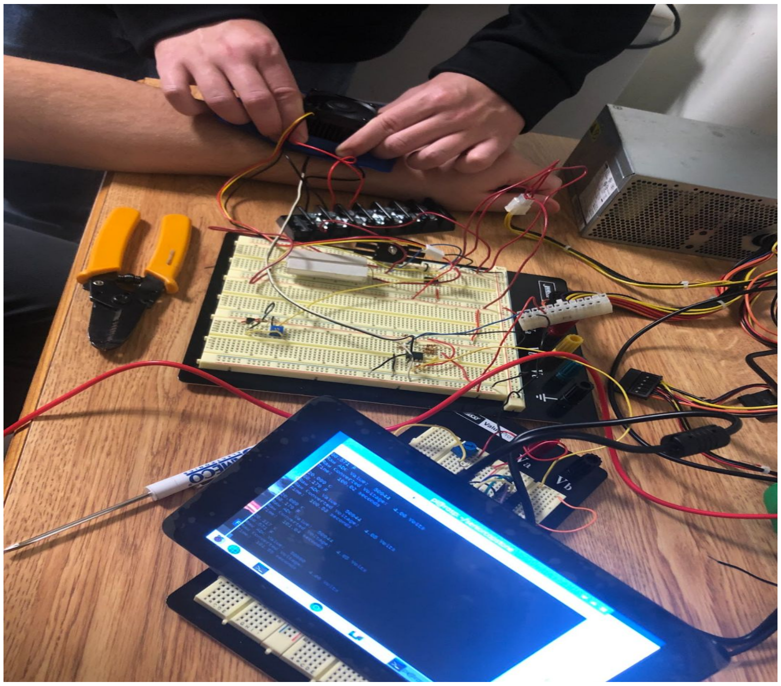

Figure 37: Gel Pack, Heatsinks, And Peltier On Herschel's Arm

For this test, we placed the gel pack on top of Herschel's arm and placed the thermistor between the gel pack and his skin as seen in Figure 37. After running it, we saw that the temperature got down to around 60^{o}F, which we thought was still promising given the lower power we were running our system at (Fig. 38).

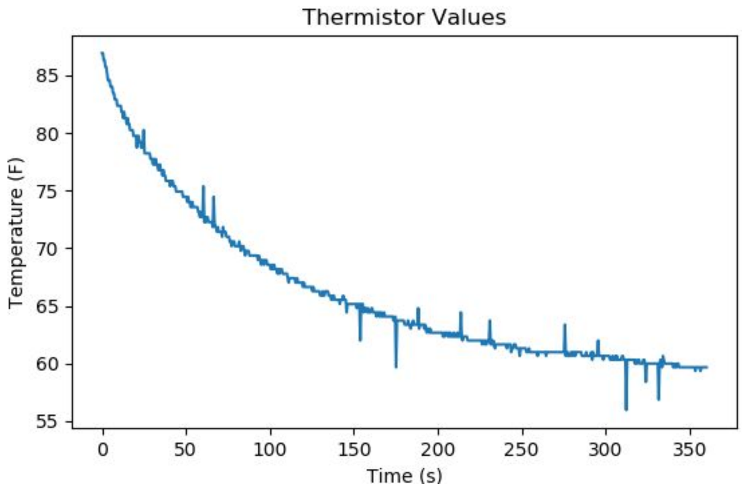

Figure 38: Test 3. Thermistor Between Table and Human Arm - Directly Under Peltier For 6 Minutes

For our final test, we decided to see how well the gel pack dissipates its temperature. We moved the thermistor three centimeters away from the peltier units and placed it under the gel pack. We made sure to apply pressure to both the thermistor and the peltiers to create good thermal contact. However, as Figure 39 shows, the temperature did not decrease at all. In the future, we hope to conduct more trials of this to ensure the validity of the result.

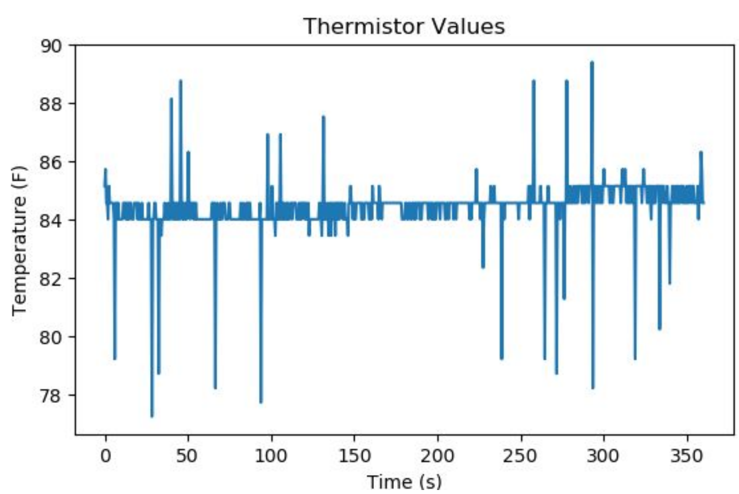

Figure 39: Test 4. Thermistor Between Table And Gel Pack - 3cm From Peltier For 6 Minutes

If the test results above are to be believed, our device may have a serious problem with uneven distribution of heat transfer. Fortunately, we considered this beforehand and already had a proposed solution. To mitigate this effect, we will place copper plates between the gel pack and the peltier units. Until we acquire the copper plates, we have used an aluminum plate from Professor Buma. Though aluminum has a thermal conductivity only about half that of copper, the dimensions of the plate were close to what we wanted for our final design. We repeated the set up of the second test of the system except with the aluminum plate placed between the peltier units and the gel pack; the results of this test are shown below (Fig. 40).

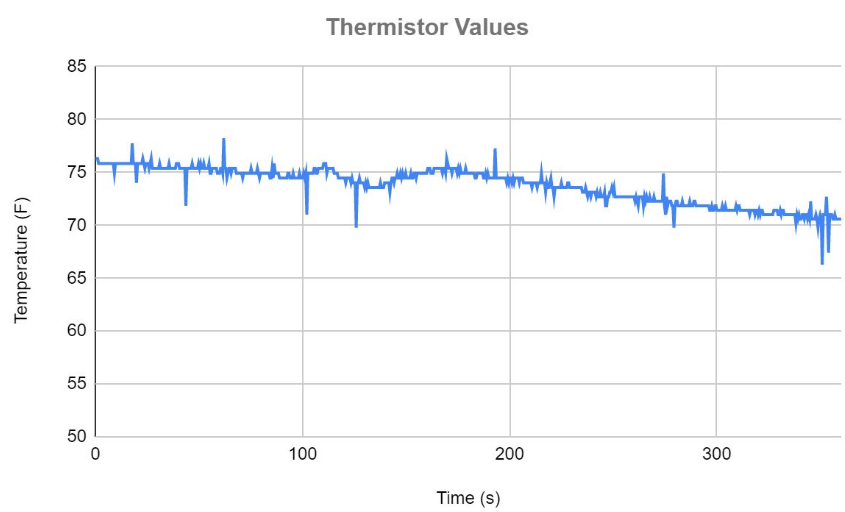

Figure 40: Preliminary Test #4. Aluminum Plate - Directly Under

Overall, the temperature dropped by only 5°F, which was much less than what we saw without the plate. This is likely due to a number of factors. Firstly, compared to our previous test, the peltier units were likely cooling a much larger area due to the plate. The plate itself also would have had a temperature gradient across it vertically, which could have also led to the decrease in cooling. Ultimately, there will be many factors to correct for this in our final design. We will be using copper instead of aluminum, which will cut the temperature gradient across the plate in half. Second, the peltier units will be running at higher currents, which will increase cooling power. Finally, we plan to use a thinner gel pack for the final design, which will decrease the gradient across the pack.

Our next test was to determine the effectiveness of the plate at smoothing out thermal transfer. We repeated the set up for the previous test, but we moved the thermistor 3cm from the edge of the peltiers, still underneath the gel pack; the results are shown below (Fig. 41).

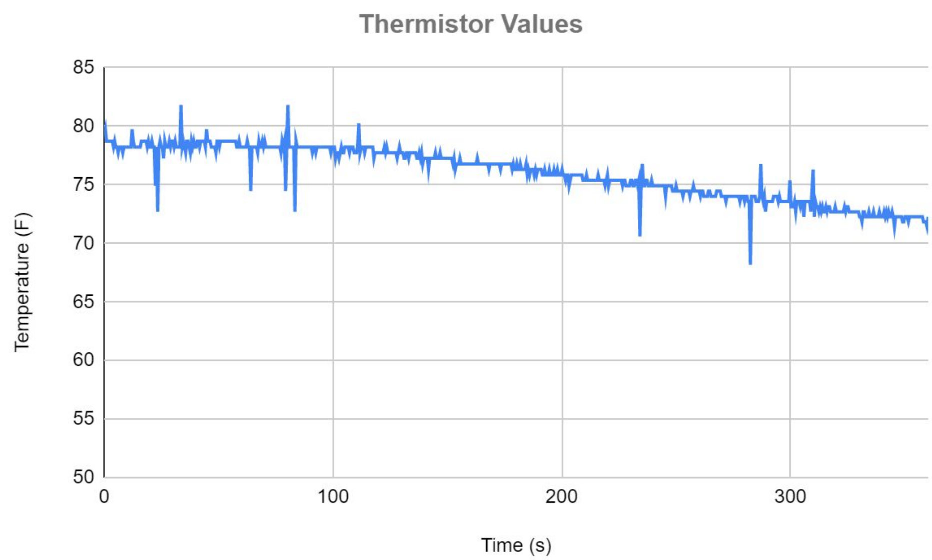

Figure 41: Preliminary Test #3. Aluminum Plate - 3cm Difference

These results are very promising. The system was able to cool down to nearly the same temperature seen directly underneath the peltier units. This stands in stark contrast to our fourth test in Figure 4. The temperature distribution should be even more smooth when we switch to using a copper plate in our final design.

Additionally, there are two issues with the gel pack that we are currently using which is causing us to have to choose a new gel pack. One is that all the compartments are not perfectly isolated from one another so there is flow between them. Secondly, the strap for this gel pack does not work with our intended system. We intend to select a new gel pack over the break. Once we have selected a new gel pack we will need to find a sleeve cover that can cover up all the wiring and fans to protect the user from harm.

Implementation Schedule

<u>Winter Break:</u>

- Cleaning up prototype breadboard wiring to make implementation easier.
- Choose components we still need and decide on implementation strategies. These components include perfboards, a different gel pack, a safety sleeve, external fans, and we will need to decide on methods to cut out space for the touch screen in the case.
- Testing certain parts of the system such as the outputs of the power supply and how to wire wall cable to power supply and power supply outputs to loads.
- Develop initial prototype of GUI on Raspberry Pi.

<u>Winter Term:</u>

Weeks 1-3: Scaling up prototype and constructing each electrical subsystem, ie. current sources, peltier drivers, and temperature sensor system. Since there will be many identical repeated sub-circuits in our system, this will focus on building these modules and making sure they operate correctly.

Week 4: Case and sleeve modifications. We will make needed adjustments for the case. This includes making a place to put a touch screen and spots for external fans. Furthermore we will set up how we will cover our sleeves.

Week 5-6: We will focus on layout and connection. This includes, for example, putting all components neatly in case and in sleeve and making all needed connection between all systems.

This will be centered on wiring everything together, making sure all wiring is firmly attached and all components on the sleeve are held totally together.

Week 7-8: Testing will be performed, taking measurements and monitoring systems and performances.

Week 9-10: Analysis and Write Up will be completed. The focus of these two weeks will be analysing the results of our testing and writing up our final report. This will also include visiting the Union College training room to get their feedback on the device.

References

[1] Rockwood, Cheryl; Crary, Jill, personal communication, Apr.-Nov 2020.

[2] Murray, A., Cardinale, M. Cold applications for recovery in adolescent athletes: a systematic review and meta analysis. *Extrem Physiol Med* 4, 17 (2015). https://doi.org/10.1186/s13728-015-0035-8

[3] Stöckle, U et al. "Fastest reduction of posttraumatic edema: continuous cryotherapy or intermittent impulse compression?" *Foot & ankle international* vol. 18, no. 7, pp. 432-8, Jul. 1997. [Online]. Available doi: doi:10.1177/107110079701800711

[4] *PowerPlay*, PowerPlay, 2019. [Online]. Available: https://powerplay.us/

[5] *Game Ready,* Avanos Medial, Inc, 2020. [Online]. Available: https://gameready.com/

[6] Source Ortho. (2020). *Breg Polar Care Kodiak Cold Therapy Unit*. retrieved from https://www.sourceortho.net/breg-polar-care-kodiak-cold-therapy-unit/

[7] Source Fitness (2020). *ThermaZone Temperature Therapy System.* Retrieved from https://sourcefitness.net/thermazone-thermal-therapy-system/?sku=003-99&gclid=Cj0KCQjw5eX7BRDQARIsAMhYLP8IOMaAxEn4RUb5t6uZJbQ541Pj74HGMQ-APQyfNO0Mc9hdtgukpGYaAkWXEALw_wcB

[8] *The Science Behind Refrigeration*, Berg Chilling Systems Inc., 2017. [Online]. Available: https://berg-group.com/engineered-solutions/the-science-behind-refrigeration/

[9] T.M.Tritt, "Thermoelectric Materials: Principles, Structure, Properties, and Applications", in *Encyclopedia of Materials: Science and Technology,* South Carolina: 2002, pp. 1-11, Available: https://www.sciencedirect.com/topics/chemistry/peltier-effect

[10] Gurevich, Yuri & Velázquez-Pérez, Jesús. (2014). Peltier Effect in Semiconductors. 10.1002/047134608X.W8206. Available: https://www.researchgate.net/publication/262179901_Peltier_Effect_in_Semiconductors

[11] H. Lu, "Peltier Temperature Controller," MEng. report, Cornell University, Ithaca, NY, 2013.

[12] Kordani, N., Rahmani, A., & Hasanzadeh, R. P. (2018). Smart Portable Cryotherapy System Involving Controlled Thermoelectric Cooling Modules for Medical Applications. *IIUM Engineering Journal*, *19*(1), 117-128.

[13]Mejia, N., Dedow, K., Nguy, L., Sullivan, P., Khoshnevis, S., & Diller, K. R. (2015). An On-Site Thermoelectric Cooling Device for Cryotherapy and Control of Skin Blood Flow. Journal of medical devices, 9(4).

[14] Okabe, T., Fujimura, T., Okajima, J., Aiba, S., & Maruyama, S. (2018). Non-invasive measurement of effective thermal conductivity of human skin with a guard-heated thermistor probe. *International Journal of Heat and Mass Transfer*, *126*, 625-635.

[15]Nicholas, J. J., Taylor, F. H., Buckingham, R. B., & Ottonello, D. (1976). Measurement of circumference of the knee with ordinary tape measure. *Annals of the rheumatic diseases*, *35*(3), 282-284.

[16] Zimmer MedizinSystems. (2020). *Cryo 6 Air Chiller Device*. Retrieved from https://zimmerusa.com/products/cryo-therapy/cryo-6/

[17] RecoverX. (2020). *Electric Cold and Heat Therapy in 60 Seconds.* Retrieved from https://www.recoverx.io/

[18] Melin, O. (2019) *Driving a Peltier Element(TEC): Efficiency and Aging* (Application Report No. SLUA979A) Retrieved from

https://www.ti.com/lit/an/slua979a/slua979a.pdf?ts=1601492867207&ref_url=https%253A%252F%252Fwww.google.com%252F

[19] Texas Instruments, “TPS54200, TPS54201 4.5-V to 28-V Input Voltage, 1.5-A Output Current, Synchronous Buck Mono-Color or IR LED Driver”,TSP54200, June 2018. Retrieved from: https://www.ti.com/lit/ds/symlink/tps54201.pdf?ts=1601495369446&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTPS54201

[20] Analog Technologies, “High Voltage High Current TEC Controller”, MAX1969, August 11, 2020. Retrieved from:http://www.analogtechnologies.com/document/TEC28V15A.pdf

[21] Maxim Integrated Products, “Power Drivers for Peltier TEC Modules”, TEC28V15A, May 2015. Retrieved from:https://datasheets.maximintegrated.com/en/ds/MAX1968-MAX1969.pdf

[22] Pounder, Les. “Raspberry Pi vs Arduino: Which Board Is Best?” *Tom's Hardware*, Tom's Hardware, 10 July 2020, Retrieved From: www.tomshardware.com/features/raspberry-pi-vs-arduino .

[23] Raspberry Pi vs Arduino: Top 10 Useful Differences You Need To Learn. (2020, August 10). Retrieved November 21, 2020, from https://www.educba.com/raspberry-pi-vs-arduino/

[24] Experience, W. L. in R.-B. U. (n.d.). *The Difference Between Web Design and GUI Design*. Nielsen Norman Group. Retrieved November 21, 2020, from https://www.nngroup.com/articles/the-difference-between-web-design-and-gui-design/

[25] Shturma, S. (2020, May 26). *Pyxis by Renetec, Inc.* Renetec, Inc. https://www.renetec.io/blogs/makers/7-tools-for-gui-development-on-raspberry-pi

[26] Thermonamic electronics, "Specifications of Thermoelectric Module", TEC1-04905. Retrieved from:http://www.thermonamic.com/TEC1-04905-English.pdf

[27] Wakefield-Vette. "TEC Series", TEC-30-38-71. Retrieved from http://www.wakefield-vette.com/Portals/0/Peltier%20Thermoelectric%20Coolers/Wakefield%20Vette%20Thermoelectric%20Cooler%20Full%20Data%20Sheet%20Final.pdf http://www.wakefield-vette.com/Portals/0/Peltier%20Thermoelectric%20Coolers/Wakefield%20Vette%20Thermoelectric%20Cooler%20Full%20Data%20Sheet%20Final.pdf

[28] Vishay. (January 1, 2019). *NTC Thermistors, 2-Point Mini Chip Sensor, Flexible Leads.* Retrieved from https://nexus.union.edu/pluginfile.php/563941/mod_folder/content/0/Thermistor10k_NTCLESB.pdf?forcedownload=1

[29] Wakefield-Vette. "HSF Series", HSF-55-33-B-F. Retrieved from http://www.wakefield-vette.com/Portals/0/Heat%20Sink%20Fan%20Combinations/Heat%20Sink%20Fan%20Combinations%20Data%20Sheet%20HSF%20Series%20Wakefield%20Vette.pdf

[30] The Raspberry Pi Foundation(2020) *GPIO* Retrieved From https://www.raspberrypi.org/documentation/usage/gpio/README.md

[31] Adafruit. (2020). *MCP3008 - 8-Channel 10-Bit ADC with SPI Interface.* Retrieved from https://www.adafruit.com/product/856

[32] Adafruit. (2020). *MCP4725 Breakout Board - 12-Bit DAC w/ I2C Interface.* Retrieved from https://www.adafruit.com/product/935

[33] Adafruit. (2020). *Configuring I2C.* Retrieved from

https://learn.adafruit.com/adafruits-raspberry-pi-lesson-4-gpio-setup/configuring-i2c

[34] Digi Key Electronics. (2020). *SE-600-12.* Retrieved from

https://www.digikey.com/en/products/detail/mean-well-usa-inc/SE-600-12/7706613?s=N4IgTCBcDaIMoFEC0A2ADGpBGCBdAvkA

[35] Amazon. (2020). *Buck Converter 12v to 5v, DROK 5A USB Voltage Regulator DC 9V-36V Step Down to DC 5V-5.3V 5.2V 3.5-6A Volt Transformer Power Supply Module for Phone Fast Charging.* Retrieved from

https://www.amazon.com/Converter-DROK-Regulator-Inverter-Transformer/dp/B01NALDSJ0/ref=sr_1_8?dchild=1&keywords=12v+to+5v+step+down+converter&qid=1604166099&sr=8-8

[36] Engineering Tool Box. (2020). *AWG Wire Gauges Current Ratings*. Retrieved from

https://www.engineeringtoolbox.com/wire-gauges-d_419.html

[37] Show Me Cables. (2020). *18 AWG - 5 Conductor - 600V - Stranded Conductor - Unshielded - VNTC Tray Cable - Per Foot.* Retrieved from

https://www.showmecables.com/18-awg-5-conductor-600v-stranded-conductor-unshielded-vntc-tray-cable-per-foot

[38] Amazon. (2020). *LLPT Double Sided Thermal Conductive Strong Adhesive Tape Multiple 1.2 Inches x 108 Feet for Electronic Components LED Strips Heat Sinks(TC128).* Retrieved from

https://www.amazon.com/LLPT-Conductive-Electronic-Components-TC128/dp/B07P9L

V4V3/ref=asc_df_B07P9LV4V3/?tag=hyprod-20&linkCode=df0&hvadid=459454121958&hvpos=&hvnetw=g&hvrand=4935736664993830228&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9004745&hvtargid=pla-945945765541&th=1

[39] Amazon. (2020). *Sunnyglade Plastic Waterproof Dustproof Junction Box DIY Case Enclosure (11.8"x9.8"x4.7")*. Retrieved from https://www.amazon.co.uk/Sunnyglade-Waterproof-Dustproof-Junction-Enclosure/dp/B07KR4PCD8

[40] Amazon. (2020). *Gel Ice Packs for Injuries- Adjustable Wrap for Pain Relief Ice Pack+Heat Pack , Non-Toxic Smooth Reusable, Support Rehabilitation, Flexible Therapy - Shoulder, Back, Knee, Neck, Ankle, Jaw & More.* Retrieved from https://www.amazon.com/Injuries-Adjustable-Non-Toxic-Reusable-Rehabilitation/dp/B07KWVFMLC/ref=sr_1_13?dchild=1&keywords=thin+ice+pack&qid=1603053550&sr=8-13

[41] Ashmen, Amanda, seniorcapstone, (2020), Github repository, https://github.com/amandaashmen/seniorcapstone

Appendices

1. Budget breakdown

Budget Breakdown (Total = $1,226.06) (Consumable = $926.37) (non-consumable=$299.69)
We are requesting SRG funds of $1136.15. The ECBE dept will provide 30% matching funds of $89.9 for non-consumables.

Table 1: Budget equipment **Note: * = Item is consumable and not reusable**

Stage	Part	Purpose	Supplier	Price
User Interface	CanaKit Raspberry Pi 4 4GB Starter Kit	To provide control over the device to the user and determine the signal to power peltiers	Amazon	$89.99
	7’ Touchscreen Display	Physical interactive display of user interface	Amazon	$63.40

	2 Adafruit MCP3008 8-Channel 10-Bit ADC With SPI Interface *	Converts analog output of thermistor to digital input to Raspberry Pi	Amazon	$14.18
	5 Mini MCP4725 Module I2C DAC *	Converts digital signal from Pi to analog signal for MOSFET	Amazon	$10.99
Peltier and Drivers	3 20AWG wire (red, yellow, black)*	Wire that can handle up to 6A of current and will be used for wiring up the peltiers and other components	Digi-key	$29.71
	1 Terminal blocks	Serve a a high current junction that can distribute current to multiple pelters for testing	Digi-key	$11.85
	10 10W Resistors*	Part of Current Source to Drive Peltiers	Amazon	$17.26
	7 IRL520NPbF MOSFETs*	Part of Current Source to Drive Peltiers	Digikey	$12.06
	12 Peltier Coolers *	Required to maintain cold temperature	Amazon	$138.45
	13 HSF-55-33-B-F heatsinks with fans *	Prevent the peltiers from overheating	Newark	$486.81
	5 Thermistors*	Measure external temperature of system for optimal healing	Digi-key	$10.75
Power	1 DC-power supply SE-600-12	Convert wall outlet down to 12V DC output and up to 50A.	Digi-key	$93.50
	1 Power cable 211018-06	Power cable connecting wall outlet to DC-power supply	Digi-key	$13.50
	1 18 AWG - 5 Conductor - 600V - Stranded Conductor*	Wire to handle and distribute power to peltiers and fans	Show me cable	$22.34
Regulation of Pi	2 Buck Converter 12v to 5v, DROK 5A USB Voltage Regulator DC 9V-36V Step	Step down the voltage from 12 to 5 volts and is able to provide the 3 amps needed by the pi	Amazon	$19.98
	1 AmazonBasics USB Type-C to USB-A 2.0 Male Charger Cable, 3 Feet (0.9	Used to connect the regulator output to the pi	Amazon	$7.47
Safety features	4 Gikfun 20A Range Current Sensor ACS712 Module for Arduino (Pack of 2pcs) *	Measure the current through the peltier	Amazon	$43.92
Other	Sunnyglade Plastic Box *	Case to hold user interface components and power system.	Amazon	$25.99
	1 Roll of Thermal Adhesive Tape*	Attach multiple components on the sleeve together	Amazon	$17.27
	1 Copper plate*	Evenly distribute temperature across cold pack	McMaster Carr	$76.75
	2 Gel pack*	Provide medium for heat transfer, give design flexibility	Amazon	$19.89
Total				**$1226.06**

2. Code for Reading Thermistor and Producing Data Output - seniorcapstone/input_csv.py

```
import os
import time
import busio
import digitalio
```

```
import board
import numpy as np
import csv
import adafruit_mcp3xxx.mcp3008 as MCP
from adafruit_mcp3xxx.analog_in import AnalogIn
from matplotlib import pyplot as plt

# steinhart-hart coefficients
K0 = 0.00113414
K1 = 0.000233106
K2 = 9.32975E-8

# create the spi bus
spi = busio.SPI(clock=board.SCK, MISO=board.MISO, MOSI=board.MOSI)

# create the cs (chip select)
cs = digitalio.DigitalInOut(board.D22)

# create the mcp object
mcp = MCP.MCP3008(spi, cs)

# create an analog input channel on pin 0
chan0 = AnalogIn(mcp, MCP.P0)

# begin reading
start_time = time.time()

# length of time program will run
DURATION = 360

last_read = 0       # this keeps track of the last value
tolerance = 250     # to keep from being jittery we'll only change
                    # volume when the pot has moved a significant amount
                    # on a 16-bit ADC


tempList = []       # creates an empty list of temperature values read
timeList = []       # creates an empty list of time values per temperature

def convert_V_to_T(V):
    # takes a voltage value from amplifier to ADC
    # maps to internal resistance of thermistor
    # calculates temperature in Celcius and Fahrenheit from Steinhart-Hart
Equation
    # returns temperature value in Fahrenheit

    # voltage to resistance
    R = (5.2*100)/(.5*V + 2.6) - 100

    # resistance to temperature
    term1 = K0
    term2 = K1*(np.log(1000*R))
    term3 = K2*(np.log(1000*R))**3
    c = (term1 + term2 + term3)**(-1) - 273.15  # degrees celcius
    f = c*(9/5) + 32                            # degrees fahrenheit

    #print formatting
```

```
    print('{:.3f}'.format(c) + " C")
    print('{:.3f}'.format(f) + " F")

    return(f)

def remap_range(value, left_min, left_max, right_min, right_max):
    # this remaps a value from original (left) range to new (right) range
    # Figure out how 'wide' each range is
    left_span = left_max - left_min
    right_span = right_max - right_min

    # Convert the left range into a 0-1 range (int)
    valueScaled = int(value - left_min) / int(left_span)

    # Convert the 0-1 range into a value in the right range.
    return int(right_min + (valueScaled * right_span))

def graphData(dataList, timeList):
    # creates csv file to write data to
    filename = 'test11_4.csv'
    with open(filename, mode='w', newline= '') as data:
            tempData = csv.writer(data, quoting=csv.QUOTE_MINIMAL)
            tempData.writerow(["Time    Temperature"])

            xList = []
            yList = []
            for point in range(len(dataList)):
                temp = dataList[point]
                time = timeList[point]

                xList.append(time)
                yList.append(temp)
                tempData.writerow([str(time)+'\t'+str(temp)])

    plt.ylabel('Temperature (F)')
    plt.xlabel('Time (s)')
    plt.title('Thermistor Values')
    plt.plot(xList, yList)
    plt.show()


while True:
    # we'll assume that the thermistor didn't move
    therm_changed = False

    # read the analog pin
    therm = chan0.value

    # how much has it changed since the last read?
    therm_adjust = abs(therm - last_read)

    if therm_adjust > tolerance:
        therm_changed = True

    # convert 16bit adc0 (0-65535) thermistor read into 0-5.2V voltage value
    set_voltage = remap_range(therm, 0, 65535, 0, 5.2)
```

```
    volts = round((chan0.value*5.22)/65535, 2) # DO i need both of these

    degrees_f = round(convert_V_to_T(volts), 2)
    elapsed_time = round(time.time() - start_time, 2)

    tempList.append(degrees_f)
    timeList.append(elapsed_time)

    # print statements to console
    print('Raw ADC Value: ', chan0.value)
    print('Raw Converted Voltage: ', str(volts) + ' Volts')
    print('Time: ', str(elapsed_time) + ' seconds')
    print()

    # save the thermistor reading for the next loop
    last_read = therm

    # hang out and do nothing for a half second
    time.sleep(0.5)

    # end program after specified time in seconds
    if elapsed_time > DURATION:
        break

graphData(tempList, timeList)
```