Smarty Pants: Better Biomechanics Product Design Report

Rebekah Bond, Annes El-Krewi, Laura Heinze, and Allison Ray

BIOE 492 - Winter 2022

Table of Contents

3 Executive Summary **3**
4 Mission Statement and Accompanying Information **4**
5 Project Management Plan **6**
6 Competitive Benchmarking **8**
7 Metrics and Final Specifications **9**
8 Design Solution Concepts Considered **9**
9 Concept Selection **10**
10 Final Project Concept **11**
11 Engineering Analysis of Design/Prototyping Efforts **13**
12 Human Factors Considerations **19**
13 Design for Manufacturing **20**
14 Design Economics and Costs Analysis **21**
15 Regulatory Review and Strategy **22**
16 IP Review and Considerations **23**
17 Design for the Environment **25**
18 Summary and Conclusions **28**

Appendix **33**
Proof of Poster **33**
Appendix A **35**
Appendix B **36**
Appendix C **37**
Appendix D **38**
Appendix E **39**
Appendix F **40**
Appendix G **41**
Appendix H **41**

Executive Summary

Running is an essential aspect of training in numerous sports and is a part of many people's regular exercise routines. According to the *Running/Jogging Participation Report 2020* from the Sports and Fitness Industry Association (SFIA), over 50 million Americans participate in some form of running or jogging[1]. Statistically, 50-70% of runners get injured annually, meaning up to 35 million Americans will incur an injury from running this year[2-3]. This presents a major opportunity in the sports medicine industry. In 2020 the market value was $5.5 billion USD, and it is expected to grow up to $7.2 billion USD by 2025[4]. Despite its size, this market is failing to provide runners with the solutions they need, as evidenced by frequency of injury. Current solutions fall short in that they are hard to access, expensive, and largely reactionary instead of preventative. Examples of these shortcomings can be seen in physician prescribed treatment, physical therapy, kinesiology tape, and orthotics. The first two solutions fall short because they are time-consuming, expensive, and reactionary instead of proactive. The last two solutions can be preventative, but they are mainly reactionary and if used incorrectly can cause more harm than good. In the face of these failures, what smart solution can be offered?

A smart solution is preventative, accessible, and comparatively affordable. This is where Smarty Pants come in. Smarty Pants are athletic leggings with silver conductive patches of fabric sewn over four different muscle groups. These conductive patches utilize electromyography (EMG) technology to determine relative activation of muscles. The patches connect to a power pack that records and sends EMG data to an application which in turn analyzes the data and reports injury predispositions. Based on that analysis, the application offers exercises and recommendations to strengthen weak muscle groups and train in a way that minimizes injury occurrence. Smarty Pants are made of washable material and the power pack is removable for ease of use. They are easily accessible, simple to use, and provide valuable feedback that can save the user the cost of treating an injury as well as the pain of enduring one.

Mission Statement and Accompanying Information

Smarty Pants - dedicated to innovative solutions that combat injury by thorough and thoughtful analysis, enabling runners to stride ahead of pain.

The Current Problem and Accompanying Needs

Running is an easily accessible method of exercise performed by a significant percentage of the population[5]. Of the 50 million runners in the US, 50-70% of them will get injured this year[2-3]. Some of those runners will ignore the pain and push through or perhaps RICE the injury into healing (likely suffering chronic pain or decline in performance due to incomplete healing afterwards). Those who wisely seek treatment will be faced with long wait times, high costs, or insufficient cures.

Current methods for addressing injury include doctor appointments, physical therapy (PT), kinesiology tape (KT tape), and orthotics. Doctor appointments are expensive and hard to book. Similarly, it is difficult to find money in the wallet or space in the schedule for regular PT appointments. While KT tape and orthotics are more easily accessible and much more affordable (though still not cheap), they also fall short. KT tape especially can be applied incorrectly and thus rendered ineffective. Correctly fitted orthotics often require a professional opinion, which reiterates the first two issues of being accessible and affordable. Beyond this, all of these methods are reactionary instead of preventative. A healthy, sound athlete doesn’t go to physical therapy. A runner doesn’t put KT tape on when there is no pain.

An astute reader may notice that training an athlete to have proper form has not yet been mentioned in the face of this injury-prevalence afflicting modern runners. We believe this solution has potential. It is preventative, and it is more accessible than a doctor’s appointment booked for a month in the future and costing a month of rent. But the running world is lacking proper tools for runners who don’t have access to a competent coach. Even trained coaches face a flood of new and diverse information on sources of injuries and how to prevent them. What is needed is a quantitative method of preventing injury that is accessible and affordable. That is where Smarty Pants step in.

Benefit Proposition including customers/users/stakeholders

Smarty Pants will provide a product that can benefit society in many ways. Exercise has been shown to improve mental health, increase productivity, and otherwise bring joy to life. This means that preventing injury and enabling runners to keep their regular exercise routine will have an impact far beyond just the running community. Runners are also employees, parents, engineers, pilots, flight attendants, architects, accountants, entrepreneurs. Preventing injury can have an impact beyond measure.

Those most directly affected, of course, are the runners themselves. Smarty Pants customers consist largely of the excited novice runner just beginning to increase their mileage and include the occasional seasoned marathon runner who desires to know their gait in a deeper, more quantitative way. As Smarty Pants take off, a database can be gathered to make future iterations of the product even more effective. As effectiveness of prevention increases, injuries will decrease, minimizing demand on physicians and physical therapists. In that sense, Sports Medicine Professionals are stakeholders. The sad reality is that injuries will occur and freak accidents cannot be avoided. As Smarty Pants progress and become popular, I believe Sports Medicine professionals won't notice a terrible decline in business but perhaps patients will notice it may be a little easier to squeeze in an appointment as the industry will be less overwhelmed. More than a negative impact of losing business, professionals will find the positive impact of an increased database and increased tool-box for assisting patients in their recovery. Products like these can aid professionals in injury analysis. Future generations of Smarty Pants will likely include more specific and comprehensive analysis that can inform caregivers.

Key Business Goals including primary and secondary markets

Smarty Pants' goal in business is an extension of what is stated in our mission statement - "combat injury by thorough and thoughtful analysis, enabling runners to stride ahead of the pain." In order to combat injury Smarty Pants must become available to customers, and it must earn enough profit to fund research for future iterations of the product in addition to producing current iterations and supporting the livelihood of employees. Details of these economics are seen in section 14, "Design Economics and Costs Analysis."

The primary market purchasing Smarty Pants are the ameatur runners who will learn how to modify their gait to avoid injury. A secondary market would be the trainers and coaches who advise runners, the seasoned long-distance athletes writing the blog posts many of those ameature runners read, and fitness trainers who coach amature runners on their gym days.

Key Assumptions and Constraints

Smarty Pants assumes the majority of those 50-70% of runners injured are injured due to an incorrect gait and that correcting the gait can prevent injury. Smarty Pants assumes gait can be corrected by determining muscle activation and then providing the user feedback based on that EMG reading.

Smarty Pants isn't afraid to dream of an injury free future. It does not do to dream if the dreaming departs from reality. Reality is that Smarty Pants face many constraints. For all the talk of being affordable, Smarty Pants are made of expensive metals and will be constrained in design (number of muscle groups to be analyzed, processing power, etc) to meet that need of being affordable. These constraints make it difficult, but not impossible. Smarty Pants will allow these constraints to inspire creativity to innovate a product that redefines what is possible.

Project Management Plan

Needs, Specifications, and Metrics

Smarty Pants are designed to meet several needs. Various needs the product should meet are prioritized in Figure 1, with three stars corresponding to the highest needs down to one star corresponding to the lesser-important needs. Metrics used to measure the product's ability to meet each need are denoted as well. When the needs are generalized, we can organize them into larger groups.

Metric	Hydrostatic Head (around 1000mm)	Displacement after use (<5 mm)	Voltometer (volts)	Consistent results temperature testing from (-10 - 45 degrees celcius)	comfortable material (gel/breathable)	Electrode measurements (voltage large enough to pick up)	Manufacturing Cost <$200	Time needed to learn <45 min	Device size(s) <size of shoe	Maximum time for single use, battery life >24 hr	Power source options last longer than 3.7 V lithium ion battery without recharging	Product colors are neutral	Time to recharge (<= 4 hours)	Fatigue testing (lasts > 1 year in simulated aging test)	Made with recyclable materials	Spedometer matches readout from device (100% accuracy)	Physician diagnosis matches device feedback	analyze movement with and without device attached (% difference)	pressure sensor <5 mm in diameter	Time from activity to viewing information on alternate device	Survey shows less than 10% of people remember noticing object	Operation of device is consistent in dry and wet environments
Needs																						
The device detects movement.***																x						
The device is form-fitting. ***					x																	
The device is durable.***		x		x										x								
The product shares information with other devices.***																				x		
The product avoids interference with natural biomechanics.***					x				x									x				
The device is discrete.**									x			x									x	
The device is waterproof. **	x																					x
The device works in extreme temperatures. **				x																		
The device can be used for long periods of time. **										x				x								
The device can be operated with its own power source. **										x	x											
The product is reusable.**													x	x	x							
The product is affordable. **							x															
The product is intuitive to use. **								x														
The product is rechargeable. **			x								x											
The product is customizable. **					x				x			x										
The product measures muscle activation.**			x			x																
The product provides real time feedback to user.**																	x					
The product can be used on all terrains.*		x												x								
The product detects predisposition to specific injuries.*																						
The product measures bony alignment.*																	x					
The product assesses stress to integral anatomical structures.*																	x					
The product offers biomechanical solutions to excessive stress observed.*																	x					
The product is environmentally friendly.*											x				x							

Fig. 1: Needs and metrics for Smarty Pants product

Using this list, we determined the top three requirements for our product. The highest priority need Smarty Pants fulfill is analytical accuracy. The processing center is able to predict injuries, detect movement, and monitor muscle over- or under-stimulation. Accurate acquisition and analysis of body mechanics data provide a viable product for injury prevention. Additionally, the pants are customizable, form-fitting, and unrestrictive. The second need to meet is that the product is easy to use. Included in this is that Smarty Pants are intuitive to use, provide real time feedback to users, and share information with other devices. Finally, Smarty Pants must be durable. This includes withstanding all terrains, varying temperatures, and all weather conditions. Durability enables multiple, reliable uses for a long-lasting product.

Prototyping Plan:

To meet our highest priority, our electrode must be accurate. This will be tested through multiple iterations of the electrode at different spots, while keeping the experiment as constant as possible in order to determine accuracy. In order for the product to be easy to use, the final product has to be easy to put on, and straightforward in its application. To guarantee this, the pants will have a detachable power pack. This will not only allow the user to use the pants like any other pants, but once the battery pack is plugged in, the device is on and ready to go. The aid of a manual will help the user learn how to connect their pants to the application on their phone, and through there access real-time data of their muscle activity. Finally, in order to meet the durability need, the power pack must be made of material that can withstand different temperatures, withstand being dropped, and be water resistant to a certain extent. The electrodes must also be able to survive multiple wash cycles without affecting the performance of the device.

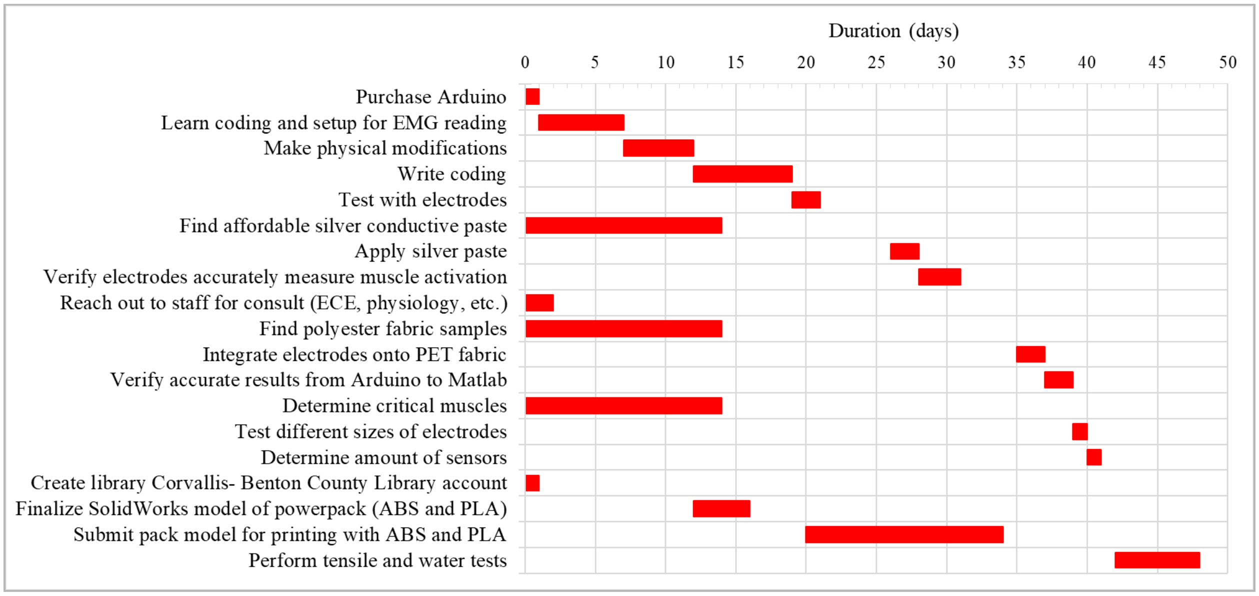


Fig. 2. Gantt chart detailing the different days and lengths of time allocated for each part of the prototype production process.

Competitive Benchmarking

There are currently no products that offer gait analysis utilizing sEMG to the general population. General protocol is to visit a physical therapist who will connect the patient to a machine, record them, and watch them run in order to determine where there are inefficiencies in their gait. As far as personal-use products, what currently exists is very expensive and difficult to obtain. One of the very few companies that sell clothes with sensors, Xenoma[22], charges hundreds of dollars for an article of clothing. Prices this high inhibit the majority of runners from accessing them. Consequently, this technology is instead most often used in research labs, where the sEMG's are used for tracking muscle activity and gait analysis for specific projects. The electrodes are often sticky, one-time use, and restrict movement.

Metrics and Final Specifications

Our final product includes our silver-based electrodes (1x1 cm) integrated into PET fabric, the Teensy 4.1, and the battery pack design. The silver-based electrodes were integrated by painting several layers of silver nano-particle paint onto the PET fabric. Two electrodes will be stitched into the fabric over each muscle on both legs. There will be one additional ground electrode per leg as well, stitched into the pants to rest on a bony part of the leg. Each electrode will be coupled with wires leading toward the battery pack. The wires connect to the Teensy 4.1. The battery pack is made from PLA+ and has dimensions of 80mm by 32mm by 34.15mm. The dimensions of the battery pack accommodate the Teensy 4.1. The battery pack also houses two lithium coin cell batteries at 3.7V, which has been made to be easily switched out once one dies. The consumer would be receiving a pair of pants of their size with everything listed above, as well as a manual detailing how to use the device.

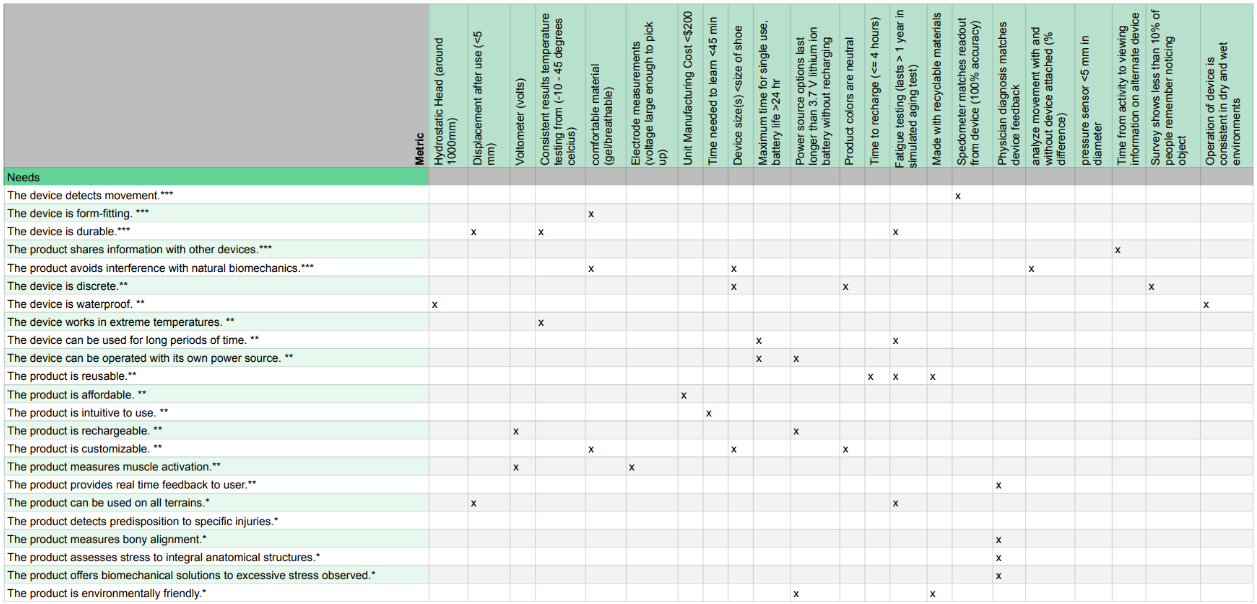
Design Solution Concepts Considered

We initially had three concept ideas to address running injuries: Smarty Pants, Smarty Socks, and Smart Insoles. Socks and insoles seemed codependent and interactive with a smaller scope of monitoring. Smarty Pants offered a wide range of applications, and therefore, we decided to develop them over our other concepts. Prior to the final specifications, there were a variety of concepts considered. One prototype considered was the number of electrodes. At first, seven electrodes were considered due to the range of muscles present in gait. However, the electrodes were reduced to 4 since the four major muscle groups were found sufficient to assess muscle activity and gait analysis. On the topic of electrodes, another prototype taken into consideration was the application of the silver nano based particles onto the PET fabric. The original idea was to use silver-based paste made for screen-printing, however issues arose with the ordering and shipping of the product and it became backlogged until May. Because of this, a silver nanoparticle paint was used instead, where multiple layers were able to achieve the same result. Another consideration was the type of arduino being used. The first consideration was the Teensy 3.2 as the team was lucky enough to be given one for free, however after looking at the specifications of the Teensy 3.2 and what it could do for the project, it was found insufficient. The Teensy 4.1 became the final alternative. The last prototype considered was the sizing of the battery pack. The sizing of the battery pack was changed in order to accommodate the transition from the Teensy 3.2 to 4.1.

Concept Selection

Selection

We broke the technical concepts that needed to be addressed, as illustrated in Appendix A. Using these technical concepts, we developed a hierarchical list of needs that was subsequently tabulated and ranked based on importance (Figure 3). The most important needs have three stars, and the lesser important ones have one star.



Metric	Hydrostatic Head (around 1000mm)	Displacement after use (<5 mm)	Voltometer (volts)	Consistent results temperature testing from (-10 - 45 degrees celcius)	comfortable material (gel/breathable)	Electrode measurements (voltage large enough to pick up)	Unit Manufacturing Cost <$200	Time needed to learn <45 min	Device size(s) <size of shoe	Maximum time for single use, battery life >24 hr	Power source options last longer than 3.7 V lithium ion battery without recharging	Product colors are neutral	Time to recharge (<= 4 hours)	Fatigue testing (lasts > 1 year in simulated aging test)	Made with recyclable materials	Spedometer matches readout from device (100% accuracy)	Physician diagnosis matches device feedback	analyze movement with and without device attached (% difference)	pressure sensor <5 mm in diameter	Time from activity to viewing information on alternate device	Survey shows less than 10% of people remember noticing object	Operation of device is consistent in dry and wet environments
Needs																						
The device detects movement.***																x						
The device is form-fitting. ***					x																	
The device is durable.***		x		x										x								
The product shares information with other devices.***																				x		
The product avoids interference with natural biomechanics.***					x				x									x				
The device is discrete.**									x			x									x	
The device is waterproof. **	x																					x
The device works in extreme temperatures. **				x																		
The device can be used for long periods of time. **										x				x								
The device can be operated with its own power source. **										x	x											
The product is reusable.**													x	x	x							
The product is affordable. **							x															
The product is intuitive to use. **								x														
The product is rechargeable. **			x								x											
The product is customizable. **					x				x			x										
The product measures muscle activation.**			x			x																
The product provides real time feedback to user.**																	x					
The product can be used on all terrains.*		x												x								
The product detects predisposition to specific injuries.*																						
The product measures bony alignment.*																	x					
The product assesses stress to integral anatomical structures.*																	x					
The product offers biomechanical solutions to excessive stress observed.*																	x					
The product is environmentally friendly.*											x				x							

Fig. 3: Selection matrix with each component (need) of the product's design rated based on importance as well as how it would be measured (metric). Needs were given a "*" rating, with more stars corresponding to higher importance.

After prioritizing the needs, metrics were assigned to each need that provided the best ways to measure each concept. The needs assigned two and three stars were addressed first through our prototypes. This led to the creation and testing of our prototypes. We first decided to go with an Arduino type of data acquisition device because of its small size and large data capacity. Then research was done to determine what information would be useful as user feedback. Coding was developed and tested in order to provide adequate analysis and helpful user feedback. The powerpack went through a couple of size changes in order to provide the most structure and stability. Finally, electrodes were made through using silver-based ink painted on PET fabric to be tested. This will ultimates be sewn into the pants, but for prototyping purposes we had each electrode separated on its own patch of fabric in order to test different distances and positions over the muscle.

Final Project Concept

Product Description

To use Smarty Pants the user must simply plug the electrodes into a computational unit (battery pack), calibrate it with four max contractions specified by the app, go for their run, and then review the app with their data afterwards. This data will show which muscle groups were activated sufficiently for proper running form and which muscles were under-activated. Additional feedback will include exercises to strengthen the relevant muscle groups and tips to ensure proper form. Data can be tracked in the app and stored to monitor progress over time.

Electrodes incorporated into Smarty Pants use conductive fabric to read EMG signals of relevant muscles. The data is compiled data in the processing unit then sent via bluetooth capability of the device to an app that processes the information. Pre-programed feedback corresponding to the user's performance including a comprehensive review and recommended exercises will be displayed and stored on the app. Main aspects of the design focused on below include the electrodes, placement of electrodes, and power source housing.

The pants' smart design consists of groundbreaking technology using silver nanoparticle sensors connected to rubber-coated aluminum wiring. Aluminum serves as a cost effective transmission line that can be paired with the silver nanoparticles. The wiring is stitched into the spandex fabric as are the silver nanoparticle electrodes. The polyester/elastane (Under Armor) blend fabric is affordable and supplies sufficient weight and elasticity to maintain its form. These aspects are paired with a rechargeable lithium ion battery powered EMG device. Each electrode contains gold coating on the bottom layer to reduce irritation from the conductive silver that contacts the skin without inhibiting muscle activity readings, as seen in Figure 4. There is a nonconductive PET/cotton layer on top of the silver which can easily be sewn into the pant fabric. The information from the EMG is sent to the user's smartphone via the bluetooth capability of the device.

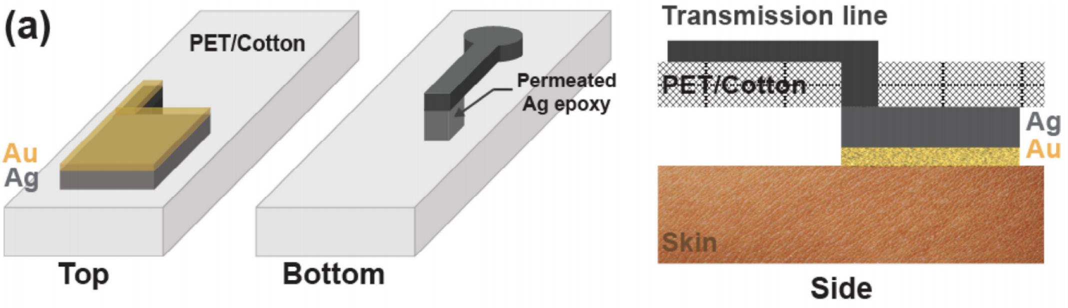


Fig. 4: Electrode configuration with gold plating and a PET/Cotton layer that the wiring will be stitched into to contact the aluminum, rubber coated transmission line.

Not only is this device discrete, but it is also washable for multiple uses. The signal to noise ratio (SNR) of EMG signals in the electrodes stabilizes after 5 washes, indicating that the fabric is indeed washable for multiple uses at a SNR value of 7.2 decibels [6]. SNR measures the amount of background noise vs. EMG signaling. Each product has a certain range for viable function of power signal to noise signal, and 7.2 decibels falls within that range for EMG devices. There are 4 muscles on each leg that will be assessed as shown in Figure 5. Each sensor patch will have aluminum wire leading to the EMG battery pack, which will be in a pocket on the front side of the pants.

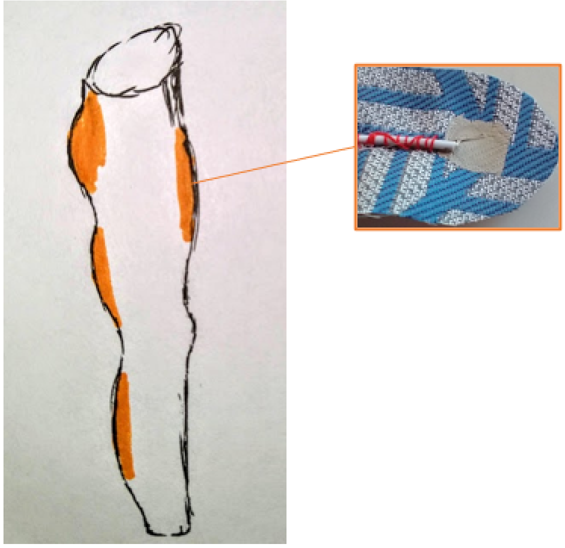


Fig. 5: Electrode placements (orange) on the Smarty Pants fabric.

Another major model includes the powerpack component. The pack needs to store the computational device (Teensy 4.1), batteries, and relevant wiring. It will be made of PLA+

plastic in order to provide a strong, waterproof housing for the electronics. Additionally, it must not be bulky or cumbersome in order for the runner to maintain their natural running form. Figure 6 shows the 3D models of the powerpack components. For the design, there are 4 model pieces in total, but 12 printed pieces. The two models on the bottom, the battery pack body and pull-tab battery cover, were only printed once. The side pieces, top right, were printed twice. The cylindrical screw, top left, was printed 8 times for each screw hole. The side pieces were screwed into the battery pack body via the cylindrical screws, securing the model in place.

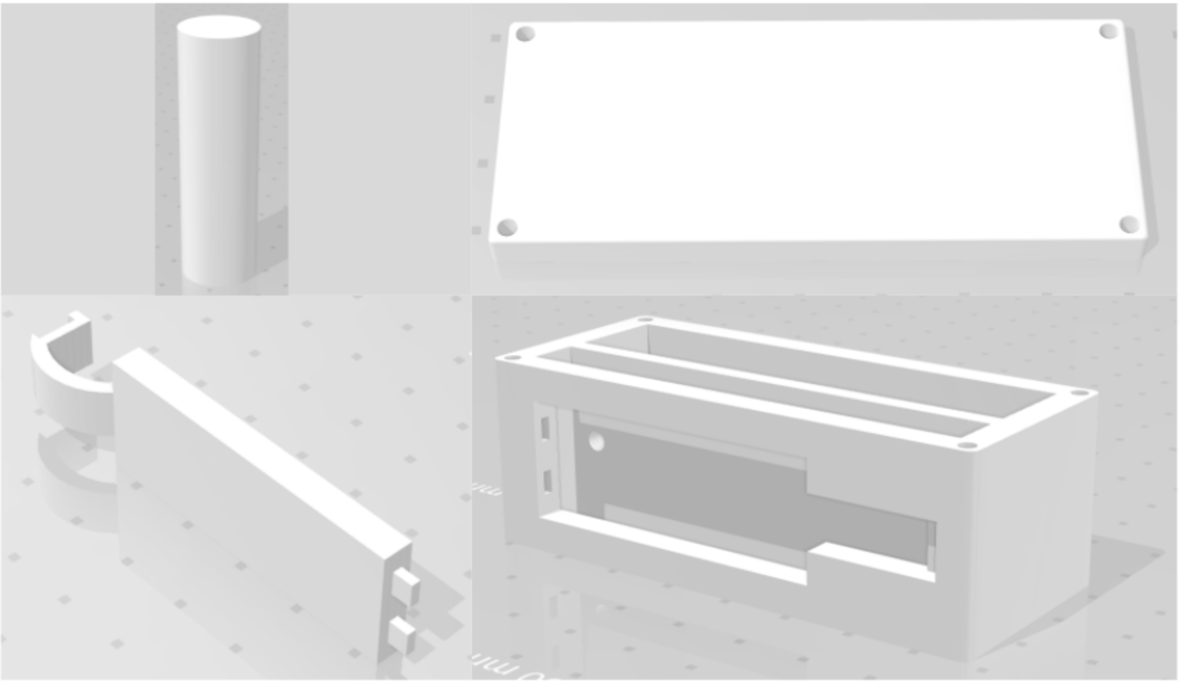


Fig. 6: 3D model of powerpack components. Clockwise from the top left are the screws, the sides panels, the battery access latch, and the body of the powerpack.

Engineering Analysis of Design/Prototyping Efforts

In selecting prototypes for our design, there were three crucial things to consider: the processing unit, the battery unit, and the EMG sensors. These were the key components in creating Smarty Pants. First and foremost, we needed to determine the competency and consistency of the Teensy Arduino 3.1 to compute and pick up EMG signaling. The EMG sensors needed to be investigated to test for optimal size, number, and shape of patches to create viable signaling from muscle activation. Finally, a specialized power pack needed to be designed for small scale processing and monitoring abilities.

Prototype Description, Testing Efforts, and Results

Battery Pack

For the battery pack prototype, there were originally three models that were developed in SolidWorks with different thickness throughout the device. The parameters were decided to ensure that a double coin cell battery pack and a Teensy Arduino 4.1 could fit inside. There were also side pieces for manufacturing access and a pull tab battery cover to give the consumer the ability to charge or switch out batteries. After consulting with Peter Bond, a computer aided design mechanical engineering specialist, it was determined that our thinnest model with a thickness of 1 millimeter was not stable enough for printing or the compartmentalization necessary, so it was discarded. Our first model had a thickness of 1.5 millimeters and the second model had a thickness of 4.5 millimeters. The secondary model was created to allow for screw holes to secure the side pieces of the battery pack to create stability instead of relying on glue for the sides. This model also took into consideration the shortcoming in the first model, which was battery exposure via the pull-tab. Two pull-tab battery covers were also designed with different radius bendable bridges. We were also working with two different plastics, PLA and PLA+, to compare the durability and flexibility of the material that would best suit our product. In conclusion, the 4.5 thickness model printed with PLA+ was the superior version of our battery pack prototype. The larger radius pull tab had the most ease of use.

In testing the battery pack, there were three specific parameters to consider: thermal resistance, durability drop tests, water resistance, and a pull-tab bridge bend test, as seen in Appendix C. Thermal resistance was tested due to the body heat created by consumers, the heating of the Arduino and batteries, and environmental impacts. Thermal resistance measures whether or not heat impacts a material, if heat loss is more prevalent, and whether there is a great amount of heat transfer to the material. The thermal resistance for each model was determined by dividing the thermal conductivity of PLA by the thickness. Using the thermal conductivity of PLA, 0.13 W/(m*K), the model with a thickness of 1.5 millimeters had a thermal resistance of 0.0115 W/K. The thermal resistance of the 4.5 millimeter thickness model was 0.0346 W/K, giving a better result.

The second test performed was drop tests from varying heights. This was done to model a consumer accidentally dropping the battery device to see how each model could withstand the impact. Since one model had glued-on sidings while the other was screwed and glued on, we wanted to observe which would be more durable. None of the models were affected by drops from different heights, as seen in Appendix C.

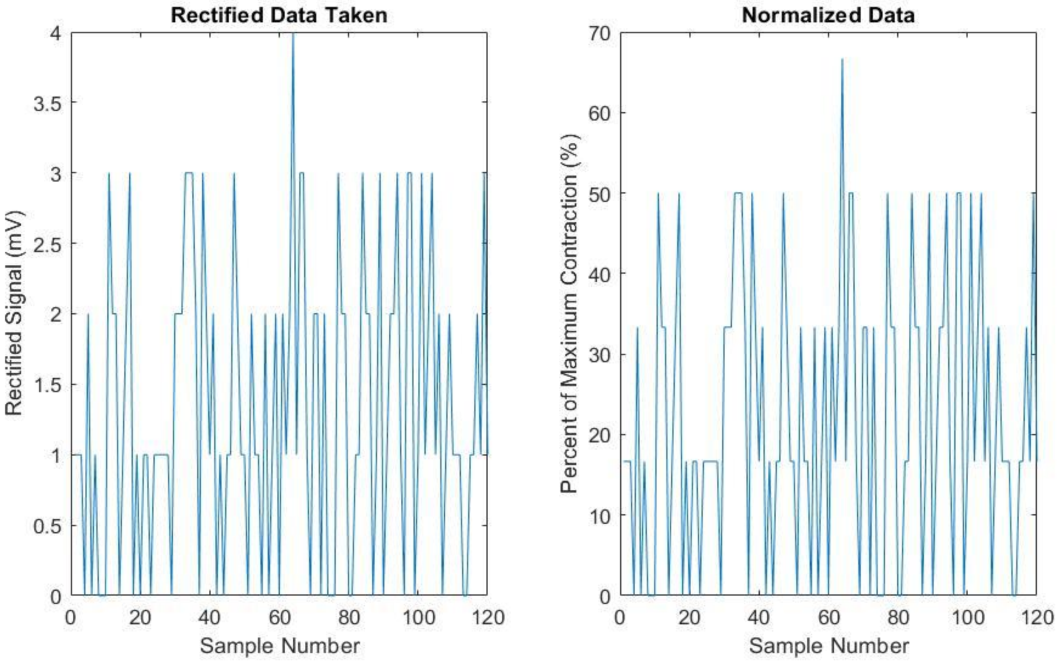
Water resistance testing was done to ensure that users would not damage the device in water and to see if the battery pack would be able to float. Each model was placed into a water basin and the float time was recorded. All models never sank or dipped into the water, exemplifying that both the models were exceptionally water resistant. There was also no leakage. The only pack that did have some water entry was on the top side of the first battery model due to the pull-tab exposure.

Finally, the two pull-tab designs were investigated. This was done by taping the cover on a flat surface next to a ruler and applying pressure onto the tab to see how far the top of the tab would bend backwards, experimentally determining the ease of use. The displacement measurement from the ruler showed that the first model with a smaller bridge radius only bent 4 millimeters with PLA and 2 millimeters with PLA+ while the second model with a larger bridge radius printed with PLA+ bent 5 millimeters. The PLA+ larger radius also had the most ease of use when it came to bending, making it easier to remove the battery cover from the battery pack because the thickness of the bending bridge was smaller than that of the shorter radius model. Based on all three of these testing methods, the second model with a thickness of 4.5 millimeters and printed with PLA+ was the most sufficient model. The pull-tab battery cover had the most ease of use because of the larger bendability and lowered thickness.

Teensy 3.2-Matlab Coding

In order to analyze the EMG readings, we have to be able to record and send the data to an application that can process the data. In our final product this will be done using a Teensy 4.1 and relevant software. Our prototype uses a Teensy 3.2 (Arduino) that was accessible to our team, which provides the same functionality as the 4.1. Unfortunately, EMG signals require amplification to be recognized by the Arduino. We did not have access to an amplifier, so artificial EMG signals were developed using a Digilent Discovery 2 oscilloscope. The artificial EMG readings were randomly generated with a frequency of 20 Hz, period of 50 ms, and amplitude of 6 mV. The data was offset at 6 mV in order to prevent negative readings. The random data was graphed for 30 seconds, with samples taken at constant intervals to mimic our electrode testing

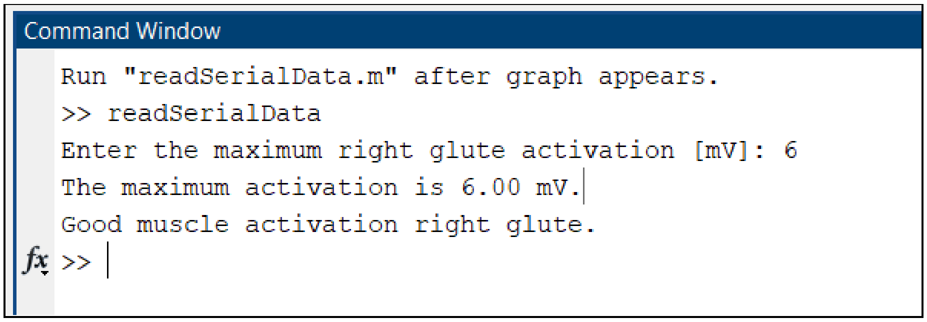
Coding was written and developed in Matlab which graphed the resulting readings (Appendix G). The data was then analized by the code to produce two more graphs: Figure 7a takes into account the offset and then takes the absolute values of each sample, and Figure 7b normalizes the data so that the measurements can be evaluated as a percentage of the maximum contraction, which in this example is 6 mV.



(a) (b)

Fig. 7: Figure 7a displays the rectified signal from the artificial EMG readings produced by the oscilloscope. Figure 7b shows the normalization of the data as a percent of maximum contraction.

The percent of maximum concentration format allows us to evaluate the data and determine muscle over or under activation. In practice this would be done with multiple muscle groups, but for our prototype we focused on one EMG reading at a time to verify our coding worked well. The feedback given in Figure 8 provides the example feedback that was given based on the generated data.



```
Run "readSerialData.m" after graph appears.
>> readSerialData
Enter the maximum right glute activation [mV]: 6
The maximum activation is 6.00 mV.
Good muscle activation right glute.
>>
```

Fig. 8: Resulting feedback from the data generated in our sample artificial EMG data.

This window displays an example of feedback, “Good muscle activation right glute” because the averaged Digilent-generated, normalized data is within the acceptable range based on a maximum right glute activation of 6 mV. Personal analysis of the data confirmed that this was indeed the correct result and that the code effectively works to provide the desired feedback based on specifications we determined.

Electrodes

For the electrode prototype, the initial model that was developed was a silver-based paste that could be screen printed. After some setbacks, it was decided that a silver nanoparticle paint would be the best choice. The model included a 1x1 cm area of the silver paint, painted over a wire 3 times. One layer of paint would be used, dried, then reapplied. This was all done onto the PET fabric, such that the wiring would be attached to the PET fabric. The model would then be sewn onto the pants as a final product.

There are many factors related to the electrodes including placing, type, size, sensitivity, and analysis of data. Placing can further be broken down into muscle groups measured and location on that muscle group. With our limited access and equipment, we found that the most useful prototypes looked at only one or two factors at a time; however, each factor is closely connected to and influences the others. Increasing size will increase sensitivity (and noise). Placing the electrodes on different muscle groups will require a different analysis.

First, we determined which muscle groups would be most helpful in modifying gait to reduce injury prevention. Upon consulting Dr. Norcross, a Human Biomechanics Specialist, determined the most important muscles for the Smarty Pants to look at were the calf muscles (soleus and gastrocnemius), the quad muscles, the hamstrings, and the gluteus maximus.

Simultaneously, we were putting together our electrodes. Initially we had planned to screen print silver onto PET fabric following the example in previous literature[6]. That did not happen due to logistical difficulties, so we innovated our own electrodes with silver paint painted onto PET fabric.

In order to read the signal from an electrode connected to a muscle, much processing and filtering of that signal is required. Professor Johnston generously provided use of his lab's Cyton board which performs all the necessary processing. Utilizing this Cyton board we were able to test the accuracy of our electrodes with the procedure described below.

To test the electrodes, a Cyton Board was used coupled with Matlab coding. First conventional electrodes were used in order to establish the baseline data. This data was pulled from the gripping muscles in the forearm, as they are the most commonly used for testing EMG signals (appendix H). Once this had been performed, the silver-based electrodes were used in order to check its accuracy. The person with the electrodes attached would wait 15 seconds before flexing their muscles for 5 seconds, and then relax for another 10. This was repeated 4 times in order to see discrepancies. Our data was saved through the Cyton Board application and then uploaded to Matlab in order to compare the results. Appendix E shows the coding used in order to upload the data, and Appendix F shows the results of testing. Across multiple trials the code output shows increased voltage at 15 seconds and it returns to baseline shortly after 20 seconds proving the electrodes are picking up the signal generated by the muscle contractions.

After determining our electrodes worked, we decided to ascertain how the electrodes would function being worn on a set of pants and in a different location on the muscle for users of varying leg shapes and sizes. The electrodes were moved 2.5 cm medially, laterally, and distally to the literature position in order to test the signals given if the electrodes were to move during running. The test is analogous to the one previously mentioned, and the results were to be expected. The signal was observed even when moved, however different amounts of noise were recorded in each position and the strength of the signal varied depending on position. This is something to keep in mind going forward, but won’t affect the ability of Smarty Pants to do their job well because 2.5 cm movement isn’t realistic in tight/compression pants. This experiment proved the signal of muscle activation for the rectus femoris can be picked up 2.5cm away from electrode placing suggested by literature. From that we conclude that different leg sizes and shapes ought to work with Smarty Pants’ electrodes.

Human Factors Considerations

There are multiple components to this design which means that many human factors will be taken into consideration upon the design and manufacturing of our product. The first and arguably most important involve the design of the wiring and electrode components of the pants. Users will be sweating and possibly participating in running activities in a variety of weather conditions. Additionally, the pants are likely to get dirty and need to be washed. For all of these instances the pants, wiring, and powerpack need to be water-safe. In order to accommodate this need we are using washable fabric with water resistant silver conductive paste. For future models, we will be performing wash tests on the silver paste to see how the EMG signaling is affected by washing over time. Accomplishing these tests will give us a bigger picture for the lifespan of our product and how well the conductivity of the electrodes stays intact. The battery pack is completely waterproof and buoyant, ensuring that if a user were ever to drop the pants in water, the processing and power to the device will not be impacted.

For future models, we will be incorporating gold nanoparticle flakes to ensure that there is no irritation to the skin of the user. While there was no irritation from the silver conductive paste during our prototype testing, we understand that there may be irritation after long term use. The silver nanoparticles may cause irritation when creating friction against the skin with movement, and while it may not be considerable discomfort, we aim to ensure that all users are completely comfortable.

Another factor to consider is the actual movement of the user and how that impacts EMG signaling. Since the electrodes are integrated into the pant fabric, the areas of monitoring could be misplaced. People also have varying body types and proportions, so the muscular distribution is not consistent across patients. For our testing scheme, we mimicked the displacement of electrodes by moving them 2.5 cm in the medial, lateral, and distal directions to see if the signal strength from muscle activation still gave a significant output. The test results led to the conclusion that the displacement or movement of electrodes did not affect signaling, therefore it will not interfere with patient analysis.

When it comes to calibration and set up of the device, we want to ensure that the software is easy to use and customizable to the user. Currently, we are using our easiest determination as a Matlab output that tells the user whether or not they have good muscle activation. In future models, we plan on using a bluetooth application that can give a full scale analysis of each muscle and how it is firing. We also want to incorporate exercises that are given to the user to address their outputs from signaling. When it comes to device calibration, we wanted to consider that each individual has different levels of muscle activation. Thresholding EMG signals should be specific to the actual patient, so we will be incorporating a way to calibrate the device to see good activation versus bad activation. We have considered giving instructions to the user to complete certain movements so that the device can accurately assess good muscle activation.

Referring to the battery pack, there were many considerations to allow ease of use for product consumers. First and foremost, we wanted to ensure that users do not have any contact with the processing unit, or the Arduino. We also wanted to give users the option to replace or charge the coin cell batteries in the unit instead of needing customer support to power their device. To address these considerations, the battery pack was compartmentalized with the Arduino in one section and the battery holder in the other. We also created a battery cover so that the user can access the batteries, while we designed screw-in side pieces for manufacturing access to the Arduino processing unit in case any repairs were ever needed. The access to the top compartment has a specifically created pull-tab battery cover mimicking that of a TV remote to give a familiarity to users. Testing was done on multiple pull tab models to ensure that it was easy to remove, but secure enough to stay in place during activities. Finally, we downscaled the battery pack as much as possible so that it does not interfere with running or activity.

Design for Manufacturing

For our cost analysis, we categorized each item that we would order and custom components, as seen in Appendix D. The main products that were ordered were a Teensy Arduino 3.1, silver conductive paste, pant fabric, aluminum wiring, an Arduino BT module, a double coin cell battery holder, and a Powerizer LiR CR2032 40mAh 3.6V Protected 0.012A Lithium Ion (Li-Ion) Coin Cell Battery. All of these component costs totaled $50.90 for an individual unit. While we hand painted our electrodes, we will screen print our electrodes in the future for faster manufacturing and consistently sized electrodes, which could impact manufacturing costs. It could increase the cost of a screen printer or decrease labor fees. For custom components, the battery pack and pull-tab battery cover totaled a mass of around 0.020 kg. We decided to 3D print this model instead of custom molding for prototypes, but future models may be manufactured easier using molds. The unit price for PLA 3D printing is $0.00016 per kilogram, resulting in a raw material cost of less than a one hundredth of a cent. The thickness of the model was decreased to allow for the small mass and decrease shipping costs. Given the assumption that the final folded product could be compacted into a 28 cm by 24 cm by 5.5 cm package via air decompression, the total amount of packages that could fit in the freight shipping container was 18,633 units. The freight shipping cost came out to be $0.43, resulting in a total unit cost of $50.67. At a selling price of $99.99, the unit revenue totaled $69.99 and the unit profit was $19.32. The unit price was set because of the long lasting capability of the device that does not require much upkeep or replacement. That unit price may be heightened for further considerations due to the monitoring capabilities and extensive applications this product can give to consumers.

Design Economics and Costs Analysis

Base Case Model, Cashflow Model

We built our base case model using the AB-100 coffee maker example from the *Product Design and Development* book by Eppinger et.al for the general market inputs (marketing, product development, etc.). We reduced the marketing and support costs from the last quarter in order to increase the net present value, figuring we could find creative ways to market the product at a lower cost. We based the initial retail price we calculated using the cost estimator tool from the beginning of the project, which is $50.38 per unit. To estimate the number of pants sold, we took the lower estimate of the number of runners injured per year that we researched in our final pitch (25 million), and multiplied that by 1%, Assuming that the majority of injured runners in the United States are not extremely competitive or wanting to participate in injury-preventative practices post-recovery. This results in 250,000 runners. Assuming that there are uninjured athletes who will potentially be interested in this product for performance enhancement and injury prevention as well, this is a conservative estimate.

Sensitivity Analysis

Assumptions and values were chosen based on the AB-100 coffee maker example previously referenced, along with our product's specific factors that were also previously explained. Of the parameters we can control, the marketing and production costs had the most significant impact on our potential NPV (Figure 9). If we could decrease the production costs and put some of the money towards marketing, that could lead to greater exposure and more sales volume. Because this has a much higher best-case scenario NPV, it would be worth it because there is so much room to move up and increase sales.

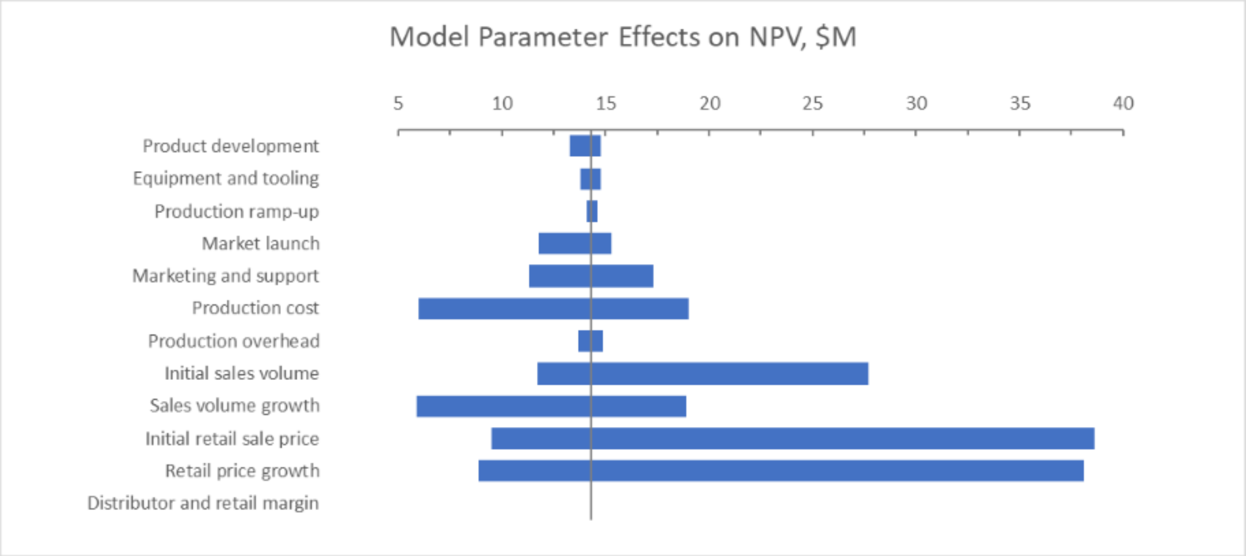


Fig. 9: Tornado Plot of the cost analysis for Smarty Pants and the effect on the Net Present Value.

Regulatory Review and Strategy

Device Classification and Pertinent Regulations

Upon reviewing FDA classifications and comparing our product to a similar EMG device, we determined that our product would be considered a Class 2 medical device and we would proceed with the 510(k) submission route to approve our product for market[23]. Since certain regulations and controls are necessary, performance standards are necessary to define for our product. The decision to base Smarty Pants as a Class 2 was dependent on the EMG signaling, silver and gold nanoparticles, and electrical components of the device that could negatively affect the user if not handled properly.

Distribution/Recall Plan/Incident Reports

Distribution will be done via shipping containers, as outlined in the design for manufacturing. Per shipping container, 18,633 units can be shipped, meaning that about 11 shipping containers are necessary to deliver the product. In case of product error for customers, we will have them send their package back to our headquarters and ship them a new device. Repairs can be made to the faulty product and redistributed. Notably, the battery pack and inner processing system can be reused, so when customers are done with their product, they can be redistributed to other clients. Incident reports can be filed through our app to ensure that they can contact customer support immediately and that it can be addressed and/or supply reimbursement. The pants will come with an instruction manual as well as a safety packet on use. This will include step by step instructions with photos, give bolded warnings for what to avoid, and device upkeep such as battery replacement and charging. Labels and warnings on the device would instruct the user to remove the powerpack before washing the pants in order to avoid electrical hazards and damage to the product. Each component, pants and power pack, will be labeled boldly to understand the associated user instructions/considerations.

IP Review and Considerations

Below is an investigation into related patents and trademarks that may impact our design.

Patent #	Date of Patent	Patent Name	List of inventors	Summary of pertinence for our design
8170656	5/1/12	Wearable Electromyography-based Controllers for Human-Computer Interface	Desney Tan, T. Scott Saponas, Dan Morris, Jim Turner	This device is a wearable EMG controller, much like our own. Electrical signals are transported via human-computer interface, and signaling is obtained from the controller placed onto the skin. This is almost exactly like our design, but with more rudimentary principles. The actual "controller" or electrode is not discussed, only the actual system. Our design builds off of the foundation of this patented idea.
9390830	7/12/16	Conductive Paste For Screen Printing	Shou Inagaki, Hideki Etori, Hiroshi Isozumi, Masanori Kasai, Nerima-ku	The foundation for our electrodes; allows muscle activity to be measured and monitored without the use of typical electrodes. Paste can be printed on the fabric incredibly similar to our design.
2017007016	12/1/2017	Wearable Electrode	Nakashima Hiroshi, Sato, Masanobu, Arakane Toru, Hamano Yuri, Takeda Keiji, Nagai Noriko, Shigawara Takashi	The patent describes a wearable electrode that is integrated into fabric that contacts the body. The electrodes take biological signals emitted from the body and can send it off to be processed. This mimics our design, but it does not discuss the specific materials or where the electrodes are located. This is more of a brief summary of what we are doing rather than an in depth description, so patents like this can help us have building blocks for our project.

8347412	1/8/2013	Athletic Pants	Adam Clement	The patent listed describes the athletic pants that we are planning to sew our electrodes into for our product. We are planning on using the same spandex fabric, and this specificies elasticity and the form/function of the pant design.
9155487	10/13/2015	Method and Apparatus For Biometric Analysis Using EEG and EMG Signals	Michael Linderman, Valery I. Rupasov	The patent stated is for a biometric assessment using EMG signaling that is processed through the Matlab interface for said assessment. This patent focuses on fine motor control rather than gait analysis, but uses a similar process to our gait analysis in using Matlab to process the EMG signals from electrodes.

Table 5: Pertinent patent search to the Smarty Pants design.

Trademark #	Date of Trademark	Patent Name	List of inventors	Summary of pertinence for your design
76561993	6/13/15	Under Armour	Sean W Dwyer	The pants we are using to attach screen-printed electrodes, battery pack, etc. Not necessarily an important part of the design, but since they are attached to the pants the trademark must be listed for legal issues.
90384005	12/15/20	MATLAB	The MathWorks, Inc.	The application will be used to analyze the data that has been sent from the Teensy 4.1 development board.

Table 6: Pertinent Trademark search to the Smarty Pants design.

Claims

We claim:

1. A pair of spandex pants comprising:
    a. Sewn-in patches of specialized electrodes;
    b. Sewn-in protected aluminum wiring that connects the electrodes to the Teensy 4.1;
    c. A pocket on the back side of the waistband of the pants that contains the battery pack;
    d. A code that reads electromyography (EMG) input from the electrodes and provides feedback to the user that informs running form and strength training in order to prevent injury.
2. The specialized electrodes of claim 1, wherein said electrodes are comprising:
    a. PET cotton stitched into the spandex pants material in specific locations of relevant muscle groups;
    b. Conductive silver paste painted onto the inside PET fabric;
    c. Gold protective layer that has been deposited onto the inside silver of the electrode patch and is in contact with the skin;
    d. Aluminum wiring running through the electrode and pant fabric connecting to the processor input;

   e. Five electrode placements on each leg; placed over the gluteus maximus, gluteus medius, quadriceps, hamstring, and gastrocnemius/soleus muscles.

3. The battery pack of claim 1, wherein said pack comprises of:
   a. 3D printed pack, consisting of either PLA, tough PLA, or ABS plastic;
   b. Specialized compartments to house the Arduino and double coin cell battery holder;
   c. A hole between the compartments for proper wiring to connect from the battery holder to the Arduino;
   d. An input for the aluminum wiring to the Arduino for the EMG signaling from the electrodes;
   e. A snap-in latch system for the battery pack to allow for the user to have access to the coin cell battery holder;
   f. A panel that screws on giving access to the compartment that houses the Arduino.
4. The code of claim 1, wherein said code is comprising:
   a. Displays pre-loaded instructions on a series of calibration movements for the user to perform upon start-up of system;
   b. Arduino IDE programming software for acquisition of the input stream of electrical muscle activity EMG data detailed in claim 3 from the electrodes to the Teensy 4.1 development board;
   c. The sending of data from the software in claim 4-b to MATLAB for analysis;
   d. Analysis of ratios between specific, different individual electrode readings from the EMG signals detailed in claim 3 to determine if the user is running properly or is compensating to adjust for weakness of specific muscle groups;
   e. Output of analysis detailed in claim 4-d in a format the user can efficiently comprehend and utilize.

Design for the Environment

Life Cycle Assessment

Our product will study muscle activation for injury-preventing running gait analysis. A conductive gold-coated silver paste lining specific areas of the workout leggings will connect to an Arduino housed in a plastic shell (pack). The conductive areas will provide an EMG reading used to identify injury predisposition based on muscle group weakness. We will be analyzing components of our product that we are designing ourselves and not purchasing from elsewhere (like the lithium ion battery): pants material and the battery pack. Future analysis should look at the environmental impact of the silver and gold patches as those components of the design are researched, refined, and solidified. Regarding the pants and battery pack materials, the battery pack has a larger environmental impact. This conclusion was determined by comparing the greenhouse gasses contributed by each sector according to Table 7: the plastics sector produced a total of 2,510 total tons of CO_2 while the textiles sector produced 265 tons (Figure 10). Based on this discrepancy, we focused our efforts on minimizing the environmental impact of our plastic pack.

Sector[21]	**Total process CO_2 (tons)**	**Sector CO_2 (tons)**
Plastics material and resin manufacturing	2510	532.0
Retail trade	265	22.3

Table 7: LCA environmental impacts of plastics and fabric (retail trade) sectors.

Life Cycle Impact

Life cycle of acrylic and corresponding environmental impact for ABS, our initial choice, is displayed in Figure 12A. Acrylic is displayed in Figure 12B. We will be using recycled acrylic to reduce manufacturing environmental impacts. Values for Transportation and End of Life are comparable with only a slight difference in values, so they are negligible. Based on these factors, environmental impact of material is the main consideration. Figure 10 shows that the environmental impact of acrylic material is lower.

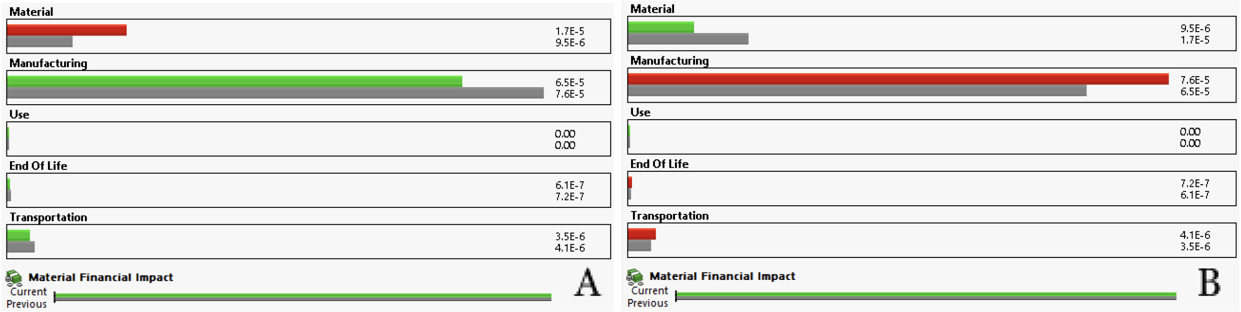


Fig. 10: Environmental impacts vs. life cycle for ABS (A) and acrylic med-high impact (B), where the material of the acrylic med-high impact has less of an environmental impact.

Life Cycle Map

The acrylic life cycle, shown in Figure 11, begins by obtaining material from recycled or primary sources. The plastic is transformed into a pack for our product, used in the pants, and eventually discarded. Redesign boundaries relevant to our process are circled in blue.

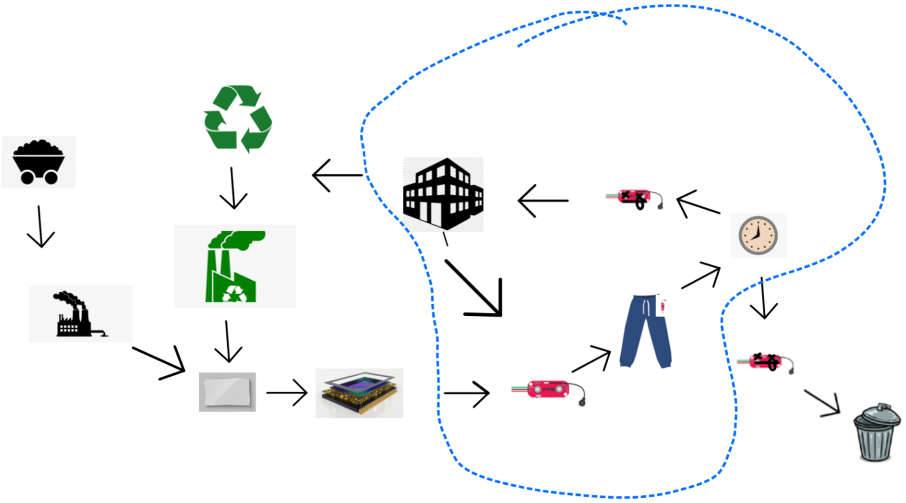


Fig. 11: Map of product's life cycle with redesign boundary encircled in blue.

Design Refinements and Design Goals Compared to Original Design

For the future of our design, our group focused on sustainable plastics for the battery box to reduce carbon impact. From our determination, the Acrylic med-high impact will be a better option compared to ABS because it consumes less energy, provides less air acidification, and also leads to less water eutrophication as seen in Figure 12. While they both had the same End of Life parameters, the other considerations led to the decision to choose Acrylic med-high plastic for our model.

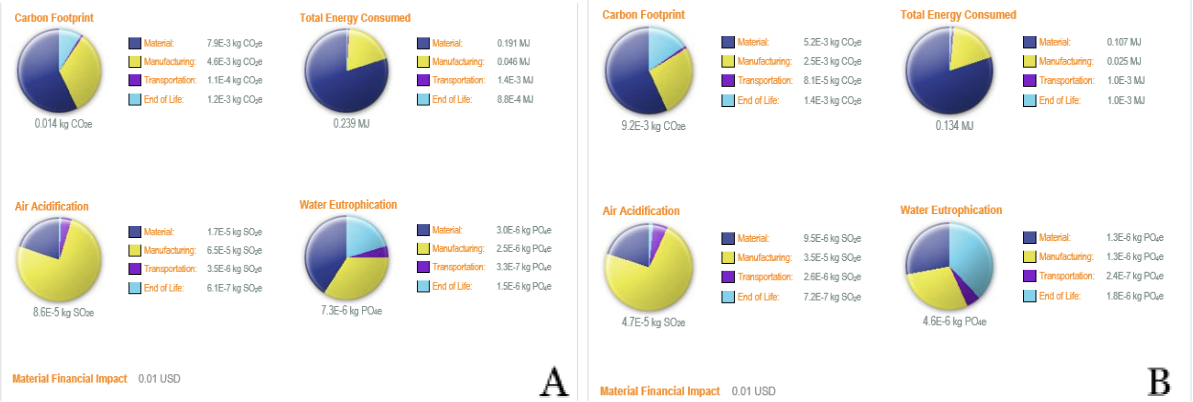


Fig. 12: ABS (A) and Acrylic Med-high Impact (B) Environmental Impact SoldWorks Report.

Reducing the thickness of the plastic on the battery pack holder will also reduce the environmental impact, as demonstrated in Figure 12. Acrylic Med-high impact plastic has a higher tensile strength, so the thickness of the battery pack holder can be smaller while still supporting the battery. When choosing the ABS originally, we wanted a plastic that was comparable to the plastic used in TV remote controls because they are able to hold shape and keep durability while containing the hardware system for the battery insertion. Acrylic Med-high impact plastic was a comparable replacement with less environmental impacts.

Due to the ability for the battery pack holder to disconnect from the electrode wiring, the battery pack can be used for multiple different sets of pants and customers. When the user is done with their pants, they can return the battery pack holder to the company where it can be sent off to another user, as signified in Figure 13. From this assumption, we wanted a plastic that can last for 10 years, allowing for less waste and production of plastic, to reduce the environmental impact. Unfortunately, Acrylic Med-high impact plastic was not available to us for 3D printing prototypes, so future models will incorporate our determined plastic. Instead, prototypes were printed using PLA and PLA+ material, which proved to be a good substitute.

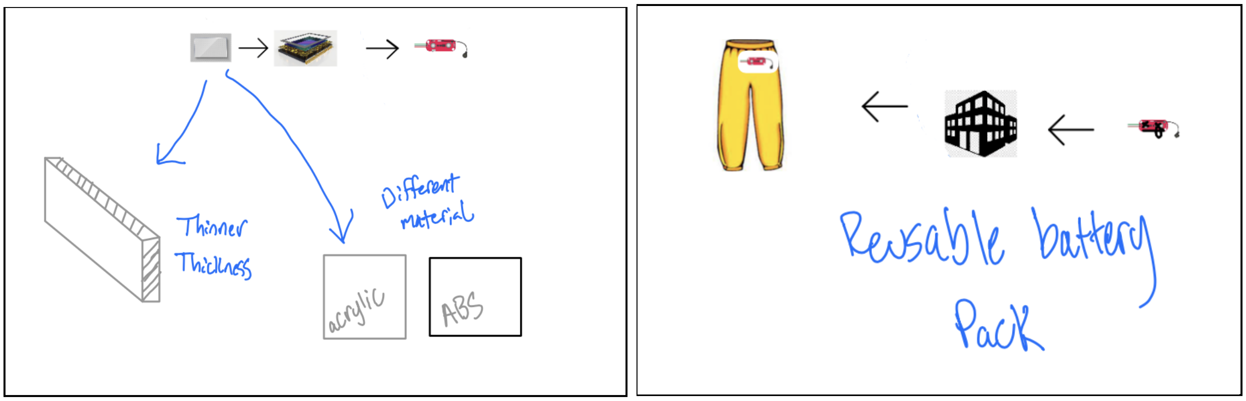


Fig. 13: Brainstorming map for possible refinements to lower the product's environmental impact.

Summary and Conclusions

Overall Summary

Smarty Pants is an EMG integrated material that processes gait analysis discreetly and affordably. Using silver nanoparticle electrodes, the muscle activation signals from the conductive paste can provide data to determine injury-preventative care and muscular maintenance. Instead of attending physical therapy or scheduling expensive doctors appointments, Smarty Pants can be used affordably at home. Our accessible product allows users to avoid copays or medical device fees and use a continuous monitoring system with a one time payment. The stitched-in electrodes, created using conductive silver paste, connect to a small battery pack that houses a processing unit and powers the system. The processing unit records EMG signals that are sent for analysis via bluetooth. Gait analysis can be viewed on an application right at the user's fingertips. Once receiving results, they can obtain exercises, workouts, and suggestions for how to improve their gait and prevent injury. The buoyant power pack and water resistant electrodes allow for multiple washes and reduced risk of damaging the processing unit.

Conclusions

In conclusion, our Smarty Pants prototype can accurately measure muscle activation using silver nanoparticle electrodes. Based on our prototype testing schemes, the signals present from the personalized electrode patches can be processed using an amplifier. Our Matlab code can successfully take those signals and give the user an output accordingly. We can analyze the data from our device and present information to users, exemplifying that this product could be a success. The personalized battery pack is small enough to avoid inhibiting activity, durable enough to withstand drops, temperature fluctuations, and water damage. The pull-tab of the battery is easy to use while protecting the inner chambers of the device. Our prototypes provide promising results for future models and potential development of a full pair of Smarty Pants.

Future Technical Models

For the future direction of our product, there are multiple technical models that need to be addressed. First and foremost, we will be investigating the signal strength output from a Teensy 4.1 Arduino versus our current model, a Teensy 3.2. The signal strength from the silver conductive electrodes was not large enough to pick up without an amplifier, and theoretically the 4.1 should have that capability due to its stronger processing power. The Teensy 4.1 will also fit into our battery pack, as it was modeled with this in mind. In relation to the electrodes, we would like to apply gold nanoparticle flakes to reduce irritation on skin. As mentioned before, there was no irritation during testing, but continuous wear could lead to the possibility of irritation. Comparing electrodes with and without gold flakes can help assess whether or not this is a necessary addition. Another consideration is the electrical connections of the battery pack to allow for power to be distributed throughout the device. We want to create an electrode connection that can be removed from the battery pack for washing, as a wash cycle can be harsh on the processing unit despite it being fully waterproof. In reference to the processing system, we also need to expand on the bluetooth capability of the Arduino. We would like to develop an app that does showcase results, exercises, and preventative care to users based on their activity. Instead of having a simple Matlab output that states the user has good activation, we want to make an interactive experience for customers. We need to determine what a "good" gait looks like, or what muscles are activated during which phase of stride in order to minimize overloading of joints and other often-injured structures. This could be done by possibly running multiple tests to find a threshold value and also by studying literature on running biomechanics and loading.

Team Reflections

Rebekah Bond

What an adventure. I can't count how many times I sat in Milam or Kelly, head spinning, simply trying to grab thoughts and put them together into something cohesive enough to move forwards. Just trying to figure out which direction forward was proved quite the challenge at times. Which opportunity do we pursue? Which concept? Which solution path? How exactly do we make electrodes? How are we supposed to test them? What is the goal of this aspect of the project again? Wait, what is a Fourier transform, and how are we supposed to perform one to process an EMG signal? Out of all the many many things I learned over the course of this project, there are two lessons that have sunk deep. The first is that it takes a team. No way could I have done any of this on my own. It took all of us working together, providing input, cutting a path forward through the tangled jungle of it all. And then our team relied on the support and expertise of many faculty and also undergraduate students from other majors. Smarty Pants is a product of many minds working together. It could only have happened because many minds worked together. The second lesson I learned is that confusion is not a dead end. Not understanding the next step doesn't mean there isn't a next step. At the beginning of the term I didn't think it was possible that within 10 weeks I'd make a real working electrode and test it on my laptop. We did that and so much more.

Annes El-Krewi

This was an incredible journey to say the least. I gained a lot of new skills that I never would have without this class, especially EMG's and Matlab (something I would like to better at). My biggest regret was not being able to use the silver-based paste for screen printing. I really wanted to learn more about screen printing and this would've been a great introduction to it. Outside help really made us move forward and I'm thankful for everyone's help, even the ones that said our project would be impossible to complete. I'm thankful for my amazing group who shouldered most of the work when I became lost, and never complained. It's definitely interesting to see our project compared to others, it seemed like a lot of other groups used assays and techniques learned from previous classes, whereas our project seemed to be learning stuff along the way. All in all, we created a product that worked when it seemed like there was no chance!

Laura Heinze

This project was a great experience for me to learn about a variety of topics that I did not learn about much through my courses. I specifically found it was super fun and intriguing to learn about electrodes, EMGs, and how one would go about analyzing the results for useful feedback. Talking with Dr. Biga and Dr. Norcross made me realize that I would enjoy studying more about physiology at some point. My biggest learning curve was with coding. I learned a lot about computers and coding that I did not know, and my respect for computer scientists, which was already a lot, grew even more. It was good to have the help of an ECE student and also research things on my own. I was surprised that in our project, the smallest portion of what we worked on was the "bio" in bioengineering. Most of what we did involved coding and more mechanical stuff. There were a little bit of electrical components as well, but not as much. I am glad we took on this challenge because I think it has increased some of our skill sets and experiences. It did require a lot of effort in terms of research and planning, but overall, we were able to meet our goal and build a prototype that actually works.

Allison Ray

This process was incredibly rewarding for me. We had a multitude of setbacks, and were even told by an advisor that this project would be nearly impossible. Through all of the challenges, we created an incredible product. Creating the power pack was a great learning curve for me, and taught me an incredible amount about computer aided design. It gave me a new passion for it and I am thankful for the opportunity to complete this project. Seeing your work in action is extremely rewarding, and I could not be more proud of our team with the results.

Sources

[1] *126 Running Statistics You Should Know*. (n.d.). LIVESTRONG.COM. https://www.livestrong.com/article/13730338-running-statistics/

[2] *Running Injuries*. (n.d.). Yale Medicine. https://www.yalemedicine.org/conditions/running-injury

[3] Fox, K. (2015, February 27). *What Kind of Runner is Most Likely to Get Injured?* Runner's World. https://www.runnersworld.com/health-injuries/a20849925/what-kind-of-runner-is-most-likely-to-get-injured/

[4] *Sports Medicine Market | Growing at a CAGR of 6.5% | MarketsandMarkets*. (n.d.). Www.marketsandmarkets.com. https://www.marketsandmarkets.com/Market-Reports/sports-medicine-devices-market-751.html

[5] *Topic: Running & Jogging*. (n.d.). Statista. https://www.statista.com/topics/1743/running-and-jogging/#dossierKeyfigures

[6] Lim, T., Zhang, H., & Lee, S. (2021). Gold and silver nanocomposite-based biostable and biocompatible electronic textile for wearable electromyographic biosensors. *APL Materials*, *9*(9), 091113. https://doi.org/10.1063/5.0058617

[7] Araujo, K. (2020). *Battery Comparison of Energy Density - Cylindrical and Prismatic Cells*. Epectec.com. https://www.epectec.com/batteries/cell-comparison.html

[8] Araujo, K. (2020). *Battery Comparison of Energy Density - Cylindrical and Prismatic Cells*. Epectec.com. https://www.epectec.com/batteries/cell-comparison.html

[9] *StackPath*. (n.d.). Www.electronicdesign.com. Retrieved December 9, 2021, from https://www.electronicdesign.com/power-management/whitepaper/21156693/green-cubes-technology-the-lithiumion-cells-and-chemistries-you-need-to-know

[10] *Battery Technologies*. SparkFun. (n.d.). Retrieved December 8, 2021, from https://learn.sparkfun.com/tutorials/battery-technologies/all.

[11] *Lithium-Ion Information Guide | Houston, Texas USA |*. (n.d.). Www.swe.com. https://www.swe.com/lithiumion/#:~:text=VOLTAGE%20PER%20CELL%3A%20Lithium%2DIon

[12] Zulifqar, D. A. (2020, July 24). *What is GSM or weight or areal density of a fabric?* Fabrieka. https://fabrieka.com/2020/07/24/what-is-gsm-or-weight-or-areal-density-of-a-fabric/

[13] *Guide to Understanding Activewear Fabrics*. (n.d.). Surge Fabric Shop. Retrieved December 9, 2021, from https://surgefabricshop.com/blogs/surges-sewing-blog/guide-to-understanding-activewear-fabrics

[14] Nike. (2021). *Nike. Just Do It*. Nike.com. https://www.nike.com/

[15] *Under Armour® Official Store – FREE Shipping available*. (2017). Under Armour®. https://www.underarmour.com/en-us/

[16] Lim, T., Zhang, H., & Lee, S. (2021). Gold and silver nanocomposite-based biostable and biocompatible electronic textile for wearable electromyographic biosensors. *APL Materials*, *9*(9), 091113. https://doi.org/10.1063/5.0058617

[17] Dack, D. (2020, July 28). *Top 9 Common Running Injuries —*. Runner's Blueprint. https://www.runnersblueprint.com/running-injuries/

[18] Luntz, R. (n.d.). *Are Weak Glutes Causing Your Injury?* https://www.melbournepodiatryclinic.net.au/are-weak-glutes-causing-your-injury/

[19] van Dyk, N., Bahr, R., Whiteley, R., Tol, J. L., Kumar, B. D., Hamilton, B., Farooq, A., & Witvrouw, E. (2016). Hamstring and Quadriceps Isokinetic Strength Deficits Are Weak Risk Factors for Hamstring Strain Injuries. *The American Journal of Sports Medicine*, *44*(7), 1789–1795. https://doi.org/10.1177/0363546516632526

[20] *Gait Analysis - Stanford Children's Health*. (n.d.). Www.stanfordchildrens.org. Retrieved December 9, 2021, from https://www.stanfordchildrens.org/en/service/motion-gait-analysis-laboratory/gait

[21] *eiolca.net - Free Life Cycle Assessment on the Internet*. (n.d.). www.eiolca.net. http://www.eiolca.net/cgi-bin/dft/use.pl

[22] https://xenoma.com/

[23] https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfPCD/classification.cfm?ID=5439

Appendix

Proof of Poster

Smarty Pants

Paving a path to better biomechanics

Why?

- 50-70% of runners injured annually
- Improper running form has huge negative impacts
- Prevent injuries instead of react to them

~ Get ahead of the pain. Stay in the game. ~

What?

- Electrodes measure muscle activity connected to power pack processing unit
- Data is compiled and sent to smartphone
- User given exercises to train weak muscle groups

→ →

Smart Electrodes: Silver paste was painted onto PET fabric and a stripped wire was painted into the patch creating an electrode.

Power Pack Model

Smart Pack: The power pack houses an Arduino 4.1 which processes the signal from the electrodes

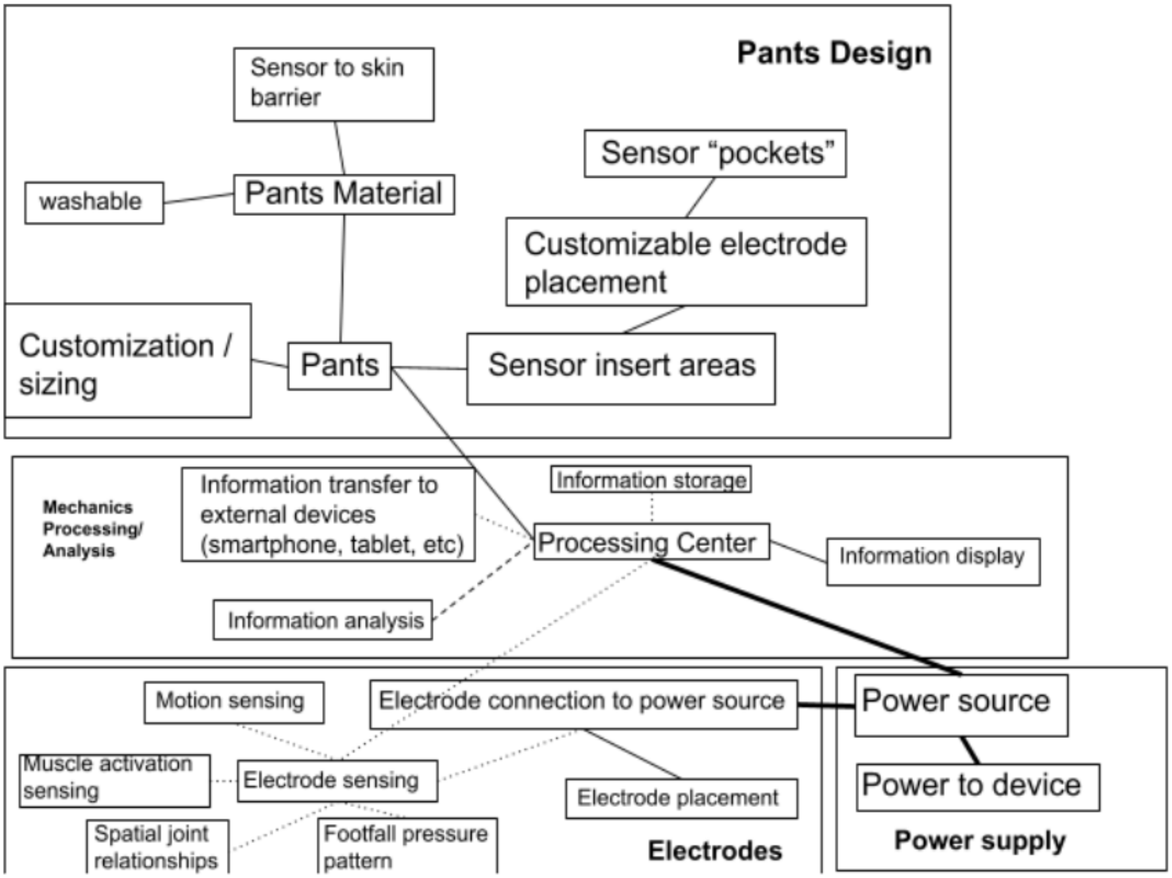
Arduino: The above graph is output from a Teensy Arduino based on signals generated from an oscilloscope

Smarty Pants

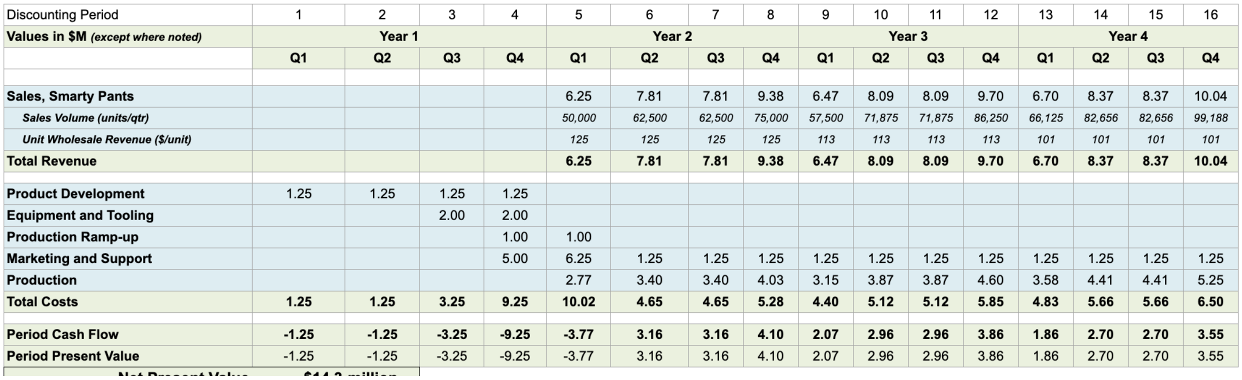
Acknowledgements

Dr. Marc Norcross
Dr. Lindsay Biga
Dr. Matthew Johnston
Peter Bond
Jahnsam Richardson
Thomas Snyder
Michael Frazier

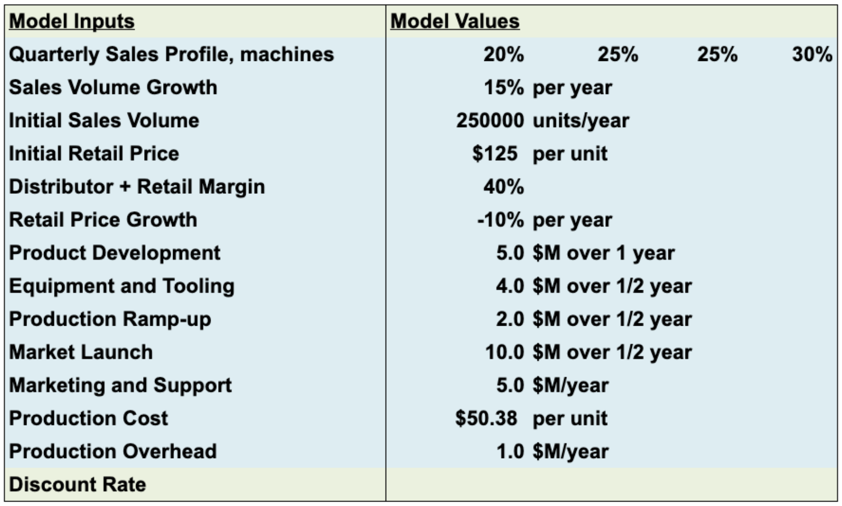
Appendix A


Pants Design
Sensor to skin barrier
washable
Pants Material
Sensor "pockets"
Customizable electrode placement
Customization / sizing
Pants
Sensor insert areas
Mechanics Processing/ Analysis
Information transfer to external devices (smartphone, tablet, etc)
Information storage
Processing Center
Information display
Information analysis
Motion sensing
Electrode connection to power source
Power source
Muscle activation sensing
Electrode sensing
Electrode placement
Power to device
Spatial joint relationships
Footfall pressure pattern
Electrodes
Power supply

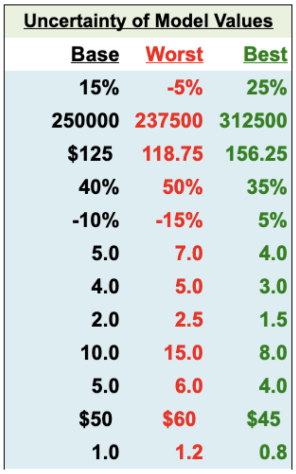
Appendix B



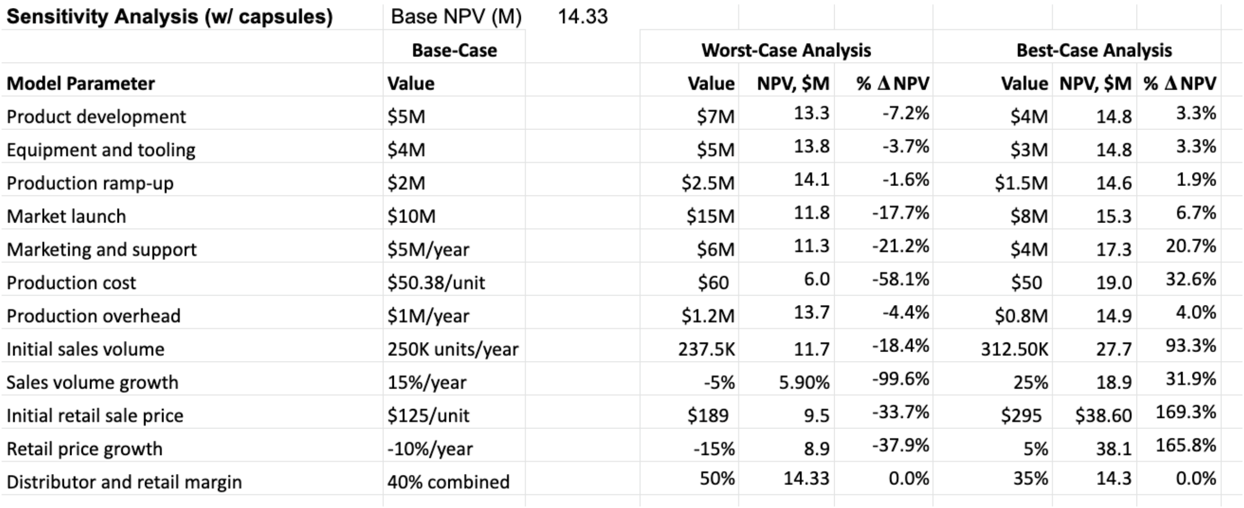
Discounting Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Values in $M ***(except where noted)***	**Year 1**				**Year 2**				**Year 3**				**Year 4**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Sales, Smarty Pants					6.25	7.81	7.81	9.38	6.47	8.09	8.09	9.70	6.70	8.37	8.37	10.04
Sales Volume (units/qtr)					*50,000*	*62,500*	*62,500*	*75,000*	*57,500*	*71,875*	*71,875*	*86,250*	*66,125*	*82,656*	*82,656*	*99,188*
Unit Wholesale Revenue ($/unit)					*125*	*125*	*125*	*125*	*113*	*113*	*113*	*113*	*101*	*101*	*101*	*101*
Total Revenue					**6.25**	**7.81**	**7.81**	**9.38**	**6.47**	**8.09**	**8.09**	**9.70**	**6.70**	**8.37**	**8.37**	**10.04**
Product Development	1.25	1.25	1.25	1.25												
Equipment and Tooling			2.00	2.00												
Production Ramp-up				1.00	1.00											
Marketing and Support				5.00	6.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Production					2.77	3.40	3.40	4.03	3.15	3.87	3.87	4.60	3.58	4.41	4.41	5.25
Total Costs	**1.25**	**1.25**	**3.25**	**9.25**	**10.02**	**4.65**	**4.65**	**5.28**	**4.40**	**5.12**	**5.12**	**5.85**	**4.83**	**5.66**	**5.66**	**6.50**
Period Cash Flow	**-1.25**	**-1.25**	**-3.25**	**-9.25**	**-3.77**	**3.16**	**3.16**	**4.10**	**2.07**	**2.96**	**2.96**	**3.86**	**1.86**	**2.70**	**2.70**	**3.55**
Period Present Value	-1.25	-1.25	-3.25	-9.25	-3.77	3.16	3.16	4.10	2.07	2.96	2.96	3.86	1.86	2.70	2.70	3.55
Net Present Value	**$14.3 million**															



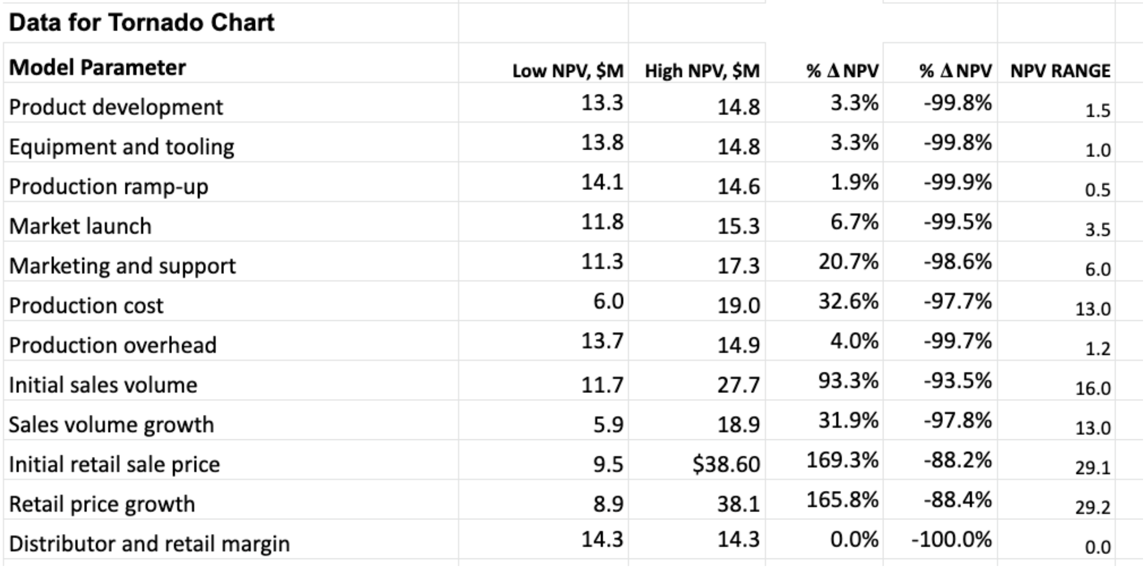
Model Inputs	**Model Values**			
Quarterly Sales Profile, machines	**20%**	**25%**	**25%**	**30%**
Sales Volume Growth	**15%**	**per year**		
Initial Sales Volume	**250000**	**units/year**		
Initial Retail Price	**$125**	**per unit**		
Distributor + Retail Margin	**40%**			
Retail Price Growth	**-10%**	**per year**		
Product Development	**5.0**	**$M over 1 year**		
Equipment and Tooling	**4.0**	**$M over 1/2 year**		
Production Ramp-up	**2.0**	**$M over 1/2 year**		
Market Launch	**10.0**	**$M over 1/2 year**		
Marketing and Support	**5.0**	**$M/year**		
Production Cost	**$50.38**	**per unit**		
Production Overhead	**1.0**	**$M/year**		
Discount Rate				



Uncertainty of Model Values		
Base	**Worst**	**Best**
15%	**-5%**	**25%**
250000	**237500**	**312500**
$125	**118.75**	**156.25**
40%	**50%**	**35%**
-10%	**-15%**	**5%**
5.0	**7.0**	**4.0**
4.0	**5.0**	**3.0**
2.0	**2.5**	**1.5**
10.0	**15.0**	**8.0**
5.0	**6.0**	**4.0**
$50	**$60**	**$45**
1.0	**1.2**	**0.8**



Sensitivity Analysis (w/ capsules)	Base NPV (M)	14.33						
	Base-Case		**Worst-Case Analysis**			**Best-Case Analysis**		
Model Parameter	**Value**		**Value**	**NPV, $M**	**% Δ NPV**	**Value**	**NPV, $M**	**% Δ NPV**
Product development	$5M		$7M	13.3	-7.2%	$4M	14.8	3.3%
Equipment and tooling	$4M		$5M	13.8	-3.7%	$3M	14.8	3.3%
Production ramp-up	$2M		$2.5M	14.1	-1.6%	$1.5M	14.6	1.9%
Market launch	$10M		$15M	11.8	-17.7%	$8M	15.3	6.7%
Marketing and support	$5M/year		$6M	11.3	-21.2%	$4M	17.3	20.7%
Production cost	$50.38/unit		$60	6.0	-58.1%	$50	19.0	32.6%
Production overhead	$1M/year		$1.2M	13.7	-4.4%	$0.8M	14.9	4.0%
Initial sales volume	250K units/year		237.5K	11.7	-18.4%	312.50K	27.7	93.3%
Sales volume growth	15%/year		-5%	5.90%	-99.6%	25%	18.9	31.9%
Initial retail sale price	$125/unit		$189	9.5	-33.7%	$295	$38.60	169.3%
Retail price growth	-10%/year		-15%	8.9	-37.9%	5%	38.1	165.8%
Distributor and retail margin	40% combined		50%	14.33	0.0%	35%	14.3	0.0%



Data for Tornado Chart

Model Parameter	Low NPV, $M	High NPV, $M	% Δ NPV	% Δ NPV	NPV RANGE
Product development	13.3	14.8	3.3%	-99.8%	1.5
Equipment and tooling	13.8	14.8	3.3%	-99.8%	1.0
Production ramp-up	14.1	14.6	1.9%	-99.9%	0.5
Market launch	11.8	15.3	6.7%	-99.5%	3.5
Marketing and support	11.3	17.3	20.7%	-98.6%	6.0
Production cost	6.0	19.0	32.6%	-97.7%	13.0
Production overhead	13.7	14.9	4.0%	-99.7%	1.2
Initial sales volume	11.7	27.7	93.3%	-93.5%	16.0
Sales volume growth	5.9	18.9	31.9%	-97.8%	13.0
Initial retail sale price	9.5	$38.60	169.3%	-88.2%	29.1
Retail price growth	8.9	38.1	165.8%	-88.4%	29.2
Distributor and retail margin	14.3	14.3	0.0%	-100.0%	0.0

Appendix C

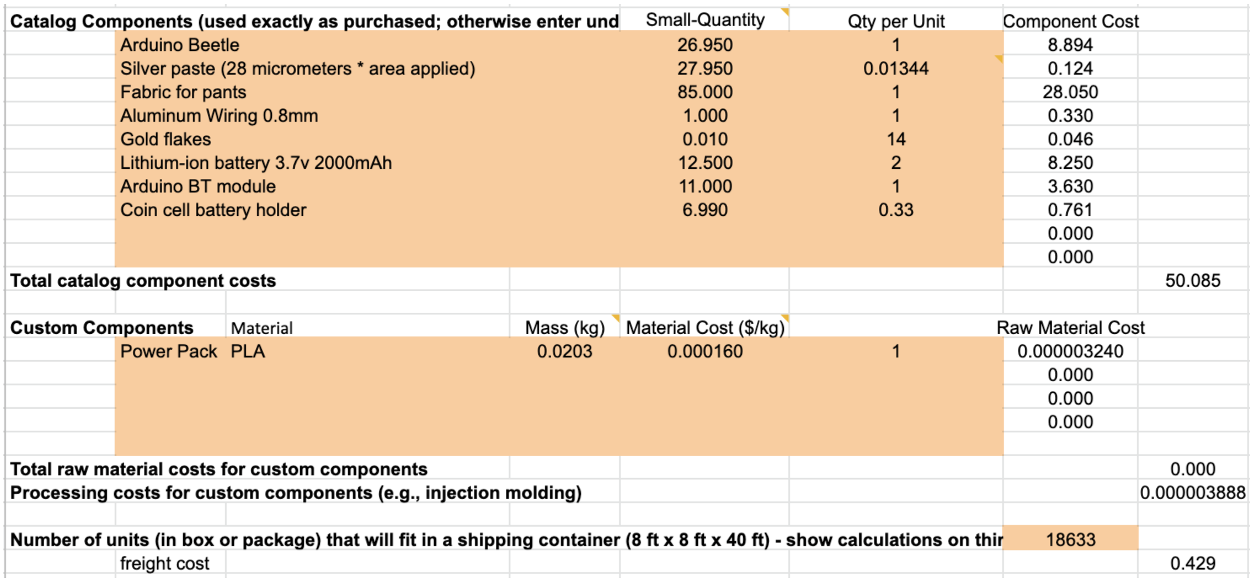
	Model 1	Model 2
Thermal Resistance (with PLA)	0.0115 W/K	0.0346 W/K

Height of Drop	PLA Model 1	PLA+ Model 1	PLA+ Model 2
1 ft	No damage	No damage	No damage
2 ft	No damage	No damage	No damage
3 ft	No damage	No damage	No damage
4 ft	No damage	No damage	No damage
5 ft	No damage	No damage	No damage

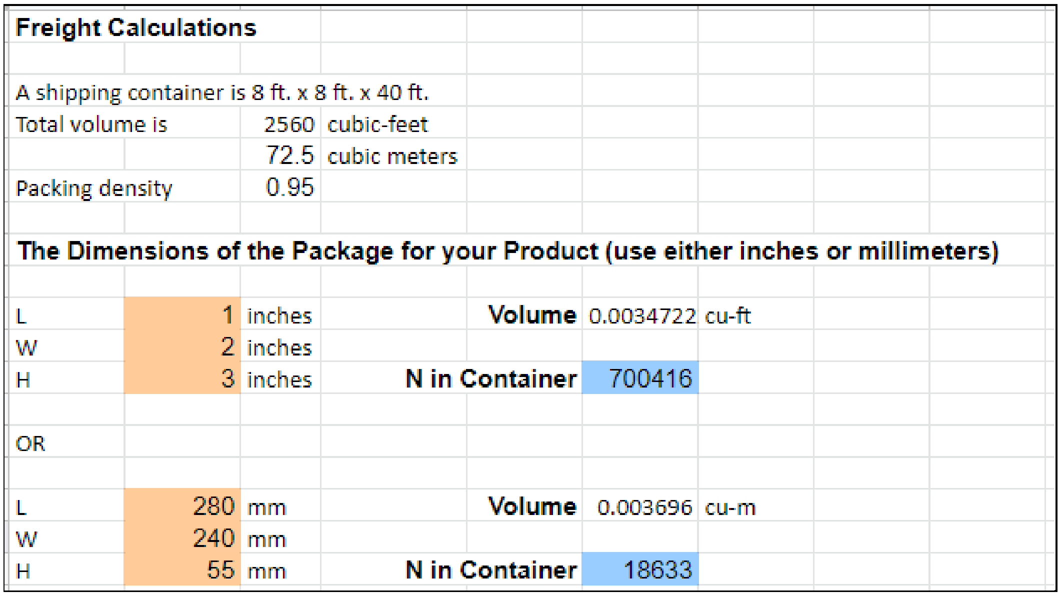
	PLA Model 1	PLA+ Model 1	PLA+ Model 2
Total bend	4 mm	2 mm	5 mm
Ease of use	Hard, but not as hard as PLA+ model	Extremely hard, bridge too thick	way easier!

	PLA Model 1	PLA+ Model 1	PLA+ Model 2
Float Time	infinite	infinite	infinite
Leakage	No water in bottom compartment	No water in bottom compartment	water in bottom compartment where the electrode wire hole is

Appendix D



Catalog Components (used exactly as purchased; otherwise enter und				Small-Quantity	Qty per Unit	Component Cost	
	Arduino Beetle			26.950	1	8.894	
	Silver paste (28 micrometers * area applied)			27.950	0.01344	0.124	
	Fabric for pants			85.000	1	28.050	
	Aluminum Wiring 0.8mm			1.000	1	0.330	
	Gold flakes			0.010	14	0.046	
	Lithium-ion battery 3.7v 2000mAh			12.500	2	8.250	
	Arduino BT module			11.000	1	3.630	
	Coin cell battery holder			6.990	0.33	0.761	
						0.000	
						0.000	
Total catalog component costs							50.085
Custom Components		Material	Mass (kg)	Material Cost ($/kg)		Raw Material Cost	
	Power Pack	PLA	0.0203	0.000160	1	0.000003240	
						0.000	
						0.000	
						0.000	
Total raw material costs for custom components							0.000
Processing costs for custom components (e.g., injection molding)							0.000003888
Number of units (in box or package) that will fit in a shipping container (8 ft x 8 ft x 40 ft) - show calculations on thir						18633	
	freight cost						0.429



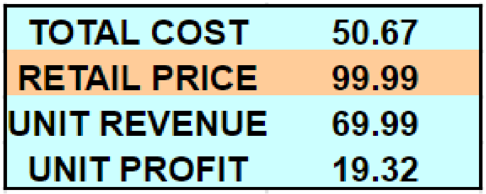
Freight Calculations

A shipping container is 8 ft. x 8 ft. x 40 ft.

Total volume is	2560	cubic-feet		
	72.5	cubic meters		
Packing density	0.95			

The Dimensions of the Package for your Product (use either inches or millimeters)

L	1	inches	**Volume**	0.0034722	cu-ft
W	2	inches			
H	3	inches	**N in Container**	700416	
OR					
L	280	mm	**Volume**	0.003696	cu-m
W	240	mm			
H	55	mm	**N in Container**	18633	



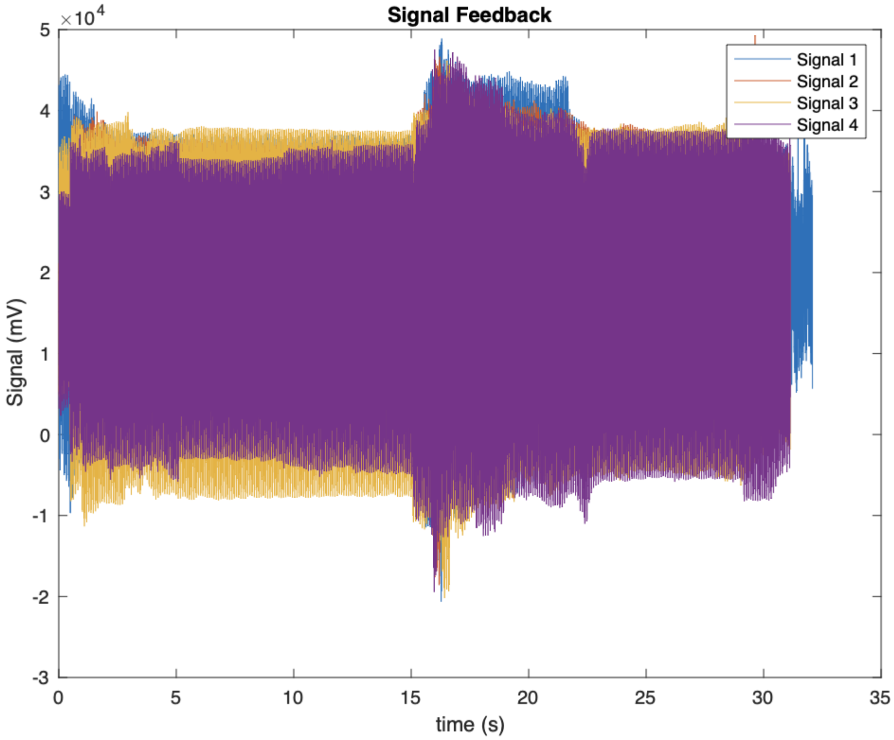
TOTAL COST	**50.67**
RETAIL PRICE	**99.99**
UNIT REVENUE	**69.99**
UNIT PROFIT	**19.32**

Appendix E

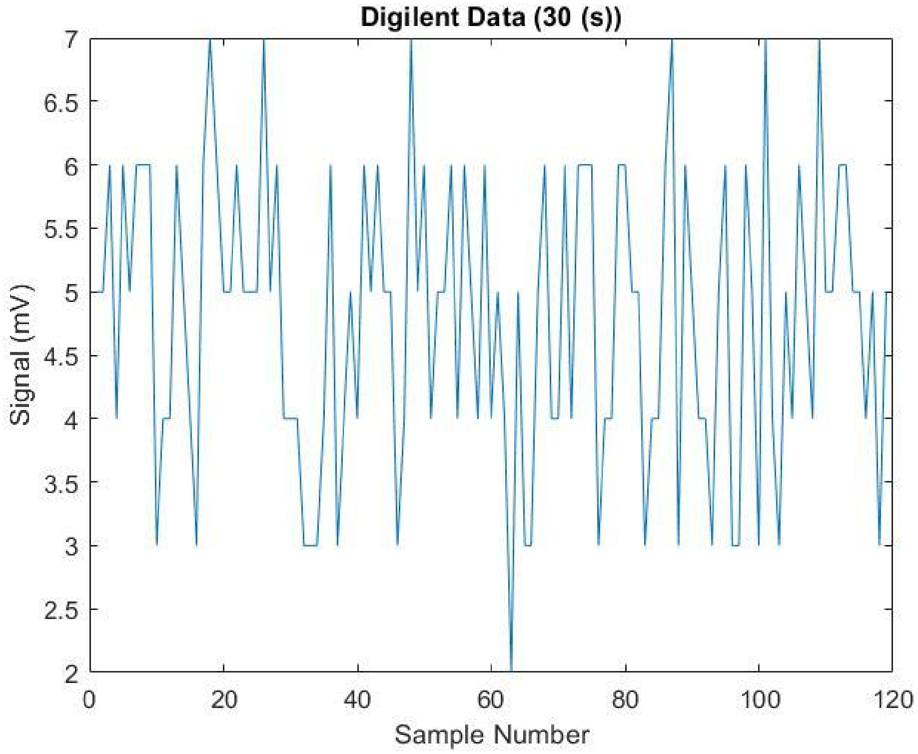
```
clear all;
clc;
close all;
load('EMG_Data8.mat','x00_38')
load("EMG_Data7.mat",'x51_11')
load("EMG_Data6.mat","x38_15")
load('EMG_Data5.mat','x29_05')
% Multiply y-values by 1/Hz to help determine area under the curve
% using the area under the curve find the riemann sums to quantify muscle
% activation and compare results
Hz= 255; % hertz
X = (1/Hz)*(1:length(x29_05)); % cyton board data is based on hertz, so
"x-values", the time in which the experiment goes on for, starts at 0 -> 255
then restarts at 0 again. therefore, this was made to reflect how many seconds
actually passed.
Y = (1/Hz)*(1:length(x38_15)); % time length of signal
W = (1/Hz)*(1:length(x51_11)); % time length of signal
Z = (1/Hz)*(1:length(x00_38)); % time length of signal
SIGNAL1 = abs(x29_05(:,1)); % column reflecting EMG signals
SIGNAL2 = abs(x38_15(:,1)); % column reflecting EMG signals
SIGNAL3 = abs(x51_11(:,1)); % column reflecting EMG signals
SIGNAL4 = abs(x00_38(:,1)); % column reflecting EMG signals
AUC = trapz(X,abs(SIGNAL1)) % area under curve
AUC2 = trapz(Y,abs(SIGNAL2)) % area under curve for second signal
AUC3 = trapz(W,abs(SIGNAL3)) % area under curve
AUC4 = trapz(Z,abs(SIGNAL4)) % area under curve
subplot(2,2,1)
plot(X,SIGNAL1)% displays plot of EMG signal
title('Literature Position') % title of plot
xlabel('time (s)') % x-axis
ylabel('Signal (mV)') % y-axis
subplot(2,2,2)
plot(Y,SIGNAL2)
title('2.5 cm Lateral Movement ') % title of plot
xlabel('time (s)') % x-axis
ylabel('Signal (mV)') % y-axis
subplot(2,2,3)
```

```
plot(W,SIGNAL3)
title('2.5 cm Distal Movement') % title of plot
xlabel('time (s)') % x-axis
ylabel('Signal (mV)') % y-axis
subplot(2,2,4)
plot(Z,SIGNAL4)
title('2.5 cm Medial Movement') % title of plot
xlabel('time (s)') % x-axis
ylabel('Signal (mV)') % y-axis
fprintf('Area under curve of signal one, two, three and four are [%4.2f] and
[%8.2f] [%8.2f] [%8.2f] mV',AUC,AUC2,AUC3,AUC4)
```

Appendix F



Appendix G



Appendix H