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MEMS 411: Self Lacing Shoes

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Washington University in St. Louis

JAMES MCKELVEY SCHOOL OF ENGINEERING

SP21 MEMS 411 Mechanical Engineering Design Project

Self Lacing Shoes

The self lacing shoes are a concept which come from the 1989 science fiction movie Back to the Future 2 in which the main character puts on a pair of basketball shoes which tighten around his feet as soon as they are put on. While there are other shoes on the market which attempt to recreate this feature, all of them are at a price point which is unreasonable for the average consumer. The target audience for our product in particular will be those with disabilities who are unable to tie conventional shoes due to dexterity, strength, or flexibility issues.

The product developed in this report is not so much a shoe itself, but rather a drop in kit which readily converts any shoe into a self lacing one. The design is based around a DC motor which will draw the re-routed laces around spools hidden in the sole of the shoe. The motor is activated by a pressure pad in the insole and the entire device is powered by a replaceable 9V battery.

This report details the entire prototype generation cycle from concept generation through the implementation of CAD models, engineering equations, and the eventual refinement of a final product which is then tested to meet three major goals. For the self lacing shoes, the goals were to keep the design under 1.5 pounds per shoe, have the battery life extend beyond 50 lacing cycles, and to have the shoes be durable enough to withstand 10 minutes of continuous athletic activity. Ultimately the shoes succeeded in every aspect, with a battery life well beyond 50 cycles, a final weight of 1.206 lbs and a durable construction which survived a simulated basketball practice.

PIGATTI, Peter
ROBERTS, Bryce
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1 Introduction

For our senior design project we have chosen to design and prototype a pair of self lacing shoes with the initial target audience being people with disabilities who are limited in their ability to tie their own shoes for a variety of reasons. However, we hope that this product will catch on in popularity and become normalized for all people. These shoes will allow the wearer to easily slip them on and then secure the shoes to the foot with the push of a button rather than tying laces as in conventional shoes. This process will be driven by a mechanical motor and ratchet system hidden in the soles of the shoes.

While alternatives such as Velcro, slip-ons, and even other self-lacing shoes are available on the market, each of these options have short comings which our product aims to improve on. From lack of foot support to lack of style and inaccessible prices, the current market does not provide a suitable option for people who want something other than conventional shoes.

2 Problem Understanding

2.1 Existing Devices

The following are existing products that perform similar functions or exist to solve the same problems as our prototype. While these products already exist in the market, each of them have measurable shortcomings that our product hopes to improve upon.

2.1.1 Existing Device #1: Nike MAG

Figure 1: Nike MAG Limited Edition Basketball Shoes (Source: Nike.com)

Link: https://news.nike.com/nike-mag
Description: The Nike MAG shoes were a limited edition self-lacing shoe model originally released in 2011 and again in 2016. The 2011 model was simply a display model intended to be a replica of the shoes worn by Marty McFly in the 1989 movie *Back to the Future Part II*. The 2016 model,

however, included the self lacing technology dubbed E.A.R.L (Electro Adaptive Reactive Lacing). A total of 1510 pairs of the 2011 model were auctioned with prices averaging around $5,000 and only 89 pairs of the 2016 model were raffled off with tickets costing $10. While the Nike MAG pioneered self lacing technology, the shoes were never intended for everyday use and were more intended as collector's items for movie fans.

2.1.2 Existing Device #2: Nike Adapt

Figure 2: Nike Adapt "BB" Basketball Shoe (Source: Amazon.com)

Link: https://www.nike.com/adapt
Description: The Nike Adapt BB shoes were released in 2019, and the Nike Adapt BB 2.0 was released in 2020. Retailing at $350, these shoes are specifically marketed for basketball players. The shoes use a custom motor and gear train to actuate and they can sense the necessary tension the shoe needs to keep snug and adjust accordingly. With the idea in mind that a foot can swell up to a half a size during a game, these shoes use Bluetooth technology to connect to an app on the user's phone to control the tightness on the fly, even by voice command. Tightness settings can also be prescribed for different moments of the day, for example, warmups before the game and different setting for during the game.

2.1.3 Existing Device #3: Puma Fit Intelligence

Figure 3: Puma Fit Intelligence (Fi) (Source: Puma.com)

Link:https://about.puma.com/en/innovation/fit-intelligence
Description: The Puma Fit Intelligence (Fi) shoes are supposed to be released within the next year and will retail at $330. As opposed to other products, Puma Fi harbors the self tightening mechanism above the foot rather than in the sole. Designers at Puma believe this is a design advantage for better comfort and performance. Computer processors control micro-motors which tighten the shoe, and this can be controlled by swiping up or down on the apparatus located where the laces would be. The shoes can also be controlled via an app. In terms of style, the shoe does have a more bulky appearance compared to other options because the tightening mechanism is above instead of below the shoe. While this system does make more room for the foot inside the shoe and possibly improve comfort, personal preference and popular culture will determine if this is a disadvantage in the style department.

2.2 Patents

2.2.1 Transmission for motorized tensioning system of article of footwear (US10405609B2)

This patent, held by Nike Inc, covers a motorized reel system to tighten the laces of a shoe in order to hold the shoe in place during rigorous activity without the need for conventional tying. Torque is transmitted from the motor shaft via a compound gear to wind a reel shaft. Rotation of the reel draws in and winds a cable which is threaded through the actual laces, resulting in the tightening of the laces as the cable is shortened. The patent covers the entire compound gear assembly, including the orientation and fitting of each component, as well as the way the mechanism is fit into the sole of the shoe.

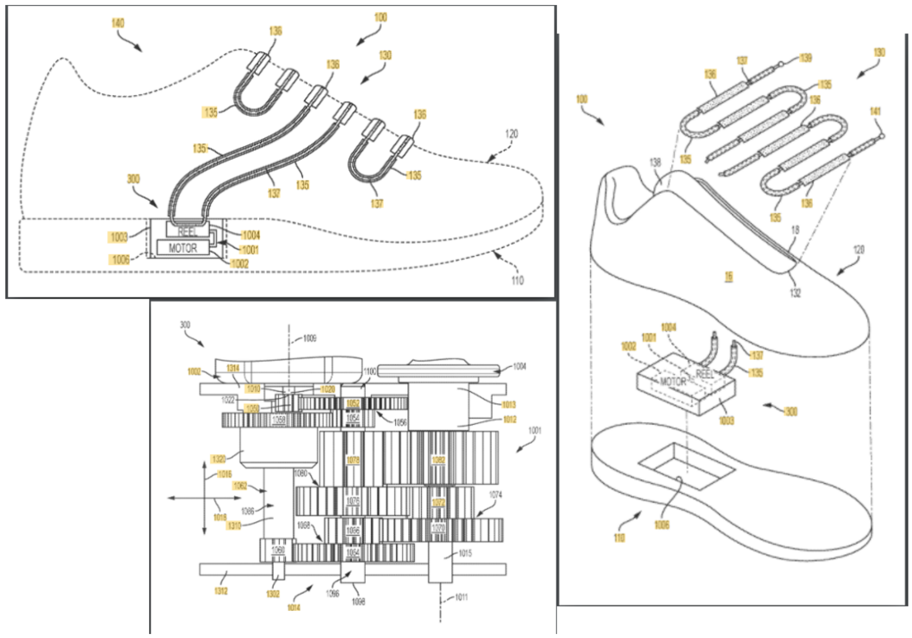


Figure 4: Patent Images for Motorized Tensioning Transmission

2.2.2 Method for lacing a shoe, particularly a sports shoe (Patent #10758011)

This patent is held by Puma SE. The patent relates to a method of lacing a shoe via a rotating closure by means of a tensioning element. The tensioning roller is driven by an electric motor and contains a closing button connected to a control system that actuates the electric motor. The lacing of the shoe is carried out by the user in generating a closing signal by means of the closing button.

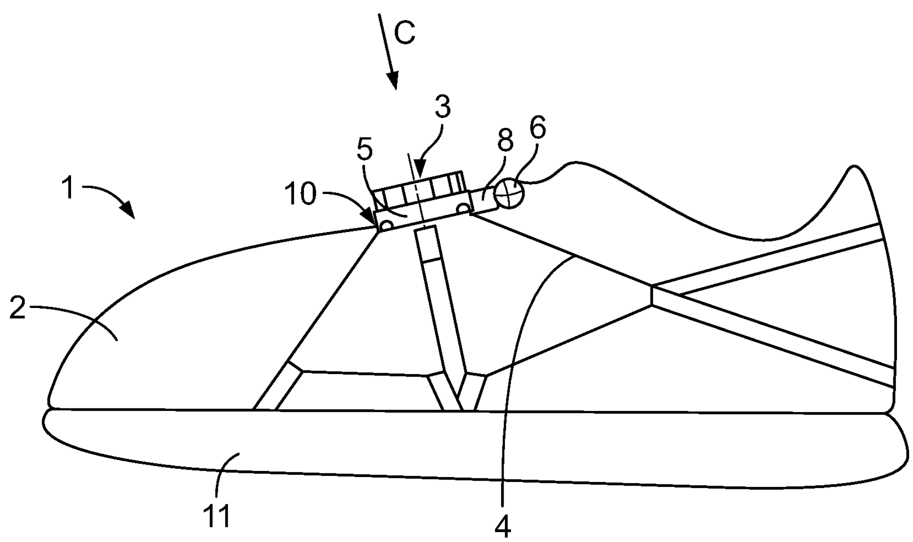


Figure 5: Patent Image for sports shoe lacing

2.3 Codes & Standards

2.3.1 Standard for Wearable Consumer Electronic Devices (IEEE P360)

Though it is still in the pre-publication stage, this standard will come to be instrumental in guiding safety standards and technical requirements for electronic devices that are meant to be worn on the body like clothing. The standard categorizes different wearable consumer electronics and defines testing methods and requirements for those electronics to ensure the safety of the wearer and the functionality of the product. Since our product will make use of on board electrical components to drive mechanical functions, this standard will define how our product is tested for durability and safety and may influence things like material selection, placement of the components in the product, and even the overall design of the components' functions.

2.3.2 Footwear - Test Methods for Outsoles (ISO 20875)

This standard, set by the ISO in 2018, specifies the testing methods for the ultimate tear strength and delamination resistance for the outsoles of shoes. Because our shoes are intended to be suitable for athletic activity, the strength of the soles will already be critical. With the soles also housing electronics which control the function of the shoes overall, the integrity of the soles will become paramount and thus this standard will direct our efforts in testing to ensure they will hold up to wear and do not allow the electronics to be damaged.

2.4 User Needs

In order to determine the needs of our users with regards to the self-lacing shoes, an interview was conducted with a potential customer. A concise summary of the questions posed and the customer's responses is transcribed below. Table 1 ranks the resulting interpreted customer needs based on importance.

2.4.1 Customer Interview

Interviewee: Annonymous
Location: Blueberry Hill, Delmar Loop
Date: February 5^{th}, 2021
Setting: A video of the self lacing shoes from the movie *Back to the Future Part II* was shown to the customer and drawings were made on scratch paper to convey our ideas for possible mechanisms and style choices for the shoes. A discussion was held about possible consumer wants and needs. Interview lasted about 45 minutes.

Interview Notes:
Based on the intended target audience, what would be the most important aspect of the product?

- Must be very easy to take on and off/tighten laces with limited dexterity or muscular strength.

Why do you think current options such as Velcro and slip on shoes are not prevalent solutions for those with disabilities?

- Kids and adults often get bullied for wearing velcro shoes. They do not look "cool" in today's culture and past a certain age it makes kids look like they simply don't know how to tie their shoes which is grounds for being made fun of.

- Slip on shoes can be fashionable as office shoes or flip flops, but they are not suitable for athletic activities as they are not secure to the foot.

What aspects do you think should be prioritized when creating a new shoe style like this?

- Definitely prioritize the things we just addressed like how easy they are to put on and how well they stay on the foot. The way the shoe looks will definitely be important for getting them to catch on in popular culture and for making people feel good about wearing them, but the style doesn't necessarily have to match current trends if you want to stand out.

- A very important part will be the wearer's experience, so things like how comfortable they are, the material quality, and possibly the weight of the shoe will want to be prioritized.

What would make our product stand out against competitors in the powered lacing market?

- The cost of competing designs is way too high to be a viable option for many people. Bring the cost of the shoe down to a more reasonable level and then make sure the shoes last for a long time so that customers do not have to spend money often.

- I know that many of the options currently available also don't have super long battery life so if you could improve on that it would be good but might not be possible with current technology.

- A cool feature would be if the laces quickly snapped into position like those seen in the movies. All the competitors have a slow, methodical tightening of the laces (likely for safety reasons) but it would stand out if the lacing was more responsive if possible.

2.4.2 Interpreted User Needs

Based on the customer interview summarized above, the following user needs were established. These needs are ranked on a scale of 1-5 with 1 being "not very important to the customer" and 5 being "very important to the customer".

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The shoes are easy to slip on	5
2	The shoes are easy to tighten	5
3	Lace tightening is fast	3
4	The shoe is secure on the foot	5
5	The shoes are fashionable	4
6	The shoes have a long battery life	3
7	If rechargeable, the charge time is low	3
8	The shoes are light	4
9	The shoes are comfortable	5
10	The shoes are inexpensive	4
11	The shoes are durable	5

From the rankings above it is clear that pure functionality and accessibility are the most important aspects of the product. Not only must the shoes be easy to operate and enjoyable to wear, cost must be reasonable for the average consumer and the shoes must be built to last so that they do not have to be replaced frequently.

2.5 Design Metrics

Table 2 lists the important specifications which our prototype will aim to meet. These metrics cover the customer needs outlined in Table 1, turning those needs into measurables that our team can work towards during the design process.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,2	Ease of putting on by focus group	avg. score	$> 6/10$	$> 8/10$
2	3	Speed of lacing	seconds	< 5	< 1
3	4	Shoe does not slip off foot during activity	binary	Pass	Pass
4	5	Shoe is comparable in ”fashion sense” to other popular shoes by focus group	avg. score	$> 8/10$	10/10
5	6	Number of full lacing cycles before battery depleted	integer	20	40
6	7	Time to full charge	hrs	< 4	< 2
7	8	Total weight	oz	19.6	15
8	9	Customer comfort experienced while wearing by focus group	avg. score	$> 8/10$	10/10
9	10	MSRP based on materials cost and profit margin	USD	< $200	< $125
10	11	Shoes and integrated electronics pass IEEE P360 and ISO 20875 safety and durability standards	binary	Pass	Pass

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

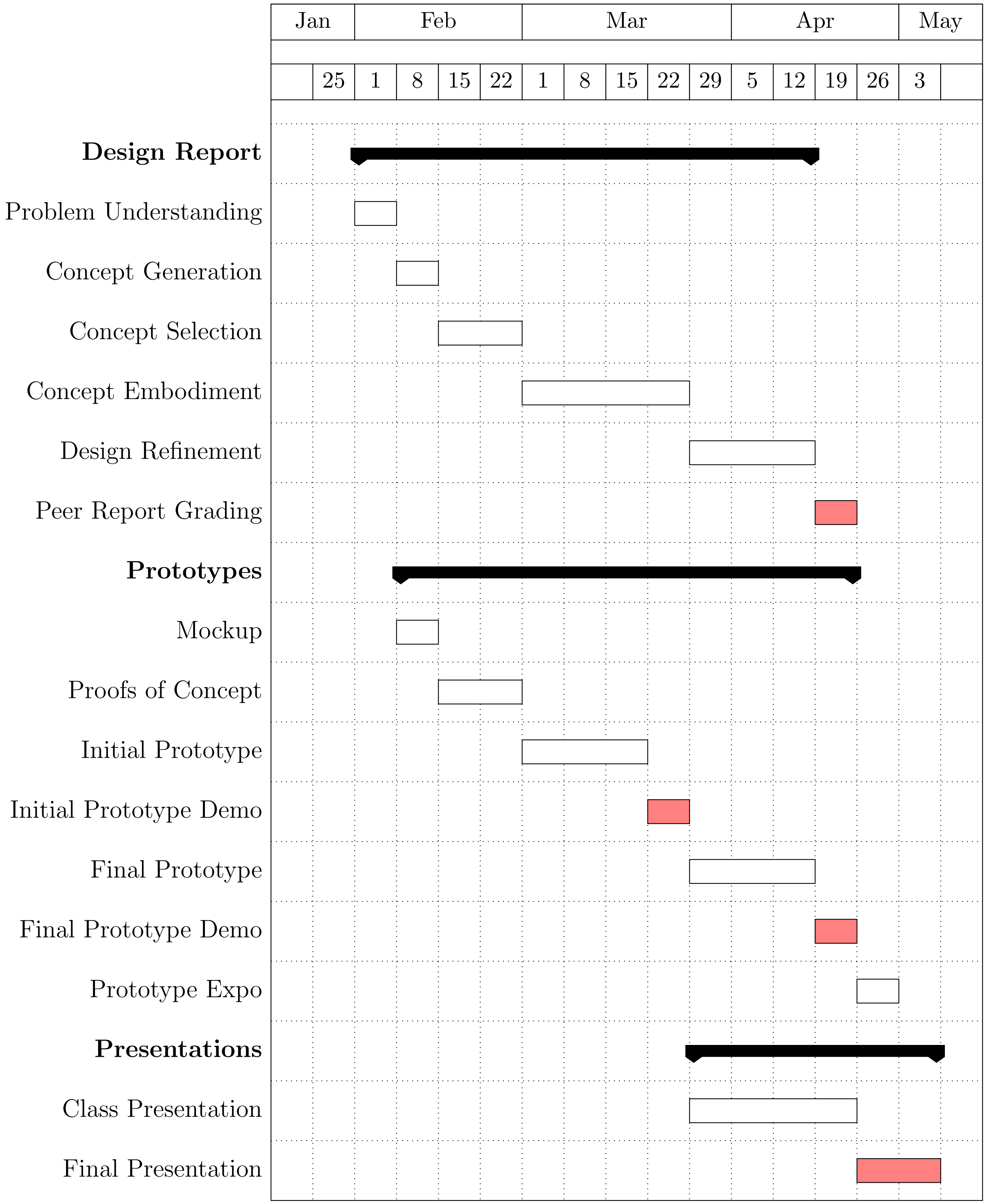


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

This mockup was originally designed as a proof of concept for the motorized cylinder design. The mockup proved that the rotating cylinder would work as a way to tighten the laces of our self-lacing shoes, but the prototype quickly gave insight into some other design decisions and hurdles the group will have to discuss and overcome.

For the purposes of the mockup, it was simplest to use two flaps in place of laces, given the materials we had to work with. While the ”flaps” idea was toyed with for the actual project, the group has seen the shortcomings of this design in terms of security to the foot, as multiple cables would have to be used to keep the entire flap secure and these cables could easily become tangled in the mechanism. This has lead us to focus on cables running through the existing laces of the shoes so that each cable can have its own designated channel.

The other major design consideration that arose from this mockup is the actual design of channels for the lace cables once they exit the exterior laces. Once the cables run through the laces they must go through the shoe and into the sole where they will interface with the cylinder. In order to make this happen while keeping the shoe comfortable for the user, the team will have to devise a way to run the cables between the layers of fabric that make up the shoe and then carve or drill channels in the soles of the shoes that the cables can run through. Additionally, the entire path of the cable may need to be reinforced with rubber tubing so that the the cables do not rip the shoes or pinch the wearer uncomfortably. Clearly, the creation of this low-fidelity mockup has had a beneficial impact on the project, as it forced the team to consider some design features which had been previously overlooked.

Figure 7: Photos of mockup prototype (Left: Loosened state, Right: Tightened state, Bottom: Mechanism)

3.2 Functional Decomposition

Figure 8 shows a "function tree" which lays out the various functions our product must be able to perform alongside sketches of existing designs which can help to accomplish those functions.

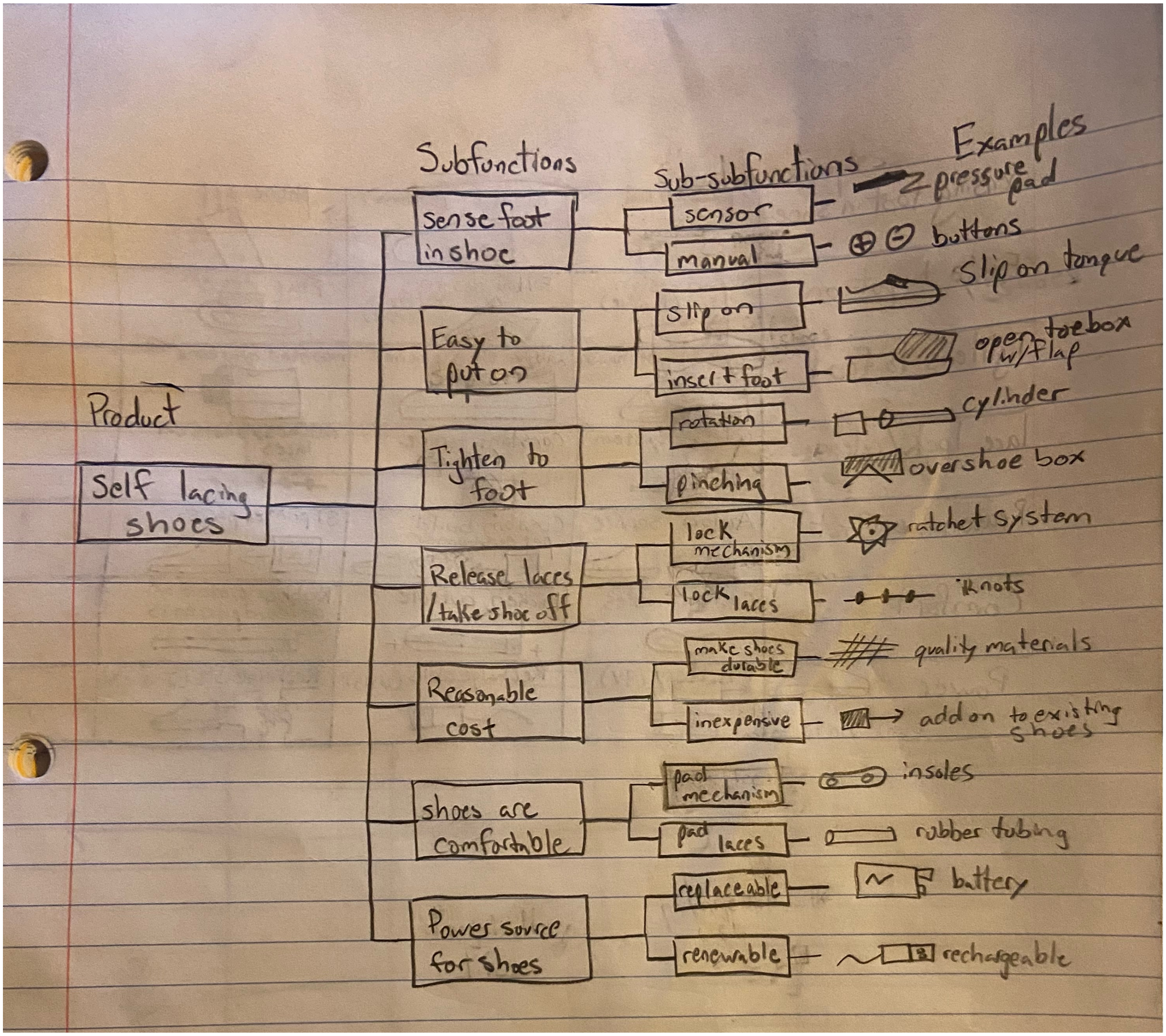


Figure 8: Function tree for Self Lacing Shoes, hand-drawn and scanned

3.3 Morphological Chart

Figure 9 shows a morphological chart where ideas for each of the functions of the product are further fleshed out. Each function has three possible design choices that are quickly sketched in the chart and serve as an "idea pool" from which the final design will draw.

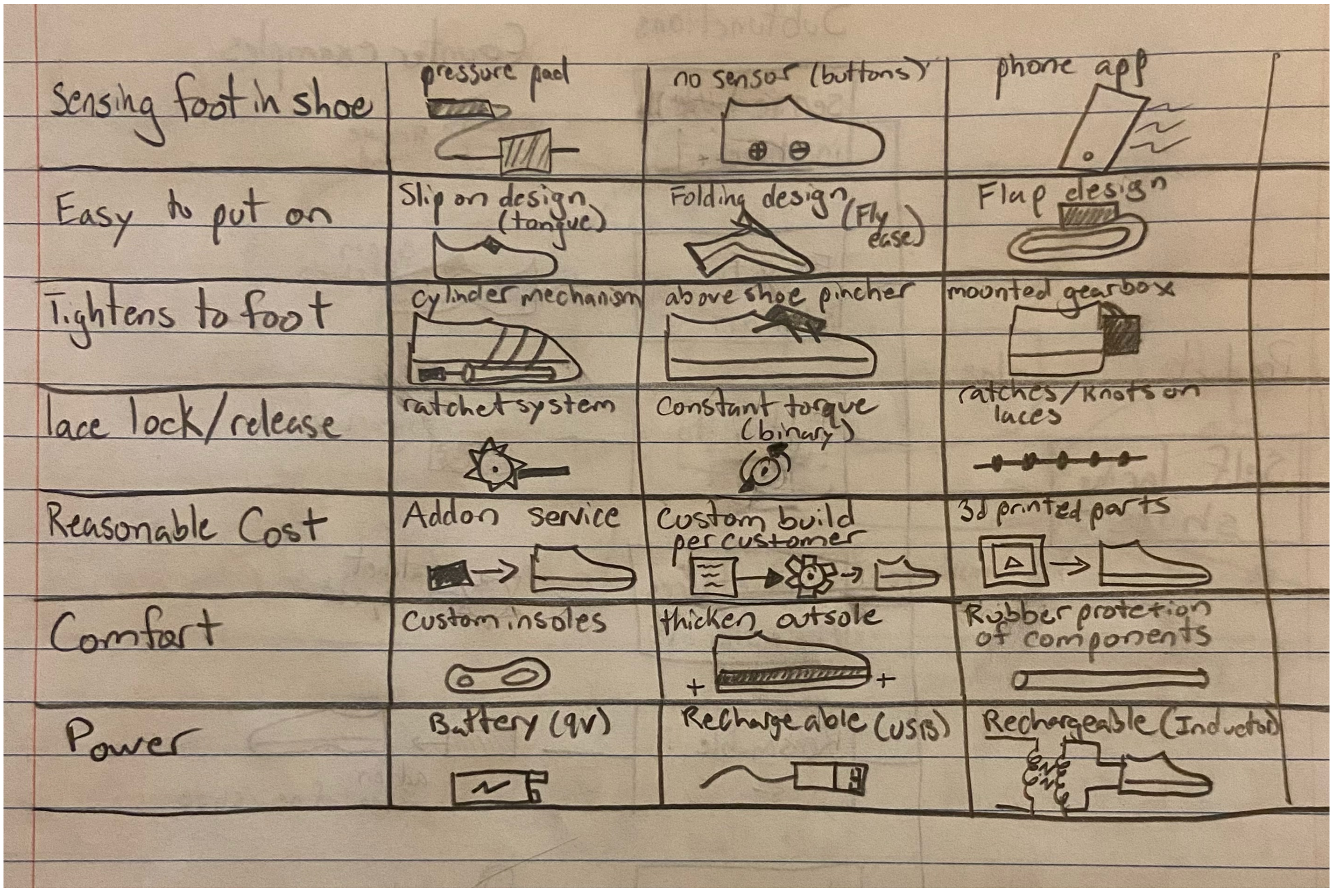


Figure 9: Morphological Chart for Self Lacing Shoes

3.4 Alternative Design Concepts

3.4.1 Motorized Cylinder in Sole (Peter Pigatti)

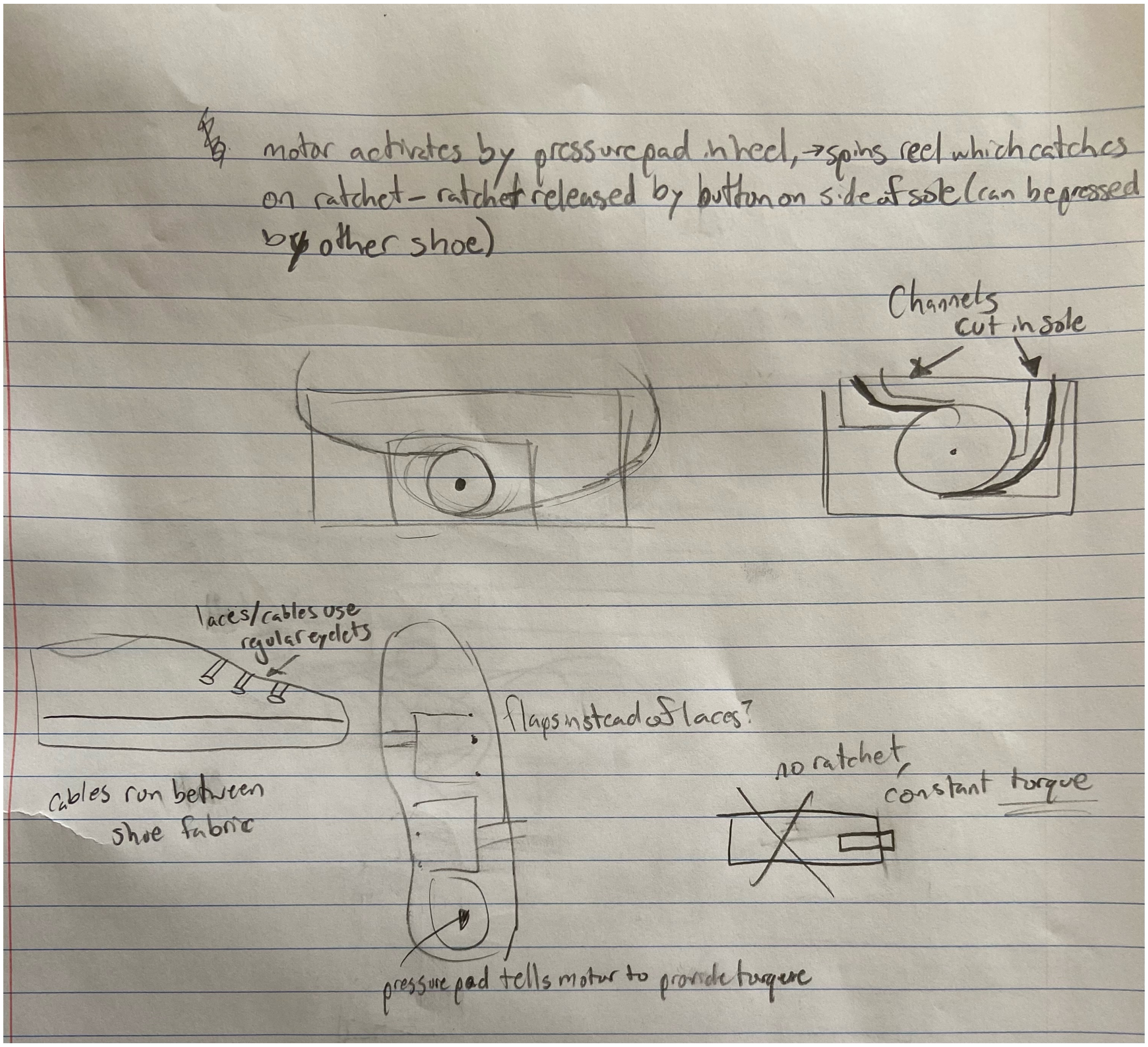


Figure 10: Preliminary sketches of Motorized Cylinder concept for self lacing

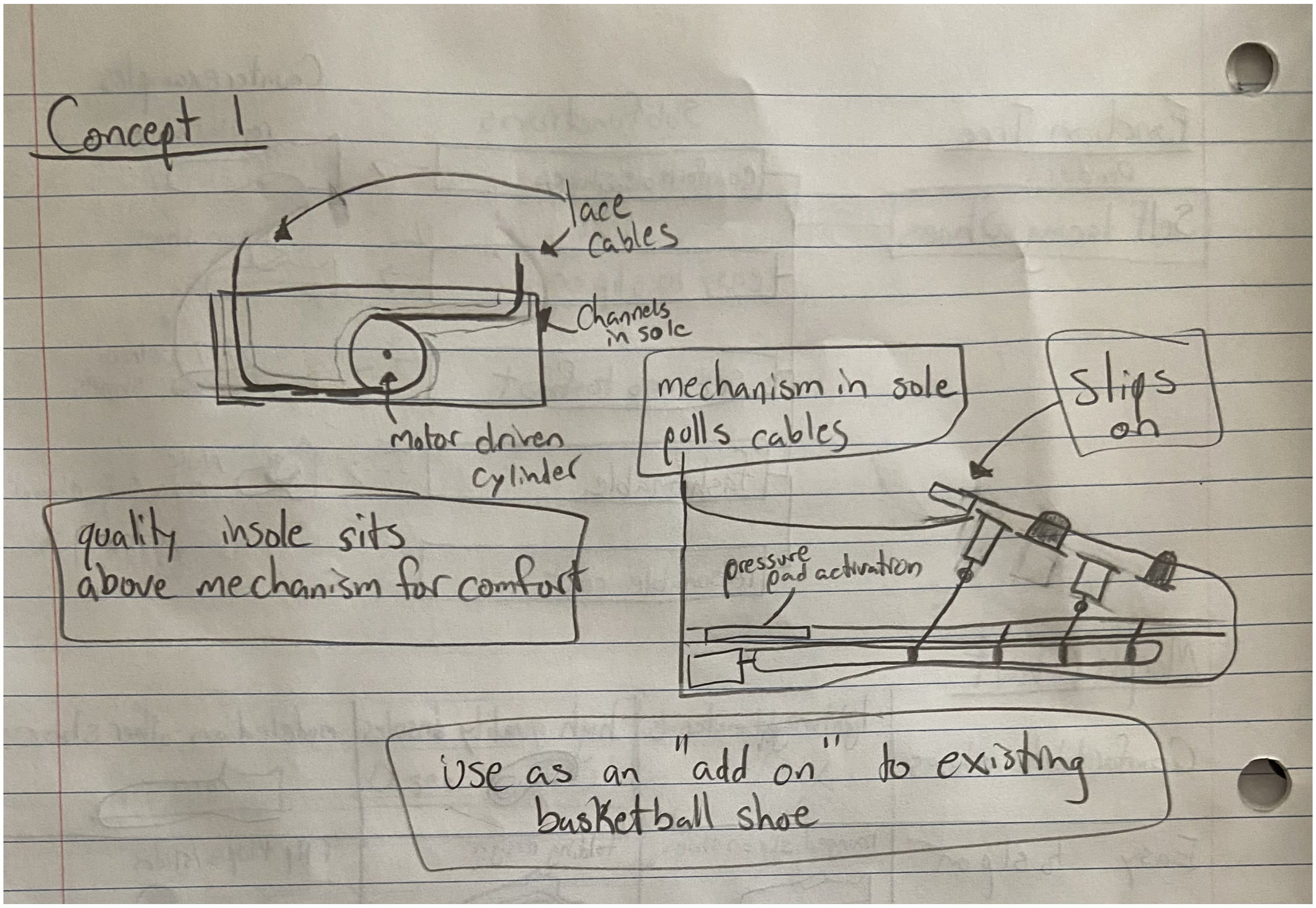


Figure 11: Final sketches of Motorized Cylinder concept

Solutions from morph chart:

1. Pressure pad in sole of shoe
2. "Slip on" design
3. Motorized cylinder in sole
4. Constant torque from motor
5. "Add on" service to existing shoes
6. Quality insoles to protect mechanism and add comfort
7. Replaceable batteries

Description: A pressure pad in the heel of the shoe activates a motor which drives the cylinder hidden in the sole. The winding of the cylinder reels in the cables through channels in the sole and fabric of the shoe which are reinforced with rubber tubing. This draws the laces tighter around the wearer's foot, effectively lacing the shoe. As long as a foot is inserted in the shoe, pressure on the pressure pad will keep the cylinder wound. The laces can be loosened by slightly pulling the foot out of the shoe so that pressure is released. The pressure pad and motor system can also be customized for tightness level by programming the number of turns of the cylinder before the motor holds its position.

3.4.2 RC-INSPIRED CONCEPT (Al Amin Yusuf)

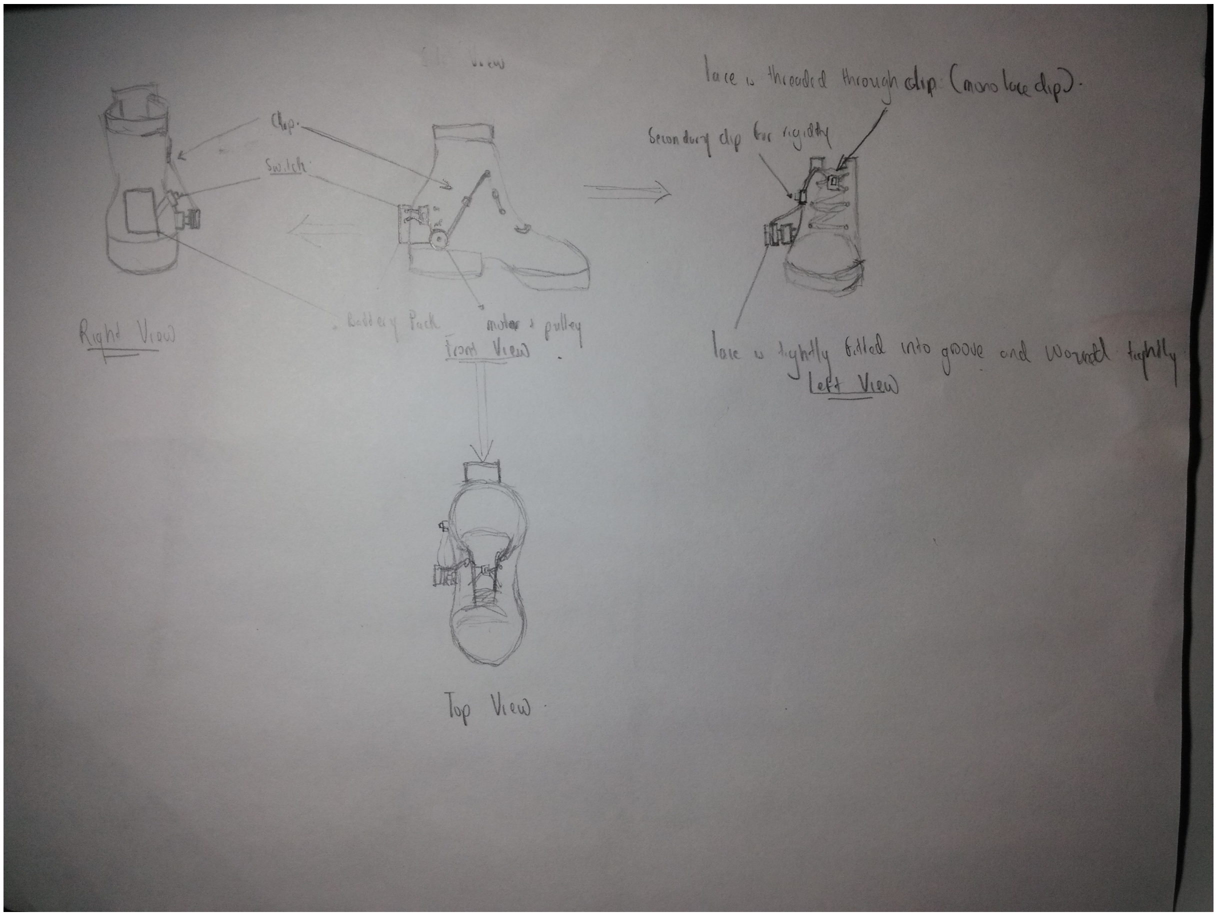


Figure 12: RC-Inspired Concept Design(initial)

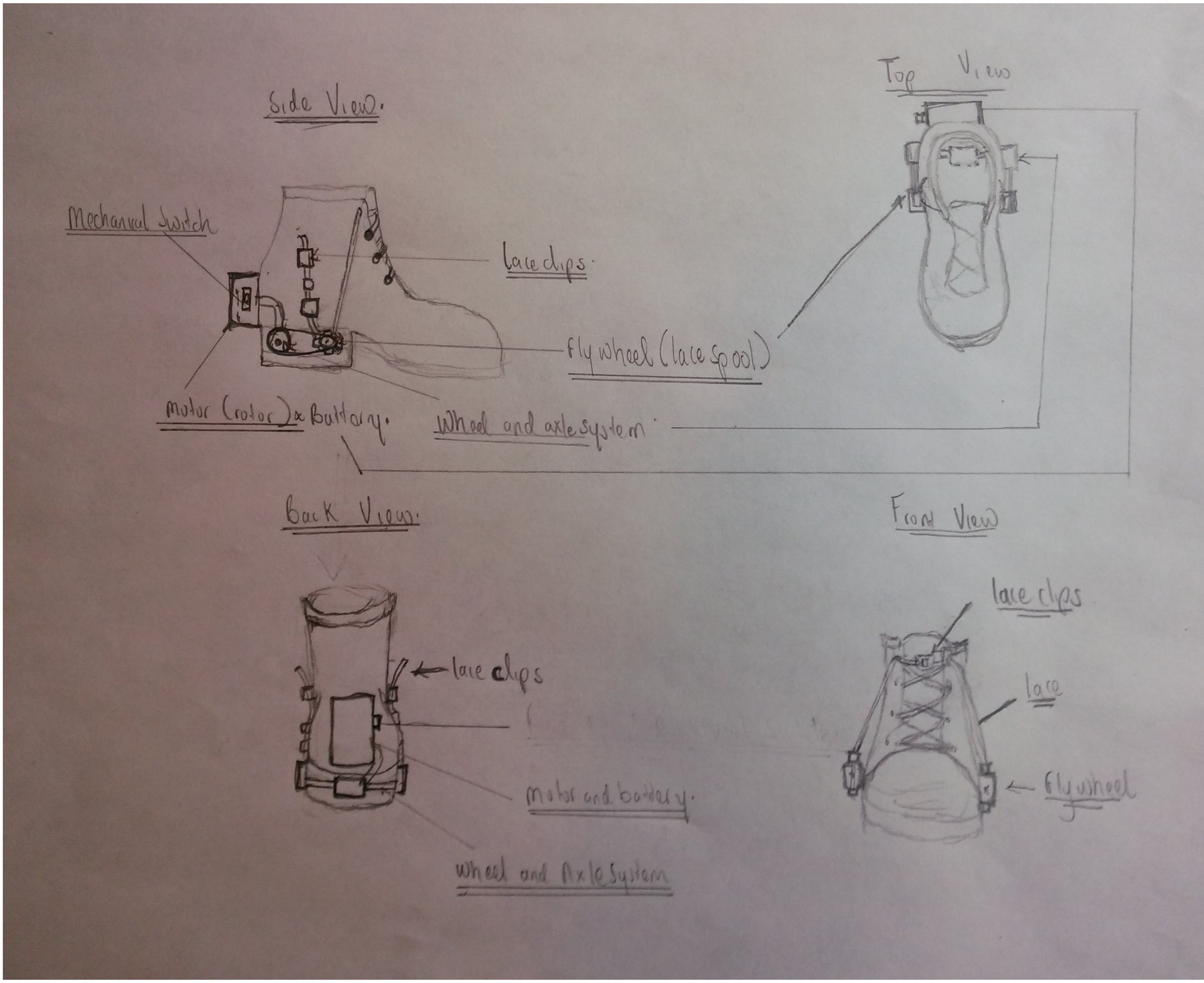


Figure 13: RC-Inspired Concept Design(final)

<u>Solutions from morph chart</u>:

1. Toggle switch (button) on shoe
2. Slip on design
3. Mounted gearbox
4. Locking motor (constant torque)
5. "Add on" design
6. Protected components outside shoe
7. Replaceable Battery

Description: This concept works on the premise of an modified RC Car. A stepper motor is fastened securely to the back of the shoe and connected to a wheel and axle system. A hole is threaded through the sole of the shoe, lined with aluminum in a tight interference fit, to accommodate the axle. The gear mechanism controlling the rotation of the wheels is placed securely in a hole drilled in the middle of the sole and connected to the stepper motor via cables. The wheels of the system on the outside are then lined with an elastic band and connected to the spinning groove of the 3-D printed wheel. This wheel has enough room for several wounds of lace. The lace is secured fastened to the sides of the shoe by use of clips. Flipping the switch in a forward direction drives the gear and axle system which spins the 3-d printed wheel and causes the laces to tighten. Flipping the switch the other direction reverses the motion of the wheels, hence the laces are loosened.

3.4.3 Cheaper Alternative (Bryce Roberts)

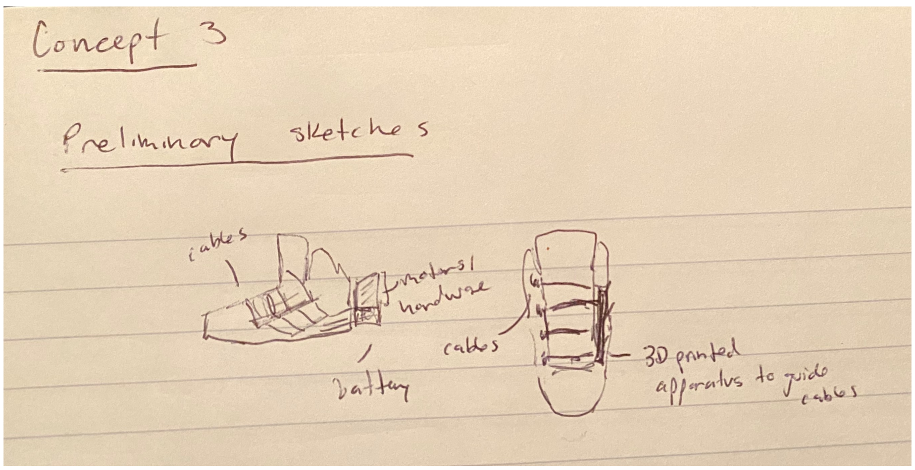


Figure 14: Preliminary sketches of Cheaper Alternative

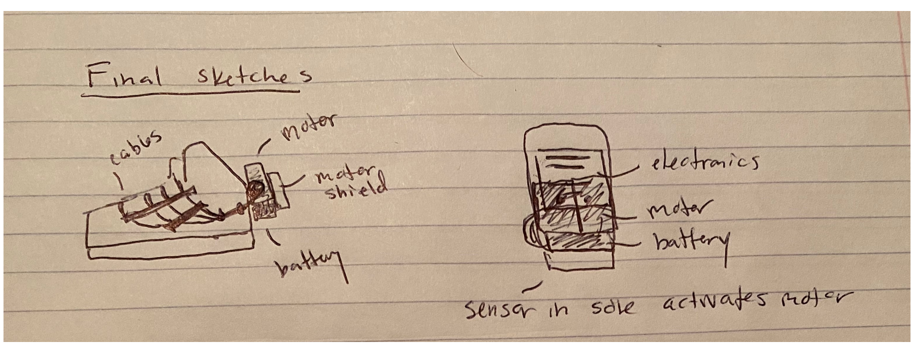


Figure 15: Final sketches of Cheaper Alternative

Description: This concept uses a motor accompanied with a motor shield to control the working speed and direction of the motor to tighten the laces. The laces are connected to an external rotating component of the motor. The laces are attached on one end of the tongue and wrap around to the other side where they are connected. To help control the directions of the laces, they are funnelled through two 3D printed structures to control their direction. The motor can be controlled through the software, or by button on the motor shield. A force sensor in the sole of the shoe detects if there is a foot in the shoe, and tells the motor that it can be activated. The laces are also 3D printed. Multiple batteries can be used for this setup depending on the optimal direction and placement of the laces. If it was preferred to have multiple laces traveling in different directions, multiple motors could be used.
Solutions from morph chart:

1. 3D printed parts
2. Button on shoe
3. pressure pad (force sensor)
4. Slip on design
5. Mounted gearbox
6. Locking motor (constant torque)
7. Protected components outside shoe
8. Battery

4 Concept Selection

4.1 Selection Criteria

Figure 16 presents an Analytical Hierarchy Process Table. Using five different customer needs criteria obtained from the "Problem Understanding" process, the table weights these criteria against each other to determine which features of the product are most important. From the table, it is clear to see that ease of putting the shoes on is by far the most important, but security to the foot and comfort are also very important qualities.

	Security to Foot	Easy to Put On	Fashionable	Comfortable	Reasonably Priced		Row Total	Weight Value	Weight (%)
Security to Foot	**1.00**	0.33	3.00	1.00	5.00		10.33	0.26	25.88
Easy to Put On	3.00	**1.00**	5.00	1.00	5.00		15.00	0.38	37.56
Fashionable	0.33	0.20	**1.00**	0.33	1.00		2.87	0.07	7.18
Comfortable	1.00	1.00	3.00	**1.00**	3.00		9.00	0.23	22.54
Reasonably Priced	0.20	0.20	1.00	0.33	**1.00**		2.73	0.07	6.84
						Column Total:	**39.93**	**1.00**	**100.00**

Figure 16: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Figure 17 shows a Weighted Scoring Matrix fro the three alternative self lacing shoe designs. This matrix uses the criteria set up in the previous section to score each design based on how well it accomplishes the goals set by customer needs.

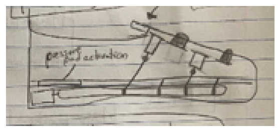
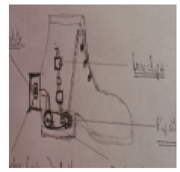
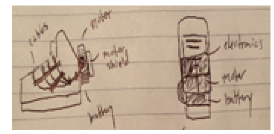
Alternative Deisgn Concepts		**Motorized Cylinder**		**RC-Inspired**		**Cheaper**	
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Security to Foot	25.88	5	1.29	5	1.29	5	1.29
Easy to Put On	37.56	4	1.50	3	1.13	4	1.50
Fashionable	7.18	3	0.22	2	0.14	1	0.07
Comfortable	22.54	4	0.90	3	0.68	3	0.68
Reasonably Priced	6.84	3	0.21	2	0.14	5	0.34
	Total score	**4.119**		**3.377**		**3.886**	
	Rank	**1**		**3**		**2**	

Figure 17: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

From the AHP and WSM tables seen in Figures 16 and 17, the motorized cylinder concept has come out as the top ranked concept. This concept seems to do the best job of accomplishing the functions deemed "most important" by our customer research, and so our final design will be based mostly on the concepts generated for this prototype idea. However, the idea is not perfect and some features may be taken from the other two concepts in order to produce the best possible product.

For the "Security to Foot" criteria, each of the concepts scored the highest possible rating because they all produce a secure fit to the wearer's foot as a necessary function. Similarly, all three of the concepts use a slip on design and so scored highly in the "Easy to Put On' category. The reason concepts one and three only scored a 4 out of 5 is because the slip on design is not perfect and still requires mild coordination for a wearer to put the shoe, while the second concept's design as a boot makes slipping it on less simple.

The "Fashionable" criteria is a fairly subjective one, but the reason the motorized cylinder idea scored the highest is because all of the components for this design are hidden. This allows the concept to most closely resemble a regular shoe as opposed to the other designs which have gear boxes or 3D printed parts attached to the outside. The next criteria, "Comfortable", is also a fairly subjective one, however the motorized cylinder concept scored highest in this category because it is the only design which attempts to pad the interface between the user and the shoe components using an insole or rubber tubing around the lace cables. Finally, the "Reasonably Priced" category is the only one in which the motorized cylinder did not score highest. This is simply because the third concept is specifically designed to be cheaper to produce. While the motorized cylinder concept is still meant to be cheaper than other alternatives on the market, it will be middle of the road in price when compared to the other two concepts presented.

4.4 Engineering Models/Relationships

Engineering model one is the equation which relates torque to force as seen below.

$$T = r * F * sin(\phi) \tag{1}$$

Where T is torque [N*m], r is radius [m], F is force [N] and ϕ is the angle of rotation [rad] [1]. This equation will allow us to determine exactly how many rotations are needed from the motor and cylinder or how much torque the motor must be capable of in order to create the necessary tension on the laces to keep the shoe in place.

Engineering model two showcases an equation model which describes the relationship the electric power, supplied to the motor, to the torque of the motor and the angular velocity of the motor. of the it is defined as shown below.

$$T = \frac{P}{\omega} = \frac{60 * V * I}{\pi * 2 * N} \tag{2}$$

Where power, P [W], is given by the product of Voltage [V] and Current, I [A] supplied to the motor via the rechargeable battery. Angular velocity, w [Hz], is also obtained as a relationship to the number of turns, N. This would help us determine how big of a power supply we would need for a certain amount to rotation of shoe laces that to be retracted and how fast we want this to happen.

Engineering model 3, seen in Figure 18, shows the ground reaction force curves for rearfoot and midfoot strikers, the two most common foot striking positions for runners. Rearfoot strikers are the most common of the two, and as seen in the plot, they have an initial high frequency peak corresponding to the heel hitting the ground. Considering that our shoe will most likely have precious hardware stored inside of the sole, understanding this model is vital for our future design parameters. The hardness of the midsole of the shoe is measured in something called durometer. The lower the durometer, the softer the sole. Corresponding tests have shown that the higher the durometer, the higher the impact force runners experience. Higher impact forces are not ideal, however we have to consider the protection necessary for the hardware located inside the sole. For maximum protection the midsole would be very hard, however this would decrease running comfortability for the user. So these are trade offs that will need to be considered during the design process.

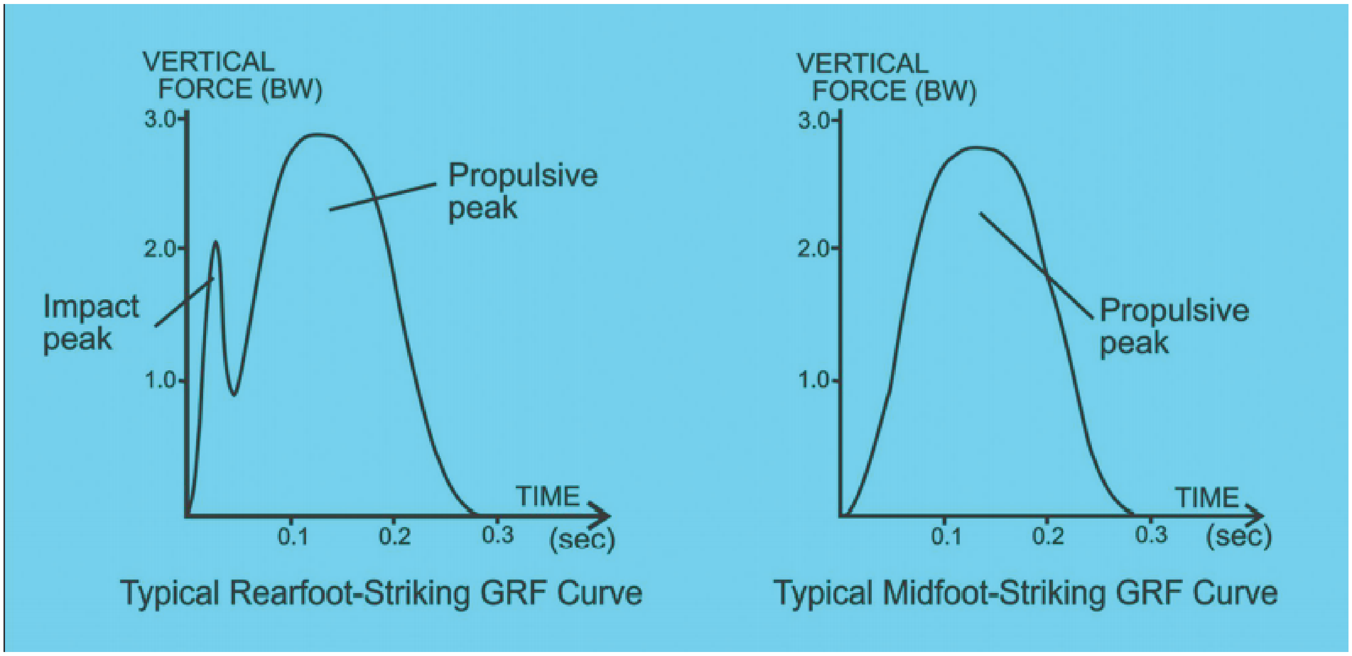


Figure 18: Ground Reaction Force Curve

5 Concept Embodiment

5.1 Prototype Performance Objectives

Transitioning from creating and evaluating design concepts to creating a physical and workable model, or prototype of the design model, it is paramount that we set a list of specific goals as a means to achieving the consumer needs. For this project, our performance goals are enumerated as follows;

- 1) Based on the primary objective to make the shoes self-lace locking; it is optimal that the shoe be fastened and unfastened at least fifty (50) times without requiring maintenance.
- 2) It would be ideal to see the shoes be used in a high level sporting activity such as tennis, basketball, etc for at least ten minutes without becoming unlaced or requiring maintenance.
- 3) For portability and comfort, it is essential that the shoes and the model installed collectively weigh less than 1.5 lbs.

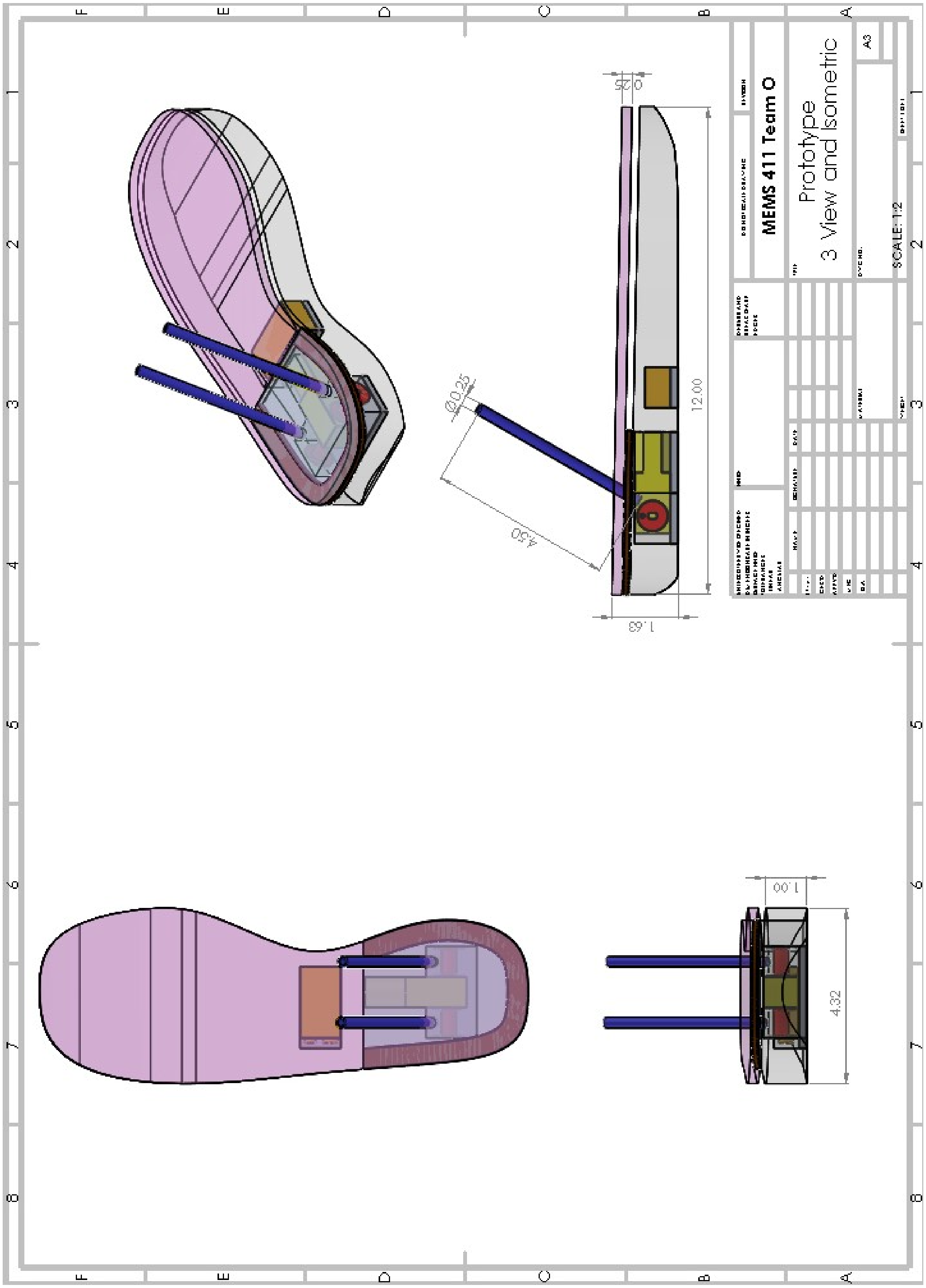


Figure 19: Assembled projected views with overall dimensions

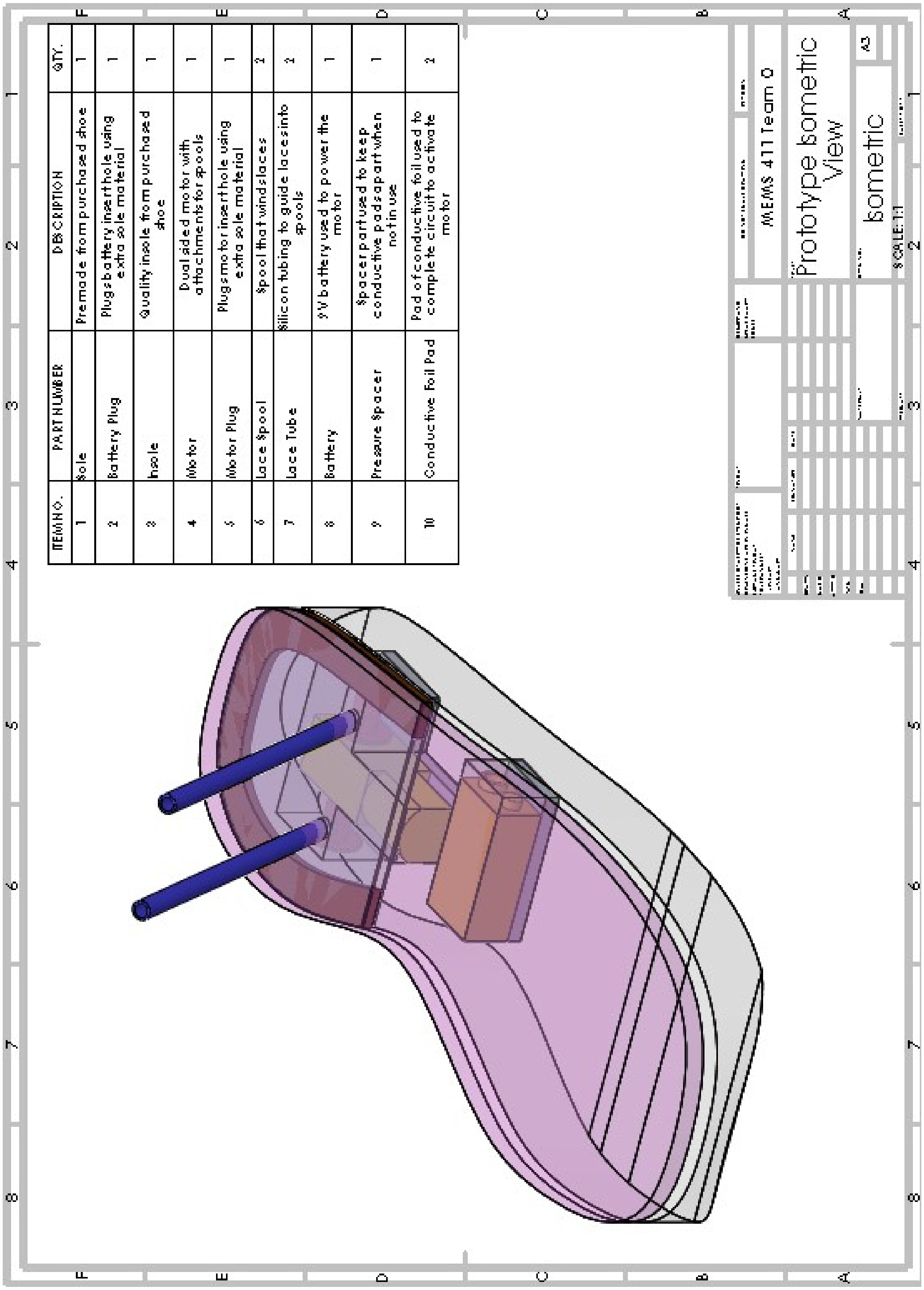


Figure 20: Assembled isometric view with bill of materials (BOM)

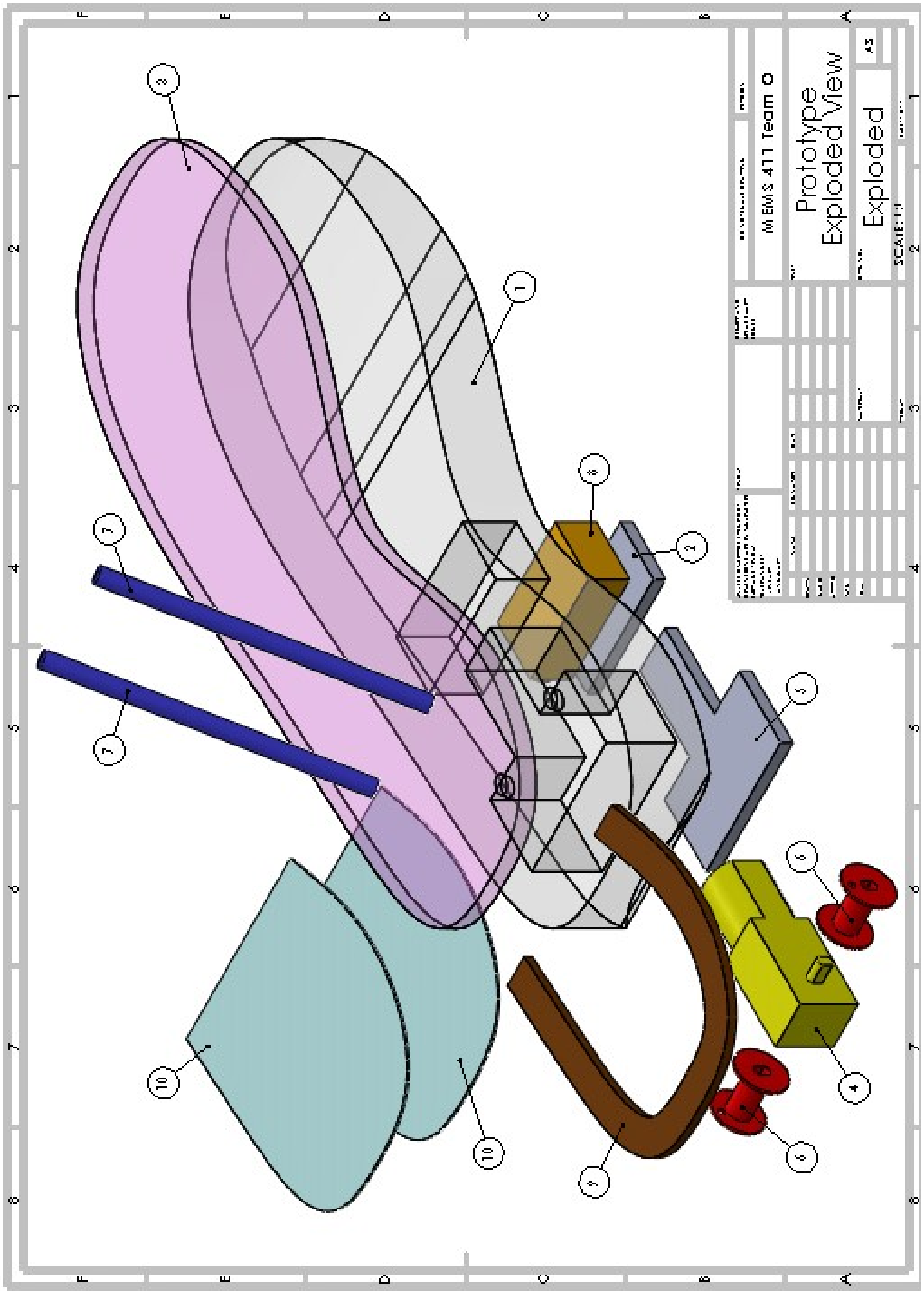


Figure 21: Exploded view with callout to BOM

5.2 Proofs-of-Concept

The proof of concept testing helped us visualize the benefits of different design concepts and to try our best at using the optimal combination. For example, when creating the mock-up prototype we quickly became aware of design features which would have to change for our ideas to come to fruition such as the placement of holes in the sole of the shoe which we changed to run inside the fabric rather than outside the sole. Then, going through the process of creating a weighted scoring matrix and ranking each of our prospective prototype designs further revealed to us how each of the different designs would and would not work. While one design seemed to come out on top, it quickly became clear that different design aspects from each of the prototypes would have to be implemented and combined to create a functional final product. For example, a single rotating cylinder simply did not fit well within the sole of the initial proof of concept prototype and was clearly too fragile to be put under heavy use, and so it was replaced with a gearbox motor which was originally proposed in one of the other designs.

The two main differences between our selected concept and the initial prototype we created are the replacement of the single rotating cylinder with a dual axle gearbox and changing the laces to be a crossing pattern rather than a straight across pattern with multiple strands.

As mentioned above, the decision to replace the rotating cylinder with a gearbox was made because the cylinder design both did not fit well inside the sole and was too fragile to undergo much stress. When hollowing out the sole of our proof of concept prototype, we found that there simply was not enough clearance for the large cylinder to rotate freely while also reeling in the laces with an adequate amount of torque. We also performed stress testing on that design by putting the shoe on and putting a person's body weight on it, which quickly caused the cylinder to crack near the toe. The new gearbox design places the gearbox in the thicker heel of the sole so that it is much more protected from the stress of athletic activity, and so that the reels that pull the laces taught have much more clearance to spin freely.

The decision to change the lacing pattern was made because we deemed the original design to be more complicated than necessary. The original design would require at least four separate strands of lacing, with a stronger cable running through the center of each, which would combine into two separate strands before reaching the motor/cylinder. This proved to be more complicated than necessary as the crossing pattern we devised using the shoe's original laces functions just as well while requiring much less work to implement and being much easier to replace should damage be incurred.

6 Design Refinement

6.1 Model Based Design Decisions

When selecting components to build our initial prototype, the engineering models introduced in Section 4.4 were essential for ensuring that our parts would be able to perform as needed.

Using Eq. 1, our team was first able to determine the torque required from the chosen motor to tighten the shoes properly. From our testing it was determined that the average person laces their shoes with about 30 lb of tensile force on the laces when intending to use them for heavy athletic activity. This was tested by using a handheld force tester and pulling on one side of the laces until

a user determined that the laces were adequately tight.
Knowing this force value, we were able to take the radius of the spool we designed and solve the equation for the torque output needed from the motor. Note that for the angle of rotation, 90 degrees was used because it is at this angle that torque requirements are highest (since sin(90) = 1) and thus the motor must be able to overcome this hurdle. From the equation it was found that the chosen motor must be rated for at least 0.6Nm of torque to lace the shoes. Figure 22 shows the calculations to determine this value.

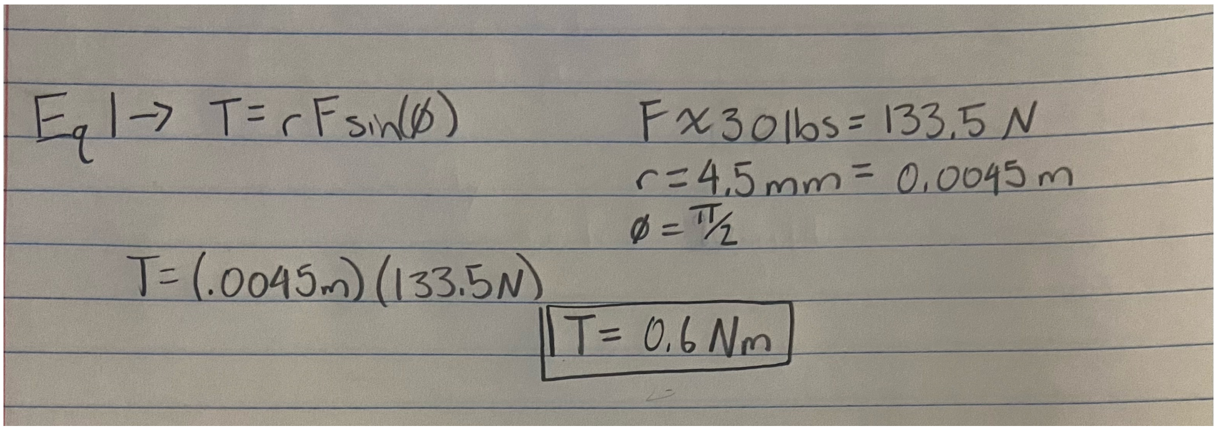


Figure 22: Calculations to Determine Motor Torque

The selected motor for our project was an Adafruit 3777 dual shaft motor which has a torque output rating of exactly 0.6 Nm.

With the necessary motor torque determine, Eq. 2 was used to determine how much power must be supplied to the motor in order to achieve proper lacing. The two options for battery power of the motor were AA and 9V batteries, so the equation was used to test both options and see which would be best for powering our device. From our research [2] we found that typical AA batteries provide 1.5V and 50mA of current while 9V batteries supply 500mA of current. Figure 23 shows the calculations for both options.

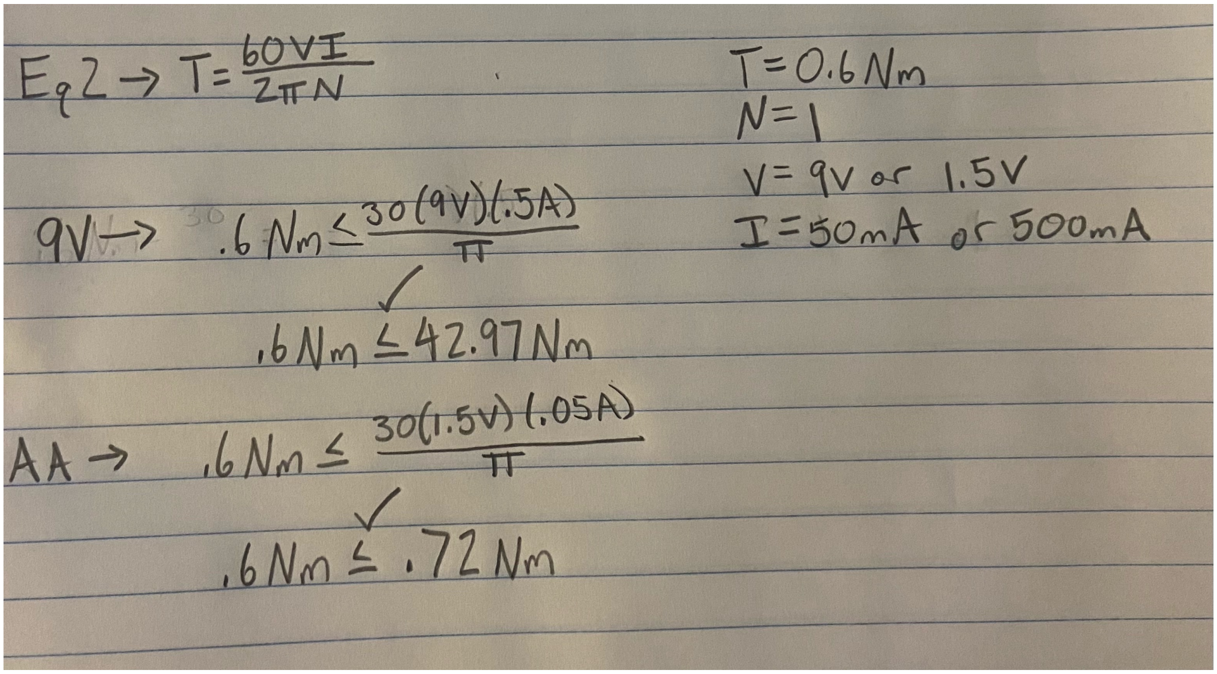


Figure 23: Determination of Battery Source

While both kinds of batteries would be capable of supplying the necessary power to our motor, the low margin for error in the AA batteries was a deal breaker. If the batteries started to die even a small amount they would no longer be able to power the shoes and this would severely limit the battery life of the shoes. Therefore the 9V battery was chosen to be the power source of our device with the "quick change" plugs allowing easy battery changes when needed.

The third engineering model used to drive choices in our prototype was the ground reaction force curve seen in Section 4.4. According to both the rear-foot and mid-foot striking curves, the force experienced by the shoes will be just under 3x the person's body weight. With athletes getting larger and larger each year, we must assume that a user of our shoes could weigh up to 350 lbs. This translates to 1,557.5 Newtons of force on the shoes while standing or up to 4,672.5 Newtons of force while running. In order to protect the delicate components in the shoes, the soles and insoles must be able to sustain this massive force without deforming so much that the components within become damaged.

In order to determine the necessary thickness of the soles of our shoes, the following equation can be used [3].

$$F = \sqrt{\frac{mghAE}{y}} \tag{3}$$

Where F is the force the shoe withstands [N], m is the mass of the wearer [kg], g is gravity [m/s^2], h is the distance the person's center of gravity moves during running [m], A is the area of the sole hitting the ground [m^2], E is the elastic modulus of the sole [N/m^2], and y is the thickness of the sole and insole combined [m]. Research [4] suggests that most shoe soles have an elastic modulus of about 70,000 N/m^2. Given the ground force of a 350 lb person while running and assuming that this person is of average height for an athlete of this size, we will assume that the person's center of gravity shits 0.25 m while running. Figure 24 shows the calculations for determining the necessary sole thickness of 0.034 m, which was used in our prototype design.

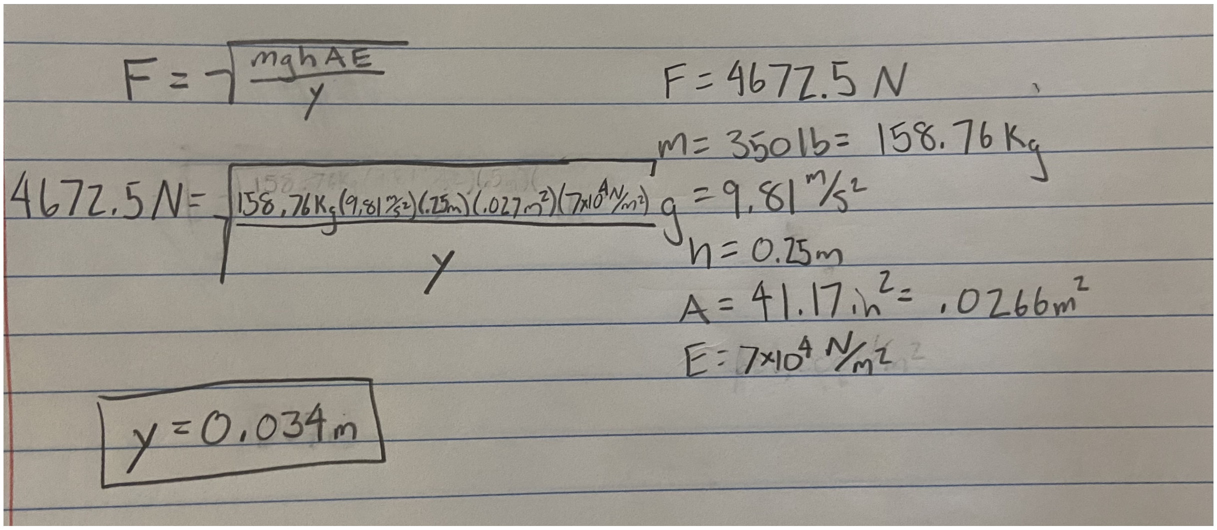


Figure 24: Determination of Necessary Sole Thickness

The shoes chosen for our prototype had a sole + insole thickness of 1.5 inches, or 0.0381 m, in the heel where the components of the lacing mechanism will be stored. Since this value is above the necessary 0.034 m for safe use, we determined that the chosen design of the shoes should withstand use from even the largest athletes.

6.2 Design for Saftey

The following are possible risks associated with the Self Lacing Shoes. After compiling the severity and probability of each risk a heat map was created to visualize the highest priority concerns with the design.

6.2.1 Risk #1: Electrocution

Description: Due to the unsealed conductive plates hidden in the insole of the shoe, there is a chance of the user experiencing mild electric shock if sufficient standing water gets into the shoes and around the foot.

Severity: The severity of such an incident would be mild due to the shoes only being powered by a 9V battery. However such an incident would cause a sudden and sharp pain in the foot and/or leg of the user and if the user has any medical implants, such an event could potentially disrupt the function of the implant.

Probability: Very low. In order for such an event to happen the user would basically have to fully submerge the shoes in water while wearing them.

Mitigating Steps: In future designs of the shoes, the conductive plates could be sealed with a rubber shell in order to make them fully water-proof. In the absence of this sealing, warning labels can be printed on packaging to not wear the shoes in or around standing water.

6.2.2 Risk #2: Battery Acid Leakage

Description: Because the device is being powered by a simple 9V battery, and such a battery is not meant to be under heavy physical loads, there is the possibility that the battery could break open and leak battery acid onto the shoes or into the environment if it is not properly padded.

Severity: Such a failure would be a very severe issue resulting in contamination of the environment or burning the user.

Probability: Such an event is moderately likely depending on how much abuse the user puts the shoes through. Obviously the shoes are designed to take impacts from normal wear and even heavy athletic activity as discussed above, but over-aggressive use or intentional tampering may cause damage.

Mitigating Steps: In order to mitigate the risk of battery damage, the battery itself will be more heavily cushioned and waterproofed than other components.

6.2.3 Risk #3: Uneven Pressure and Spool Breakdown

Description: If enough pressure is placed on the wrong part of the foot, it is possible that the spools could become caught on the sole of the shoe from within the cutouts. This uneven pressure could cause the spools to either wear down or snap completely

Severity: If the spools breakdown overtime or snap, this will cause a severe loss of function of the self-lacing shoes. At this point either the spools or the entire shoe will need to be replaced.

Probability: Due to the design of the sole of the shoe and the strength of the walls around the cutouts, it is unlikely that enough elastic deformation will occur for the spools to get caught on the sole.

Mitigating Steps: While the current design should be enough to prevent this from happening, each of the cutouts for the components could be reinforced with either more sole material or a strong/lightweight metal or plastic.

6.2.4 Risk #4: Overheating

Description: With the battery and motor components being snugly fit and insulated inside the shoe soles, there is a possibility that the motor overheats because there is no airflow to cool it off.

Severity: This would be very severe because it would render the motor useless due to a fried circuit board. While this does not pose a risk to the user, it will require the user to replace either the motor or the entire shoe.

Probability: Such an event is moderately likely. This will depend on the temperature of the environment around the shoe and the amount of constant use that the user puts the shoe through.

Mitigating Steps: In order to mitigate this risk the motor can be programmed to stop when full tightness is achieved rather than continue running at full power. This will significantly reduce the work load on the motor and reduce overheating.

6.2.5 Risk #5: Altitude

Description: There is a possibility that the motor would overheat at very high altitudes because of the low air density. This includes altitudes above 3300 feet. Most motors are designed for air density at sea level. At higher altitudes, the lower density reduces the air-cooled motors ability to dissipate the heat generated.

Severity: This risk can be described as marginal. It could wear through the insulation and potentially burn the user, but it is not life threatening.

Probability: The probability of this occurring is unlikely. It would require the user to be above 3300 feet for a very long time and for the motor to be in constant use, which is not the case for our product.

Mitigating Steps: To mitigate this risk, the motor could be de-rated by 3 percent per 1000 feet above 3300 feet. If not this, there could be a cooling mechanism installed to deal with the issue.

Figure 25 shows a heat map of each of these risks based on their severity and probability as described above. This map will be used to prioritize the concerns in future prototypes.

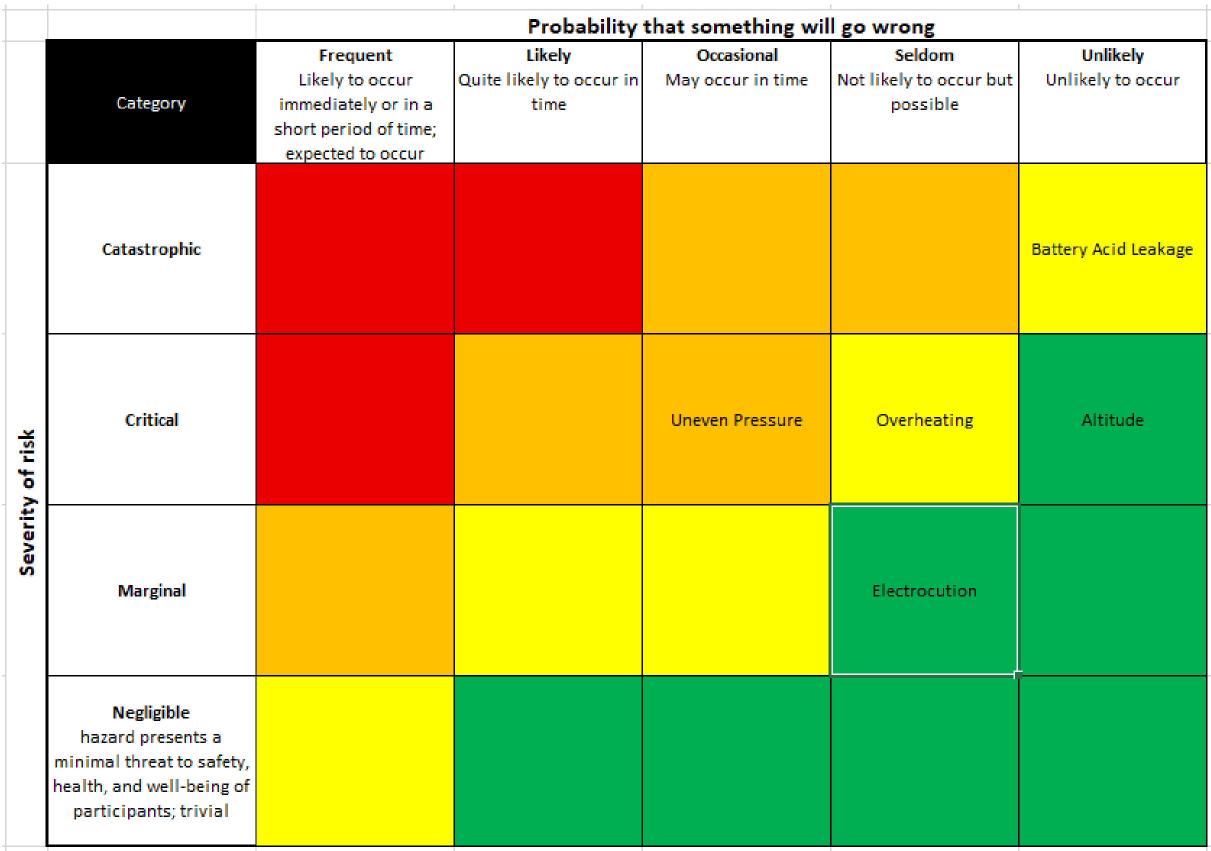


Figure 25: Heat Map for Prioritization of Design Risks

As seen by the heat map, uneven pressure on the spools and overheating of the motor are the two most important risks that the team will focus on. The colors on the heat map represent priority with green being the lowest and red being the highest. Uneven pressure lands squarely in the orange zone and is therefore the number one priority because it is both moderately likely and severe. Therefore the team will focus first on reinforcing the housing for the motor and spools to prevent uneven pressure from deforming the sole to touch the spools.

While both overheating and battery acid leakage are in the yellow zone, battery acid leakage is very unlikely to occur unless the user intentionally punctures the battery housing. Overheating on the other hand is more likely to occur from heavy use and due to the heavy insulation used around the components. To solve this, an automatic shutoff feature will be researched for future prototypes in order to reduce strain on the motor and thus reduce the likelihood of overheating.

6.3 Design for Manufacturing

Theoretically Necessary Components

- 2 DC Motors
- 2 9V Batteries
- 2 Spools
- 2 Shoes
- 2 Pressure pads
- Laces for shoes
- Ratchets for each motor

The motor is a separate component and is necessary because it is what rotates the laces and tightens the shoes.

The batteries are separate and necessary because they are what supply the motors with power to be able to tighten the shoes.

The pressure pads are necessary because they are assembled in conjunction with the motor and battery such that when the user steps onto the pad it initiates the tightening of the shoes.

The spools are separate and necessary because they are what the laces wrap around when they are constricted in the tightening process.

We already have a fairly minimal number of components for our design, but the layout could be assembled a different way. Right now the way we have it is our motor has two external rotating pieces where each of the spools are attached for each shoe. The laces on each end wrap around each spool and tighten each shoe from either side. We could change out motor to only have one rotating external piece and only one spool per shoe. This would require us to fasten the laces to one side of the shoe, and be tightening to the other side. The way we currently have it set up is that they tighten toward each other, like normal shoes. This method would also increase the number of laces we need per shoe. To mimic a normal shoe, we would need upwards of four laces to fully cover the entire length of a user's foot to get tight enough. These laces would be attached to the singular spool and motor, tightening across the one side.

6.4 Design for Usability

The objective of this prototype was to create a pair of shoes specifically aimed towards aiding those with disabilities. While the shoes are already very user friendly, itemized below is a list of impairments which were considered during the prototype phase or which could pose an issue with certain users.

Vision Impairments: Although shoes do not typically require sight to operate, a visual impairment like blindness could limit a user's ability to put the shoes on in the first place. However, we believe that a visual impairment will not affect the usability of our prototype for two reasons. First, the shoes were made with a "slip on" design so that the user does not have to keep track of the laces. Additionally, the tightening buttons which are present on other self-lacing shoes in the market have been removed in favor of the pressure pad. This was done so that no sight or dexterity is required to press the proper button for tightening.

Hearing Impairment: While a hearing impairment will not affect the usability of our design during normal operation, it may pose a risk if a failure happens with the components in the shoes. In the event of a battery explosion or overheating of the motor, a hearing impaired user would not be able to hear the popping of the battery casing or the whirring of a struggling motor. This would limit the user's ability to sense the failure and may lead to more damage than usual. One way to improve the design would be to add a tactile response mechanism which will vibrate the shoes to alert the user that something has gone wrong with the components, however the implementation of such a mechanism is beyond the scope of the team at this time.

Physical Impairment: While the shoes are specifically designed with the physically impaired in mind, they do still require some physical movement in order to function. Namely the pressure pad which controls the lacing of the shoes. If a user is unable to provide the proper pressure to complete the circuit in the sole, the shoes cannot be properly laced in the first place. While such impairments may make the shoes more difficult to operate, the team believes that the prototype has been optimized as much as possible and that alterations like buttons would only open the door to complications with other impairments.

Control Impairment: The design of these shoes is currently optimized for users with control impairments. Whether the user is intoxicated, fatigued, or distracted or has a physical dexterity impairment, the ”slip on” design of the shoes combined with the lack of exterior buttons for control makes the design especially suited for use with limited focus or effort.

7 Final Prototype

7.1 Overview

The final prototype for the self lacing shoes is based on an ”add-on” design where we install parts into an already existing shoe in order to upgrade it to be self lacing. In the following section, the final design can be seen with various images of the internal components alongside the results of our prototype testing. The functions being tested are the battery duration, overall weight, and durability, while the goals for each metric are 50 lacing cycles without battery replacement, the shoes being ¡1.5 lbs each, and 10 minutes of intense sports activity without damage.

7.2 Documentation

The following figures show the final prototype and close ups of some of the internal components. Note that the design has changed very slightly from the CAD models seen in Figures 19-21, but the overall design is the same.

Figure 26: Overall Image of Prototype

Figure 27: Closeup of Pressure Pad

Figure 28: Closeup of Mechanism in Sole

Figure 29 shows one of the shoes on a scale documenting the final weight of the prototype. The final weight of 1.206 lb is within the 1.5 lb target, and thus this prototype goal is accomplished.

Figure 29: Prototype Final Weight

The other two prototype goals covering battery life and durability are less readily shown on paper as opposed to video evidence, but it is important to note that the prototype passed both of the other two goals as well. While the battery was not taken to failure, the motor was still receiving adequate power after 50 cycles. Additionally the shoes survived 10 minutes of aggressive wear without any signs of damage, lace loosening or other failures.

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