Retractable Traction System

A Major Qualifying Project (MQP) Report
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Abstract

Pedestrians in urban New England face dangerously icy conditions which create a slipping hazard and can lead to serious injury. One way to reduce this hazard is through footwear traction systems. There are several products on the market, such as crampons and ice cleats, but they are cumbersome and inconvenient because they are removable devices that should only be worn on frozen surfaces. This forces users to attach or remove the system with every surface change. Conversely, a retractable traction system streamlines the transition between dry pavement, icy pavement, and indoor flooring. This project introduces such a system through a scale prototype of a modular half-shoe retractable spike mechanism.

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1. Introduction

Retractable Traction Systems is a design-focused Mechanical Engineering Major Qualifying Project that was conducted by a team of three Mechanical Engineering seniors and advised by Professor Eben C. Cobb. Over the course of one academic year, the team designed, analyzed, and prototyped a system that can be incorporated into modern winter footwear in order to provide retractable traction that allows safe walking for pedestrians in urban Northeastern United States winter conditions.

In most urban Northeastern United States areas, winter weather creates hazardous conditions for pedestrians. Sidewalks are often covered in a mixture of snow, ice, and slush, while also having patches of dry pavement. These conditions pose a significant danger of slipping, which can lead to injury or death. This increased slipping hazard is due to the reduced traction between footwear tread and frozen surfaces: there is less friction between ice or other frozen surfaces and tread than there is between dry pavement and tread. Common footwear is adept at handling dry pavement, but frozen precipitate reduces the friction between tread and the walking surface, increasing the risk of slips. Footwear traction systems are one way to reduce this risk.

One way for pedestrians to reduce the risk of slipping is by using a footwear traction system. Many products, such as ice cleats or crampons, are available, but to be maximally effective, these systems must also be convenient. The footwear traction systems currently on the market, even the ones advertised for pedestrians and professionals, are Although some current traction systems are marketed toward pedestrians, inconvenient.

2. Background

2.1 Target audience

This project focuses on working-age pedestrians in the urban northeastern United States. Working-age is defined here as between the ages of 15 and 65, because this age group comprises over 90% of the workforce (Age, 2018). Also, this project assumes the user has full mobility. Although other populations, such as the elderly or those with mobility-impairment disabilities, may benefit from such a retractable traction system, optimizing the device for atypical factors, such as reduced physical abilities, is beyond the scope of this project. In addition, this device is intended for adults, so the features necessary to make this device safe for children are also beyond the scope of this project. This project is also limited to urban areas of the northeastern United States. There are significant variations in winter conditions across the country, and many differences between rural and urban areas, even in the same region. By limiting the audience to pedestrians in urban northeastern United States, the intended users have a relatively consistent and manageable set of needs.

Although the intended audience of this project is constrained to ensure a manageable scope, the goal is to encompass as many possible users as is reasonable. Therefore, although atypical factors, children, and the elderly are excluded, the design will accommodate the extreme ends of the “normal” spectrum. For example, the design will fit in the smallest expected shoe size, but will also support the maximum expected weight, because the design can be scaled up more easily than it can be scaled down, and a lighter person can use a system rated for a person with a higher weight.

2.2 Falling Danger

Falls are a significant hazard for any age group; they can result in severe injury or death. Falls were the third leading cause of unintentional injury deaths and the first leading cause of nonfatal unintentional injury across all age groups in the United States in 2016 (Karwowski et al., 2003). Although falls are most prevalent among the oldest segment of the target audience, falls are a significant danger to all age groups in the target population. In 2016, there were a total of 4,957 unintentional fall deaths and 4,066,680 unintentional fall injuries among those aged 15 - 65 in the United States (Broker, N.D.).

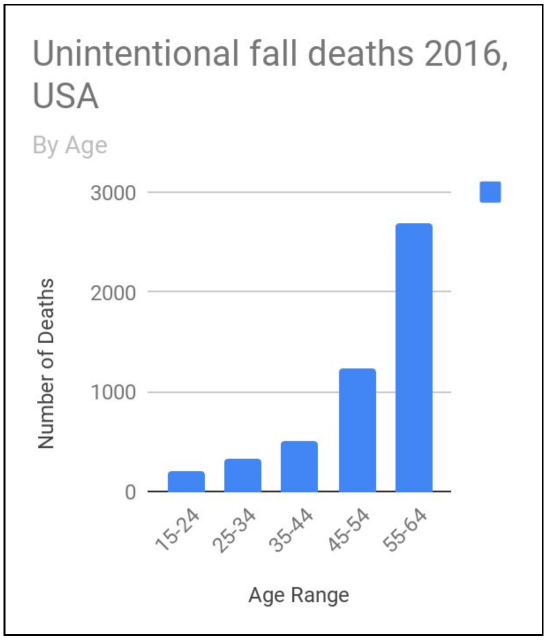


Figure 2.1 Unintentional fall deaths in the US in 2016, by age. (CDC WISQARS, 2018)

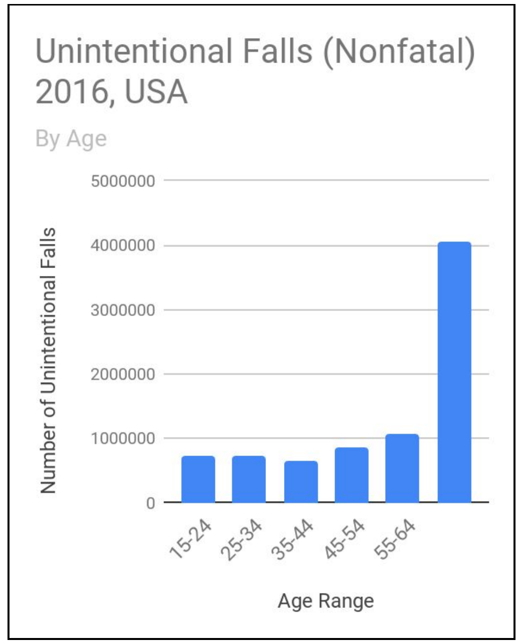


Figure 2.2.Unintentional falls (nonfatal) in the US in 2017, by age. (CDC WISQARS, 2018)

Winter conditions increase the risk of falling. The most common conditions for slips occur when there is a lubricating substance present (Karowski, 2003). Studies have shown that winter conditions, including snow, ice, and cold weather, can be related to increased rates of falls (Morency, et al., 2012). Slips are especially common in outdoor winter conditions when temperatures are close to freezing and there is water-lubricated ice (Karwowski, et al., 2003).

2.3 Human Factors

2.3.1 Mechanisms of Falling

There are many ways to fall. Karwowski et al. breaks the causes of falls into three primary categories: slips, trips, and "stepping-on-air" (2003). Karwowski et al. defines slips as "unexpected horizontal foot movement", trips as "restriction of foot movement", and stepping-on-air as "unexpected vertical foot movement" (2003). This project focuses on slips, because slips are the only of the three modes of falling that is likely to be improved with a traction system: both trips and "stepping-on-air" typically involve external factors (such as terrain variation or obstacles), while slips occur when the foot itself moves on a surface (Karwowski et al., 2003).

When a person is walking, slips are most likely to occur either during pushoff or heel strike (Karwowski, et al., 2003). If a person slips during pushoff, they will likely fall forward, which is less dangerous than slips that occur during heel strike, when the person will likely fall backward (Karwowski, et al., 2003).

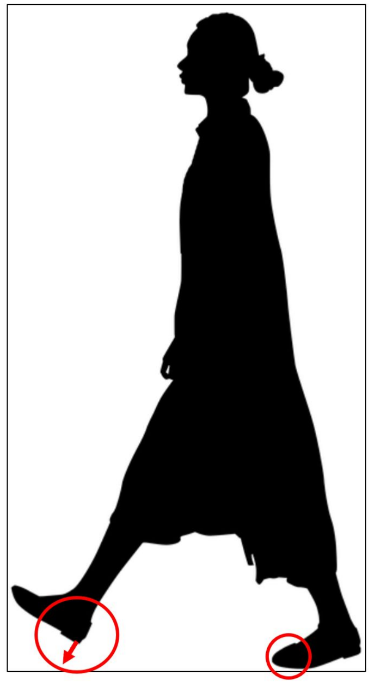


Figure 2.3. Heel strike and push-off events (Mskathrynne, 2018).

2.3.2 The Sample Pedestrian:Forces During Walking

The model pedestrians used in the designs was a 6 foot tall, 200 lbs man who commuted to work via walking in a New England city. As a commuter, they would move between surfaces ranging from compacted snow, ice, cleared asphalt, and gravel. Assuming the user spends a portion of their commute walking, the spiked system would need to last through years of use.

When walking, the user can expect one foot to bear 100% of their weight with every step. However, walking in urban environments can include stepping down from curbs and even dropping nearly half their full height. In such transitions, the device would be expected to bear anywhere up to 3.5 times the users weight (Elert, 1999). In the worst case scenario, that would mean that a single bar could bear the entire 700 lbs of the multiplied weight.

2.4 Operating Environment

The retractable traction system designed by this project is intended for use in urban northeastern United States. Not only does this region dictate the expected precipitate, but the system design must also accommodate the predicted range of temperatures and any other expected environmental factors. The primary concerns involve the expected walking surface, dimensional changes due to temperature fluxuations, material property changes due to temperature fluctuations, and corrosion due to road treatment.

Because this is being designed for an urban environment, it became important to determine what the risks the commuter faces when walking on concrete, pavement, or other aggregates. Using a study conducted at the University of Waterloo in Ontario, Canada, the team determined that the highest-risk sidewalk and pavement contaminants included bonded or compacted snow, slush, and ice, with an average Coefficient of Friction of 0.22 (Hossain et al. 2014). Because of this, the team decided to prioritize ice as a target for improving winter traction.

However, as the cities and typically use some salt to either dissolve the ice or to improve traction on walking surfaces. The majority of cities in New England use a two stage icing system, using liquid salt beforehand to prevent the binding of ice to pavement, and the second uses solid rock salt during storms to provide additional de-icing (Road Treatment Types, 2018). Despite the fact that the use of these salts provide traction for commuters, their corrosive nature can cause severe damage to metals in items such as cars, plows, and other winter gear over extended use.

The device will likely have multiple small clearances between moving parts. As theses gaps between pieces will be fairly small, there is a danger that the temperature could cause components to shrink or expand, rendering the system unusable. As such, our device must be able to function within the ranges set by the extreme temperatures of the area. The expected range of temperatures is from -30°F up to 80°F. -30 is the coldest temperature experienced by the northernmost urban area in New England (Bangor, Maine) in the past 10 years (NOAA, 2019), so this became the lower bound. This device will be used indoors as well as outdoors, so 80°F, which is a high but reasonable room temperature, was selected as the upper bound.

2.5 Commercial Viability

In order for the design to be useful to the public, it has to have a consumer base. Without such a group of users, the prototype would not move to a functional product. For the design to reach that point, the commercial viability, or ability to interest customers, must be considered.

2.5.1 Existing Technology

Traction systems for shoes are not a new concept. A brief review of store and online shopping websites show that there are many products available. Available traction systems are limited to those permanently affixed to the soles of shoes, and external devices that strap, stretch, or clamp onto shoes or boots. Traction is generally is provided by metal spikes, pins, or coils of wire. However, although external traction systems are commonly available, retractable traction systems are effectively unavailable.

One of the simplest external traction system designs uses coils of wire to provide traction. The system comprises metal wrapped around rubber straps that run across the bottom of the shoe or boot. In many designs, the spring-like coils are larger than the rubber straps holding them; this causes the coils to protrude in a series of metal ridges along the bottom of a shoe. These systems often attach to the shoe with a rubber strap that stretches from the toe to the heel, and relies on the tension in the rubber and the curve of the shoe to hold the system on. The coiled wire designs are less-expensive than the more aggressive designs, typically costing $20-$40. They are usually advertised for relatively conservative applications such as winter walking or running, and are favored by the company Yaktrax ®, which specializes in traction systems.

Another common design uses many small spikes or nubs (small cylinders) for traction. Of the three primary design types, this category has the most variation. These systems are either embedded in the sole of the shoe or affixed to rubber straps or chains. Typically, strap and chain systems have more robust mechanisms for attaching to the footwear than the coiled wire systems, such as straps that stretch across the toe of the shoe. However, most of the systems still rely on the elastic qualities of straps without any buckles or other methods of attachment. This category of products are intermediate in price and function: they can cost $20 to $100, and are advertised for many applications, from walking to hiking.

The most aggressive traction systems involve long spikes, often up to an inch long. These spikes are typically part of a rigid metal frame that extends along the sole of the shoe when attached; frequently the frame and all of the spikes comprise a single piece of metal. Sometimes the spikes are connected to sections of chain, but in these cases, there are usually two frames (one at the toe and one at the heel), each with multiple spikes, and it is these two clusters that are connected by chain. In either design, the frames and spikes are securely attached to shoes, at least with straps that go fully over the shoe, and often with buckles or velcro straps. These systems tend to be most expensive, with prices from $50 to over $160, and are advertised for more aggressive applications, such as backcountry hiking or backpacking.

The traction systems described above are all either external traction systems or embedded traction systems. Although many such systems exist for winter conditions, retractable traction systems are not commonly available to consumers. The research team has only discovered two retractable traction systems, one that was discontinued, and one that was a part of a kickstarter campaign (Gripforce, N.D.). The kickstarter campaign product was from the company Gripforce, but their website did not list product prices or have options to purchase the device. Otherwise, all temporary traction systems intended for improving grip in winter conditions are external systems that must be removed before going to an indoor environment.

Of the existing technologies, the products that are closest to the team's mission are the wire-coil or small-spike designs. These external traction systems are typically marketed for walking, running, or some hiking applications. This is different from the traction systems with long spikes, which are geared toward backcountry winter hiking, backpacking, and other more extreme activities and environments. This project assumes the pedestrian audience will be walking on somewhat-maintained pavement, and therefore mountaineering ice spikes are beyond the scope of the project. However, the goals and constraints faced by traction systems in the wire-coil or small-spike categories may be applicable to the project.

Common traits of comparable external traction systems provide a reference point for some requirements of the device, such as weight and cost. Coiled wire designs tend to weigh 4 to 12 oz per pair, and cost $20 to $40. Spike systems have a much greater range. They typically cost $15 to $90, and although their weight varies considerably, around one lb per pair is common.

2.5.2 Retractability

Retractability is the ability for an object to move back along the path it took forward. In order to make the system retractable, the lowest part of the traction device, be it spike, spring, or even sandpaper, must not protrude beyond the sole of shoe when the device is inactive. This will ensure that the user does not become inconvenienced by the removal of their winter walking devices.

The retractability of the design will also afford the wearer with balance comparable to that of the average footwear. This means that while the device is inactive, the wearer will not fall over if there is no outside input, such as being hit or pushed.

2.5.3 Integrability

To be useful, the retractable traction system must be integrable with the expected footwear of the audience: the device would not be convenient if it required users to wear specialized footwear. Because the audience of this project is urban New England pedestrians in winter, the expected footwear is a snow boot, and therefore the device must fit inside a snow boot. However, snow boots are a broad category of footwear, with a great range of sizes and dimensions. Because the audience comprises working-age adults, the device should be designed to be appropriate for the widest segment of the population possible. It will be easier to scale the device up than down, so the target footwear was determined to be a women’s size 6 snow boot: size six was selected because by designing for size six and higher, most adults foot sizes will be accomodated.

The type of footwear the traction system must be integrated in is important for providing the overall dimensions of the device. However, the manufacturing process of the selected footwear must also be understood, because to successfully integrate the device, it must be compatible with the manufacturing processes of the footwear.

Shoes and boots can be considered as two primary components, the upper and the sole. Uppers comprise combinations of leather, fabric, foam, and other polymers (L.L. Bean 2017). These parts are cut (typically with a punch), and then sewn or glued together. The sole, manufactured separately, is glued onto the upper (New Balance, 2015).

Shoe and boot soles comprise three primary parts: an upper surface, a main body, and the outsole (Davia-Aracil et al., N.D.). The upper surface affects fit and comfort, while the main body provides the structure of the sole, and the outsole, which includes the tread, determines how the footwear interacts with the environment (Davia-Aracil et al., N.D.). Shoe soles, particularly the main body, are usually formed through a molding process, most commonly compression or injection molding (Davia-Aracil et al, N.D.). These layers are connected either by glues or fusion (New Balance, 2015).

It is worth noting that footwear design is outside the scope of this project, and the details of integration would be worked out by the manufacturing department of a company desiring to use this system in their products. However, this understanding of footwear manufacture provides reasonable constraints so the device can be made of a size and shape that is plausible to integrate in a standard snow boot.

2.5.4 Weight

The weight applied at the foot are equivalent to 6 times that weight on the back (Jones, B. et al, 1983). Therefore, the weight of the finalized device will need to be kept as low as possible to make certain the finished product is something another person would want to use.

To determine a viable weight for the entire device, sites that displayed popular hiking and steel toe boot brands were analyzed. The average weights for hiking boots were compared to the average weight of steel toe work boots. Since the brands were popular and well reviewed, it could be reasoned that the difference between them would be an acceptable weight for the finalized device.

Table 2.1. Weights of Hiking and Steel Toe Boots

Hiking Boots	**Posted Weight**	**Steel Toe Boots**	**Posted Weight**
Salomon Quest 4D 2 GTX	1.5 Kg	Ariat work groundbreaker boot	2.72 Kg
Scarpa Zodiac Plus GTX	1.21 Kg	Thorogood american heritage work boots	1.36 Kg
HOKA ONE ONE Tor Ultra Hi	1.04 Kg	Redwing heritage roughneck	2.23 Kg
Keen Targhee 3 GTX	1.08 Kg	Timberland pro men's 26011	2.23 Kg
Average weight 1 = 1.2075 Kg		Average weight 2 = 2.135 Kg	

Difference in weight = Avg2- Avg1	.9275 Kg
Range of weight for design	0Kg - .46375 Kg
Range of weight for single system	0Kg - 0.2319Kg

While the range of the weights was up to 0.25 Kg, because lighter systems would be more integrable with existing boots, the target maximum weight was set to 0.125 Kg. This design constraint, the change from 0.25 to 0.125 Kg, was made at the end of the research process. The smaller established number gave the team a more precise target, but the team determined that if the target became impossible to meet, the threshold could be adjusted as necessary.

2.5.5 Cost

Cost is a common factor in a consumer's purchasing decision. Therefore, the team's product must be comparable in price to similar products, as discussed in Section 2.4.2. Below, the team has taken into consideration potential commercial manufacturing methods and materials with relation to their qualities and cost.

Materials play a large role in final product cost. The team will work to mitigate material costs by selecting less expensive materials while maintaining product integrity. The product must comply with the weight restrictions outlined in Section 4.5.3, while also maintaining the strength to endure the weight of a person on top of them. It must also be wear-resistant, and have minimal thermal conductivity as not to increase the risk of frostbite.

Common manufacturing processes for metal include milling, turning, forming, and casting. For plastics, methods include moulding, extruding, and 3D printing. With flat, thin parts such as sheets of wood or fabric, laser cutting may be used. Appropriate methods for selected materials can be chosen based on quantity from the PRIMA Selection Matrix below:

MATERIAL / QUANTITY	IRONS	STEEL (carbon)	STEEL (tool, alloy)	STAINLESS STEEL	COPPER & ALLOYS	ALUMINIUM & ALLOYS	MAGNESIUM & ALLOYS	ZINC & ALLOYS
VERY LOW 1 TO 100	[3.5][3.6] [3.7][6M] [7.1][7.4]	[3.5][3.7] [4.10] [6M][7.1] [7.5][7.6]	[3.1][3.5] [3.7][4.10] [6M][7.1] [7.5][7.6][7.7]	[3.5][3.7] [4.7][4.10] [6M][7.1] [7.5][7.6]	[3.5][3.7] [4.10][6M] [7.1]	[3.5][3.7] [4.7][4.10] [6M][7.5]	[3.6][3.7] [4.10][6M] [7.1][7.5]	[3.1][3.7] [4.10][6M] [7.5]
LOW 100 TO 1,000	[3.2][3.5] [3.6][3.7] [6M][7.1] [7.3][7.4]	[3.2][3.5] [3.7][4.10] [6M][7.1] [7.3][7.4] [7.5]	[3.1][3.2] [3.7][6M][7.1] [7.3][7.4][7.5] [7.6][7.7]	[3.2][3.7] [4.7][4.10] [6M][7.1] [7.3][7.4][7.5]	[3.2][3.5][3.7] [3.8][4.5] [4.10][6M] [7.1][7.3][7.5]	[3.2][3.5][3.7] [3.8][4.7] [4.10][6M] [7.3][7.4][7.5]	[3.6][3.7] [3.8][4.10] [6M][7.5]	[3.1][3.7] [3.8][4.10] [6M][7.5]
LOW TO MEDIUM 1,000 TO 10,000	[3.2][3.3] [3.5][3.6] [3.7][4.11] [6A][7.2]	[3.2][3.3][3.5] [3.7][4.1][4.3] [4.10][4.11] [6A][7.2][7.3] [7.4][7.5]	[3.2][3.5] [3.7][4.1][4.4] [4.11][6A][7.2] [7.3][7.4][7.5]	[3.2][3.5][3.7] [4.1][4.3][4.7] [4.10][4.11][6A] [7.2][7.3] [7.4][7.5]	[3.2][3.3][3.5] [3.8][4.1][4.3] [4.10][4.11][6A] [7.2][7.3][7.4]	[3.2][3.3][3.5] [3.8][4.1][4.3] [4.7][4.10][4.11] [6A][7.3][7.4] [7.5]	[3.3][3.6][3.8] [4.1][4.3][4.4] [4.10][6A][7.5]	[3.3][3.8] [4.3][4.10] [6A][7.5]
MEDIUM TO HIGH 10,000 TO 100,000	[3.2] [3.3] [4.11] [6A]	[3.9][4.1] [4.3][4.4] [4.5][4.11] [4.12][4.13] [6A][7.2][7.5]	[4.1][4.4] [4.5][4.11] [4.12][4.13] [6A][7.2]	[3.9][4.1][4.3] [4.4][4.5][4.11] [4.12][4.13] [6A]	[3.2][3.4][3.9] [4.1][4.3][4.4] [4.5][4.11] [4.12][4.13][6A]	[3.2][3.3][3.4] [3.9][4.1][4.3] [4.4][4.5][4.11] [4.12][4.13] [6A][7.5]	[3.3][3.4] [4.1][4.3] [4.4][4.5] [4.13][6A]	[3.3][3.4] [4.3][4.4] [4.5][4.13] [6A]
HIGH 100,000+	[3.2] [3.3] [4.11] [6A]	[3.9][4.1] [4.2][4.3] [4.4][4.5] [4.12] [4.13][6A]	[4.12] [6A]	[3.9][4.2] [4.3][4.12] [6A]	[3.2][3.9][4.1] [4.2][4.3][4.4] [4.5][4.7][4.8] [4.11][4.12] [4.13][6A]	[3.2][3.3][3.4] [3.9][4.1][4.2] [4.3][4.4][4.5] [4.8][4.12][4.13] [6A]	[3.3][3.4] [4.1][4.3] [4.4][4.8] [4.13][6A]	[3.4][4.2] [4.3][4.4] [4.5][6A]
ALL QUANTITIES	[3.1]	[3.1][3.6] [4.6][4.8] [4.9]	[3.6][4.6]	[3.1][3.6] [4.6][4.8] [4.9]	[3.1][3.6] [4.6][4.8] [4.9][7.5]	[3.1][3.6] [4.6][4.8] [4.9]	[3.1][4.6] [4.8][4.9]	[4.6][4.8] [4.9]

MATERIAL / QUANTITY	TIN & ALLOYS	LEAD & ALLOYS	NICKEL & ALLOYS	TITANIUM & ALLOYS	THERMOPLASTICS	THERMOSETS	FR COMPOSITES	CERAMICS	REFRACTORY METALS	PRECIOUS METALS
VERY LOW 1 TO 100	[3.1][3.7] [4.10][6M] [7.5]	[3.1][4.10] [6M][7.5]	[3.5][3.7] [4.10][6M] [7.1][7.5][7.6]	[3.1][3.6][4.7] [4.10][6M] [7.1][7.5] [7.6][7.7]	[5.5] [5.7]	[5.5] [7.7]	[5.2] [5.8] [7.7]	[3.5] [7.1] [7.5] [7.6] [7.7]	[3.1] [7.7]	[7.5]
LOW 100 TO 1,000	[3.1][3.7] [3.8][4.10] [6M][7.5]	[3.1][3.8] [4.10][6M] [7.5]	[3.2][3.5][3.7] [4.10][6M] [7.1][7.3] [7.4][7.5]	[3.1][3.6][4.7] [4.10][6M] [7.1][7.3][7.4] [7.5][7.6][7.7]	[5.3] [5.5] [5.7]	[5.2] [5.3]	[5.2] [5.3] [5.8] [7.7]	[7.1] [7.3] [7.5] [7.6] [7.7]	[7.7]	[7.5]
LOW TO MEDIUM 1,000 TO 10,000	[3.3][3.8] [4.3][4.10]	[3.3][3.8] [4.3][4.10]	[3.2][3.3][3.5] [3.7][4.1][4.3] [4.10][4.11][6A] [7.2][7.3][7.4] [7.5]	[4.1][4.7] [4.10][4.11] [6A][7.2][7.3] [7.4][7.5]	[5.3] [5.5] [5.6] [5.7]	[5.2] [5.3] [5.4]	[5.1] [5.2] [5.3]	[7.2] [7.3] [7.4] [7.5]		[7.5]
MEDIUM TO HIGH 10,000 TO 100,000	[3.3][3.4] [4.3][4.4] [4.13]	[3.3][3.4] [4.3][4.4] [4.5][4.13] [6A]	[3.1][3.3][3.4] [3.5][4.11] [4.12][4.13] [6A][7.2][7.5]	[4.1][4.4] [4.11][4.12] [4.13][6A] [7.2][7.5]	[5.1] [5.3] [5.5] [5.6] [5.10]	[5.1] [5.3] [5.10]	[5.1] [5.3] [5.9]	[4.11] [4.12]	[4.12] [4.13]	[4.5] [4.12]
HIGH 100,000+	[3.4][4.3] [4.4][6A]	[3.4][4.2] [4.3][4.4] [6A]	[4.2][4.3] [4.12][6A]	[4.12] [6A]	[5.1] [5.6] [5.10]	[5.1] [5.3] [5.4] [5.10]	[5.9]	[4.7] [4.11] [4.12]	[4.12]	[4.5] [4.12]
ALL QUANTITIES		[4.6]	[3.1][3.6] [4.6][4.8] [4.9]	[4.8][4.9]				[7.5]	[3.6]	[3.6]

KEY TO MANUFACTURING PROCESS PRIMA SELECTION MATRIX:

CASTING PROCESSES
- [3.1] SAND CASTING
- [3.2] SHELL MOULDING
- [3.3] GRAVITY DIE CASTING
- [3.4] PRESSURE DIE CASTING
- [3.5] CENTRIFUGAL CASTING
- [3.6] INVESTMENT CASTING
- [3.7] CERAMIC MOULD CASTING
- [3.8] PLASTER MOULD CASTING
- [3.9] SQUEEZE CASTING

FORMING PROCESSES
- [4.1] FORGING
- [4.2] ROLLING
- [4.3] DRAWING
- [4.4] COLD FORMING
- [4.5] COLD HEADING
- [4.6] SWAGING
- [4.7] SUPERPLASTIC FORMING
- [4.8] SHEET-METAL SHEARING
- [4.9] SHEET-METAL FORMING
- [4.10] SPINNING
- [4.11] POWDER METALLURGY
- [4.12] METAL INJECTION MOULDING
- [4.13] CONTINUOUS EXT (METALS)

PLASTIC & COMPOSITE PROCESSING
- [5.1] INJECTION MOULDING
- [5.2] REACTION INJECTION MOULDING
- [5.3] COMPRESSION MOULDING
- [5.4] RESIN TRANSFER MOULDING
- [5.5] VACUUM FORMING
- [5.6] BLOW MOULDING
- [5.7] ROTATIONAL MOULDING
- [5.8] CONTACT MOULDING
- [5.9] PULTRUSION
- [5.10] CONTINUOUS EXTRUSION (PLASTICS)

MACHINING PROCESSES
- [6A] AUTOMATIC MACHINING
- [6M] MANUAL MACHINING

NON-TRADITIONAL MACHINING PROCESSES
- [7.1] ELECTRICAL DISCHARGE MACHINING (EDM)
- [7.2] ELECTROCHEMICAL MACHINING (ECM)
- [7.3] ELECTRON BEAM MACHINING (EBM)
- [7.4] LASER BEAM MACHINING (LBM)
- [7.5] CHEMICAL MACHINING (CM)
- [7.6] ULTRASONIC MACHINING (USM)
- [7.7] ABRASIVE JET MACHINING (AJM)

Figure 2.4 Manufacturing Process PRIMA Selection Matrix
(Swift & Booker, 2013, Manufacturing Process Selection para. 3).

While appropriate processes must be chosen based on material type, cost is also a consideration. According to the *Manufacturing Process Selection Handbook* by Swift and Booker (2013),

> Manufacturing cost, *M*i, can be formulated as: $M_i = V*C_{mt} + R_c*P_c$ where *V* = volume of material required in order to produce the component; *C*mt = cost of the material per unit volume in the required form; *P*c = basic processing cost for an ideal design of the component by a specific process; *R*c = relative cost coefficient assigned to a component design (taking account of shape complexity, suitability of material for processing, section dimensions, tolerances and surface finish). (Component Cost para. 7)

The team will use this model to determine the most cost efficient method of production for the selected materials, and make production recommendations accordingly.

2.6 Manufacturing Resource Limitations

The design team must be able to produce a prototype of the selected design. As a result, the proposed designs must be limited to those able to be made in the Washburn Manufacturing

Labs at Worcester Polytechnic Institute. Skills available to the team include CNC Milling, CNC Turning, Laser Cutting, 3D Printing, and Welding. Because of this, the materials that the team can use are limited to aluminum, steel, brass, plywood and acrylic sheets, and PLA or PETG printing filament. Any components which cannot be made using the above materials and skills must be purchased from vendors online or in the Worcester area.

Functional Requirements

The team developed the following requirements which the selected design must satisfy. Below is a list of the basic functional requirements of the device. For a detailed explanation of these requirements, and the logic and justification behind them, see Appendix A.

The device must:

1. Reduce the falling risk of pedestrians in winter conditions
    a. Improve slip resistance on frozen surfaces
    b. Maintain user stability
2. Provide a convenient transition from indoor to outdoor icy to outdoor dry surfaces
    a. Have modes appropriate for each surface
    b. Have a convenient mechanism to switch between modes
3. Be commercially viable
    a. Be integrable with normal winter boots
        i. Fit in women's size 6 boot
        ii. Have comparable or lower weight than other traction systems
        iii. Function when encased in a sole
    b. Design can be scaled up
    c. Support user's weight
    d. Not exceed $100 in cost
4. Withstand Urban New England winter conditions
    a. Function in -30F to 80 F (-34 to 27 C) temperature range
    b. Resist corrosion from road salt
5. Be manufacturable by design team
    a. Required manufacturing processes are within capabilities of the design team
    b. Required equipment is limited to what is available at WPI
        i. Manufacturing operations can be conducted with available equipment
        ii. Tolerances can be held with available equipment
        iii. Materials are compatible with available equipment
    c. Materials are within budget
    d. Components not manufacturable by the design team are orderable stock parts

3. Design Process

This goal of this project was to design a retractable traction system for winter footwear. To achieve this objective, the team used a three-phase design process. First, design concepts were considered, both for methods of increasing traction and for mechanisms for deployment and retraction. Secondly, these concepts were synthesized and analyzed to select a traction system concept. Finally, the selected system concept was optimized. For a visual depiction of this process, see Figure 3.1.

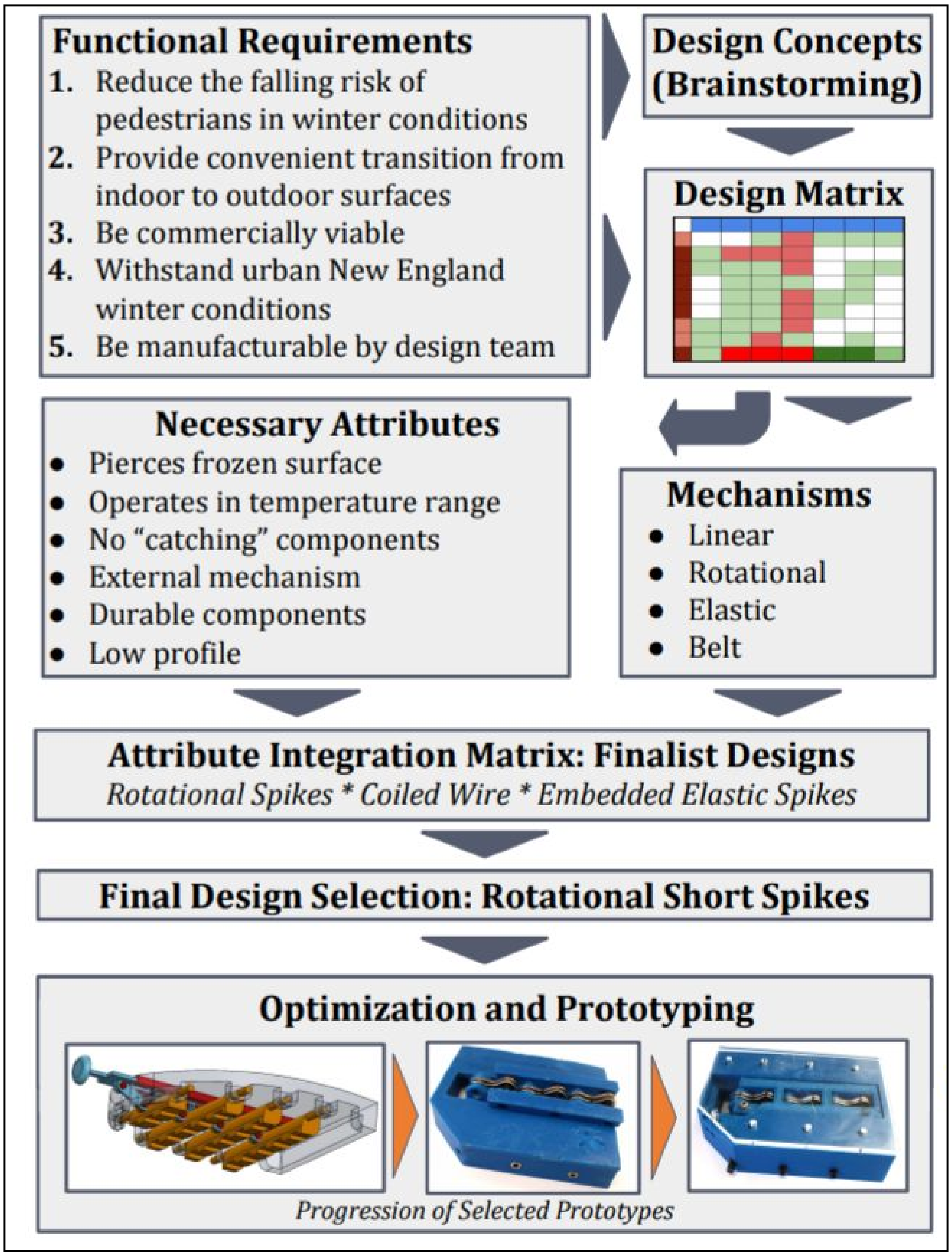


Figure 3.1. Design Process Flowchart.

The first phase of the design process involved brainstorming traction methods and mechanisms. The team initially brainstormed system concepts (both a method of providing traction and a method of retraction), but it quickly became apparent that this process was inefficient: early in the design process, the team realized that multiple mechanisms could be applied to a single way of providing traction, and multiple ways of providing traction could be applied to a single mechanism. Therefore, the team decided to design the two components of the retractable traction system separately: methods of providing traction were considered, and mechanisms were considered separately. (The team made exceptions for this process in cases that the retraction method was inherently part of the traction concept, see section 3.1.1.5.)

After a significant list of traction methods and mechanisms had been generated, the team entered the second phase of the design process: synthesis, analysis, and selection. The team conducted a simple evaluation of all the design concepts to ensure they were feasible. This process eliminated numerous design ideas. From the remaining traction concepts and mechanisms, the team identified which methods paired with which mechanisms and generated a list of plausible system concepts. The list of system concepts was then evaluated through a preliminary design matrix to narrow down the options.

The preliminary design matrix not only provided a shortened list of system concepts, but it also allowed the team to identify key features from the successful designs. After identifying these features, the team created an attribute matrix to reevaluated and optimize each of the successful design concepts. This attribute matrix resulted in 3 optimized design concepts, which were evaluated in more detail, through modeling and additional research. Of the three concepts, two were eliminated, resulting in the team's final system design concept. This system design concept was then optimized through iterations of CAD and rapid prototype models.

3.1 Ideation

The first phase of the design process comprised generating concepts for a retractable traction system. Early on, the team identified two primary components of a retractable traction system: the method of increasing traction, and the retraction mechanism itself. It became apparent that there was significant overlap between these components: different mechanisms might work with the same traction concept and vice versa. Therefore, the team approached the concept generation phase of the project in two parts, by identifying traction methods and retraction mechanisms separately.

This ideation process involved brainstorming, researching applicable features of existing technologies, and considering everyday phenomena that could be used either to improve traction or to create small-scale retraction mechanisms. During this ideation phase the team considered all reasonable concepts, without evaluating the feasibility of the designs. Concepts were evaluated as a separate step, during the second phase of the design process. For design evaluations, see 3.2.1, Viability of Solutions.

Throughout the ideation process, the team came up with five overarching methods for improving footwear traction, and four mechanism concepts. The five proposed traction methods were: spikes, coiled wire, sand paper, suction cups, and thermal adhesion. The four proposed mechanism concepts were rotational, linear, belt, and elastic.

3.1.1 Traction Concepts

The method of improving footwear traction was central to this project: not only is improving traction explicitly in the goal statement, but traction also directly affects the functional requirements.

Throughout the ideation process, the team identified five distinct methods of providing traction: spikes, coiled wire, sandpaper, suction cups, and thermal adhesion.

3.1.1.1 Spike Designs

One of the first traction-improvement concepts considered for the project was spikes. This concept was inspired by the many existing winter footwear traction systems that use spikes, such as YakTrax and Crampons (see Background).

Spikes improve footwear traction by penetrating the walking surface. The embedded spike provides a lateral force that resists slipping; for a slip to occur after a spike has become embedded in the walking surface, the surface must fracture or the spike must slide out of its hole (see Figure 3.2).

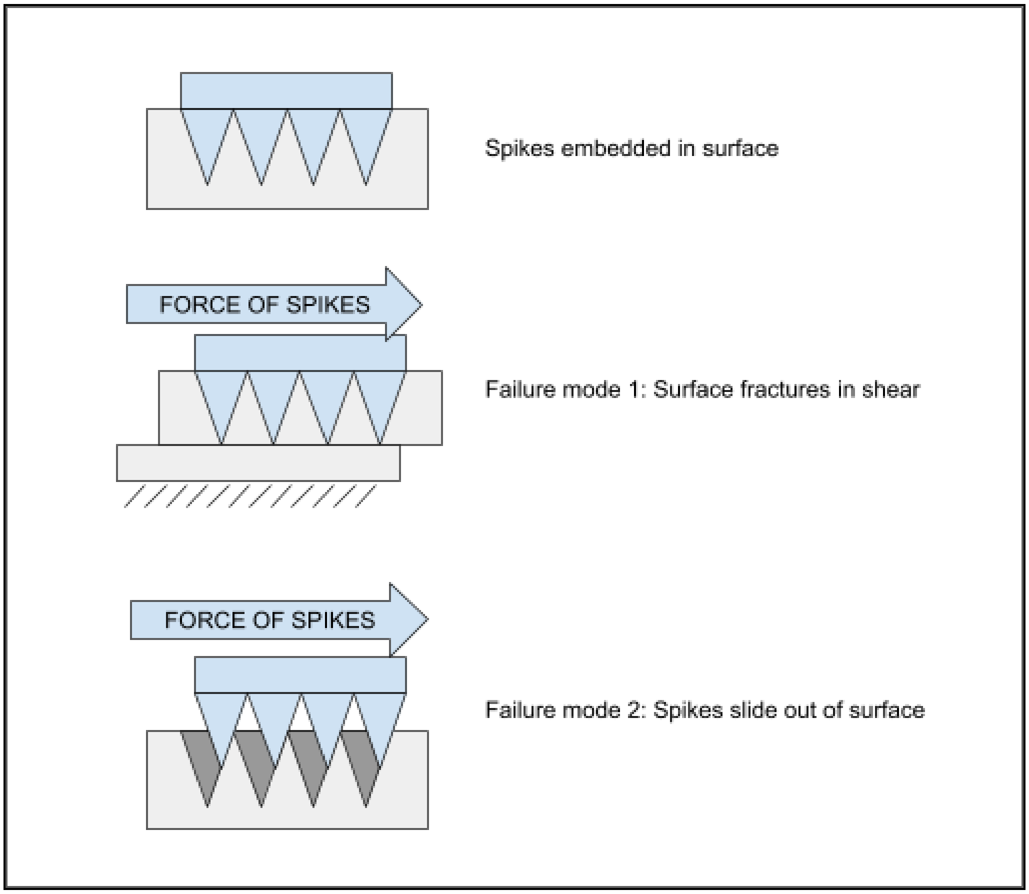


Figure 3.2. Failure Modes of Spikes

The team further developed the spike design concept based on existing footwear traction systems and existing gait studies (see Background). The proposed spike length was selected to be between ¼ and ½ inch when deployed because this is consistent with existing systems. The team also determined there should be many spikes distributed over the bottom of the sole, specifically including spikes on both the toe and heel regions, because this would facilitate a standard walking gait.

3.1.1.2 Coiled Wire Designs

The team was inspired by existing footwear traction systems for a design concept that uses coiled wire to provide traction. Coils of wire, looped around compressive regions on the bottom of footwear, concentrate the user's weight over the small radius of the wire. The concentrated force can pierce frozen surfaces, such as ice, providing resistance to slipping (see Figure 3.3).

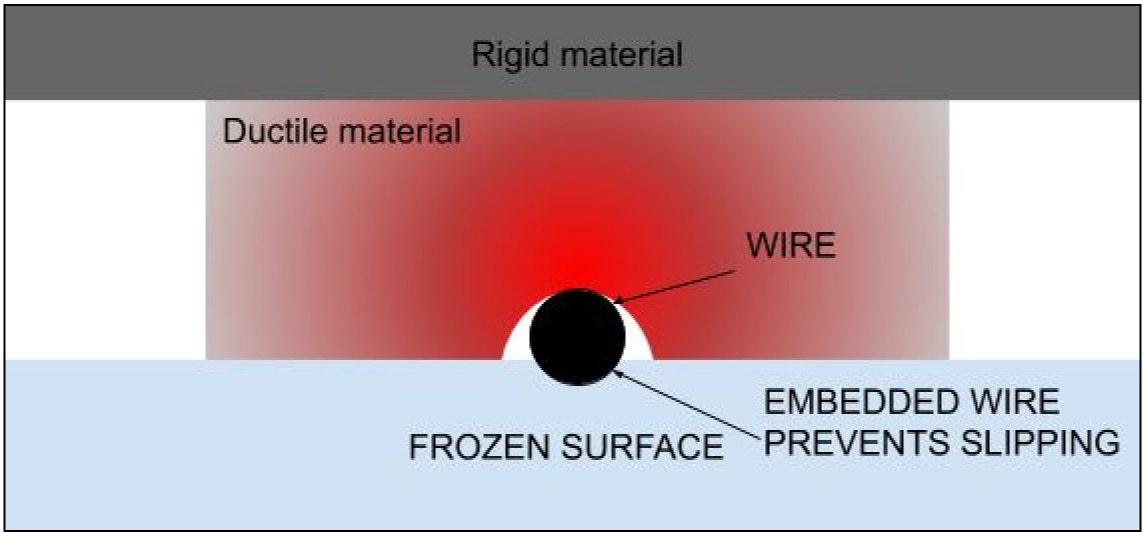


Figure 3.3. Coiled Wire System Cross Section

Like the existing products, the coiled wire design envisioned by the team involves spring-like metal wire looped around straps that cross the bottom of the sole of a shoe or boot, but unlike existing products, the mechanism would be made retractable.

3.1.1.3 Sandpaper Designs

Sandpaper was considered as a way to improve traction because it creates significant friction against most surfaces. The team considered two sandpaper concepts, either using waterproof sandpaper, or creating a sandpaper-like substance by embedding sand particles in rubber or another flexible and waterproof medium. However, both concepts would function in the same way: the hard particles would grip a frozen surface, improving traction.

3.1.1.4 Suction Cup Design

The team considered suction cups as a method of improving footwear traction, because suction cups could indirectly increase the friction force between tread and the ground, and it is this force that resists slipping.

Friction forces are calculated by the equations $F_s = \mu_s \eta$ and $F_k = \mu_k \eta$ where F_s represents static friction, F_k represents kinetic friction, μ is the coefficient of friction, and η represents the normal force. In winter conditions, the coefficient of friction between the tread and the walking surface decreases because ice and slush are less rough than pavement, while the normal force stays approximately the same (because it is primarily determined by pedestrians' weight, which is independent of weather conditions). Therefore, because the coefficient of friction decreases and the normal force remains approximately constant, the friction force between tread and the ground is reduced in winter conditions.

To restore an adequate level of friction to prevent slips, either the coefficient of friction or the normal force must be increased. Because icy conditions create an inherently low coefficient of friction, increasing the normal force is a reasonable way to prevent slips, suction cups are a viable option that create a force that pulls the cup towards the surface it is attached to, and this force could be used to increase the force on adjacent tread. By increasing the force on the tread, even without changing the material of the tread, the traction provided by the footwear would be increased.

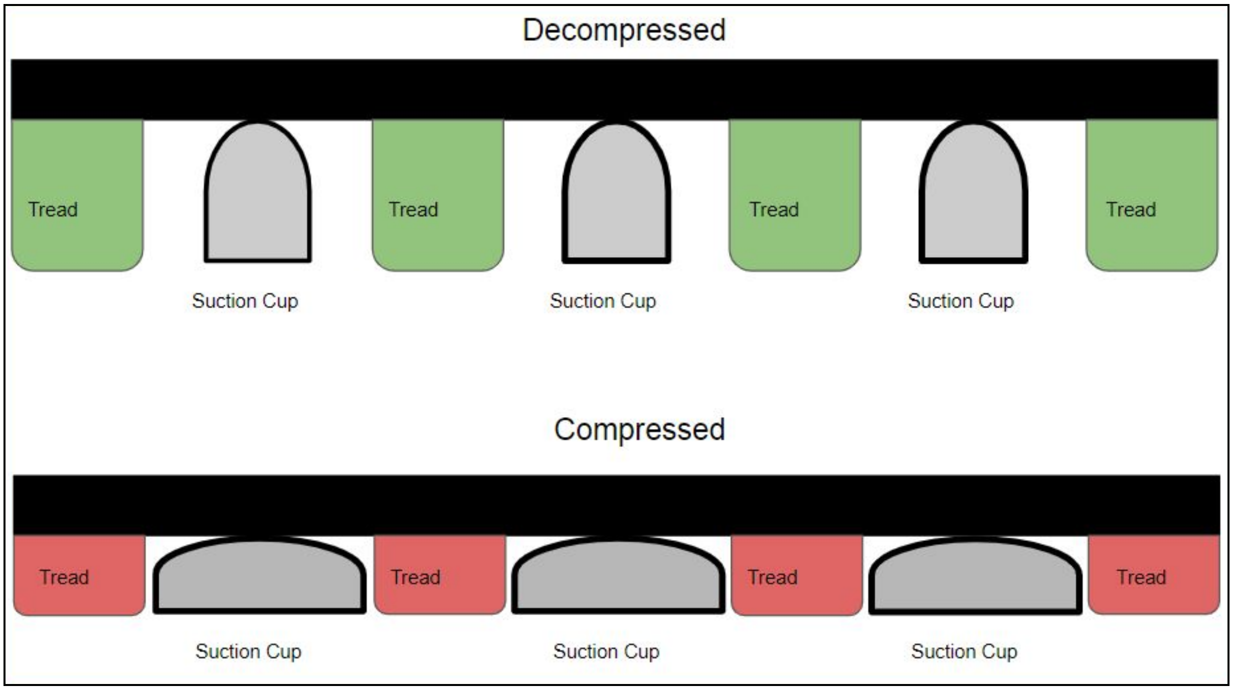


Figure 3.4. Suction Cup Design Cross Section.

Although suction cups have the potential to improve traction, the team recognized two potential issues: suction cups require a relatively smooth and flat surface to create a seal, and suction cups may not be sufficiently durable. These problems needed to be addressed before suction cups could be considered as a viable design concept.

To improve the likelihood of a seal forming, the team opted for many small suction cups instead of relatively few larger cups. The smaller cups would require less area to create a seal, and having more cups on the design would provide more opportunities for a seal to form. Overall, a design with many small cups would be more likely to attach to an imperfect walking surface. Also, reducing cup size addressed the durability concern: a small suction cup would be less likely to catch on a surface and tear: the smaller cups would be more likely to be pushed aside by an obstacle, instead of pierced, because the smaller cup has to move a relatively small distance to clear an obstacle. Also, using replaceable cups resolves the issue: the suction cups could be considered semi-disposable components.

3.1.1.5 Thermal Adhesion Designs

Inspired by the playground phenomena of children licking frozen poles and getting stuck, the team considered using ice itself as a method of improving traction. Melting a frozen surface and allowing it to refreeze to the sole of footwear would anchor the sole to the ground, reducing the likelihood of slips. The team labeled this design concept "thermal adhesion" because it uses fluctuating temperatures to create increased traction.

For the thermal adhesion system, the overarching concept is that a heat source in the sole of the footwear would melt a frozen surface, which would refreeze to unheated portions of the sole. The refrozen water would bond the footwear to otherwise-slippery frozen surfaces, thereby improving traction and reducing the risk of slips. The team came up with two designs following this overarching principle, one using passive cooling, and another using active cooling. Both systems use electrical-resistance heating coils to melt any frozen surface, and both systems use chilled portions of the tread to encourage re-freezing. However, the two designs differed based on the cooling mechanism that would allow water to refreeze to the footwear. The simpler design, referred to as the passive thermal adhesion system, would use the ambient air temperature for passive cooling, while the other design, referred to as the active thermal adhesion system, used a refrigeration cycle for active cooling.

The passive thermal adhesion system uses strategic placement of a highly conductive material to create a cold surface. Conductive material (most likely copper plates) would be set around the outside of the footwear, and would extend to the bottom of the outer ring of tread. The ambient air temperature would chill this conductive material. Heating coils would be located on the first inner ring of tread, so the melted surface would be next to the cooled portion (see Figures 3.5 and 3.6).

The active cooling system would use a miniature refrigeration system, built into the sole of the shoe, to provide cooling to sections of tread. This allows for the cooled surfaces to not be limited to the outer edge of the sole of the shoe.

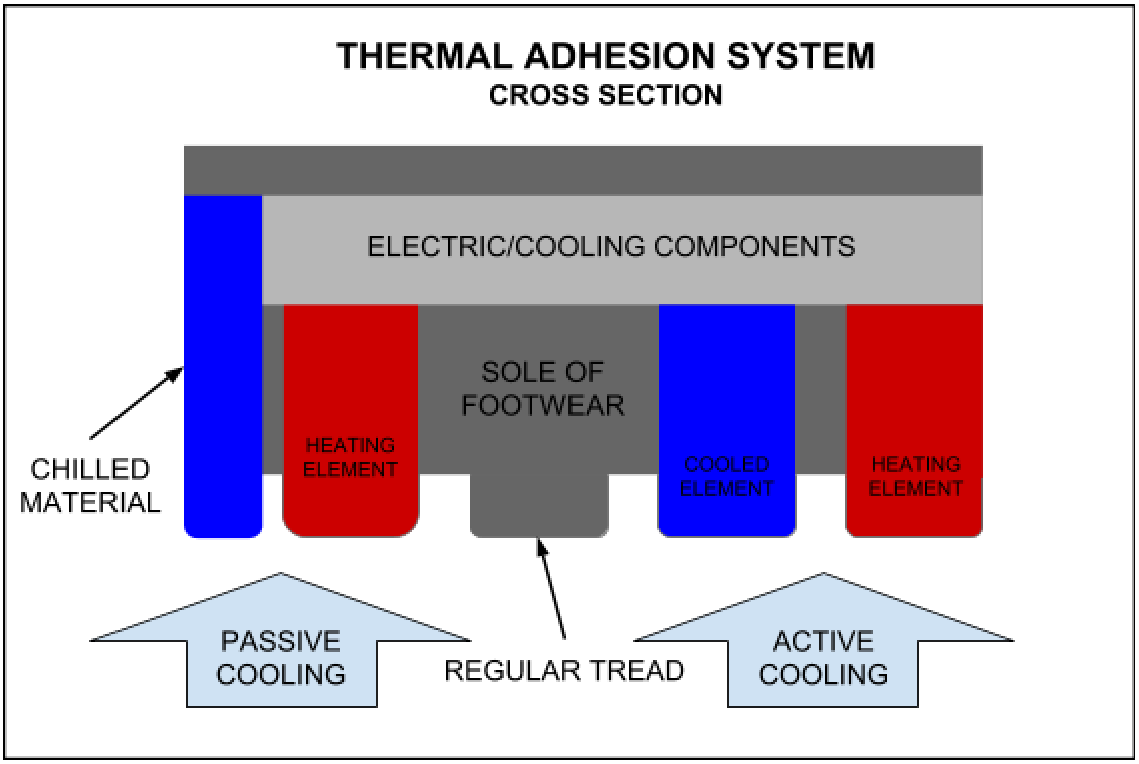


Figure 3.5. Thermal Adhesion System Cross Section, both passive and active shown

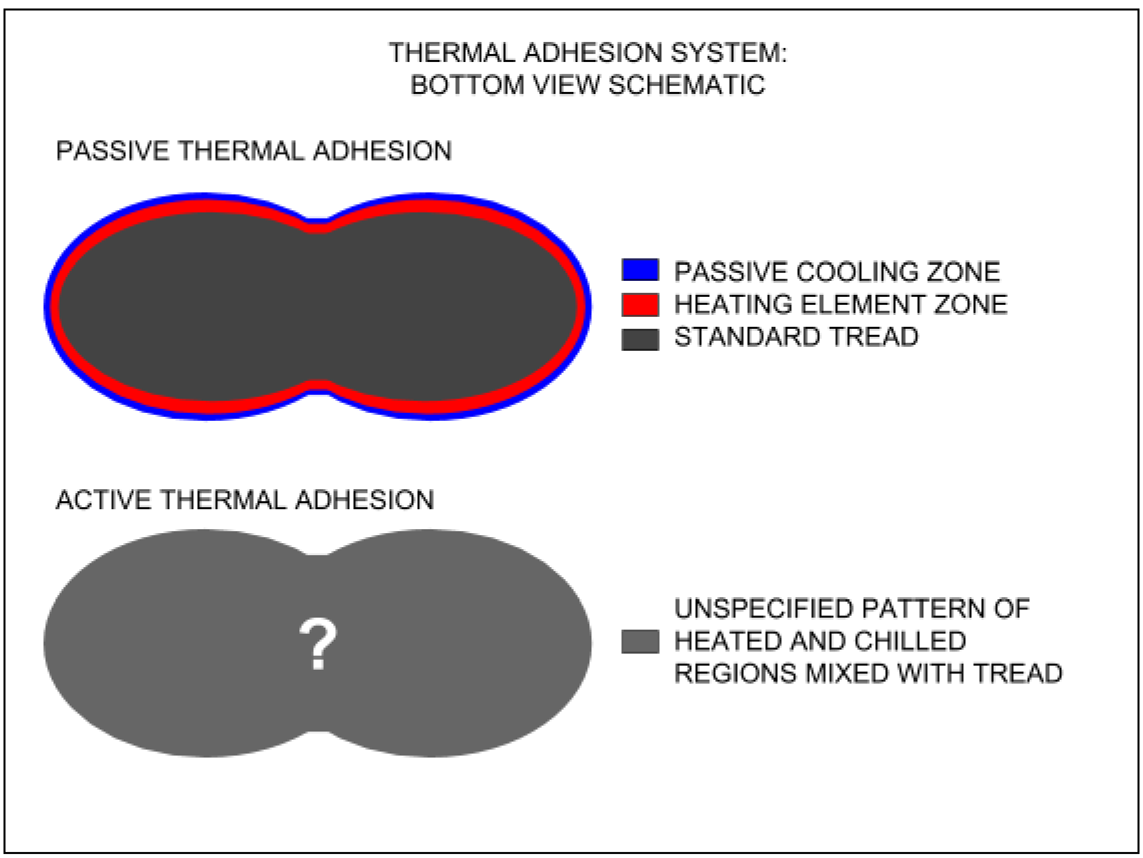


Figure 3.6. Thermal adhesion designs, bottom view schematic

3.1.2 Mechanism Concepts

For this project, the mechanism to retract and deploy a traction system is as important as the traction system itself: it is the retraction mechanism that sets this project's design apart from all the traction systems already on the market.

The team began the project by designing system concepts, by simultaneously ideating mechanisms and traction methods. However, it became apparent that this was not an efficient design process because multiple mechanisms could be used for one traction method and vice versa. Therefore, the ideation process was split into traction concepts (see section 3.1.1) and mechanism designs, which are discussed here. Ultimately, the team came up with four different mechanism concepts: linear, rotational, elastic, and belt.

3.1.2.1 Linear Mechanism

The first mechanism (Figure 3.7) incorporated channels that guide a platform down into contact with the surface. The traction system would be attached to the platform. This platform is depressed via a cam that is rotated by a geared system from a knob on the exterior. Variations of this gear-cam system would also be considered, but the channel design is the distinctive feature of the linear mechanism.

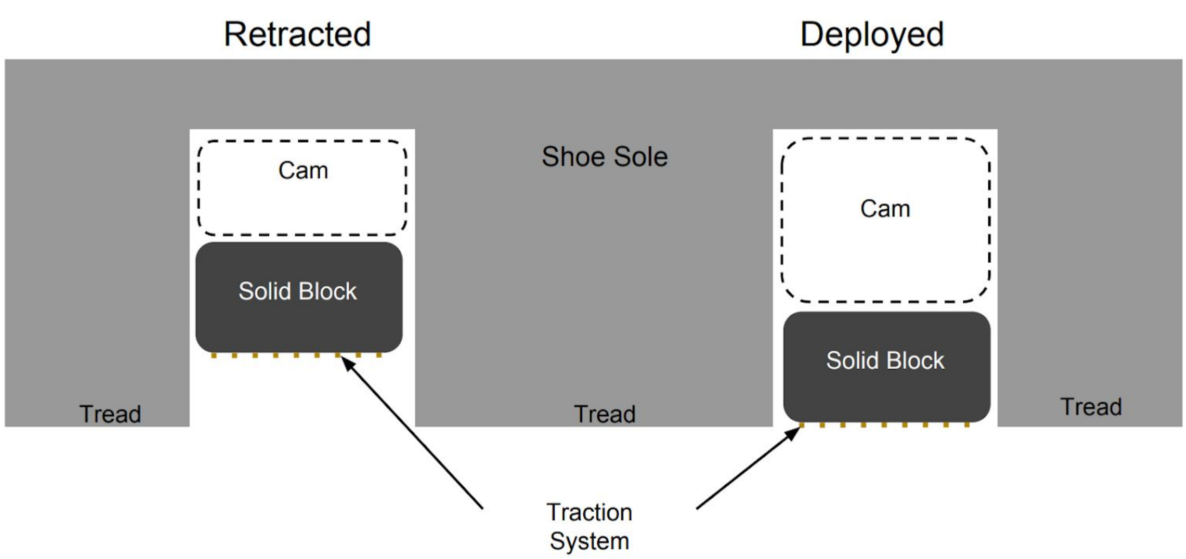


Figure 3.7. Linear Mechanism Cross Section

3.1.2.2 Rotational Mechanism

The second mechanism (Figure 3.8) utilized a series of rods mounted across the sole of the shoe. The rods are rotated by a central bar that attached to each rod with a connection link. When this main bar is moved forward or back, the bars mounted across the sole rotate. While one side of the bar could hold the traction surface, the other could be empty so as to not damage the floors.

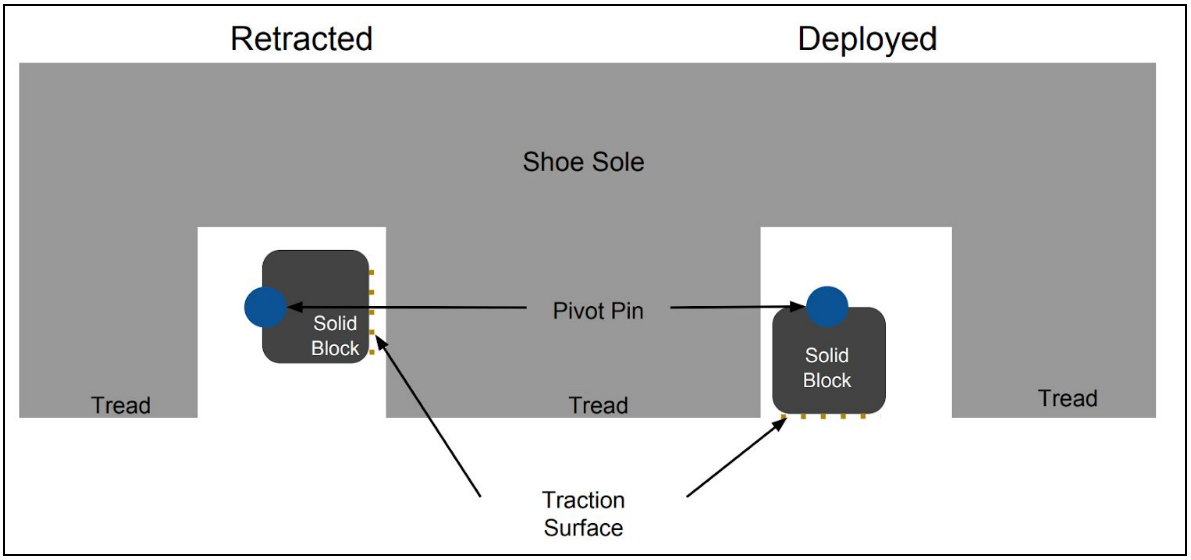


Figure 3.8. Rotational Mechanism Cross Section.

3.1.2.3 Elastic Mechanism

The third design (Figure 3.9) used elastic bands to hold a traction system in place. The bands would rest in a channel carved into the sole. When not deployed, the storage channel would be deep enough that the traction surfaces would not interact with the ground. When deployed, the bungees would be stretched across the sole, allowing the traction surface to come into contact with the ground.

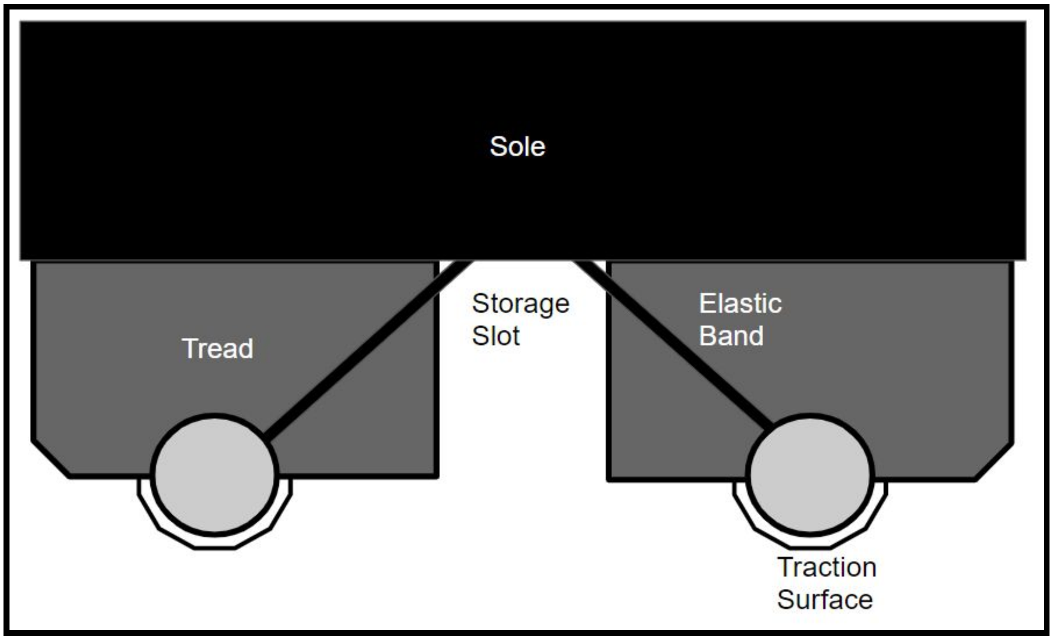


Figure 3.9. Deployed Elastic Mechanism Cross Section

3.1.2.4 Belt Mechanism

the last design (Figure 3.10), a stip of traction would be affixed to a string, belt, or chain which would loop through the sole and between the treads of the shoe. When it moves by about half of its length, the traction would be exposed along the bottom of the shoe. The rest of the time the tractional strip would be stored along the inside of the shoe.

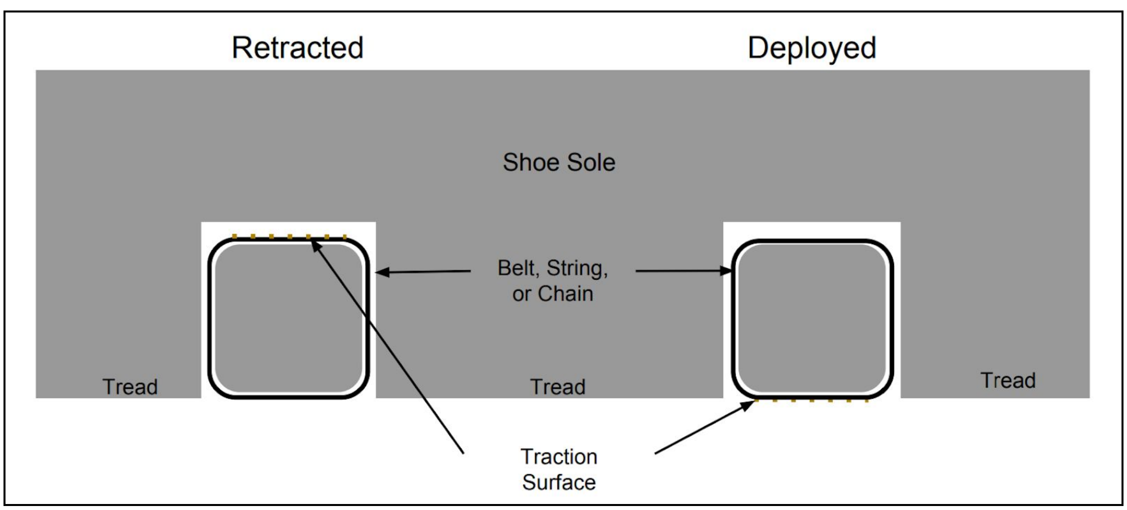


Figure 3.10. Belt Mechanism Cross Section

3.2 Synthesis and analysis

After the ideation process, the team had identified five plausible traction methods (spikes, coiled wire, sand paper, suction cups, and thermal adhesion), and three mechanism concepts (linear, rotational, elastic, and belt). The team used alternating phases of synthesis and evaluation to create their final design of a rotational spike mechanism; a process which ultimately comprised four phases. (1) The team combined traction methods and retraction mechanisms, to determine which combinations created feasible design concepts. (2) These concepts were evaluated through a decision matrix that identified the best design concepts and attributes. (3) An attribute matrix, which utilized both the concepts and attributes, identified ways to optimize successful design concepts. (4) Development of optimized design concepts. (5) Evaluation of the optimized design concepts, which resulted in the elimination of two out of the three concepts.

3.2.1 Initial Design Concept Synthesis

With workable traction methods and retraction mechanisms identified, the team moved to conceptual designs for the combined device. The team determined for each traction method, which mechanism or mechanisms could be used to deliver traction.

While the team considered each retraction mechanism as a potential pairing with each traction method, they experimented with unusual combinations to ensure no possible option was left out.

A design concept was considered distinct if there were fundamental differences in how the device would interact with the environment. For example, coiled wire and thermal adhesion were separated into sub-designs because each of the design options would interact differently with an icy surface. On the other hand, the spike design was left as a single design category, because all of the design concepts involving spikes have the same general functions; the only variation was in the retraction mechanism itself.

3.2.2 Preliminary Decision Matrix

The preliminary design matrix (Table 3.1) differentiated designs based on how they would meet the functional requirements of the project, based on the level of detail available through the preliminary designs.

Because of the low level of detail available at this early stage of the design process, every factor was scored out of three points. A score of one indicated that the design absolutely failed in the given category. A score of two indicated that the design’s relevant function was either unknown, would only partially satisfy the factor, or would only sometimes satisfy that factor. A score of three indicated that a design consistently would meet or exceed the factor. Any design that scored a one in any category was unable to satisfy all the functional requirements of the project, even if it scored well in other areas, and was therefore eliminated. Ultimately, three designs were eliminated this way. The rubric used to determine the scores for each design can be found in Appendix B.

The weights of the factors in the design matrix were selected based on the relative importance of each factor in achieving the overall project goal:

To address the lack of convenient footwear traction systems in order to improve safety for urban New England pedestrians while walking in winter conditions.

The weighting factors summed to 100 points, and the scores for each design were likewise out of 100.

Table 3.1. Preliminary Design Matrix

Factors Considered	Weighting Factor	Design 1 (Sandpaper)	Design 2 (Passive Thermal Adhesion)	Design 3 (Active Thermal Adhesion)	Design 4 (Suction cup)	Design 5 (Spikes)	Design 6 (Over Tread Coiled Wire)	Design 7 (Retractable Coiled Wire)
Fall Prevention	(30)							
Slips	10	2	2	2	1	3	3	3
Trips	10	3	1	1	1	2	2	2
Stability	10	3	3	3	1	2	3	3
Integrable with modern footwear	5	2	2	2	3	2	3	2
Operating condition range	20	2	2	3	1	3	3	2
Durability	10	2	2	2	1	3	2	2
Convenience (Usable Indoors)	25	2	3	3	1	2	2	2
Manufacturable by design team	10	3	3	1	3	2	3	2
TOTAL	100	76.67	78.33	78.33	43.33	80.00	85.00	73.33

Of the designs which satisfied all functional requirements to some level, the top three progressed to the next round of the design process. Over-Tread Coiled Wire had the highest score, while Spikes was a close second. The sandpaper design was the third highest scoring, so it was also considered. The rationale behind the the scores determined for each design is detailed below:

Design 1: Sandpaper

The Sandpaper design was among the highest ranked designs. Concerns about the durability, or wear-resistance of the sandpaper grit decreased the score in that category significantly. In addition the team noted that the grit could become clogged with slush and snow reducing its ability to prevent slips and trips in the expected conditions. However, the system provides an overall stability to the user, and is easily integrable and manufacturable by the design team, making it an effective choice for the project.

Designs 2 and 3: Thermal Adhesion

Although freezing footwear to a frozen surface could reduce the likelihood of slips, it provides an inherent tripping hazard. This tripping hazard immediately failed both thermal adhesion designs. Although the trip prevention is not an objective of this project, a system is not allowed to cause trips, so creating a tripping hazard is a terminal flaw for a design concept, based on the criteria in Table 3.1.

Design 4: Suction Cups

The immediate concerns with a suction based traction system were the lateral force that would be exerted while walking and the uneven ground surface breaking the seal of the cup. Additionally, when walking, the suction cups would be torn up and damaged by the rough surface of the ground. If these concerns were not addressed, the system would fail the design factors of durability, fall prevention, and operating conditions, thus rendering the design unsuitable for further iteration.

Design 5: Spikes

This system design hold the most promise for tractability, as the basic principle behind it has been in use for centuries. However, the matrix exposed concerns about the integrability and manufacturability of the system. Because spikes are relatively large, the integration and manufacture of the design is difficult because it would require extremely small and precise machining. These concerns could be assuaged by making the spikes smaller and creating a larger tolerance between parts.

Design 6 and 7: Coiled Wire

The over-tread coiled wire design scored the highest of all designs, doing well in integration and operating condition range, but falling short in integration and fall prevention. The main issue with this design revolved around the was the fear that the coils would cause the user to slide around when in contact with the ground. However, this relatively minor concerns can be addressed by mounting wires on intersecting paths, to maximize the directions the wires exert force in.

3.2.3 Attribute Matrix

The team hoped to optimize the final design by incorporating the best features from all of the design concepts into a single design. However, after the preliminary design matrix, there were many successful features - too many to analyze individually against each of the three top designs. The team resolved this issue by using an attribute matrix; all the successful features were condensed into design attributes based on shared characteristics. The process that lead to the attribute matrix is explained Appendix C.

The design attributes were combined based on *why* the attribute met or exceeded the functional requirements. For example, both sandpaper and the thermal adhesion designs scored highly for trip prevention, and upon analysis, in both cases it was due to their low profile. Therefore, instead of investigating the applicability of sandpaper trip prevention and the thermal adhesion trip prevention separately, designs were simply checked as to whether or not they could be made to have a low profile. Table 3.2 shows how all the successful design features were condensed into seven design attributes.

Table 3.2. Functional Requirements and successful Design Parameters to Design Attributes

Functional Requirements	Designs scoring 3 for category	Design attributes	Final Parameters
Prevent Slips	Spikes Over Tread Coiled Wire Retractable Coiled Wire	-Provide traction by piercing the first layer of the frozen surface -Provide traction by penetrating frozen surface	Provide traction by piercing just the first layer of the frozen surface Provide traction by penetrating into the frozen surface
Avoid Trips	Sandpaper	-Low Profile -Nothing can "catch" on anything	No embedding/adhering to ground, no components can "catch" on obstacles.
Stability	Sandpaper Passive Thermal Adhesion Active Thermal Adhesion Retractable Coiled Wire	-Low Profile	Low profile
Integrable	suction cup over tread coiled wire	-External mechanism can be attached to almost any footwear easily	No internal mechanism
Operating Condition range	Active Thermal Adhesion Spikes Over Tread Coiled Wire	-Systems are not affected by temperature.	Not affected by temperature
Durability	Spikes	-Substantial pieces of metal are hard to damage	No Delicate components
Convenience (usable indoors)	Passive Thermal Adhesion Active Thermal Adhesion	-System can be deployed on any walking surface without causing damage	N/A (Cannot be integrated)
Manufacturable by design team	Sandpaper Passive Thermal Adhesion Suction Cup Over Tread Coiled Wire	-Sandpaper, Suction cups, and over tread coiled wire can be/are external systems that simply attach -Components for passive thermal adhesion are small and flexible (can be easily integrated into sole)	No internal mechanism

The seven selected design attributes from Table 3.2 were incorporated into an attribute matrix (Table 3.3) that compared them to each winning design. Whether the feature could be incorporated, was preexisting in the design, or could not be incorporated, was recorded in the matrix.

Table 3.3. Attribute Matrix

Attribute	Associated Functional Requirement	Spikes	Over-tread coiled wire	Sandpaper
Provide traction by piercing just the first layer of the frozen surface	Preventing Slips	Not for long spikes	PREEXISTING	NO
Provide traction by penetrating into the frozen surface	Preventing Slips	PREEXISTING	NO	NO
No embedding/ adhering to ground, no components can "catch" on obstacles.	Not Causing Trips	Not for long spikes	YES	PREEXISTING
Low profile	Stability	Not for long spikes	YES	PREEXISTING
No internal mechanism	Manufacturability	Not for long spikes	PREEXISTING	YES
Not affected by temperatures	Operating Conditions	PREEXISTING	PREEXISTING	PREEXISTING
No Delicate components	Durability	PREEXISTING	YES	YES

Table 3.4. Attribute Matrix Key

YES	PREEXISTING	NO
The attribute can be feasibly integrated into the design	The attribute is already accomplished in the unaltered design	The attribute cannot be feasibly integrated into the design

As the matrix progressed, it became clear that the two "preventing slips" attributes were mutually exclusive: a design would either provide traction by piercing the surface or by penetrating into the surface, but not both. If a design pierced only the surface, it is inherently not penetrating, and if a design penetrates the surface, the penetration, not the piercing, is what provides resistance to slips.

It also became obvious that any penetrating slip prevention method would lead to a tripping hazard and instability. If the deployed mechanism is long enough to penetrate a surface, it would also protrude far enough to catch on obstacles and cause trips. Trips could also occur when the user lifts their foot. Long spikes, for example, must be removed from the ice along the same path by which they entered, a motion counter to the natural stepping sequence. Also, if the user is walking on a non-penetrable surface with the traction system deployed, they would be elevated by (at minimum) the length of the mechanism. This height difference could lead to instability.

This realization opened the conversation that if long spikes were replaced by very short spikes, the spikes would still provide traction by piercing the surface, but the issues with stability and tripping would be resolved. Based on this change, the team evaluated the short-spike design as its own design concept in Table 3.5.

Table 3.5. Short spike design evaluation with Attribute Matrix

Attribute	Associated Functional Requirement	Short Spikes
Provide traction by piercing just the first layer of the frozen surface	Preventing Slips	Already in Design
Provide traction by penetrating into the frozen surface	Preventing Slips	NO
No embedding/adhering to ground, no components can "catch" on obstacles.	Not Causing Trips	YES
Low profile	Stability	YES
No internal mechanism	Manufacturability	YES
Not affected by temperatures	Operating Conditions	PREEXISTING
No Delicate components	Durability	PREEXISTING

Because it was previously determined that the piercing and penetrating traction mechanisms were mutually exclusive, only one of these attributes needed to be achievable by each design. Of the four designs examined with the attribute matrices, only two designs were able to integrate all desired attributes. Both the short spikes and the over-tread coiled wire designs had the potential to incorporate six optimized elements. Therefore, out of all designs considered by the project, the short-spike concept and the over-tread coiled wire design were the most likely to produce products that met or exceeded all functional requirements. Because of this, the team modeled and further developed these designs exclusively.

3.2.4 Integration of Attributes

Once the attribute matrix had been used to determine that the desirable attributes could be integrated with the remaining two designs, the team decided how best to incorporate each feature. First, each attribute was associated with the design parameter relevant to the specific design in Table 3.6.

Table 3.6. Attribute Integration Matrix

Attribute	Over-tread Coiled Wire	Short Spikes
Provide traction by piercing just the first layer of the frozen surface	-Wire radius must be slim enough to pierce surface	-Spike length must be short enough to only pierce surface
No embedding/adhering to ground, no components can "catch" on obstacles.	-Wire, and all support and attaching components must be adequately secured	-Spike length must be short enough not to embed deeply in surface -All components must be adequately secured
Low profile	-The diameter of any loops of wire must be small	-The spikes must be short
No internal mechanism	-External mechanism	-External mechanism
Not affected by temperatures	-Use non-temperature- sensitive materials	-Use non-temperature- sensitive materials
No Delicate components	-All materials must be durable -Wire diameter must be adequately large	-All materials must be durable

After the design parameters were defined, the team held a brainstorming session to identify the best ways to physically integrate the attributes into the designs. Certain design parameters were neglected for this level of design: all material concerns will be investigated as part of the final design optimization. Also, some design parameters, such as spike length, wire radius, and adequately secured were self-explanatory, and did not require extensive discussion. The primary concern at this stage was identifying a mechanism for deploying the traction system that would be external, and would not violate any functional requirements.

3.2.4.1 Elastic Coiled Wire Attribute Integration

The over-tread coiled wire design initially scored poorly in the trip-hazard category because of concerns that the coils of wire could catch on obstacles or the terrain, or the bungees could break. Considering this allowed the team to conclude that if the coiled wire loops were tight enough, and if all components were adequately secured, the tripping hazard would be eliminated.

The coiled wire design also scored poorly for durability. The main concerns were the fragility of the wire itself and the wear properties of the material that would be supporting the coils. To achieve the necessary durability, constraints were added to the design, so that the wire would be of sufficient thickness to alleviate the concerns.

The only category where the coiled wire design was not able to achieve a maximum score for was convenience, because the criteria for the maximum score for convenience required the mechanism to not be damaging to indoor walking surfaces, even when deployed. This criteria is impossible for any mechanisms that are based on piercing the walking surface to meet. Because both of the remaining designs utilize piercing as their traction method, convenience factor was determined instead based on ease of retraction. In this case, the team determined that the most convenient external mechanism for coiled wire would involve elastic bands which run along the bottom of the shoe with wire coiled around them. These elastic bands could be placed in tension in a channel over the tread when deployed, and moved to storage channels in the shoe to retract. In this way the user would only have to shift the location of the elastic to deploy and retract.

3.2.4.2 Short Spike Attribute Integration

In the preliminary design matrix, the spike design only achieved the maximum score for three categories: slips, operating condition range, and durability. However, by considering additional features through the attribute matrix, it was possible to bring four of its remaining five scores to the maximum score.

The trip hazard and stability issues posed by the preliminary spike design, which initially involved relatively long spikes, were ultimately resolved through the incorporation of the same design feature: shorter spikes. When the team discussed incorporating the attribute "Provide traction by piercing just the first layer of the frozen surface," it was determined that shorter spikes would meet this requirement. In shortening the spike length, the team also lowered the under-shoe profile, thereby resolving the stability and trip prevention concerns.

Similarly, the manufacturability and the integrability criteria were satisfied by incorporating a single design feature. The maximum score for the manufacturability category required the traction system use an external mechanism. The team was initially hesitant as to whether a spike mechanism could be created that would not involve internal components. However, they later realized that the meaning of "internal" had more to do with whether the components were built into the sole of a shoe as the design and manufacture of the shoe itself was deemed to be outside of the scope of the project. Therefore, since the spike mechanism could be encapsulated and inserted into or onto the bottom of the shoe, it was not truly internal.

3.2.5 Evaluation of optimized concepts

The first stage of design evaluation eliminated impossible design concepts, and selected those that were most likely to succeed. The second stage of the design process determined how to optimize the most-likely-to-succeed designs, and eliminated any that could not be maximally optimized. Two designs made it past this second stage of the design process, to the final phase of design selection: external coiled wire, and short spikes.

The last stage of the design process involved determining which of these finalist designs would be fully developed as a solution to the project goal over the remaining duration of the project. The designs that were considered satisfied all the functional requirements with identical scores; therefore there was no credible justification for selecting one design over the other.

The team considered using additional rubrics, matrices, or theoretical analyses to determine which design was most promising, but ultimately decided against this approach. At this stage of the design process, all the design selection had been concept-based, and no attempts had been made to model or prototype them. This raised the concern that a design that looked good on paper might encounter physical problems that would not be exposed by a conceptual analysis. Prototyping at this time would have been time-consuming and expensive, so the team compromised by creating Solidworks models of each of the final designs.

3.2.5.1 Elastic Coiled Wire Design Evaluation

As the coiled wire model was created, the team realized that the design would not be practical design due to physical constraints and an unforeseen safety hazard. Although the mechanism was still theoretically viable, there was no way to securely attach it to footwear: all available anchoring points on the sole of the footwear risked being too flimsy, forming the straps to the tread was beyond the manufacturing resources of the team, and the level of modification to the footwear that would be necessary for secure anchoring fell outside of the “integrable with modern footwear” criteria. In addition to the lack of anchoring points, physical sizing also was an issue: for the components to be large enough to meet the durability requirement, the amount of space required for storage lead to an abnormally deep channel in the tread, which could compromise the structure of the sole, and could require additional thickness on the sole.

Finally, the team discovered a safety hazard through the realization that there was no good release mechanism for the coiled wire design: users would need to use both hands to deploy the mechanism, and the sole of their boot would need to be off of the ground (and likely facing the user) for them to manually release it. This would require users to balance on one foot, while having the other foot significantly elevated while having both hands unavailable for balance. The required high level of athleticism to safely perform this deployment process was not stipulated in the target audience, so it is predicted that this mechanism would result in many dangerous falls.

3.2.5.2 Elastic Strap Spike Design Evaluation

The elastic mechanism for spikes was similar to that used in the preliminary modeling for the coiled wire design: an elastic strap embedded with spikes was to be stretched across the bottom of the footwear. When not in use, the strap would sit in a channel between the tread sections, and when deployed, the strap would sit on top of the tread, in shallow grooves for stability. Several iterations of this design concept were created, each resolving a design flaw that was uncovered in the preliminary evaluation. These iterations are described in Table 3.7.

Table 3.7. Progression of the elastic mechanism for short spikes

Iteration	Concern	Modification
1 (Preliminary Design)	N/A	Elastic strap (bungee cord) with embedded spikes stretched along bottom of the shoe
2	Spikes set on a rounded cord could easily be misoriented under the shoe.	Elastic strap will be flat (rectangular cross-section)
3	The hole in the rubber through which spikes are attached will stretch while spikes are deployed. This could cause the spikes to fall out.	Secure spikes with a nut or washer on the back of the strap.
3	Cutting a hole in the rubber for the spikes could cause tears; the shape of the holes could cause a stress concentration that leads to failure	Replace the elastic under the she with a flat metal plate. Spikes are attached to the metal, and elastic is used only on the ends.
4	Plate with spikes could be dangerous for user to move manually	A cam or linkage will be needed to move the plate.

Ultimately, the team could not identify a cam or linkage that would work for moving the plate. Any linkage the team considered involved extremely small parts, which would be both fragile and difficult to manufacture. This issue resulted in the elastic mechanism concept being dropped, because the rotational mechanism had no such flaw, and it was therefore not necessary to put extensive research and engineering into resolving the impasse for the elastic mechanism.

3.2.5.3 Rotational Spike Design

The rotational spike mechanism was nearly the same as the preliminary models, only making minor changes. The traction bars were still turned with a movement bar and connection links. When not in use, the wearer would slide the movement bar forward and rotate the traction bars 90° so as to remove the spikes from contact with the surface.

As the team proceeded with the rotational spike design, numerous issues prominent with other designs, such as elastic bands systems, lessened drastically. The problem inherent with the coiled wires, the way the traction face could slip on the surface, could be addressed by forcing the spikes to intersect with the surface at a right angle, removing the slip factor. Spikes would also be effective at improving traction because the length and number of spikes would distribute the weight of the user across a number of small points, piercing the surface of the ice. With this penetration, the shear forces exerted against the ice would not enough to sufficiently fracture the surface. Furthermore, the depth at which the spikes penetrate also keep the spike from sliding out of its hole.

Since this design was synthesized without the terminal problems of the others, it was clear this style was the best choice for the team to move forward on.

4. Finalization of Retractable Short Spikes

The retractable short spike design was the only traction system design that passed the first and second round of design evaluation and was still deemed possible to build after preliminary modeling. Therefore, retractable short spikes were selected as the final design concept for the project.

All modeling at this point of the project was limited to the front (toe) portion of the mechanism because the front and rear portions have identical mechanisms for the short spike design, but the front mechanism has more stringent space limitations. If the design works for the toe portion of the footwear, it will work for the heel, and because the design is likely to undergo several iterations, the team decided it was senseless to perpetually duplicate the same modifications at this stage of the process.

4.1 Refinement of Retraction Design

The rotational rod mechanism was ultimately selected as the mechanism concept for the preliminary short-spike traction system model. It comprises a sturdy rod with a series of spikes and a section of tread, offset by 90°. When the spikes are "retracted," the rod is tread-side down; when the spikes are deployed, the rod is spike-side down, see Figure 4.1.

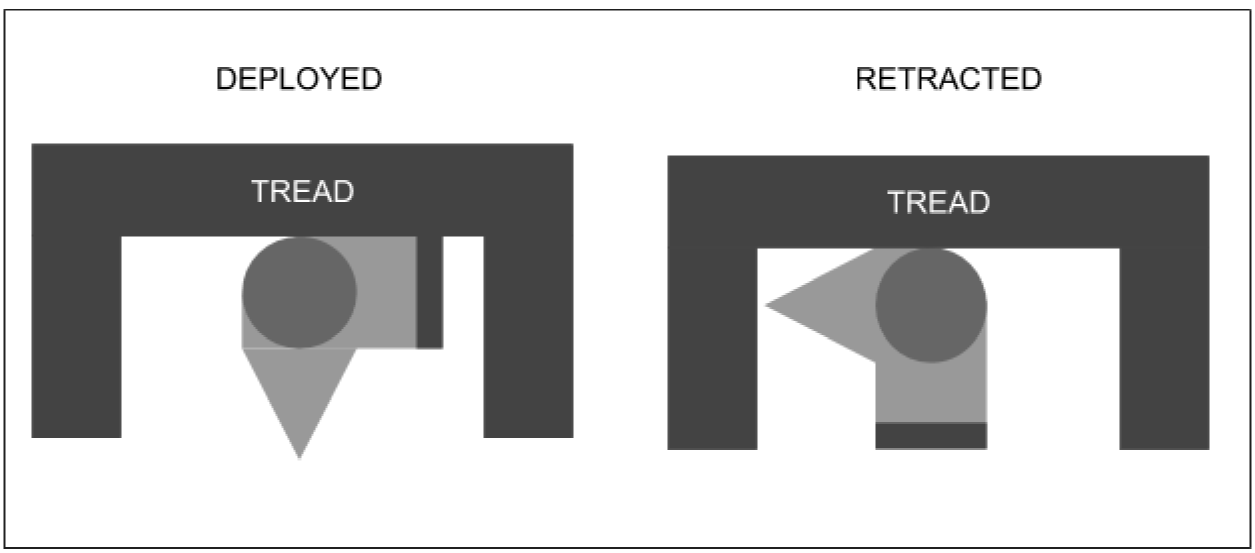


Figure 4.1. Concept sketch of rotating spike mechanisms showing deployed and retracted configurations, showing cross section view.

Table 4.1. Key features of Rotating Spike Rod Design

Key Features of Rotating Spike Rod Design
Spike protrudes past lower point of fixed tread, but rotating tread is level with fixed tread
Flat edge of tread provides support against sole for spike, and flat portion where spike connects to rod provides support against sole for tread.
Space is allocated between sections of tread to allow for 90 degrees of rotation
Tread side is covered in a indoor-floor-safe materials
Multiple spike-tread pairs exist along a single rod.

Once the team selected the rotating rods as the method of deployment for the spikes, the orientation of the rods needed to be determined, as did the mechanics behind the rotation.

4.1.1 Placement and Direction of Spiked Rods

The orientation of the spiked rods was a significant design consideration. The lateral orientation had two significant advantages: the horizontal forces from a user walking would not be tangent to the rotation of the spikes, and there would be less individual spike rods, so anchoring and creating the mechanism might be easier. However, there were two disadvantages as well: having a single rigid rod running the length of the foot would affect gait, and a rod the length of the foot could pose a tripping hazard because there would be an increased chance of it becoming loose or catching on something because of the length of the rod relative to the number of connection points. The alternative to lateral rods was to put shorter rods crosswise along the sole. This resolves the issues associated with rod length, as well as the concerns about impact on gait, but shorter rods would inherently involve smaller parts, and would put the rotation of the rod tangent to the horizontal forces from walking, which could cause unintentional retraction or deployment.

The team considered both configurations, and determined the horizontal rods to be the better option because the issues were more resolvable. The biggest flaw with the lateral rods was that the impact on gait could not be resolved without shortening the rods. The team briefly considered using shorter lateral rods, but found that it would be difficult to anchor the rods mid-sole. Also, the team did find ways to resolve the problems with the crosswise rods: the only necessarily smaller part would be the rod itself, and a rod the width of the sole of a shoe is plenty large to work with; also, and more importantly, the unintentional retraction or deployment could be resolved with a locking mechanism.

4.1.2 Actuation System

Once the team determined that the rotating spike mechanism with crosswise rods was the best design concept available, the team focused on designing methods to generate the rotation in the rods. The main challenges were adhering to size constraints, keeping components sufficiently durable, and creating a system that could be operated with few actions by the user. It would have been easy to design each rod with a separate turning mechanism, but that would be impractical because the user would need to turn at least a half-dozen individual rods to deploy their spikes. Also, the team quickly realized that creating a mechanism that both deployed and retracted a mechanism was another significant design challenge: creating a deployment mechanism or a retraction only involves one direction of rotation; creating a multipurpose mechanism requires rotation in both directions.

The team considered gears, belts, a string-wrapped knob, and a sliding mechanism for retraction concepts. Gears were eliminated because of concerns with jamming if there was grit or buildup in the system, as well as the fragility of the system, and the manufacturing challenges that would come from the small size of the parts. Belts were considered problematic because the tension in belts might be difficult to maintain across temperature fluctuations, the belts could provide a tripping hazard, and the belts might not fit inside the profile of footwear while staying an external mechanism. A string-wrapped knob was found to be unidirectional, as well as potentially fragile and, as an external mechanism, a possible tripping hazard. However, a sliding mechanism was deemed possible, with the correct linkage.

After the sliding mechanism-linkage combination was selected, the team had a design concept, a method for deployment and retraction, and a mechanism to create the necessary motion selected. Therefore, the next step was iteration and optimization.

4.2 First Round Design Optimization by Part

The first solidworks model created for the short spike design functioned as a proof of concept: the model demonstrated that the linkage and the sliding bar retraction mechanism moved as expected, that all components fit inside the available area, and that anchoring points existed for all the necessary components. The parts were not designed to be manufacturable (internal corners were not chamfered, large parts were not split up into easy-to-machine pieces, etc), but critical dimensions were based on what was expected in the final design.

The preliminary model had three primary components: the guiding platform, the sub assembly comprising the movement bar and connection links, and a simplified traction bar.

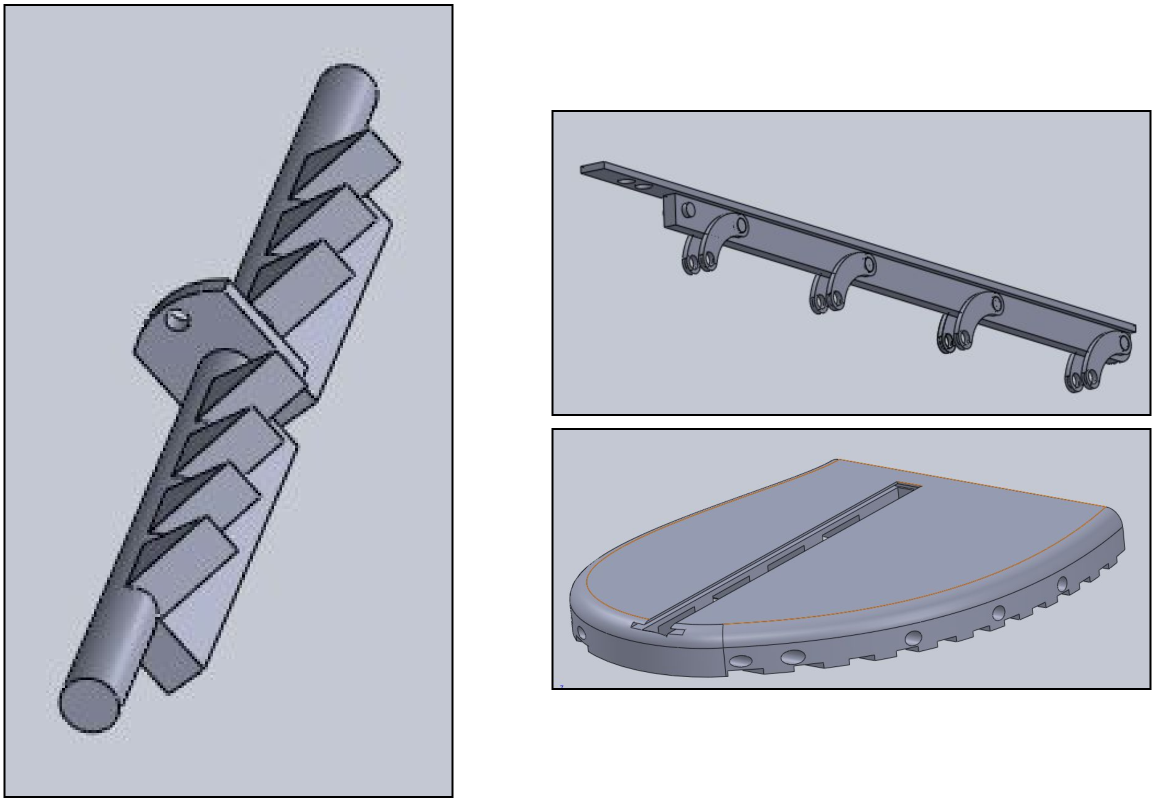


Figure 4.2. Short spike retractable traction system preliminary model components: Clockwise from left: Traction Bar, Sub Assembly of Movement Bar and Connection Links, Guiding Base Plate

The sliding bar ran along the grove in the base plate, while the traction bar attaches to the links in the sliding bar assembly, and sits in the holes visible along the base plate edge. As the bar is pulled laterally, the spikes and tread switch orientations causing either retraction or deployment.

This model did not provide ready-to-manufacture components, nor did it account for many factors in engineering design, such as materials or tolerances. It simply demonstrated that the linkage functioned as expected, the components satisfied the size constraints, and overall, this design concept was feasible and could be iterated upon.

As systems are optimized by iterating on the components, the components of the design were were re-evaluated and selected before more advanced individual component optimization occured. The preliminary model for the short spike design comprised three primary components: the spike rod, the base plate, and the movement bar assembly which contained the linkage. The team reviewed these components, and determined that for improved manufacturability and optimum performance, several of these elements should be broken into function-specific parts. These evaluations are detailed in Table 4.2.

Table 4.2. Component Re-Evaluation

Component	Function	New Component	Function
Base Plate	• Provide structure for the mechanism • Hold spike rods •Provide space and path for movement bar	Modified Base Plate	• Provide structure for the mechanism • Hold spike rods
		U-Channel	•Provide channel for movement bar •Support and distribute forces transferred from movement bar
Rotational Spiked Rod	•Pierce ground for traction •Interface with movement bar •Stay secure in base plate •Provide harmless surface when spikes are retracted	Track Spikes	•Pierce ground for traction
		Threaded Rod	•Stay secure in base plate
		Linkage Tab	•Interface with movement bar
		Tread Block	•Provide harmless surface when spikes are retracted
Movement Bar Assembly	•Provide a method of manipulating linkage.	Modified Movement Bar	•Provide a method of manipulating linkage •Provide a convenient interface for the user with the mechanism
		Dowel Pins	•Connect linkage components
Curved Links	•Connect linkage components •Determine path of motion	Curved links	•Connect linkage components •Determine path of motion

4.2.1 Base Plate:

The original base plate was intended to not only provide structure for the whole assembly, but also to hold the spike rods, as well as providing a channel for the movement bar to slide along. The number of functions demanded from the base plate led to complex geometries, and would have caused difficulties with materials selection in future: the different functions require different properties, which will be harder to meet all the needs must be met by a single component.

The team broke the base plate into three components: one modified base plate and two U-channels. The base plate retained the roles of providing structure to the whole mechanism, but the weight-bearing and channeling requirements were transferred to the U-Channels. This allows a strong material and high level of precision to be used for the U-Channels, which require these features because of the channeling role of the component. However, the base plate could be made of a potentially-cheaper material because the higher-level demands had been transferred to the U-Channels.

4.2.2 Rotational Spiked Rod

The original spike rod was a single component that was designed to pierce the ground, interface with the movement bar, fix the component in the base plate, and provide a harmless surface when the spikes were retracted. Although material conflicts are less of an issue for the rod than in the base plate--all the components in the spike rod require strength, durability, and overall good mechanical properties--the large number of functions resulted in a highly complex geometry that would have been nearly impossible to manufacture.

The team broke the spike rod into four components: commercially-available track spikes, a threaded rod, a linkage tab, and a tread block. The use of track spikes reduced the number of small components the team had to manufacture for this design; track spikes are inexpensive and readily available through many retailers. The threaded rod was incorporated to improve assembly and manufacturability. Initially, there was no way to insert the spike rod into the base plate, but threaded rods allow the spike portion to be placed in the base plate, and connected with the rods, which can be set from the outside. Also, threaded rods are commercially available, which prevents the need to custom-manufacture small components. The linkage tab was added to fill the same role as the tab already on the preliminary model; the modification is simply to make the tab compatible with the other newly-separated spike rod components. Finally, the tread block was isolated to allow a softer material on the tread block, in order to make the retracted surface safer for indoor surfaces.

4.2.3 Movement Bar Assembly

The movement bar assembly initially comprised a complex plate that both provided the necessary motion, and provided a method of connecting the links to the system. The geometry was unnecessarily complicated, so the bar was modified to use press-fit pins to connect the links, instead of necessitating the manufacture of cylindrical bosses on the surface of the plate, as the preliminary design had. Also, though the movement bar provided a method for manipulating the linkage, there was not a way for a user to conveniently grip it. A knob was added to the front of the bar for user convenience.

4.2.4 Connection Links

The curved links that comprised key components of the linkage had two functions: connecting linkage components and determining the path of the linkage. Those functions were necessary in both the preliminary and the optimized design, and as the geometry of the links was already minimalistically simple, the original component moved on to the component optimization phase.

4.3 Second Round Design Optimization by Part

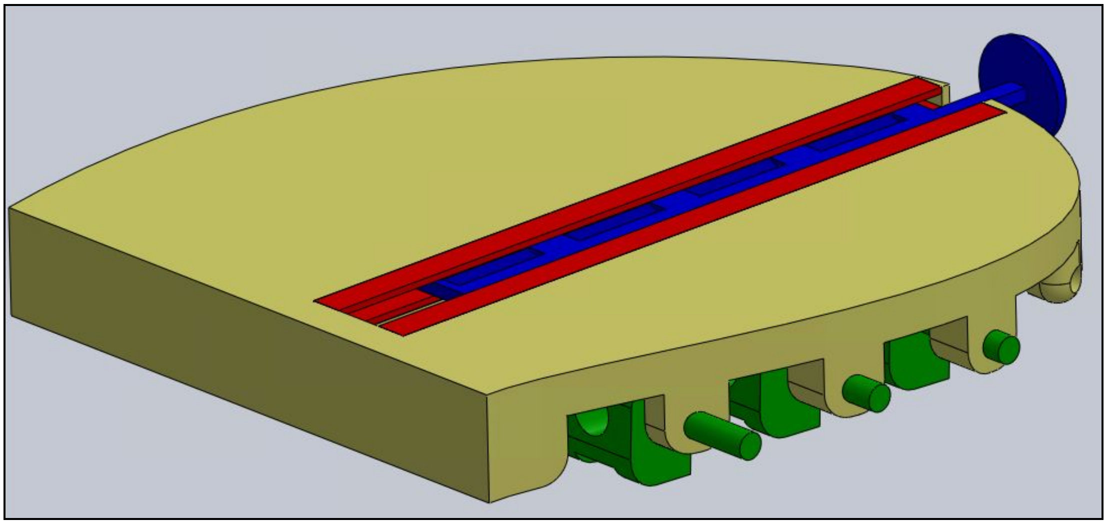


Figure 4.3. Isometric view of initial assembly

The final result of this first design process was a retractable short-spike traction system, designed to provide traction by piercing just the surface of frozen groundcover. The design incorporates a relatively low profile, an external mechanism, and durable and manufacturable components. Overall, the system comprises 20 components: three long spike rods, one short spike rod, eight connecting pins, one base plate, four links, movement one bar, and two u-channels (see Figure 4.3). The system also requires 18 commercially-available quarter inch track spikes: this design provides standard-sized threaded holes for track spikes in place of integrated spikes, for ease of manufacturability and customizability.

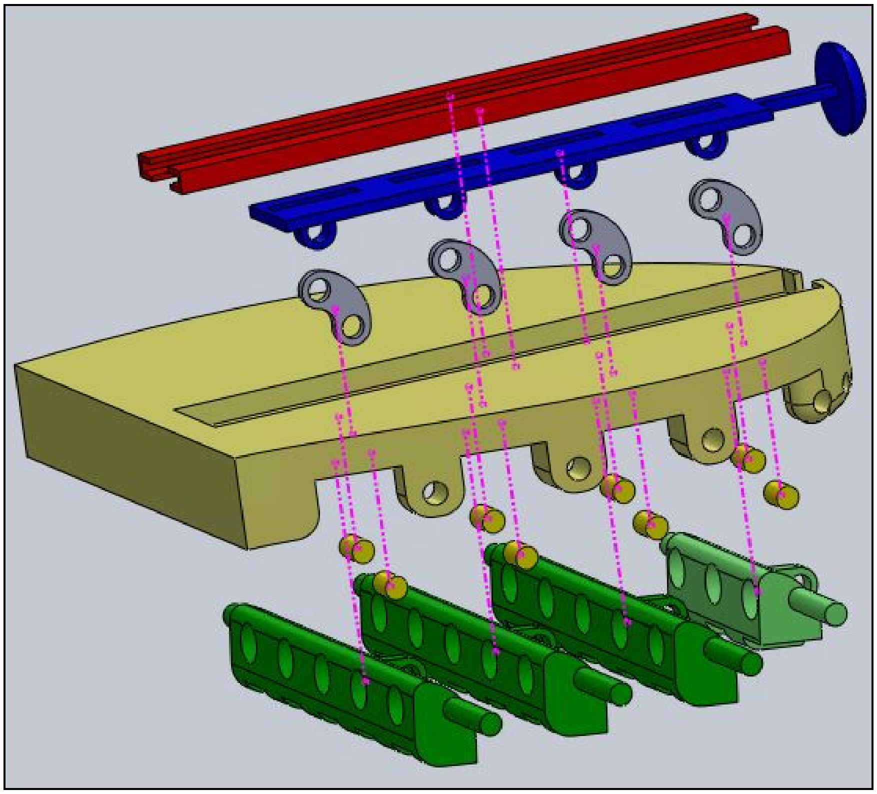


Figure 4.4: Isometric exploded view of initial assembly

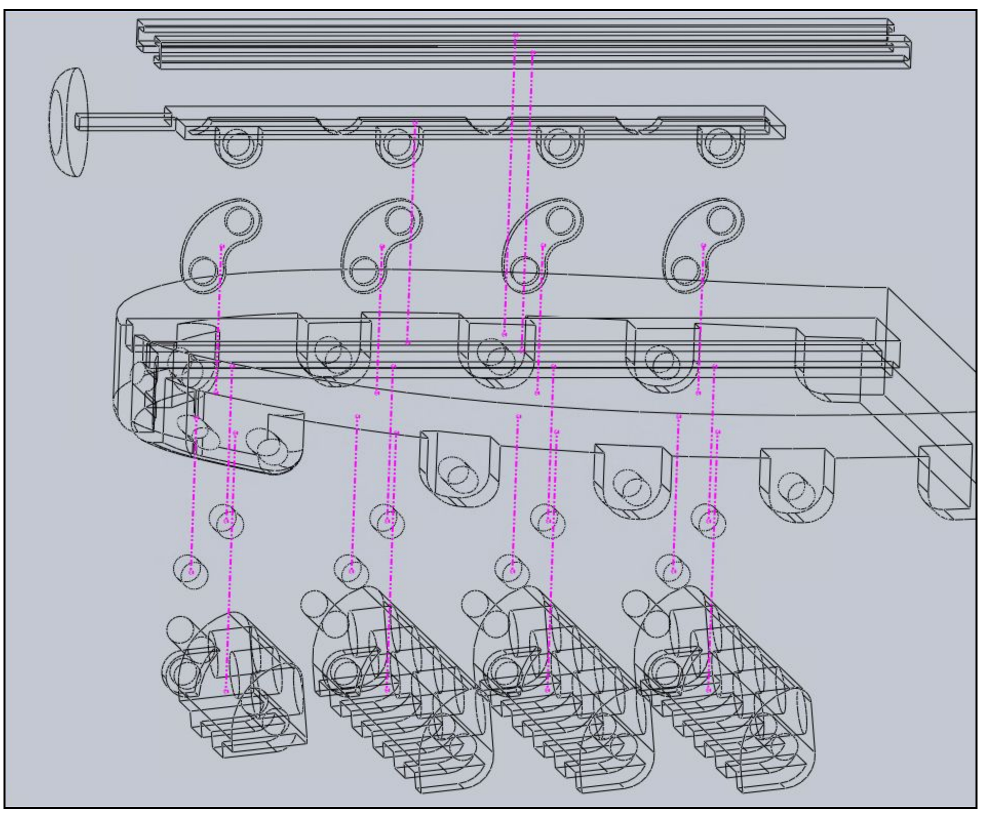


Figure 4.5. Exploded wireframe view of initial assembly

The retraction mechanism for the final design comprised a linkage involving the movement bar, curved links, dowel pins, and the spike rods. As the movement bar is moved back and forth, the spikes rotate down (into their deployed position) or up (retracted).

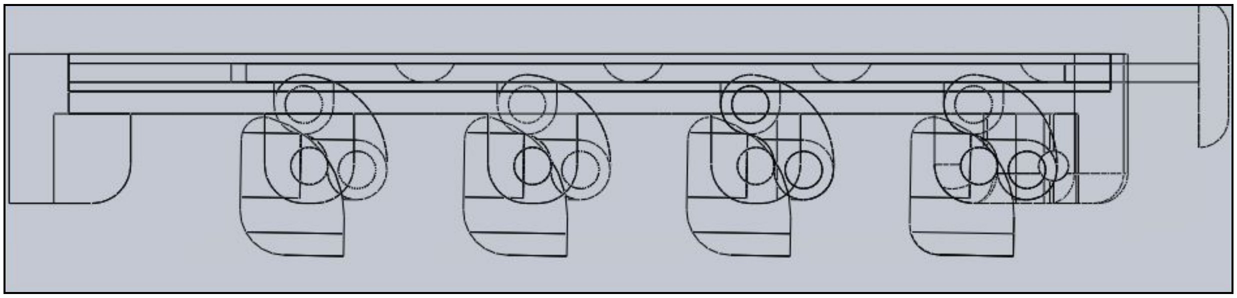


Figure 4.6. Cross-section wireframe of retracted initial retraction mechanism (spikes not shown)

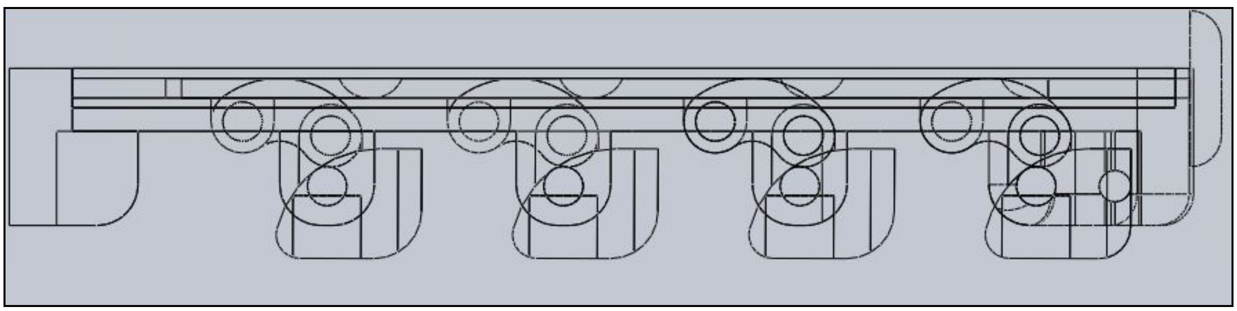


Figure 4.7. Cross-section wireframe view of deployed initial retraction mechanism (spikes not shown)

4.3.1 Component Optimization

After redefining the major sub-systems in the design, the team optimized individual components. Parts were optimized for both durability and manufacturability.

To optimize the components for durability, the team identified critical areas on each of the components that would experience significant stresses during use. These are compiled in Table 4.3.

Table 4.3. Potential Failure Points for Updated Components

Component	Function	Critical Areas
Modified Base Plate	Provide structure and support for all components; hold rods	Holes for rods
U Channel	Provide structural support for movement bar; provide channel for movement bar	Risk of pinching at opening of channel
Threaded Rods	Connect spikes and linkage components to base plate; provide rotational ability	Rod diameter
Pins	Connect linkage components	Pin Diameter
Linkage Tab	Connect linkage to spike rod assembly	Hole dimensions, thickness, thickness of material around mounting point, stress concentrations
Tread Block	Provide a safe surface for walking indoors	Connection to threaded rods
Modified Movement Bar	Provide method of manipulating linkage	Thickness; any holes for connecting other components
Curved Links	Connect linkage components; determine path of linkage	Thickness

Most of the critical areas identified during the durability optimization were concerned with the thickness of the component, holes, or diameters. In all these cases, the underlying concern was that there would not be enough material to support the predicted loads, either by too thin a piece, too little material surrounding a hole, or too small of a rod or pin. These components were optimized by verifying thicknesses were reasonable for the expected applications, and increasing the part dimensions as needed.

After components were optimized for durability, manufacturability was considered. The manufacturability optimization involved looking for impossible geometries (such as internal corners), and removing hard-to-manufacture features that had no physical benefit to the system.

4.3.1.1 Base plate

In order to make the base plate manufacturable, the team replaced the curved sides with right angled pieces in order for it to be machinable. This approach extended to every section of the piece, with the curved toe being replaced by a 45° angled cut. Additionally, the thickness of the piece was made constant, the cutouts on the side to hold the rotational bars were removed and filled in to remove any stress concentrations that could appear.

On the top face of the base plate 8 holes were drilled to hold the top plate on. In addition to these through holes, a rectangular cut was made at 45° to the main trench, providing space for the lever to rotate.

4.3.1.2 Spiked Bars

The initial spiked bars were curved across their tops so as to provide more room between them and the bottom of the base plate so the bars could rotate freely. As this arrangement would cause trouble in the manufacturing process, the curve was replaced with another 45° angled cut. Additionally, the extrusion in the center of the bar was thickened and a small trench was cut into the center. This trench was sized to fit the connection links inside so the movement bar that they connected to would only need the smallest gap between tines, preserving its structural integrity.

Finally, instead of the bar resing on rods that were a solid part of the piece, the rods were replaced with holes drilled into the sides of the bar. These would provide the location for a pin to be inserted into the base and bar, securing them. This removal ensured that this design was fully manufacturable by the team.

4.3.1.3 Movement Bar

The movement bar allows the spiked bars to rotate. In order to improve the strength of the bar it was formed into a U shape with cross bracing and thickened substantially. Furthermore, a small ledge was carved into each side so the bar could rest comfortably on the base plate without protruding from the top.

The initial movement bar could have been made with additive machining, but not the drilling operations the team needed to use. The redesign from a thin, flat bar with several extrusions to a thick bar with a deep trench cut into it allowed the team to successfully manufacture it.

4.3.1.4 Chain Links

The initial connection links used in the design were thin, heavily curved strips of metal with holes drilled through at the ends to accommodate pins. Since these pieces would have been manufactured by the team, they were replaced with bike chain links. Bike links are commercially available, are standardized across the world, and allowed the design to continue to function with minor adjustments.

4.3.1.5 Actuation System

The movement bar would cause the rotational spike bars to switch from tread to spike, but there needed to be an item that actuated the movement bar. Initially, the bar had a long extension, and was actuated by depression or pulling the end that stuck out of the design. However, as this would cause a significant tripping hazard, the team designed a small lever that rests on the top face of the movement bar. The other end protrudes out of the base plate at the 45° angled cut, allowing the user to turn the lever to move from deployed to retracted without the worry of tripping.

However, when assembling the final prototype, it was found that the lever exerted a force perpendicular to the path of motion for the movement bar. Though there was some sticking before, it had been attributed to the material properties of the PLA plastic which the earlier prototypes had been made from. The team broke down the the prototype and proceed with a piece by piece diagnostic, offering solutions to the problems before iterating the upon them to propose new ones. With minor modification to the lever and it's orientation, the system actuated smoothly, indicating a fully functioning prototype.

4.3.1.6 Top Plate

The final portion of this design was the addition of a top plate to prevent foreign material from entering the system from above. This plate was the exact size of the base plate with through hole drilled into it to match up with those on the base plate. These holes would secure the piece to the base plate whilst also providing a stopping plate for the movement bar to press up against when in use.

5. Detailed Design Description

With the final design made ready to be manufactured, the team organized a detailed drawing and description of each part. In the views of the model, each piece is colored to show its purpose in the system. The red parts are all purchased hardware bought from sources such as McMaster Carr, and are used exclusively as pins and fasteners. The blue color indicates that the piece is a purchased part, though it is involved in the actuation and movement of the system. The golden pieces are indicative of the parts that the team designed, iterated upon, and manufactured. All golden pieces are directly involved with the actuation of the system (they are all moving parts). Finally, the greyed out pieces are structural, necessary for holding all other pieces of the mechanism together.

5.1 Design components

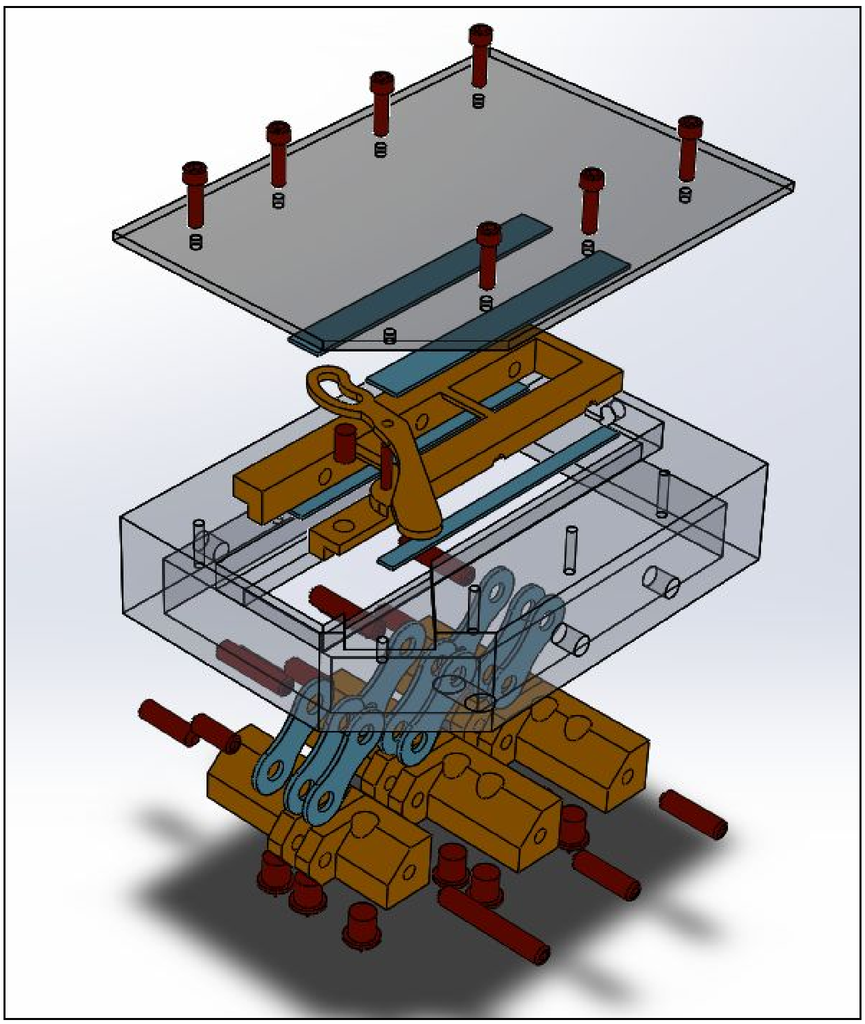


Figure 5.1. Exploded Final Design

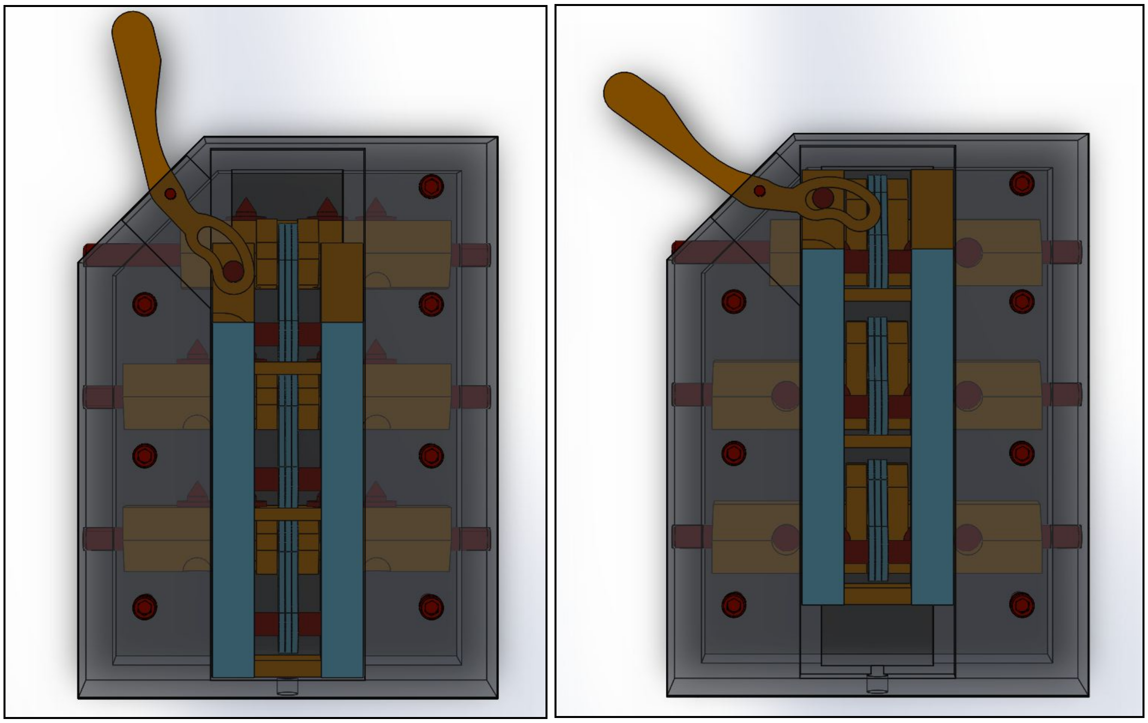


Figure 5.2. Top View of Design: Retracted, Deployed

5.1.1 Base Plate

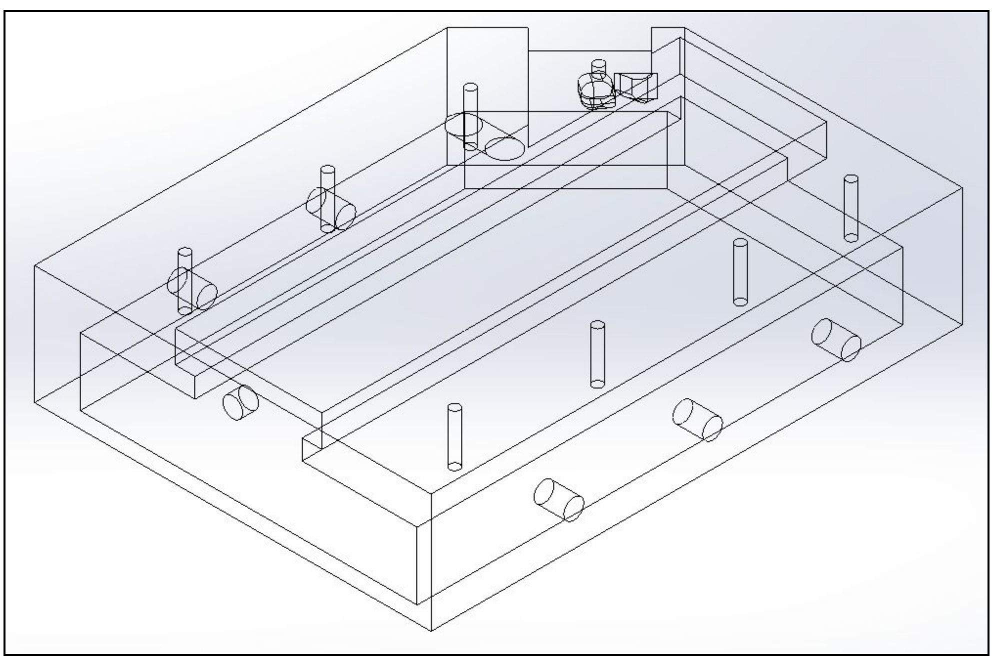


Figure 5.3. Wireframe Base Plate

The central piece of the design is the base plate in which the totality of the system is contained. With a length of 3.35 inches, a width of 2.5 inches, and a thickness of 0.75 inches, the whole design can fit easily within the sole of a size 6 shoe. The outer corner on the front of the design was cut at a 45 ° angle to mimic the natural curve of the human foot.

The main cutout that the upper movement bar sits in is 0.93 inches wide, with a shelf of 0.125 inches one either side. The shelf is cut 0.125 inches into the plate from the top is a channel set at 135 ° angle from the main cutout. This removed section allows the lever to rotate with enough distance to bring the upper movement bar fully forward.

In order to secure the upper plate to the base, holes were drilled with a radius of 0.06 inches to provide guides for connection rods. Each hole is 0.4 inches from the side of the base and had 0.9 inches between them.

On the side of the base plate are the holes which the rotating rods would turn about as the device moves. Each hole is 0.14 inches in diameter and is spaced .88 inches from the other. The rear most hole is placed a full 0.90 inches from the edge, as it must accommodate the 0.1 inch thickness of the interior wall. The most forward hole is 0.75 inches from the front of the plate, and also allows space to accommodate the 0.1 inch wall of the slot without striking the edges.

To catch the spring loaded pin of the locking mechanism, two 0.125 inch diameter, 0.125 deep holes were drilled into the angles face 0.5 inches from the edge. The holes were drilled with an angle of 48 degrees between them, so that each could accommodate the locking pin at both extremities of motion.

Once the main body of the design was created, the final cutout of material from the bottom of the piece was made. This section was set to maintain a wall thickness of 0.19 inches throughout the base plate, allowing the design to maintain its rigidity and strength. The cutout extended 0.425 inches down into the metal, providing enough space for the rotating bars to move unobstructed.

5.1.2 Movement Bar

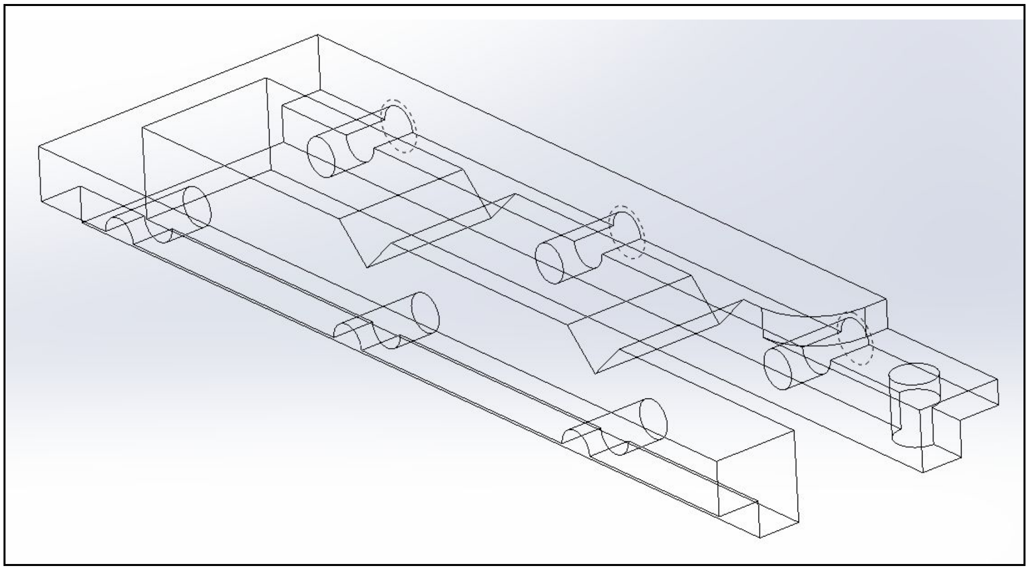


Figure 5.4 Wireframe Movement Bar

The movement bar rests in the trench of the base plate and slides back and forth when prompted by the lever. With an overall thickness of 0.25 inches, a width of 0.9 inches, and a length of 2.6 inches, it is small enough to fit within the base plate with ease.

In order to move, the bar rests on 2 cutouts that reach 0.13 inches into the sides of the bar. At 0.1 inches tall, the bar to falls low enough to be positioned just below the top plate, allowing movement with minimal friction.

In the center of the bar is a channel 0.5 inches thick that runs nearly unobstructed for the entire length of the bar. The only exceptions being the triangular structural crosspieces along the topmost edge, and the 0.1 inch thick wall at the rear. These crossbars are 0.2 inches across at their thickest, with the point falling 0.1 inches below the top surface of the bar. The rearmost crossbar is 0.86 inches from the edge, the second one is located 0.68 inches from the first, with the third being 0.67 inches from second.

On the side of the movement bar, 3 through holes with diameters of 0.11 inches were drilled. Each hole was sized to fit the chain link assembly and was located .88 inches from one another.

In the order to give the lever room enough to rotate, a section was milled down from the front of the bar to .42 inches inward. This section was 0.07 inches deep, just enough for the lever to move. The interior of the cutout was then filleted into a curve that extended a full 0.6 inches on the interion wall of the channel.

To provide a point of rotation, a hole was drilled into the top of the milled down section. This hole had a radius of 0.13 inches and was located in the center of the section 0.12 inches from the front edge.

5.1.3 Large Rotating Bar

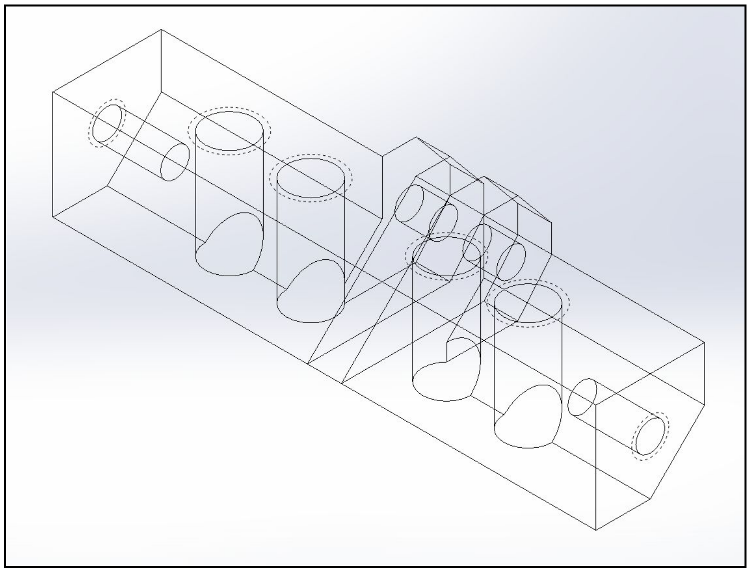


Figure 5.5 Wireframe Large Rotating Bar

The main body of the large rotating bar was a square with sides of 0.4 inches. This bar has holes of diameter 0.1257 inches drilled in each side. These holes are threaded to match the set screws which in turn connect to the main body of the base plate. The top right corner of the bar is cut at a 45 degree angle from both sides inward towards the centerpiece to allow for easy rotation..

In the middle of the bar is an extrusion 0.25 inches tall with a hole of diameter 0.11 inches drilled through the center, 0.3 inches away from the central holes of the main bar. Both corners of the extrusion are removed at 45 degree angles, allowing it to mimic a fully rounded design. This gives the movement links something to attach to and exert power on as the device rotates.

On the bottom of rotating bar four holes with diameter 0.18 were drilled through the entire piece. Once drilled, they could be threaded and fitted with spikes, offering a traction system. The holes were arranged in groups of two, each group having a hole 0.45 inches from the outer edge, and one 0.3 inches inward from the first.

Finally, in order for the chain links assembly to fit, a central trench of 0.13 inches width was removed from the extrusion in the center of the bar. This left it with two walls of the same thickness as the trench on either side, allowing the chain link to rotate, but not break.

5.1.4 Small Rotating Bar

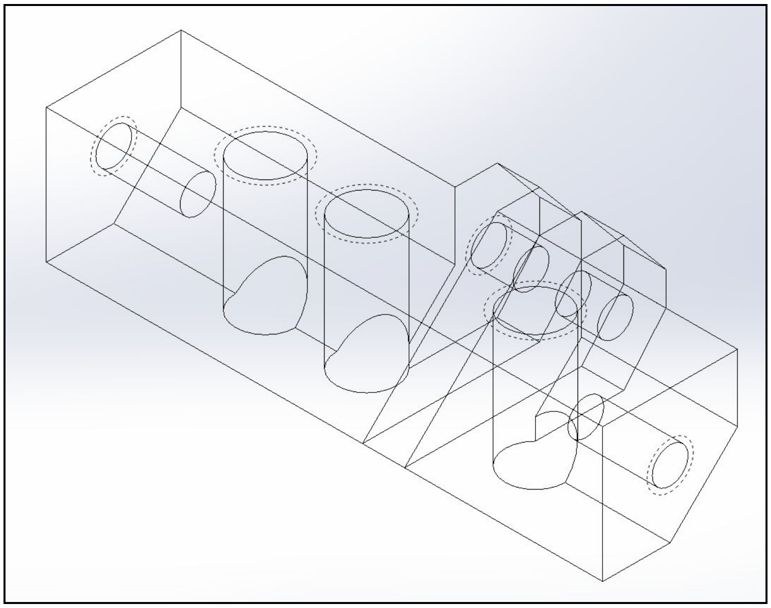


Figure 5.6 Wireframe Small Rotating Bar

The smaller, forwardmost rotating bar is constructed in the exact same manner as the larger bars in the rear of the system. The only difference between the pieces with that while the larger bars posses 4 holes for the spikes to be fitted in to, the forward bar only has 3.

The 3 holes on this bar are each 0.18 inches in diameter and are located along the base with the leftmost 0.45 inches from the edge, the next one 0.3 inches inward from the first, and the third 0.5 inches from the second.

5.1.5 Top plate

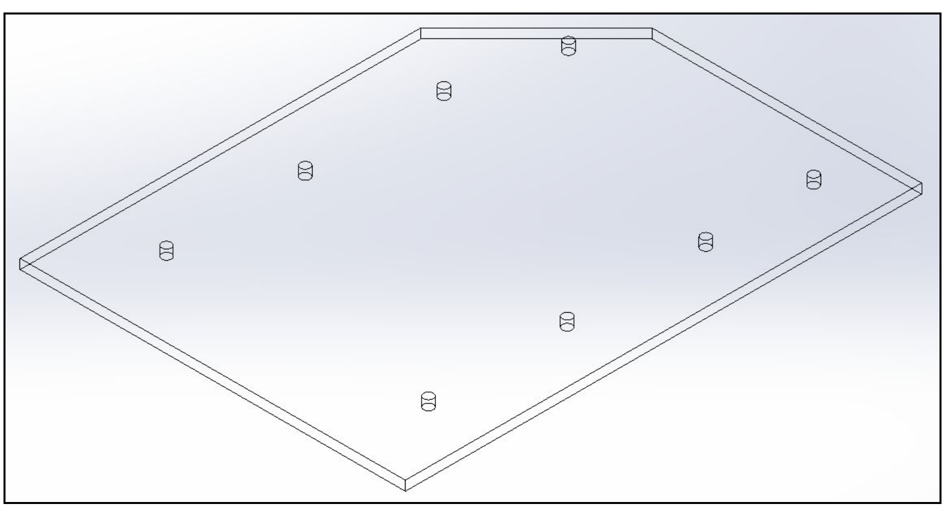


Figure 5.7. Wireframe Top Plate

The top plate of the mechanism is one of the simplest piece in the system. It is only designed to provide a downward, guiding force on the movement bar, so it merely needed to match up to the base plate. As such, the holes are drilled through at the same locations and with the same size bits as the base plate. Though now they only go through the thickness of 0.05 inches, as opposed to 0.75 inches.

5.1.6 Lever

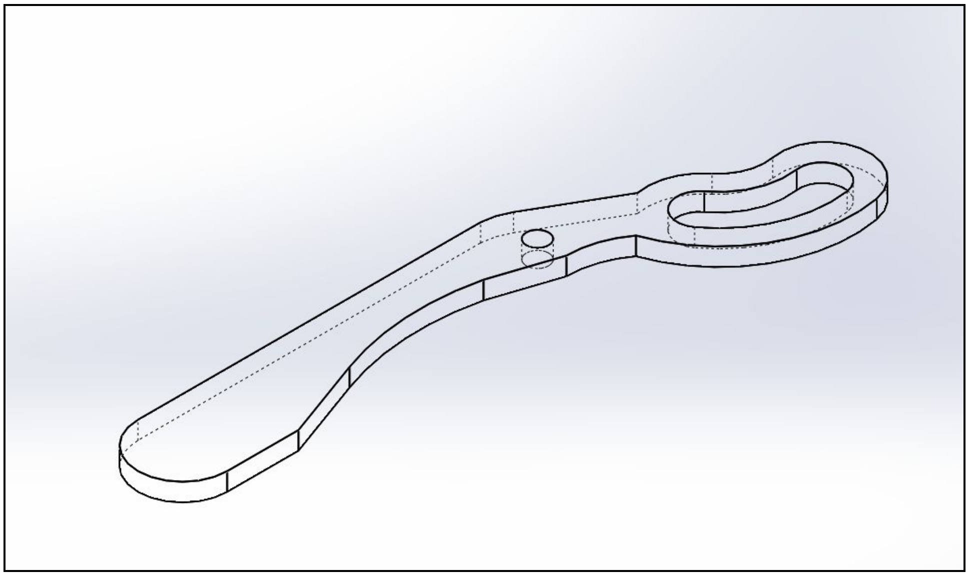


Figure 5.8. Wireframe Lever

The lever provides the movement bar with the force required to slide back and forth. To fit in this confined space, the lever is only 0.05 inches thick. It rotates around a hole with a diameter of 0.07 inches. This hole is located 0.25 inches from the forward edge of the lever that extends into the base plate.

Off of the same end of the lever is a quarter circle arc with the same width. In the center of the arc, a channel with a width of 0.125 inches was cut to fit around the pin inserted into the movement bar. The wall of the lever in the channel section are 0.06 inches.

5.1.7 Chain Link

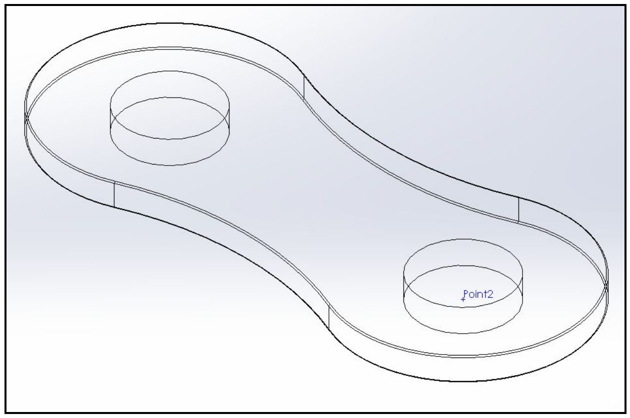
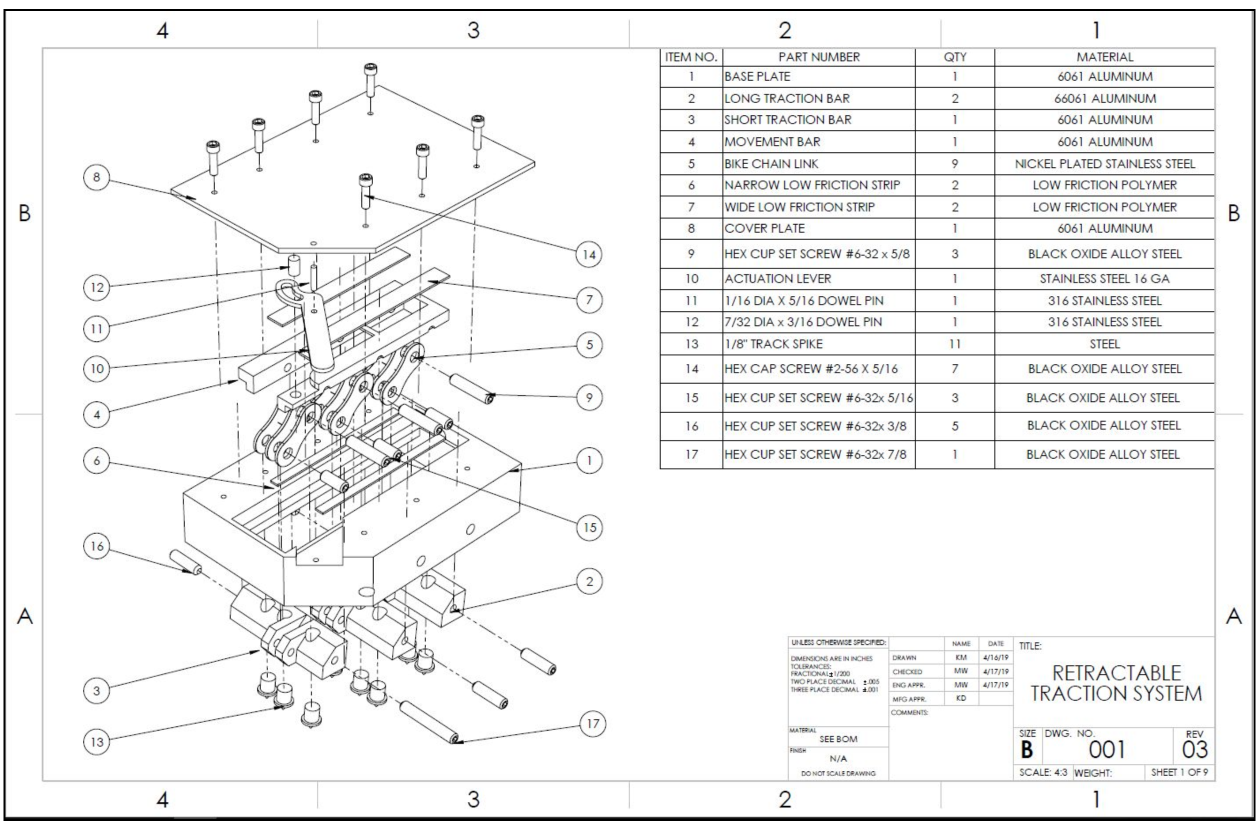


Figure 5.9 Wireframe Chain Link

Each link is sized from a standard bike chain. A piece consisting of 2 circles of radii 0.5 inches apart from one another, with holes of diameter 0.14 inches drilled through the centers. The 0.5 inches between the main circle are bridges by a curve with a radius of 0.48 on both sides. Each chain link piece is 0.05 inches thick, the standard for commercially available bike chain.

5.2 Bill of Materials



ITEM NO.	PART NUMBER	QTY	MATERIAL
1	BASE PLATE	1	6061 ALUMINUM
2	LONG TRACTION BAR	2	66061 ALUMINUM
3	SHORT TRACTION BAR	1	6061 ALUMINUM
4	MOVEMENT BAR	1	6061 ALUMINUM
5	BIKE CHAIN LINK	9	NICKEL PLATED STAINLESS STEEL
6	NARROW LOW FRICTION STRIP	2	LOW FRICTION POLYMER
7	WIDE LOW FRICTION STRIP	2	LOW FRICTION POLYMER
8	COVER PLATE	1	6061 ALUMINUM
9	HEX CUP SET SCREW #6-32 x 5/8	3	BLACK OXIDE ALLOY STEEL
10	ACTUATION LEVER	1	STAINLESS STEEL 16 GA
11	1/16 DIA X 5/16 DOWEL PIN	1	316 STAINLESS STEEL
12	7/32 DIA x 3/16 DOWEL PIN	1	316 STAINLESS STEEL
13	1/8" TRACK SPIKE	11	STEEL
14	HEX CAP SCREW #2-56 X 5/16	7	BLACK OXIDE ALLOY STEEL
15	HEX CUP SET SCREW #6-32x 5/16	3	BLACK OXIDE ALLOY STEEL
16	HEX CUP SET SCREW #6-32x 3/8	5	BLACK OXIDE ALLOY STEEL
17	HEX CUP SET SCREW #6-32x 7/8	1	BLACK OXIDE ALLOY STEEL

Figure 5.10. Exploded View of Assembly with Bill of Materials

Table 5.1. Bill of Materials

Part Name	QTY	Description	Material
2-56 5/16” Hex Cap Screw	7	(Stock Part) Screws to anchor cover	Steel
Cover Plate	1	Cover for upper surface of device	6061 Aluminum*
Low Friction Strips (Wide)	2	Friction reduction between cover plate and movement bar	Vinyl
Actuation Lever	1	Interface to move movement bar and linkage	16ga Stainless Steel
3/32nd Dowel Pin	1	(Stock Part) Actuation Pin	Steel
1/16th Dowel Pin	1	(Stock Part) Actuation Pivot Pin	Steel
Movement Bar	1	Actuates and synchronizes linkage	6061 Aluminum
Low Friction Strips (Narrow)	2	Friction reduction between movement bar and base plate	Vinyl
Base Plate	1	Housing for mechanism	6061 Aluminum
Bike Chain Links	9	(Stock Part) Linkage connection between rotating bar and movement bar	Stainless Steel
6-32 5/8”Cup Point Hex Set Screw	3	(Stock Part) Movement Bar - Linkage Connection Pins	Black Oxide Alloy Steel
6-32 5/16” Cup Point Hex Set Screw	3	(Stock Part) Linkage-Rotation Bar Connection Pins	Black Oxide Alloy Steel
Rotating Bar (Long)	2	Housing for spikes that rotates	6061 Aluminum
Rotating Bar (Short)	2	Housing for spikes that rotates	6061 Aluminum
6-32 ½” Cup Point Hex Set Screw	5	(Stock Part) Rotating Bar Support Pins	Black Oxide Alloy Steel
Track Spikes	11	(Stock Part) Provides Traction	Steel

6. Manufacturing

All components used for testing or presentation in this project were either off-the-shelf parts or fabricated by the team. Early prototypes consisted of off-the-shelf parts and 3D printed components, while the final prototype parts consisted of machined metal and off-the-shelf parts. The manufacturing was conducted almost exclusively in the facilities provided to students by Worcester Polytechnic Institute.

It is worth noting that the processes used for manufacturing prototypes in this project are not representative of the process that would be used in a commercial, mass-production setting. The manufacturing in this project was intended to create individual devices, using the available resources, while staying within the project budget. For a discussion on the commercial manufacturing process and considerations, see future work.

6.1 Available Resources

The equipment available for the manufacture of the custom parts for this project was limited to what was available in the student-use facilities at Worcester Polytechnic Institute (WPI). WPI has many manufacturing resources available, including 3D printers, mills, lathes, laser cutters, and welding facilities. The team primarily used The Washburn Manufacturing Laboratory in Washburn Shops and the Higgins MQP Laboratory.

Washburn shops has six Haas CNC Mills and four Haas CNC Lathes ranging in size and capability. In addition, students are able to utilize a Universal Laser Systems VLS460 Laser Cutter, a Prusa i3MK2 3D Printer, and several pieces of unguarded machinery including drill presses, bandsaws, etc. The Higgins MQP laboratory has three Prusa i3 MK2 and MK3 3D printers for use by Mechanical Engineering MQP teams.

6.2 Rapid Prototyping

The team produced four 3D printed prototypes which allowed them to physically study the shape and scale of parts as well as the interaction of the assembly. In studying the rapid prototypes, the team identified weak areas, part interference, frictional interference, and opportunities for optimization so that design changes could be made for future prototypes.

The team used Prusa i3 MK2 and MK3 3D printers and 1.75mm PLA filament for all rapid prototypes. The speed of production made it possible to produce prototypes in a matter of hours. However, many variables impact the accuracy of 3D printed parts, and without extensive experience, the team was unable to hold tight tolerances on these prototypes. Because of this, when the 3D printed prototype would stick or jam, it was unclear whether the issue was due to a flaw in the design itself or due to material properties of PLA plastic and tolerancing issues related to the 3D printing process itself. To overcome these problems and better represent the intended product, the team moved on to aluminum prototypes.

6.3 Metal Prototyping

To produce a more robust prototype, the team turned to the CNC equipment available in The Washburn Manufacturing Labs. Custom parts including the base plate, traction rods, and movement bar were milled using Haas Mini Mills with an accuracy of two thousandths (0.002) of an inch. The team made design adjustment such as maximization of flat and parallel edges were made to allow parts to be clamped within the machine. These changes are described in Section 4.3, Second Round Design Optimization. Some geometry could not be achieved in the mill alone due to limitations of the ESPRIT Computer Aided Machining software. In these instances, the team made fine adjustments using the various unguarded machines and hand tools available in the shop.

While the size and complexity of the movement bar and traction rods made them difficult to clamp and machine, the height and curve of the lever made clamping impossible. The team considered a solution which involved using superglue to affix the stock to a sacrificial plate of aluminum for machining, but found that the surface area of the part was insufficient to withstand machining forces. Without the necessary equipment to perform a two-dimensional cut of sheet metal, the team procured the custom part from a vendor called SendCutSend. The stainless steel lever was then adjusted with unguarded machines and hand tools to address the concerns described in Section 5.1.6. In the future, this part could be ordered directly as needed from SendCutSend.

7. Analysis

To ensure satisfactory performance of the device, individual components and the complete system were evaluated against modes of failure. If the device ceases to meet the functional requirements, the device has failed. Therefore, the functional requirements formed the basis for identifying modes and causes of failure of the device. The primary functional requirements are listed elaborated on in Appendix A.

Functional Requirements

- Reduce the falling risk of pedestrians in winter conditions
- Provide a convenient transition from indoor to outdoor icy to outdoor dry surfaces
- Be commercially viable
- Withstand Urban New England winter conditions
- Be manufacturable by design team

Of these functional requirements, only three are applicable to this stage of analysis: the manufacturability and the commercial viability of the design were evaluated throughout the design process. Therefore, the modes and causes of failure discussed here are limited to those related to (1) the ability of the device to reduce falling risk, (2) the convenience of the transition between surfaces, and (3) the ability of the device to withstand the intended environment. This analysis assumes that the as-designed device meets the requirements; the evaluation is to ensure that a device that meets these requirements would not cease to meet these requirements during expected use.

To define the loading for the device, a 200 lb person walking and jumping is assumed. A user with these characteristics would produce a max force of 700 lbs. It is also assumed that the device will be used in New England Winter Conditions, as defined in the functional requirements.

7.1 Stress-related fracture or deformation

Any component fracturing would likely result in the failure of the device. Therefore all components need to withstand the expected loads. Components were evaluated to determine how the expected loads compared to the material's capabilities. If the expected loads were close to the limit of the material, corrective actions were considered.

The team used two methods to evaluate the likelihood of failure for critical components. For the connection pins, which were simple enough to be evaluated analytically, the worst-case loading scenario was determined, and a simple calculation was used to estimate the stress on that component. For more complex parts, including the base plate and spike rods, Solidworks evaluation software was used to determine if excessive deformation or failure was likely. Non load-bearing components were qualitatively analyzed to ensure critical stresses would not be experienced by the part.

7.1.1 Pin Evaluation

One of the pins supporting the spike rods could experience a load of half the maximum force applied by the user, in worst-case scenario loading. This maximum force is estimated to be 700 lbs, see section 2.3.2 for details.

If the user steps with the maximum predicted force on a small hard object, such as a rock, the entire load may be transferred to a single spike rod. In this worst-case scenario, the entire load would be transferred to the two pins holding the rods to the base plate; therefore each pin could experience half of the worst-case scenario load.

The pins supporting the spike rods are 6-32 set screws made of black oxide alloy steel. The yield strength of this material is 140,000 psi (Gamut). The predicted worst-case scenario loading conditions can be represented by the following equations.

$$700 lbs / 2\ pins = 350\ lbs/pin$$

$$350\ lbs / ((0.0997\ in/2)^2 * \pi) = 44,831.973\ psi$$

The worst-case scenario loading of the pin results in a stress of about 45000 psi. This falls below the yield stress of the pins, which is 140,000 psi. Therefore, the pins are not expected to fail with the expected use of the device.

7.1.2 Traction Bar Evaluation

The traction bar had too many features to be reasonable analyzed through a simple, analytical, stress-analysis calculation, and given the size and material of the part, complete fracture was deemed unlikely with the loading conditions. Therefore, the spike rod was evaluated through solidworks software, and the evaluation focused on identifying regions and magnitudes of deformation of the part.

The evaluation was conducted with worst-case scenario loading, which comprised a 700 lb load concentrated on a single spike rod. The 700 lb load is the greatest load expected during intended use (see section 2.3.2), and although it is rare that any walking load will be exclusively concentrated to one traction bar, it is possible that the user could step on a hard surface, such as a rock, which could concentrate the load to one bar.

Only the large traction bar was evaluated because the stresses associated with the loading would be worse for the large bar: both bars were supported by pins of the same size in holes of comparable depths. Therefore, the additional length of the large bar, which did not have more support than the small bar, would maximize undesirable moments and have a more problematic “worst case scenario” then the shorter bar

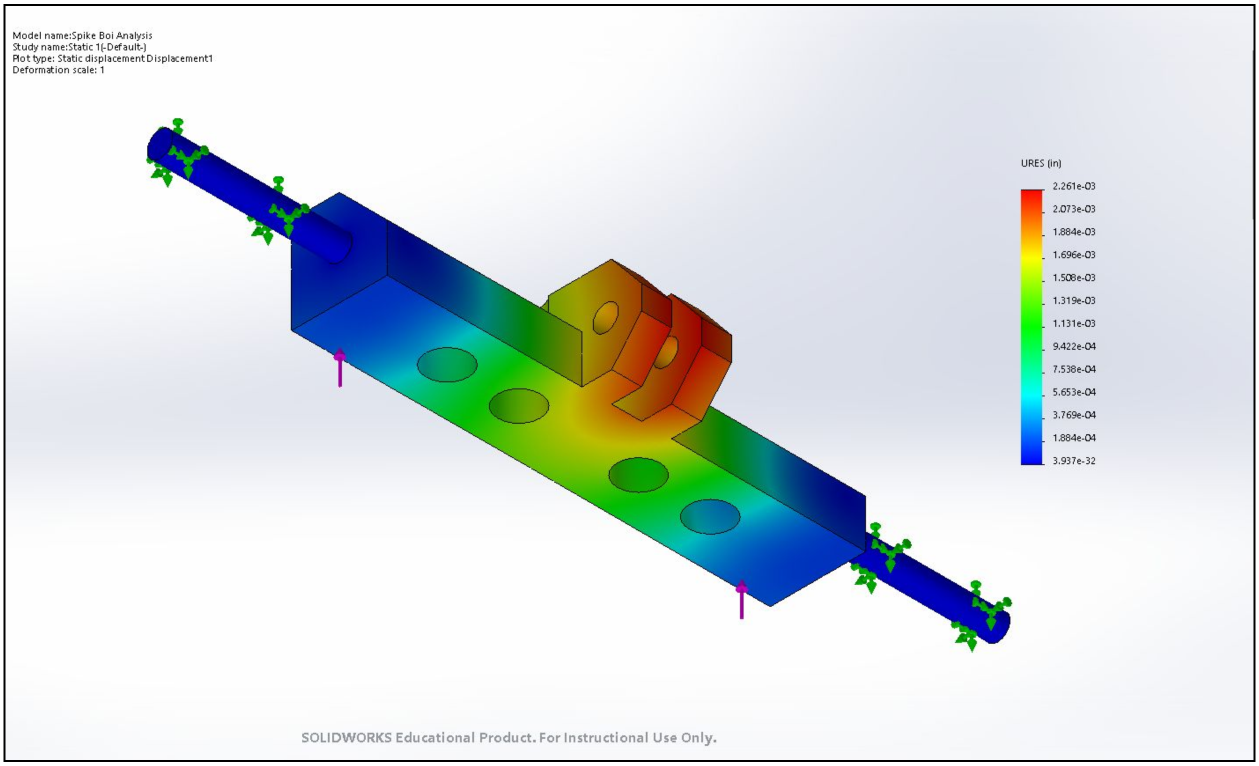


Figure 7.1. Stress Analysis of the Traction Bar

7.1.3 Base Plate Evaluation

The base plate was evaluated using Solidworks software. The analysis assumed a worst-case-scenario loading of the maximum expected applied force (700 lbs) applied solely on the one plate, and the entire load being transferred to the pins that connect to the spike rods. This assumption is a worst-case scenario because:

1. The 700 lb force is a worst-case-scenario load (see section 2.3.2)
2. It is rare for the entire load to be concentrated to a single base plate
3. In an actual application of the device, there would be tread around the base plate that would partially support the load

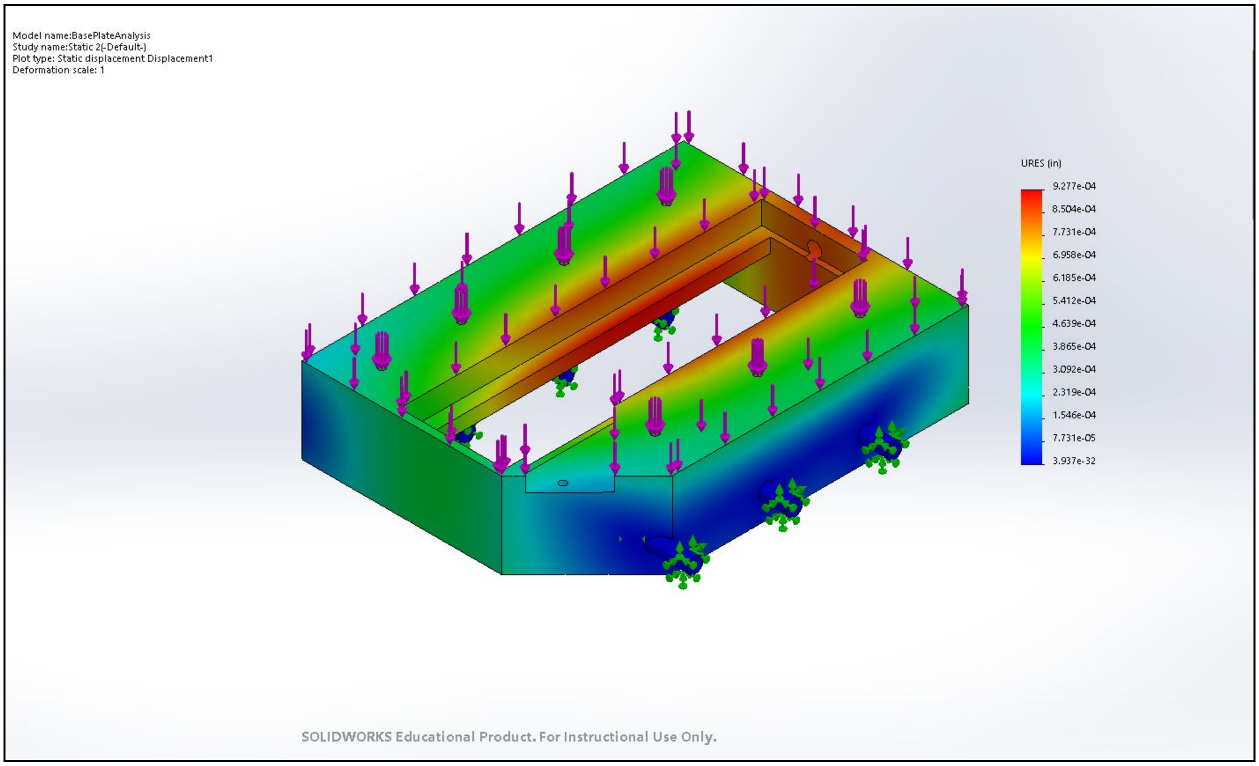


Figure 7.2. Stress Analysis of the Base Plate

7.1.4 Stress Failure Analysis Exempt Components

Certain components were exempted from extensive stress-related evaluations because it was clear that the loading on the part during expected use would not cause stresses anywhere near the material's maximum capacity. These components and their associated rationale are outlined below in Table 7.1.

Table 7.1. Components which stress forwent analysis

Component	Rationale
Set Screws Securing Top Plate	The screws will interact with the cover plate and the base plate. The majority of the force from expected use will be held by the base plate, so the plate the screws are holding will experience little force against the screws. There may be compressive stresses imposed by the user standing on the plate, but these would be supported by the interface between the cover plate and the base plate. Tensile stresses, which tend to be more damaging than compressive stresses in this situation, would also be small because there is nothing in the design that would create a force pulling the cover off of the base plate. Also, many screws were used to secure the top plate.

Cover Plate	The cover plate is primarily intended to prevent the actuation mechanism from catching on parts of the sole of a boot; it is not a critical load-bearing component. Boot soles tend to include soft materials, which could become compressed into the channel that houses the linkage in the base plate if a cover is not present. However, it is unlikely the cover plate will experience significant loading because any loads are transmitted directly through the cover plate into the base plate.
Friction-Reduction Strips	Friction-reduction strips will function even if they are significantly deformed. The strips will experience compressive stresses, which is likely to cause some level of deformation, but because the thickness of the tape is so small, deformation in this dimension is negligible to the overall structure. Also, the strips will be fully supported when the stresses occur, and due to the compressive nature of the stresses, it is unlikely the strips will tear.
Actuation Lever	The only forces that will occur on the actuation lever during intended use are those applied by the user's hand. Although it is possible for a relatively strong person to bend the levers along the flat of the lever (this was experimentally verified by the design team), the loading will be perpendicular to the flat face, so the effective thickness of the material when considering loading is much higher then when bending along the flat face. Most people do not have the strength to bend the lever in this perpendicular direction. Overall, for the actuation lever to be damaged, a user must deliberately attempt to bend it, and because unintended device use is outside the scope of this project, within the scope of this project, the actuation lever is plenty strong to support the loading from expected use of the device.
Movement Bar	The movement bar only experiences the forces from associated with the actuation of the system. The user's weight is supported through the base plate, and therefore those forces are not transmitted to the movement bar. Because the the movement bar will only experience a relatively low set of forces, stress-related failure is not a significant concern.
3/32 Dowel pin	The 3/32 dowel pin is used as a connection between the actuation lever and the movement bar. As a part of the actuation mechanism, this component is not bearing the user's weight directly. Also, because this dowel pin is quite short, and there is very little (vertical) distance between the pin's hole in the base plate and the slot in the Actuation Lever, so there should be no concerns with forces being magnified due to leverage.
1/16 Dowel Pin	The 1/16 dowel pin is a pivot for the actuation lever. Although this component experiences the brunt of the forces associated with the

	actuation mechanism, it is a steel component which can withstand these loads. Also, this pin is anchored on both ends, preventing the formation of a moment when stresses are applied.
Bike Chain Links	The bike chain links, like the rest of the actuation mechanism components, will only be bearing forces from the user's hand when they move the lever. These relatively-low stresses are within the capabilities of prefabricated bike chain.
Other Set Screws	All set screws not used for connecting the traction rods to the base plate will experience less forces than the set screws used for that purpose. Because these other set screws are experiencing significantly lower loads (with comparable loading patterns) and an analysis has already been conducted to verify the functionality of the set screws in the higher-stress state, the team is confident that all other set screws are being loaded will within their capabilities.

7.2 Fatigue Failure

Walking will produce cyclic loading on the traction system mechanism, and this makes fatigue failure a significant concern. The fatigue strength of a material is significantly lower than its yield strength, so this project must design for this lower threshold. However, although most of the stress-related analyses involved worst-case scenario loading (see section 7.1), this assumption is not necessary when calculating fatigue failure. Calculations do not need to predict worst-case scenario loading to be typical of walking because it can be assumed that most steps will follow expected walking conditions with loading being distributed across all spikes.

The assumed loading is a 700 lb force, with the maximum load applied when all spikes are in contact with the ground. This scenario creates a load of 700lbs distributed across three traction bars, each of which is supported with two screws. Ultimately, each screw is supporting about 117 lbs per step. The resultant stress can be calculated as follows:

$$117\ lbs\ /\ ((0.0997\ in/2)^2 * \pi) = 14,987\ psi$$

To determine the constraints of the loading situation, the team estimated how many cycles the device would experience. 10,000 steps a day is a generous estimate for steps per day for most of the target audience, and to ensure that worst-case situations were considered, it was assumed that this number of steps was conducted 365 days a year. Therefore, the device experiences around 3 million cycles per year. The device ought to last many years, so for a 10-year device lifespan, the design must be rated for at least 3.65X10^7 cycles.

Steel, which is the material the screws are made of, demonstrates a distinct endurance limit (ASM, 2008). As long as this the stresses stay below the endurance limit, theoretically the device can be cycled infinitely without problems due to fatigue. The endurance limit for steel develops at around 10^7 cycles, so ensuring the stresses remain below the endurance limit would remove the constraint of a finite lifespan: because the parts could be cycled indefinitely, the device would not be limited to a certain lifespan.

The endurance limit of steel is between 40 and 50 ksi. Because under expected (not worst-case scenario) loading, the stresses on the bars are less than 15 ksi, the design falls well under the endurance limit given expected loading. Therefore, fatigue failure is not a significant concern in this project.

7.3 Thermally-Induced Failure

The team determined it was important to evaluate if thermally-related material behaviors would cause problems or failure in this design. Because the project has a wide range of operating temperatures (-30 to 80 degrees F), there were concerns that the components might expand or contract to the point of falling out of tolerance.

To determine the thermal expansion likely to be seen in this project, the team calculated the maximum dimensional change of the largest component in the project. To do this, the team used the well-known relation:

$$\Delta L/L = \alpha_l * \Delta T$$

The coefficient of expansion for aluminum: $\alpha_l = 23.94 * 10^{-6}$ (Hodgman, 1949)
The longest dimension in project (Base Plate length): 3.35 in
Temperature range (converted to C for consistency with coefficient): -34.44 to 26.67 degrees C

Using this, the maximum dimension change is:

$$\Delta L/L = .001463$$

$$\Delta L = .005120''$$

This maximum dimensional change is consistent with the tolerances for this design. This is also looking at the maximum change of the longest dimension, effectively a worst-case scenario, so individual features would not be shifted by this maximum value. (For example, a hole in the middle of the plate would only be displaced half this length relative to either end.)

Due to this analysis, the team can conclude that thermal expansion is not a concern in this project.

7.4 Corrosion Failure

Urban winter environments tend to be corrosive because of the use of salt to reduce freezing on roads and sidewalks. The materials in the system also will undergo cyclic loading. The combination of cyclic stresses and corrosion can cause catastrophic failure of some materials due to stress corrosion cracking. Also, even without the cyclic loading, materials will degrade in such environments.

The team did not evaluate corrosion failure through calculations, instead, materials were deliberately chosen with regard to their corrosion resistance properties. In this project, all parts fabricated by the team are aluminum, which is corrosion-resistant. The dowel pins were selected to be 316 stainless steel, which is relatively corrosion-resistant when considering steel alloys. Most of the off-the-shelf parts were coated, either with a black oxide coating (in the case of set screws), and nickel plating, in the case of the bike links. Other off-the-shelf components are designed for outdoor use: the spikes exact materials were not listed by the supplier, but because they are designed for a very similar purpose to their use in this project, it is reasonable to assume that their material is adequate.

8. Discussion

8.1 Prototype Conclusions

The design was iterated upon numerous times in order to improve each aspect of the system. Though recommendations for further work on the prototype are detailed below, the presented design meets or exceeds the expectations laid out the the beginning of this project.

The metal spikes reduce the falling risk to pedestrians when walking on icy sidewalks, as they are able to dig in a pierce the ice for traction. The lever provides a convenient way to for the user to switch the spikes from deployed to retracted, allowing easy transition between surfaces. The prototype was created well under budget, indicating commercial viability. Finally, the prototype is constructed with primarily with aluminum and stainless steel, allowing it to easily withstand the range of temperatures and environments it will encounter during intended use.

Table 8.1. Comparison of Functional Requirements and Prototype Reality

Functional Requirement Goal	**Prototype Reality**
Reduce the falling risk of pedestrians in winter conditions	Spikes reduce the risk of slips on frozen sidewalks
Provide convenient transition from indoor to outdoor surfaces	Convenient transition achieved through lever mechanism
Be commercially viable	System meets price, weight, and size targets
Withstand urban New England winter conditions	Aluminum-based design withstands expected temperature range and corrosive environment
Be manufacturable by design team	Non-stock components are manufacturable by design team

8.2 Recommendations

The rotational spike design prototype presented has met all the requirements set before it. However, it is, as many prototypes, not truly complete. In order for this design to move beyond this stage and become a commercially viable product, it is recommended that several steps be taken. The design must be completed with the introduction of the heel section of the traction system, and the means to connect both the toe and heel portions. Additionally, it is extremely important to increase the manufacturability, the ease of use for the wearer, the durability, and commercial viability of the system before it can enter the market.

8.2.1 System Completion

The prototype designed is the first of a two part system, one part sitting in the toe, the other in the heel. In order to construct a full system, the heel portion must be designed and added. This portion should be relatively simple, as the mechanism for retraction, movement, and actuation and already created. The base plase will need to be redesigned to wit in the smaller confines, and the rotational bars will need length adjustment, but nothing more.

Since the design is made to be used with a single hand, the heel and the toe actuators must be connected. It is recommended that a metal strip running the length of the sole, similar to a shank in a work boot, be added. However, this was not included in the design, so it is unknown what may be the most effective method of connection.

8.2.2 Ease of Manufacturability

In order to move the design from a prototype to a viable system for mass production, the manufacturing process needs to be adjusted. The current process allows the manufacturer to remove the piece and check that the cuts are properly made before moving on to the next operation. This allows users to conserve as much stock as possible and avoid mistakes in the manufacturing process. However, this technique is much too slow and arduous to construct numerous samples.

Additionally, as the current prototype is designed to fit within the boundaries of a size 6 women's shoe, the design will need to be scaled upward to be useful in larger sized shoes. To accomplish such a task, a design optimization parameter matrix will have to be constructed so as to easily scale designs for mass production. This would allow the manufacturers to easily adjust the design for vastly different weights, heights, and sizes.

For this prototype, the team was confined to machines available in Washburn Shops. These machines have an accuracy of 0.002 inches and a repeatability of 0.001 inches. This is acceptable for prototyping, but in order to ensure mass production and repeatability, the team recommends using machines with more precise tolerances. These machines would allow the user to make far more precise cuts, and would let the designer use smaller sized parts for the system.

8.2.3 Ease of Use

The design offers relatively easy movement between retracted and deployed, but in order to make this transition as smooth as possible, the team recommends several hardware changes and/or additions. To allow the upper movement bar the the smoothest motion possible, the threaded set screws should be replaced with smooth pins that lock into place in the outsides of each connection.

The current prototype in unpowered, showing the how the lever actuation changes the tread from retracted to deployed. To allow the user to truly "snap" between settings, the team suggests a spring be mounted to the rear of the movement bar and connect to the inside of the base plate. This configuration would keep the treads retracted with a force equal to the spring, ensuring there are no accidental deployments. Additionally, to lock the design in place, the team recommends a spring loaded detent pin be mounted on the underside of the lever. This pin would move forward and slide into pre cut holes in the base, preventing the movement bar from rotating the spikes.

8.2.4 Durability

The material the prototype is made with was aluminum 6061, a metal with relatively high strength and low weight. However, since the team was working in environments with lots of water, the corrosion resistance of the metal was also of high importance.

Another significant factor in the material selection decision was that aluminum is the primary metal cut on the Haas mini mills at the WPI laboratory. Though the design using this metal meets all functional requirements, a different material could greatly impact the construction of the system. For example, making the spikes with titanium, a metal with much higher strength than steel, would have allowed for much smaller thicknesses throughout the project. The team recommends that more metals be considered for each part beyond what they currently are made of.

8.2.5 Increase commercial viability

To increase the commercial viability of the design, the team suggests that the the overall dimensions be made much thinner. This would allow it to fit far more easily into a large number of shoes. The design was limited to materials and stock pieces with established strengths and properties. As such, the prototype is limited by and built around these factors. With the possibility of increased manufacturability, the size of nearly every component, from spikes to base plate, could be reduced.

However, the size of the design is not the only area of concern. As WPI is located in the urban northeast of the United States, the team designed the system around such an environment. To ensure this prototype is a viable option for a traction system, it will also need testing in extreme temperatures, environments, and surface hardness tests.

Appendices

Appendix A. Functional Requirement Justifications

Reduce the falling risk of pedestrians in winter conditions

Winter conditions create significant slipping hazards due to the snow and ice buildup on sidewalks. The overarching goal of this project is to create a device that reduces this slipping hazard, so reducing the slipping hazard is an inherent requirement of the device. However, the scope of this project is limited to reducing the risk of slips: reducing trips or other types of falls (see section 2.3.1 for an explanation of falling mechanisms) is not a functional requirement. The device should not increase a user's likelihood of tripping or other types of falls, but the device does not need to specifically reduce these risks. Therefore, the functional requirements of the device related to reducing falling risk comprise: (1) improving slip resistance on frozen surfaces, and (2) maintaining user stability.

Provide a convenient transition from indoor to outdoor icy to outdoor dry surfaces

Winter traction systems geared toward pedestrians already exist, but their major shortcoming is a lack of convenience. (See section 2.5.1 for an overview of existing technology.) The goal of this project is to address this issue by creating a more convenient system. To be considered "more convenient" the device should not need to be removed from the footwear during regular use. Therefore, the device must have a mode appropriate for icy outdoor surfaces, a mode appropriate for dry outdoor surfaces, and a mode appropriate for indoor surfaces. There may be overlap between these modes (i.e. three distinct modes are not necessary), but if there are multiple modes, the transition between these modes must be convenient.

Be commercially viable

If a product is not commercially viable, it is not useful, because there will be no funding to create it; therefore this is a significant functional requirement of the device. To define commercial viability, targets were set based on comparable products on the market.

The device must be integrable with normal winter boots. Winter boots are appropriate and expected footwear for urban pedestrians, so the device should be possible to integrate with this style of footwear. Possible to integrate means the device must fit inside the volume of the footwear, and the device must not add excessive weight to the footwear. Also, the device should still operate as expected when encased in a sole. For this project, a size 6 women's boot as the sample winter boot for dimensional reference, because it will be easier to scale the device up than down, and size six is the smallest shoe size consistently stocked in stores.

This leads to the next requirement of commercial viability: the device design should be scalable because boots come in a variety of sizes. In addition, the boot needs to support the user's weight (because otherwise the product is useless). The final requirement when considering commercial viability is that the device must not exceed $100; this value is consistent, and somewhat generous, when compared with existing external products.

Withstand Urban New England winter conditions

New England is a harsh climate in winter, when considering temperatures and precipitation, and urban areas have the additional challenge of the corrosive environment produced by road salt. The device must be able to withstand all expected operating conditions. Therefore, the device should function in temperatures ranging from -30 F (the lowest realistic temperature, see section 2.4 for details) to 80 F. This range covers the lowest realistic outdoor temperature to a generously warm estimate of indoor temperatures. Also, the device must withstand a corrosive environment comprising road-salt dissolved in water, because salt is used heavily on roads and sidewalks in urban New England.

Be manufacturable by design team

In order to produce a prototype, the device prototype must be manufacturable by the design team. Therefore, the necessary manufacturing processes must not exceed the capabilities of the design team, the necessary equipment must be available at WPI, the materials must be within the project budget, and anything not manufacturable by the design team must be an orderable stock part. For more details on the available resources at WPI see section 6.1.

Appendix B. Preliminary Decision Matrix Scoring Rubric

Table B1. Scoring Rubric for Design Matrix

Factors Considered	Weighting Factor	1	2	3
Fall Prevention	(30)			
Slips	10	•Will cause user to slip •Will not prevent any slips	•Will only prevent slips under narrow range of conditions •Will inconsistently prevent slips	•Will prevent most slips
Trips	10	•Will cause user to trip frequently	•May cause a few trips	•Will not cause trips
Stability	10	•Will cause a loss of balance	•Stability comparable to high heels on dry pavement	•Balance distribution is comparable to that of a normal shoe (i.e. sneaker or boot)
Integrable with modern footwear	5	•Parts do not fit •Will cause weight so excessive user cannot comfortably lift foot •Mechanism would destroy footwear	•Not all components may fit inside regular footwear but extraneous components will not affect gait •Weight exceeds heavy mainstream footwear but is within average physical abilities	•All components fit inside a regular sole/ footwear •Resulting product "looks" like a normal boot/shoe •Resulting product has comparable weight to regular footwear
Operating condition range	20	•Components will not function in winter conditions	•Components may not work at extremes of operating condition range •Winter contaminants may impact effectiveness of traction component	•Components can function in all intended conditions without risk of failure from regular use
Durability	10	•Components are too delicate to assemble or will wear excessively	•Components/Mechanism have reduced lifespan compared to regular footwear	•Lifespan of components will be comparable the the lifespan of regular footwear
Convenience (Usable Indoors)	25	•Device should not be worn indoors	•Mechanism allows system to be used indoors	•Seamless transition between indoor and outdoor use
Manufacturable by design team	10	•Design team cannot manufacture device	•Design team may be required to order or outsource manufacturing of some parts	•Design team can easily manufacture all components with tools available at WPI
TOTAL	100			

Appendix C. Creating the Attribute Matrix

The creation of the Attribute Matrix was a trial-and-error process. The original plan was to create a list of all successful attributes from the first design matrix, and compare each attribute with each other attribute to determine which attributes could be "paired". The "pairs" were to be determined on a pass/fail basis: if the two features could reasonably coexist on a single design, the pair "passed", but if the features were mutually exclusive, redundant (satisfying the same requirement with no benefit to having both features), or could not be manufactured together, the pair "failed". This process is shown in Figure A1 below.

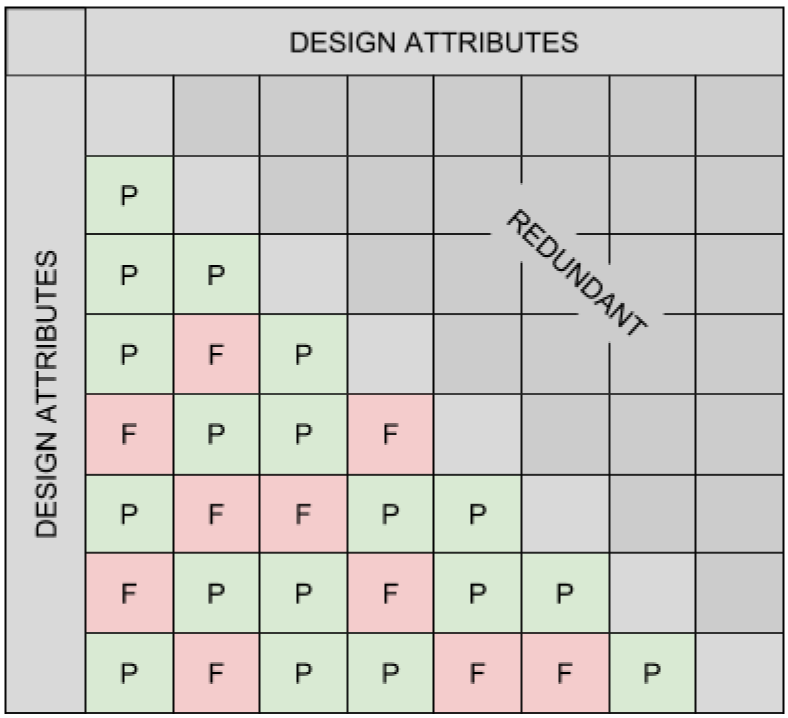


Figure C1. Concept sketch of first-level Design Attribute Matrix

The passed pairs were to then be re-compared against all the remaining attributes (see Figure C2), resulting in triplets. Triplets would then be compared again to form quartets, and so on. Eventually, this elimination process would lead to sets of eight grouped attributes, with each set satisfying or exceeding each of their respective functional requirements. Those groups of attributes would form the basis for the final designs, as shown in Figure C3.

	DESIGN ATTRIBUTES							
DESIGN ATTRIBUTE SET	F	P	F	P	F	P	F	P
	P	P	P	F	P	F	F	F
	P	P	F	P	P	F	P	P
	F	F	P	P	F	F	F	F
	F	P	P	F	P	P	P	P
	P	F	F	P	F	F	P	F
	F	F	P	F	P	P	F	P
	P	P	P	P	F	P	P	P
	F	F	F	F	P	P	F	F
	P	P	P	F	P	P	P	P
	F	F	P	P	F	F	P	F

Figure C2. Concept sketch of non-first level Design Attribute Matrix

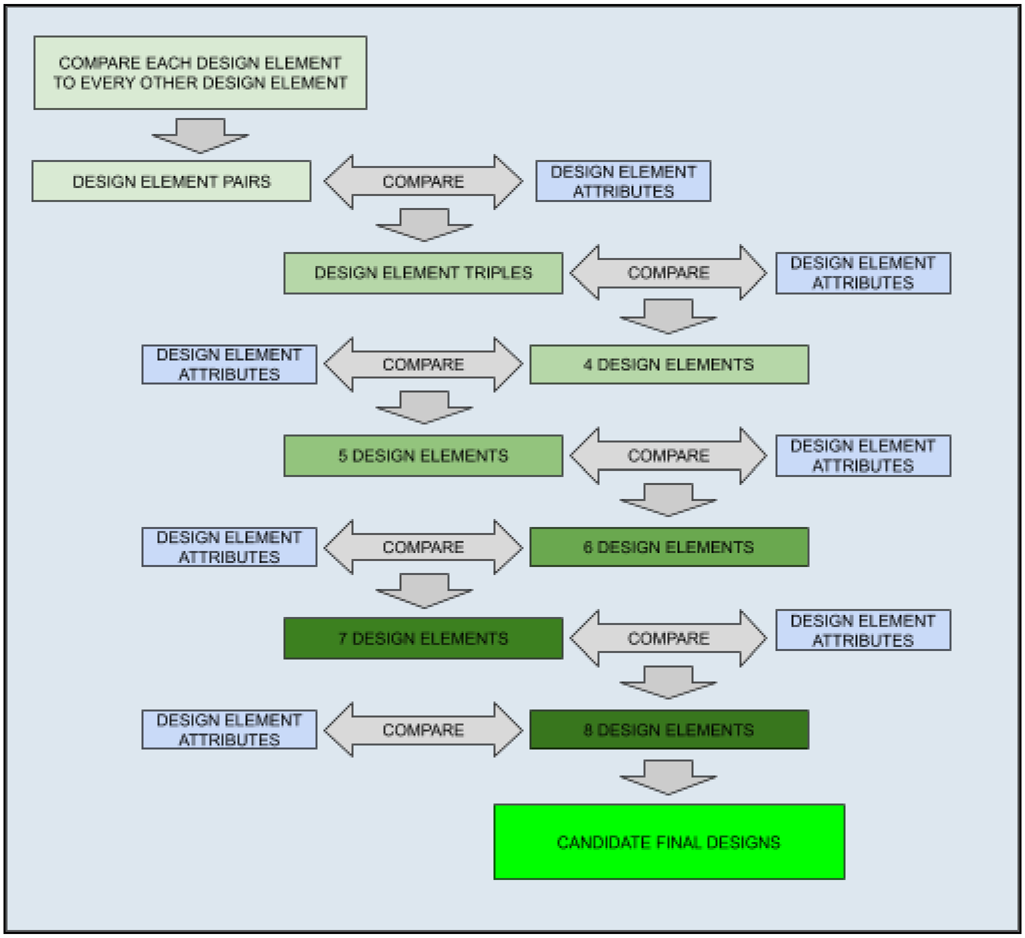


Figure C3. Concept sketch of design original attribute matrix process

This original attribute matrix plan had three significant flaws: scale, simplicity, and value. There were twenty design attributes that scored full points in the preliminary design matrix. Therefore there were 380 possible pairs to be evaluated in the first round of comparisons alone. The second round, there would still be 18 comparisons needed for each passed pair, so although by the seventh or eighth comparisons the matrix might be manageable, the lower-level attribute comparison matrices would be close to impossible to complete due to the thousands of comparisons that could be necessary.

The simplicity of the matrix also limited its usefulness. The matrix demanded a pass-fail distinction, which did not allow for qualifying answers. In many cases, a quality would be pairable under some conditions, but not others. The sheer number of comparisons required for the attribute matrix series made a more thorough evaluations impossible, but a simple pass-fail approach eliminated the steps of considering how things could be made to work together and any thorough evaluation of what might not work. Ultimately, the oversimplification of the original attribute matrix could very easily lead to invalid designs being "passed" and valid combinations being "failed".

The third issue with the attribute matrix plan is that it would not reliably provide anything of value to the design process. The attribute matrix series might lead to un-thought-of combinations of attributes that could be combined into a phenomenal design. However, the matrix could also result in combinations of attributes which would be difficulty to physically connect. Also, the matrix could simply fail to provide full sets of attributes--it would be possible that no combinations would form a complete and integrable set of eight attributes.

Since the design team deemed this form of attribute evaluation ineffective for design generation, a new evaluation system was adopted in its place. Instead of comparing the list of attributes to itself one-to-one, the team instead determined whether each of the existing designs which were not eliminated by the initial design matrix could be integrated with and improved by the identified attributes. The team details this process in Section 3.2.3, Attribute Matrix.

Appendix D. Additional Images of the Initial Design

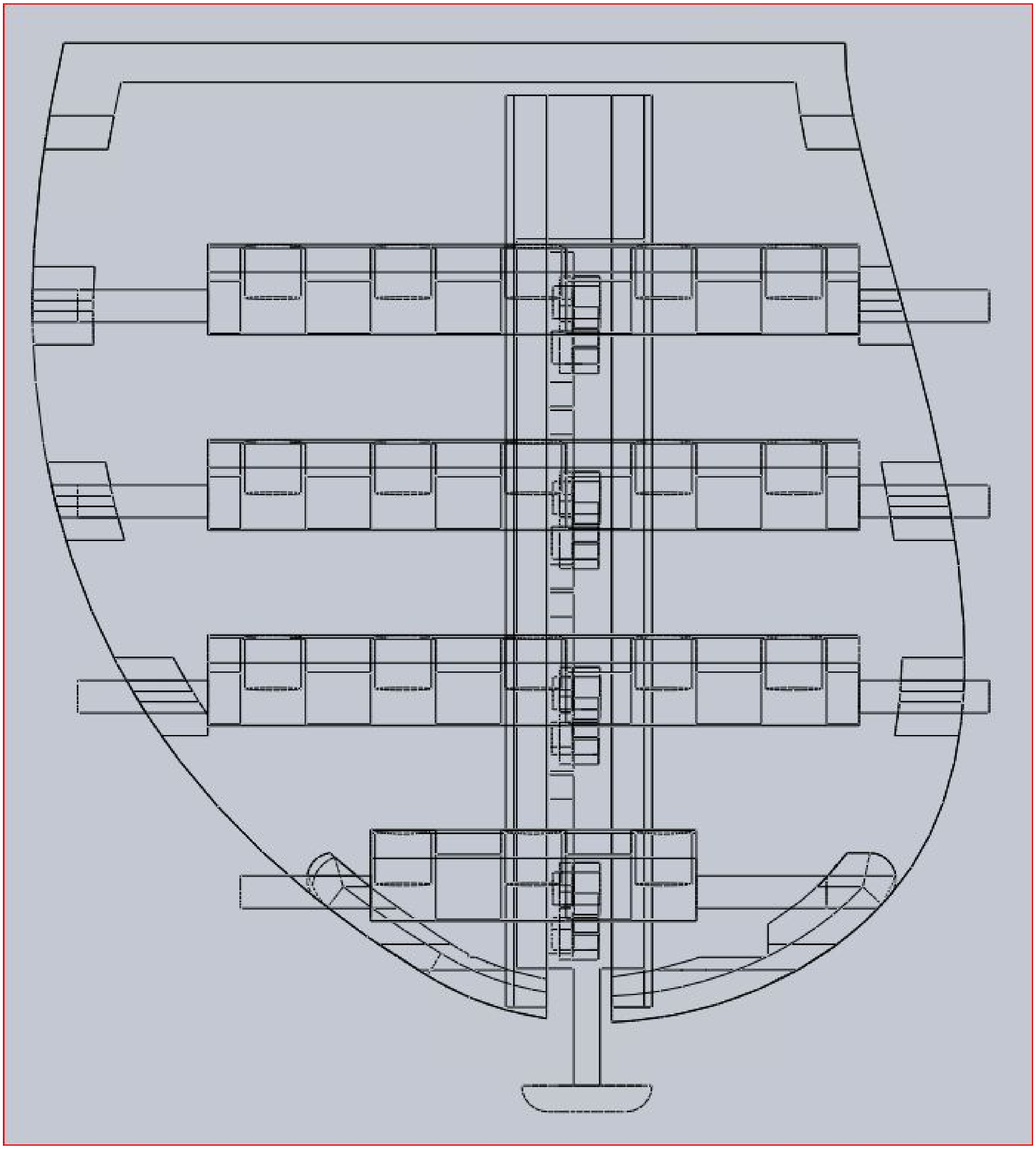


Figure D1. Top-View Wireframe of initial design

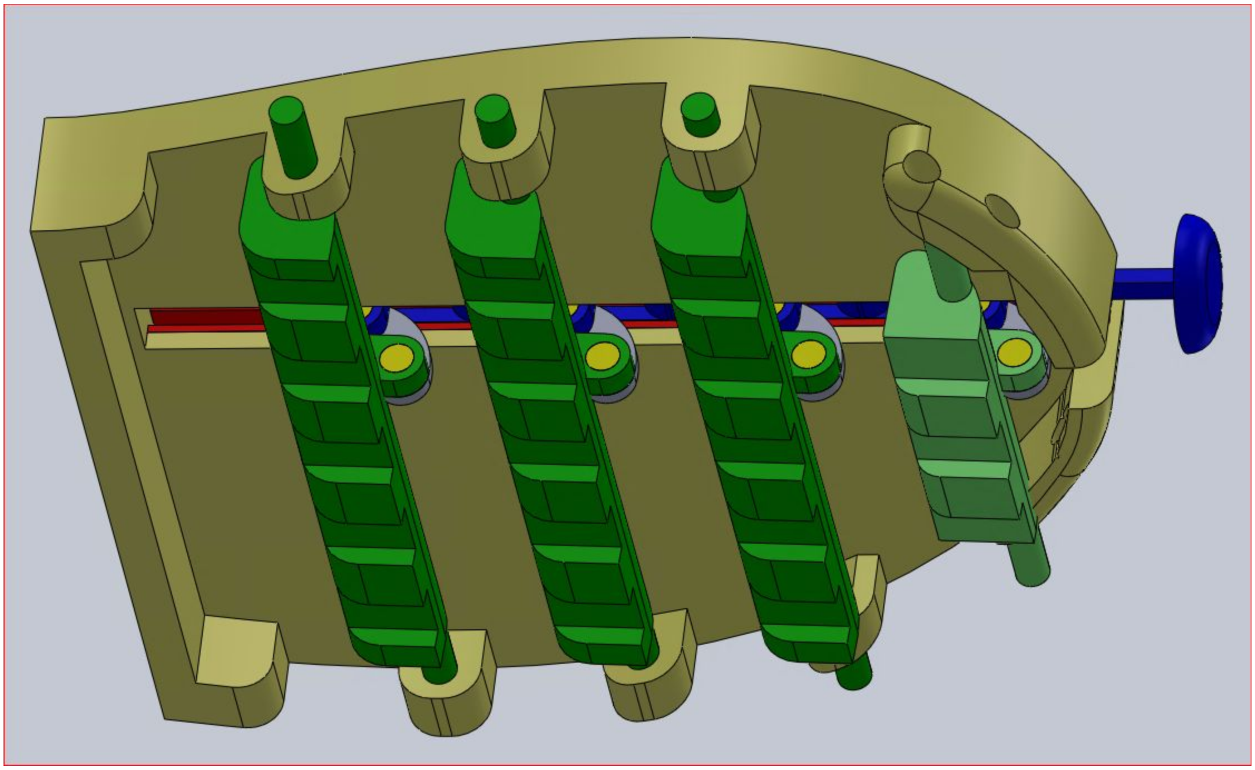


Figure D2. Underside of mechanism.

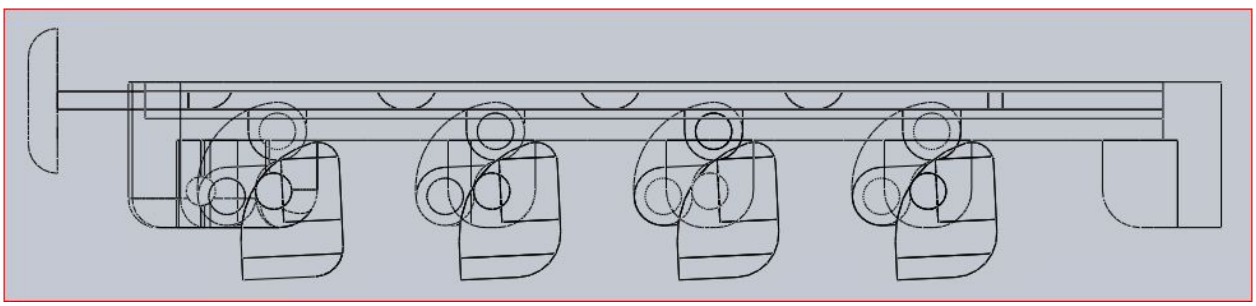


Figure D3. Wireframe of movement bar and linkage assembly, side view, base plate not shown

Appendix E. Detailed Drawings of Custom Parts

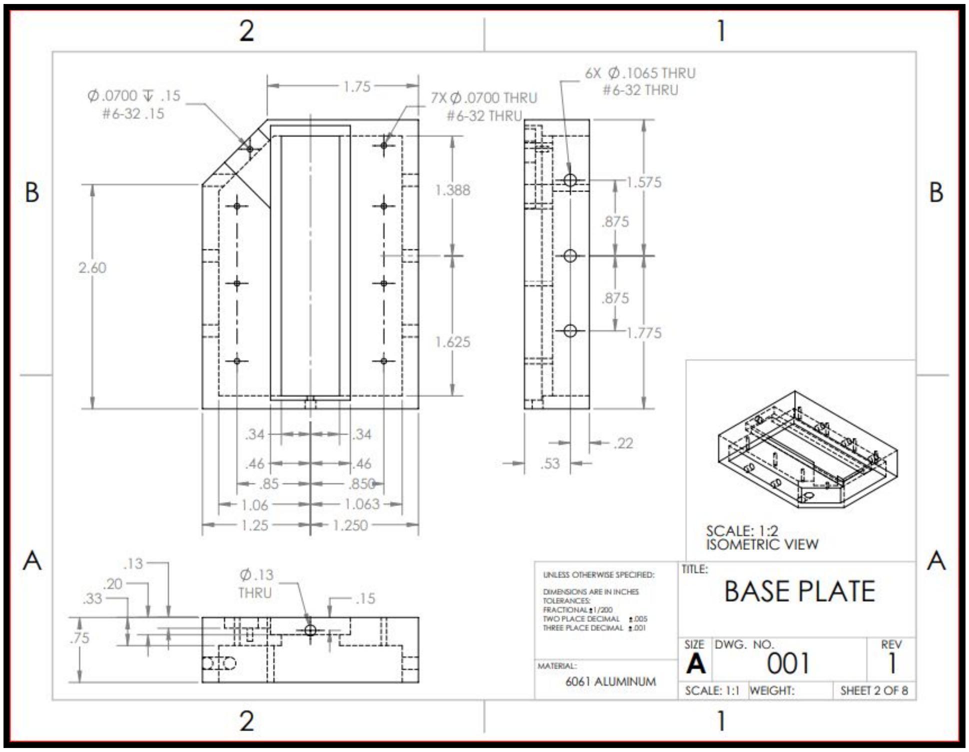


Figure E1. Detailed Drawing of Base Plate

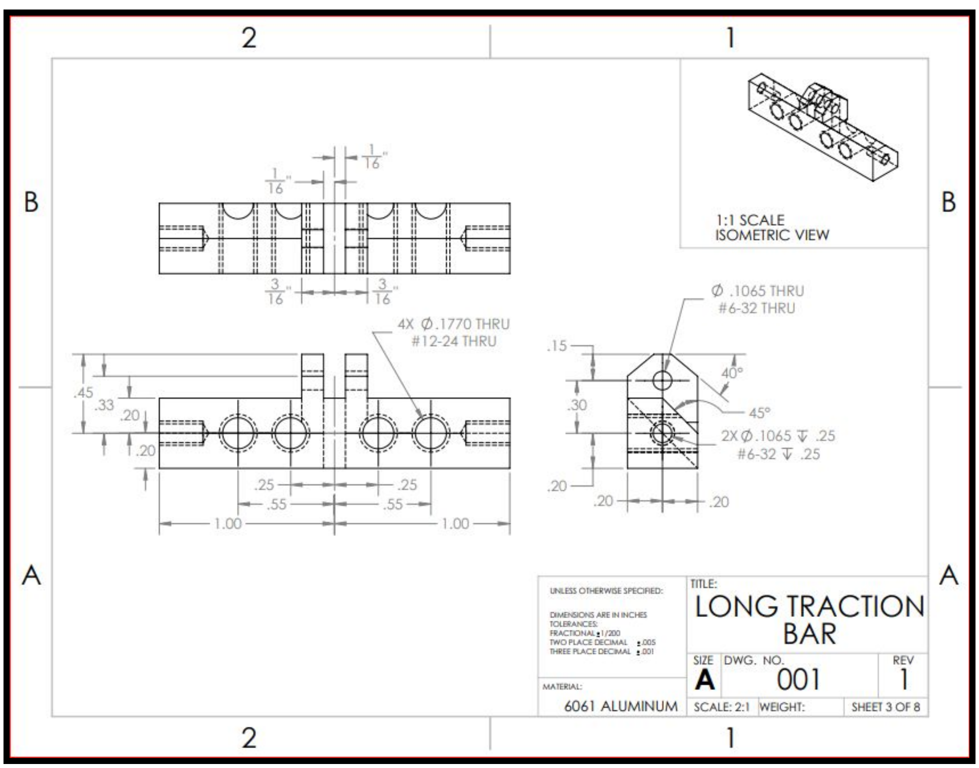


Figure E2. Detailed Drawing of Long Traction Bar

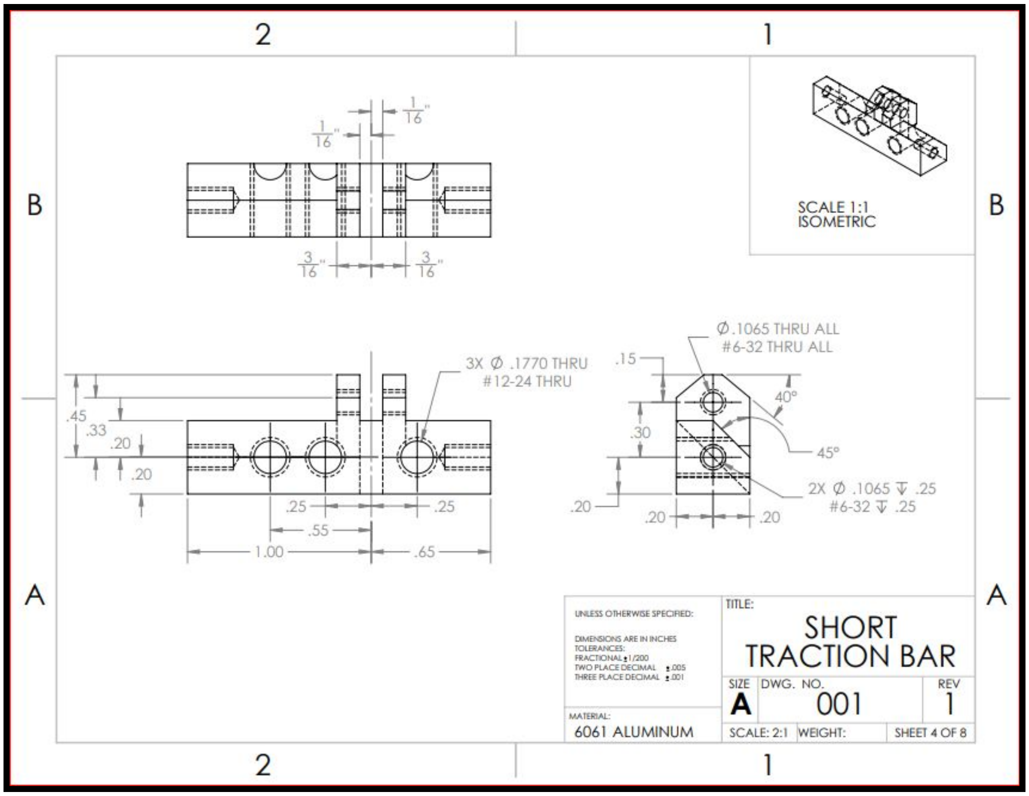


Figure E3. Detailed Drawing of Short Traction Bar

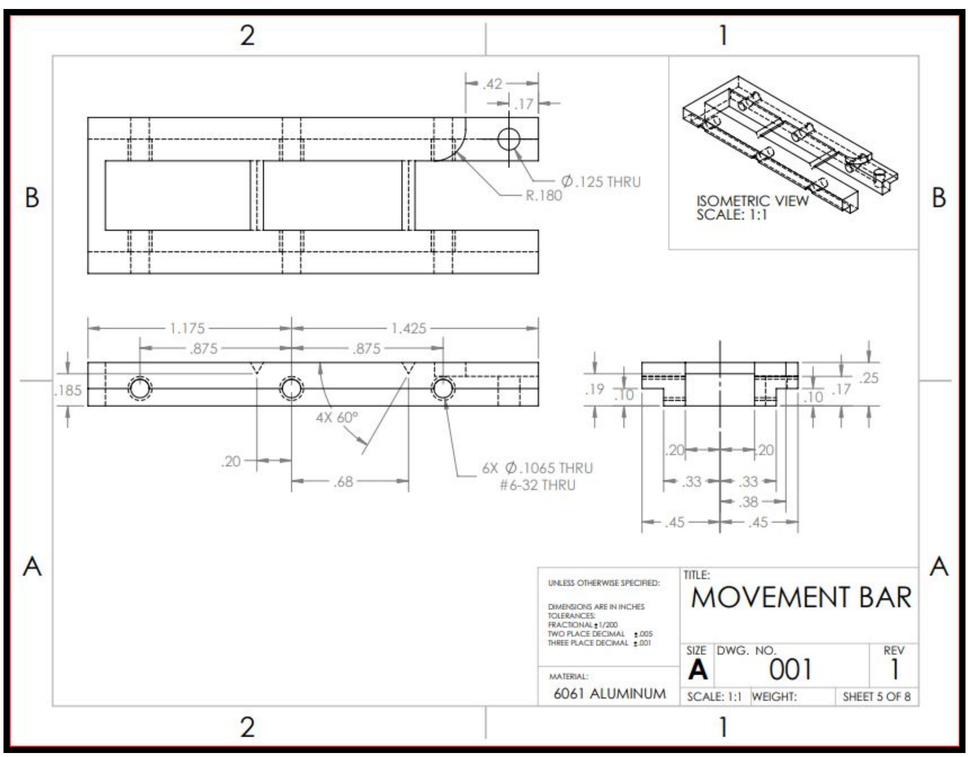


Figure E4. Detailed Drawing of Movement Bar

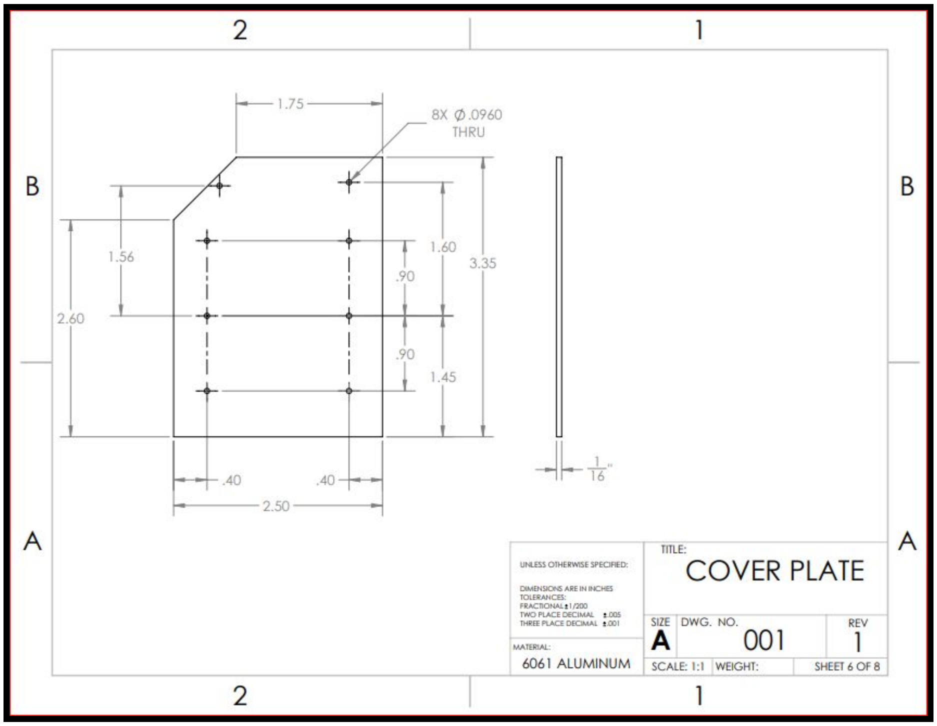


Figure E5. Detailed Drawing of Cover Plate

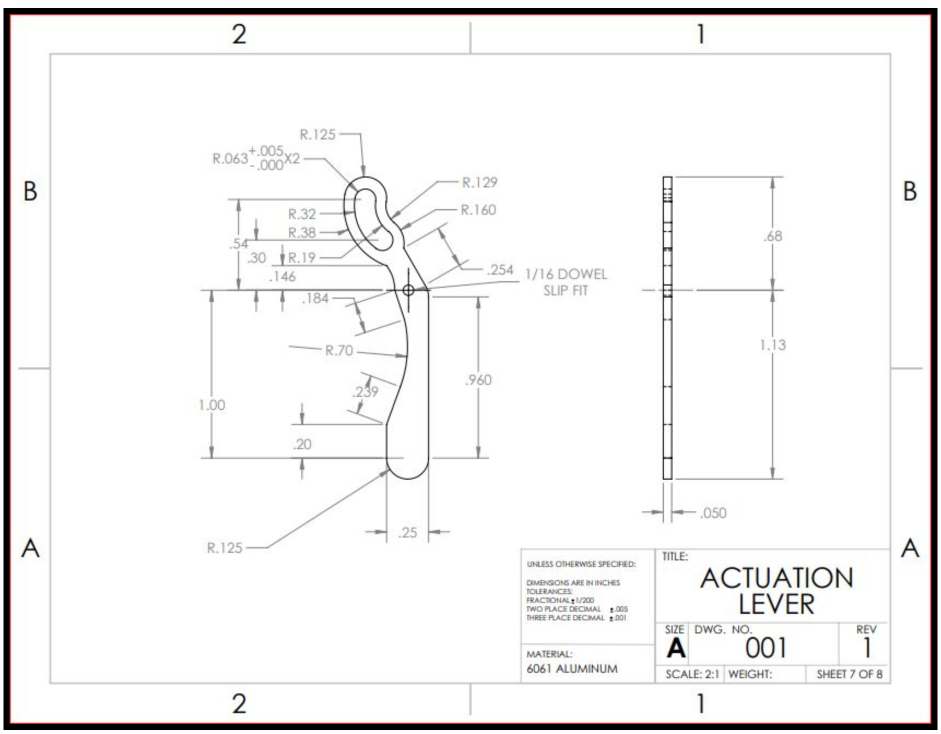


Figure E6. Detailed Drawing of Actuation Lever

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