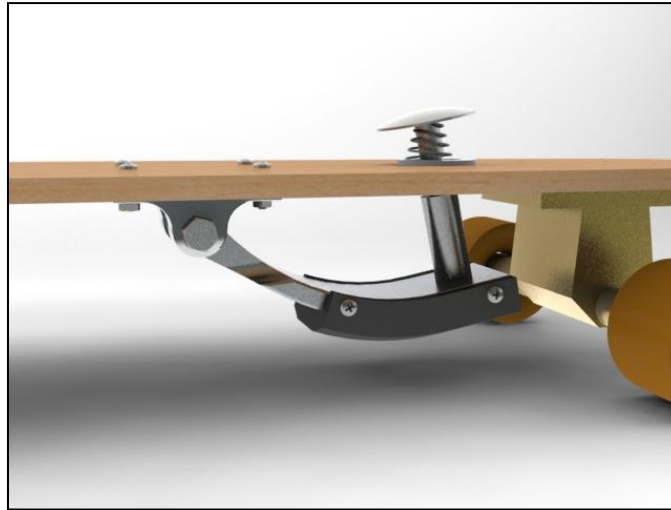


REPORT
as a requirement
for
MAJOR QUALIFYING PROJECT (MQP)
Braking System for a Longboard
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Abstract

The goal of this project was to design, manufacture and test a braking system for longboards that allows for controlled deceleration of the board and the rider. Currently longboards do not come with a system for controlling speed or stopping, and alternative methods for braking on a longboard are difficult and can result in injury. Our system allows the rider to use a pedal to transfer stepping force to a friction interface with the ground. The design process was guided by the principals of axiomatic design. The prototype was manufactured using CNC machines, rapid prototyping and urethane casting. Tests were performed for functionality, ride-ability and braking performance.

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1 Introduction

1.1 Objective

The objective is to design a braking system for longboards that provides the ability to control the speed of the board and its rider, and is attachable to existing boards. It will allow for increased control and safety during riding that is currently not available on longboards.

1.2 Rationale

The inability to safely slow down on a hill while riding a skateboard can result in serious injury due to falls or collisions. In many skateboarding accidents, the inability to slow down is a major factor. A news article from Utah in 2006 describes a 17 year old who got brain damage from a longboarding accident, and another boy who died after hitting a patch of gravel while travelling down a steep hill. The doctor treating the 17 year old said "...unlike in-line skates, longboards have no mechanism for slowing down other than the rider dragging his or her foot, which at 20 mph is not a good idea" (Page, 2006). There are methods for stopping but they require difficult maneuvers. One maneuver to slow down is to drag the sole of your shoe along the ground, but this is hard to do at high speeds. From personal experience, this causes fast deterioration of shoes. Also, the risk of losing balance and falling still exists because one foot needs to come off the board. Another method for slowing down is turning the board ninety degrees and sliding (like a snowboard), sometimes called power-slide (L3m0n, 2005). This is effective, but requires a high level of skill. It is also dangerous to perform at high speed, even for an experienced rider. A safe method for controlling speed on a skateboard could prevent or greatly reduce the chances of speed related injuries on longboards.

1.3 State of the art

Four patents and two existing products were found that provide braking functionality to skateboards. A full table with images of each can be found in Appendix A . There are currently several existing patents for skateboard brakes that could be applicable to longboards. For ease of comparison we divided the brakes into five different parts:

- Activation system: how the user activates the brake
- Transmission system: how the activation system connects to the actual brake
- Friction system: how the energy is dissipated through friction
- Attachment system: how the braking loads are transferred to the board
- Return system: how the brake returns to its off position.

1.3.1 Activation system

The Pogo Brake (Yogi, 2009) is activated by foot using a domed plastic pedal attached to vertical shaft. The pedal needs a hole through the board and it's located in front of the rear trucks. Another foot activated brake system is the 5th wheel patent (Johnson, 1977), in which there is a pedal fixed to vertical shaft, but instead of going through the board it hangs off the back of the deck. This eliminates the need to make a hole through the board, but this only works for boards that have flat tails. Another braking system that eliminates the need of a hole through the board is the Side Lever Wheel Brake system (Maloney, 1978). This one is also activated by foot, but the pedal is an angled lever that is on the side of the board.

The only hand activated system the team found available was the SkateBrake (SkateBrake's Technology, 2009). It's activated using a hand lever attached to Bowden cable. This braking system works similar to a bicycle braking system.

1.3.2 **Transmission System**

In order to activate any braking system the load from the user must be transferred from the activation system to the friction system. Most patents use levers or a shaft to transfer energy. The 5th wheel patent makes good use of the shaft transmission by adding a fifth wheel and the shaft presses on that wheel to stop. The Pogo Brake also makes good use of the shaft transmission by having the shaft directly above the friction system that contacts the ground. It's like stepping directly on the ground without the danger of your foot slipping and falling off the board.

1.3.3 **Friction System**

The Pogo Brake has a rubber pad that slides against the ground to provide a frictional force that could slow down the rider and board. Another design also applies friction to the ground, but instead of a rubber pad it uses a metal wire brush pad. The 5th wheel design has a fifth wheel that is suspended off the ground until it's activated. Then, a friction pad interacts with the fifth wheel preventing its rotation consequently slowing down the board and rider. Other patents and designs apply friction directly to the wheels of the board (Appendix A).

1.3.4 **Attachment System**

The attachment system transfers the loads from the friction system to the board. The attachment systems for most designs were the same, attaching to the board with either screws or bolts. The team assumed that this was the safest way to attach anything to the board.

1.3.5 **Return mechanism**

In order to give some control to the rider in braking there has to be a mechanism that returns the brake to its original position because the brake can't turn on and stay on. Most

systems use metal springs for either translation or angular springs. The pogo brake gives a unique approach to the use of springs by using a cantilever spring. This design is good because it is simple and aesthetically pleasing. The drum brake is returned by spring action of a bending metal plate (Berry, 2002). The side lever brake is returned to its initial position by the greater weight of one side of the lever (Maloney, 1978).

1.4 Approach

We studied existing designs for skateboard braking systems, and synthesized the positive aspects of each of them into a new design. We also developed a set of customer needs based on our experiences, as well as input from skateboarders in the area. We utilized axiomatic design to create an improved braking system that is more discreet, less costly, and requires less board modification and replacement of parts than the currently available systems.

2 Design Decomposition

Our design process started by defining what customer needs needed to be satisfied. This was important in determining what solutions could meet these needs and which would be the best choice. These needs were based on the opinions of ourselves as longboard riders as well as the input of other longboard riders that we had the chance to question. Once these needs and constraints were developed they acted as guides along with the principles of Axiomatic Design. From these principles a list of function requirements and design parameters were developed as the backbone of the design Appendix B.

Axiomatic design was helpful in braking down the design into functional requirements and helped to clarify what our design was trying to accomplish. The method of hierarchical functional requirements helps to ensure that the design fulfills what it really intends to. Thinking in the mindset of axiomatic design helped in the design review process to identify unnecessary features and to understand the specific function of each part. For example, the original design of the pin holders had unnecessary features, and when it was reviewed based on its functional requirements it was easy to identify features that didn't serve a purpose and were removed.

Although mostly helpful, it also slowed down the design process. Many times we went back and forth on how the FR's should be broken down and ordered. This is something that would become easier with experience, but proved to be frustrating during the process. One way in which the software might be improved is to offer a better way of organizing alternative DPs. We found that having to store the alternative DPs in notes made them hard to access and update, which made the flow of decision making within the software a challenge. These difficulties caused us to shy away from using the Acclaro software. The concepts of axiomatic design are

sensible and improved the thought processes that went into our design, but the procedure of using axiomatic design within the software turned out to hinder progress at times.

2.1 Customer Needs

Many of the design decisions were made based on the customer’s needs (CN). Below is a table showing what we and a few subjects at a skateboard shop believe to be the main customer needs, in no particular order.

CN1	Simple to use
CN2	No major or expensive modifications
CN3	Low cost
CN4	Easy to attach/detach
CN5	Durable parts
CN6	Reliable
CN7	Controllable and gradual
CN8	Aesthetically pleasing (looks good)
CN9	Safe
CN10	Maintenance
CN11	Manufacturability

Table 1 - Customer Needs (CN)

Some customer needs are more important than others, for example safety of the rider is more important than any other customer need. To quantify the relative importance of each CN, pairwise comparisons were used for all CNs to construct a ratio scale that is useful in making design decisions (Kemper E. Lewis, 2006).

	CN1	CN2	CN3	CN4	CN5	CN6	CN7	CN8	CN9	CN10	CN11	Total
CN1		.5	.5	1	.5	0	0	1	0	1	1	5.5
CN2	.5		.5	1	.5	0	.5	.5	0	1	.5	5
CN3	.5	.5		1	.5	0	.5	0	0	.5	1	4.5
CN4	0	0	0		.5	0	0	.5	0	.5	.5	2
CN5	.5	.5	.5	.5		0	.5	.5	0	.5	.5	4
CN6	1	1	1	1	1		1	1	.5	1	1	9.5
CN7	1	.5	.5	1	.5	0		.5	0	1	1	6
CN8	0	.5	1	.5	.5	0	.5		0	1	1	5
CN9	1	1	1	1	1	.5	1	1		1	1	9.5
CN10	0	0	.5	.5	.5	0	0	0	0		.5	2
CN11	0	.5	0	.5	.5	0	0	0	0	.5		2

Table 2 - Pairwise Comparison of Customer Needs

0 – less important, .5 – equally important, 1 – more important

Reliability and safety of the rider were the top customer needs, while manufacturability, maintenance and ease of attachment and detachment had the lowest ranking. Not all design decisions were based on the ranking of the customer needs but it helped in some cases, like when deciding between an easy part to manufacture that is not good looking or spending a few more hours in the machine shop to get an eye-catching part.

2.2 Design constraints

Our braking system was designed to the dimensions of our board (Figure 1), which is relatively short compared to other longboards and has not tail, with that said, it's not guaranteed that the braking system will work with boards with extreme differences in length or with a tail. If the board is too short, then the brake will not fit between the trucks and it's uncertain if there is a limit to how long the board could be. Other than that, some of the design constraints were:

- Use same size screws the board already has to mount brake to the board
- Must not affect normal board riding

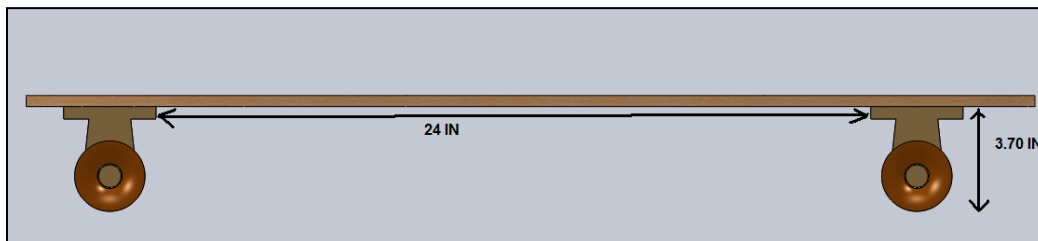


Figure 1 - Board dimensions

2.3 Provide controlled deceleration (0)

Based on the objective the main functional requirement is to provide controlled deceleration to the board and rider. To accomplish this a braking system was developed consisting of a pedal activation system, shaft transmission system, a lever and rubber pad friction system, a hinge attachment system and a spring return mechanism.

2.4 Provide controlled activation (1)

An important functional requirement that contributes to controlled deceleration of the rider is the ability for the rider to control the amount of braking applied. This requires a system of activation that allows for variable control over the amount of braking applied while still allowing normal use of the longboard's functions. The braking system will provide for control of the rider's speed as well as the ability to bring the rider to a complete stop. The acceleration from braking should be controlled gradually so the rider will not be thrown off the board due to a rapid change in acceleration. The upper limit of deceleration should be lower than the amount that would cause the rider to be thrown off the front of the board. The lower limit of activation will be no braking at all, and the activation will be normally set to this position.

The two major methods of activation that were considered were activation by hand and by foot. These two methods provide for adequate control with short ranges of motion. There were two main reasons for choosing a foot activated system. The first is that a frictional braking system with the ground was chosen, which requires a large normal force to the ground. The estimated normal force required for a full stop at constant acceleration from 20 mph in 42 ft is about 105 pounds of force. A hand lever cable assembly might be used, similar to those used in bicycle brakes, but there is a trade-off between output force and output distance, making it difficult to achieve both the required force and travel distance of the brake. The other reason is the concern of having a mechanical connection between the rider's hand and the board. This is a concern because it can be considered unaesthetic to have a cable coming off the board, and because of the possible hazards of the cable getting stuck under the wheels while the rider is holding onto the other end.

2.4.1 **Provide for ease of activation (1.1)**

The rider must be able to activate the brake so braking can be achieved quickly and safely. The action required by the rider to activate the brake must be intuitive and he/she must be able to do it fast enough to accommodate for dynamic situations on the road such as an upcoming intersection. Several alternatives were considered for activation system.

A pedal located off the surface of the board, similar to the one from the Side Lever Wheel Brake system in the state of the art, was considered. The advantage of this is that the surface of the board is left free. The disadvantage is that the foot must be moved off the board in order to reach it. The motion of the foot off the board to one side will result in a weight shift off the center of the board, and will cause an imbalance. Although a pedal on the board takes up some of the space of the surface of the board, it requires less movement of the foot to access than a pedal off the side of the board. The rider can maintain a more centered stance during breaking as well, which allows for increased stability.

2.4.1.1 ***Provide for ability for activation with sliding foot(1.1.1)***

Lifting one's foot off the board while riding, especially while travelling quickly, can cause the rider to lose balance. Because of this, it is important for the pedal to be activated with a sliding motion from the foot. Some alternatives were considered in achieving this functionality. A sloped surface would allow for the rider to move his/her foot onto the pedal using a horizontal motion of the foot. A collapsible domed surface was considered because it would not only provide activation with a sliding foot motion, but it would also provide for activation from all sides, which is the next functional requirement. This concept was never integrated due to time constraints. A dome on the top surface of the pedal was used because it is simple to manufacture.

2.4.1.2 *Provide for activation from all sides (1.1.2)*

Footing positions (stances) on the board vary among riders. It was important to provide for the ability to actuate the pedal from all sides. Symmetry in the shape of the pedal can allow for access from all sides. A circular shape of the pedal was used because it provides for the ability to use the same motion regardless of the direction that the foot moves from.

2.4.2 *Provide resistance to pedal movement (1.2)*

If the brake is applied too quickly, the assumption was made that it will cause a spike in deceleration causing the rider to be forced off the board. This can be quite dangerous and result in a fall. Resistance must be provided to the pedal movement so that the rider can activate the system without accidentally applying too much force to the brake, causing the undesired spike in deceleration. Several alternatives were considered to provide this. Since the lever must be returned to its original position to keep it in a normally off position, the same design parameter can be used to fulfill both of these requirements. The resistance force is greater than the force required to return the brake to its off position. Although coupling is normally avoided, in this case it's acceptable because the additional force does not affect the fulfillment of the FR, once sufficient force is provided to return it, any additional force will not change this.

2.5 *Transfer Loads (2)*

2.5.1 *Transfer vertical loads from foot to sliding friction interface (2.1)*

For full activation of the braking system the loads from the rider stepping downward have to travel to the sliding friction interface. This will provide the friction force necessary to slow or stop the board and rider.

2.5.1.1 *Transfer load from foot to pedal (2.1.1)*

For the rider to activate the brake with his or her foot there must be a surface on the activation that can be stepped on. The pressure on this surface will be transmitted downward to the sliding friction interface through a series of mechanisms. The top surface of the pedal fulfills this functional requirement.

2.5.1.2 *Transfer load from pedal to shaftn(2.1.2)*

With the activation pedal being above the board, shaft going through the board, and the rest of the system being below the board, the shaft must be detachable from the pedal so that the entire system may be assembled and disassembled on the board. The connection must be secure so that it stays sturdy during constant vibration of riding and several activations. It must also be strong enough to withstand the rider's stepping force. The pedal and shaft could be connected by inner threads on the shaft and outer threads on the pedal, inner threads on the pedal and outer threads on the shaft, or a threaded bolt connecting the pedal and shaft in which both would have inner threads.

Having the shaft and the pedal made of aluminum aided in having the brake be lightweight while still being able to withstand braking loads and lowering the chance of corrosion. This brought the problem of not being able to have outer threads on the shaft or pedal. Aluminum outer threads wouldn't be able to take the sheer force so either the threads would get stripped upon activation of the brake or they would deform in such a way that the connection from the pedal to the shaft is no longer secure. However inner threads are more stable on aluminum so having a threaded bolt that connects both the pedal and the shaft was the best solution. The bolt was not only stronger, but could be easily ordered.

2.5.1.3 *Transfer load from shaft to lever (2.1.3)*

With the loads from stepping being transmitted directly downward to the lever from the shaft, the connection between these two components must be secure. The connection must also be stable enough to withstand the loads so the transmission happens the same way every time the brake is applied. The solutions that were considered to solve this problem were (Figure 2):

1. Lever and shaft as one piece
2. Joint connection between the lever and shaft
3. Depression in top of lever face with rounded end at the bottom of the shaft
4. Machine screw through the lever into the bottom of the shaft

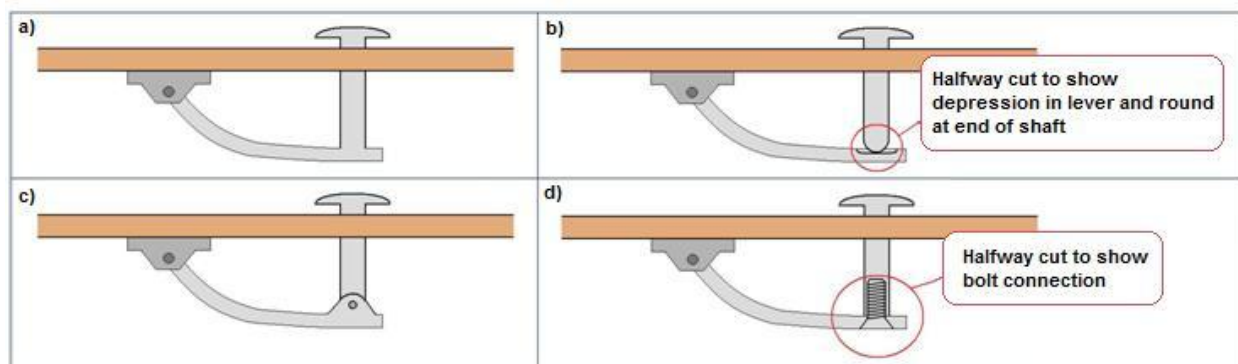


Figure 2 - a.) First alternative; b.) Second alternative; c.) Third alternative; d.) Fourth alternative

It was mutually decided that the first two alternatives would be difficult to machine. It's best to make the machining process as simple as possible to reduce machining time and cost. The third alternative had the shaft and the lever disconnected which brought up the issue of how the shaft was going to stay stable so the activation could be consistent. The machine screw through the lever turned out to be the best out of the four alternatives and was applied to the final design.

2.5.1.4 *Transfer load from lever to rubber pad (2.1.4)*

The loads transferred from the lever to the rubber pad transfer automatically upon full activation because the surfaces are parallel and touch each other. The only requirement for vertical load transfer was that the pad had to be at least as wide as the lever and long enough so the lever doesn't touch the ground unless the pad is completely worn out.

2.5.2 **Transfer horizontal loads from sliding friction interface to board** **(2.2)**

Once the loads from the rider are transferred to the ground, ending at the rubber to ground interface, a horizontal friction load is created. This load needs to be transferred to the board so that the rider activating the brake will actually be able to slow or stop the board. There were two methods accomplishing this (Figure 3):

- A system where the shaft is connected to a lever that is connected to the board at a pivot point and the friction interface is at the bottom face of the lever.
- A system where the shaft is connected directly to the friction interface and the back of that system would push on the rear truck upon activation.

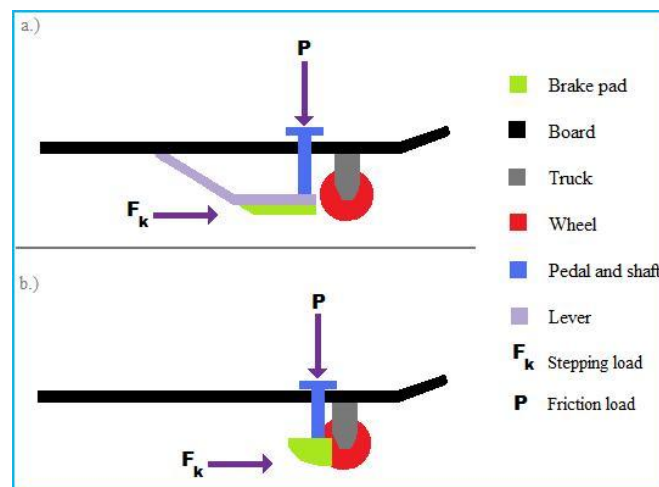


Figure 3 - a) Loads transferred through a lever to board. b) Loads transferred to rear truck

The problem with the second system was that pushing on the trucks for a brake would interfere with riding. The trucks' connection to the board isn't rigid as they actually rotate slightly for turning (Figure 4). It was decided that this design was unacceptable based on the constraint that the brake must not affect normal riding ability. The levered system doesn't interfere with the trucks because it transfers the frictional loads through the lever to a hinge that would be connected to the board.



Figure 4 - Board with front wheels strait (left) and with wheels slightly turned (right)

2.5.2.1 *Transfer load from rubber pad to lever (2.2.1)*

In order to be sure that the friction interface transfers the frictional loads to the lever effectively, the interface must be attached securely to the lever. The solutions found to address this were to adhere the pad directly to the lever, adhere the pad to a thin rigid plate that would be bolted to the lever, and bolt the pad directly to the lever. Bolting the pad to the lever was the best choice because it allowed for the pad to be removed easily if worn out which wasn't allowed by adhering directly to the lever. Also, the pad was hard enough (Appendix D) so that it wouldn't have excessive deformation to fall off the bolts and could handle the shear stresses so there wouldn't be failure in the material if bolted properly.

2.5.2.2 Provide hinge for lever (2.2.2)

For the lever to be attached to the board at the lever pivot there must be a proper hinge system. The hinge must be able to securely connect the lever to the board and be able to withstand the loads from braking.

2.5.2.2.1 Reduce stress concentrations around pin holder

(2.2.2.1)

The pin holders are two components that will be taking all the frictional loading upon brake activation and it is critical that stress concentrations are avoided in the design. Stress concentrations can be detrimental in the design of the pin holders as they can cause cracks and failure at locations where there are sharp corners or abrupt changes in the cross section. These locations bring all the stress to one point and actually act as amplifiers for the stress (Noble, 1997). Chamfering the outer corners and filleting the inner corners would better disperse the stress in the structure.

2.5.2.2.2 Provide for tight fit around pin in the pin holder

(2.2.2.2)

Because the braking system would be on a system that was in motion most of the time, the team agreed that it would be best to minimize moving parts in the brake while still being effective. This meant that the pin (mentioned in section 2.5.2.3) would have to be fixed in either the lever pivot hole or the pin holders. Having the pin fixed to one of these structures would also keep the pin fixed to the system so it doesn't come apart and cause failure. Because either fixture would yield similar results the decision was made to have the pin fixed in the pin holders. To accomplish this, the tolerance of the hole in the pin holder was made to be +0.006in (Lieu &

Sorby, 2009). This dimensional tolerance would provide a tight fit around the pin keeping it secure.

2.5.2.2.3 Provide for smooth sliding around pin in the lever

(2.2.2.3)

With the brake undergoing constant use there will be constant rubbing between the pin and the inner surface of the lever pivot point. This being said, there must be as little friction as possible to allow for smooth rotation about this point as well as to lower the chance of corrosion. The solutions considered to address this problem were to use copper bushings or to have nylon bushings. Although both solutions would provide smooth sliding around the pin and reduced chance of corrosion the nylon bushings were easier to find and cheaper to buy or replace if needed. Regardless of what type of bushings used, the hole in the lever pivot point had to be tight around the bushings so the tolerance of the hole was made to be an interference fit.

2.5.2.3 *Transfer load from lever to pin holder (2.2.3)*

In order for the hinge mechanism to be complete for the brake there must be a pin that connects the pin holders to the lever pivot point. This pin must be inexpensive and able to withstand the loads from braking. It was decided that a shoulder bolt pin would work because it was cheap, easy to order and therefore reduced the amount of machining, and could withstand the braking loads. The shoulder on the pin along with the other end of the pin being threaded allowed for the pin to be secured in the system with a nut ensuring it won't fall out after constant use.

2.5.2.4 *Transfer load from pin holder to board (2.2.4)*

Transferring the braking loads to the board is crucial for the design to actually bring deceleration to the board and rider. It was possible to adhere the pin holder to the board, tie the pin holder to the board, or bolt the pin holder to the board. Bolting the pin holder to the board was the best design parameter because it allowed for the brake to be detachable from the board if desired and the bolts could efficiently transfer the braking loads to the board and therefore cause the board and rider to decelerate. Due to the design constraints that the brake must not interfere with normal riding ability and that the board mounting must use standardized parts the bolts chosen for this were 10-32 countersunk screws.

2.6 Optimize sliding friction interface (3)

To stop the longboard from moving, friction has to be applied to either the ground or wheels. The team assumed that a system that applies friction to the wheels is able to stop the longboard smoothly since the wheels are rolling over the ground, but if too much friction is applied then the wheels will stop spinning making the board skid or make the rider fall. Also, friction on the wheels will cause the wheels to wear faster than normally. On the other hand, if friction is applied to the ground the board might not stop as smoothly (depending on the surface of the ground) but the board will not skid because the wheels will continue to spin. The decision was made to use a rubber pad that applies friction to the ground, because a design that applies friction to the wheels would most likely need alteration to the trucks.

2.6.1 Optimize contact surface between rubber pad and ground (3.1)

Ideally the rubber pad should be parallel to the ground when the brake is activated. Since the rubber pad is attached to the lever, this directly affected the design of the lever. The two alternatives were to design a straight lever with an angled brake pad or a curved lever with a

rectangular braked pad (Figure 5). Although the straight lever would've been easier to machine, the rubber pad wasn't optimal shape because it would wear faster on the thinner end. The conclusion was made that the curved lever was the better choice in order to optimize contact surface between the rubber pad and ground.

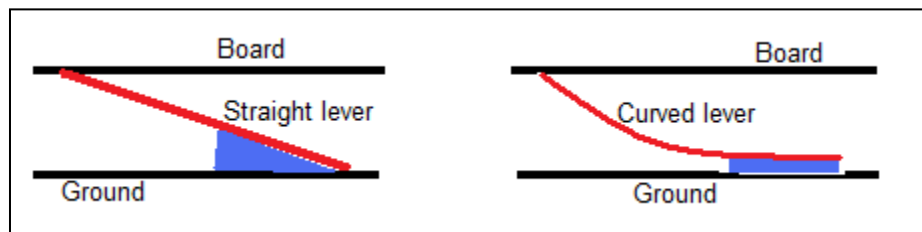


Figure 5 – Straight lever vs. Curved lever

2.6.2 Reduce wear of rubber (3.2)

The rubber pad could've been small because the friction force doesn't depend on the surface area, but heat dissipation and wear had to be taken into consideration. To reduce wear, the rubber pad was made wide enough for the heat to dissipate more efficiently and because, intuitively, the team believed that a larger contact surface area would make the pad last longer. Also, the width of the rubber pad would provide stability to the brake. Because of the limited time of the project, no detailed analysis was done in order to optimize the size of the rubber pad.

2.6.3 Provide removable interface (3.3)

Given that the wear of the rubber pad is inevitable, an important functional requirement is to provide the ability to replace the rubber pad whenever it wears down. The detachable rubber pad has to be easy to replace, yet it should be reliable and not unfasten while the brake is being used. The decision was made to use bolts on the side of the rubber pad to attach it to the lever. One alternative was to glue the rubber pad to a removable metal plate, but this idea was discarded because it was relatively complicated with no improvements in the final result. What

size bolts and how many were needed to attach the rubber pad to the lever will be discussed in section 3.5.

2.6.4 Minimize the effects of inconsistent ground surface (3.4)

Again, inconsistency in the ground surface is inevitable unless the user is riding the long board in a skate park. One of our assumptions was that bumps in the road could become dangerous if the brake was activated accidentally because the rubber pad touched the ground. The team believed that a curved rubber pad surface would provide gradual contact with the ground thus minimizing the risk of the brake being activated accidentally.

2.6.5 Provide consistent braking while turning (3.5)

Another of our assumptions was that braking while turning is a necessity in order to provide a controlled ride. To provide consistent braking during cornering the maximum tilt of the board while turning was calculated to be 17 degrees, hence, 17 degree chamfers were added on both sides of the rubber pad to provide a consistent braking surface.

2.7 Provide path from shaft to lever (4)

It was mutually decided that the loads from stepping would be transferred normally from the pedal to the shaft. This being said, there must be a pathway on the board for this load transfer to be possible. This pathway must be short, simple and controlled.

2.7.1 Simplify path (4.1)

The lever arm, which is under the board, has to connect to the pedal which is on the top of the board. One alternative was to design system that went around the board, but it would've had too many moving parts making the system complicated. Some other alternatives included using magnetism and electricity in order to not have to perforate the board, but again, it would've

been complicated and perhaps unreliable. Keeping in mind the customer need of low cost, the previously mentioned solutions were discarded. The assumption was made that a hole less than 1.00in diameter through the board shouldn't change the board's functionality. Therefore, a hole big enough for the stem of the pedal to go down, but small enough so that the shaft doesn't go up was drilled.

2.7.2 Reduce Wobble (4.2)

Since the diameter of the bottom of the pedal is smaller than the diameter of the hole through the board, the pedal had some free space to move in undesired directions. To prevent this undesired motion a grommet was used to cover the hole on the board. At the same time it would make the hole an oval shape preventing the shaft from moving in undesired directions, as shown in the figure below.

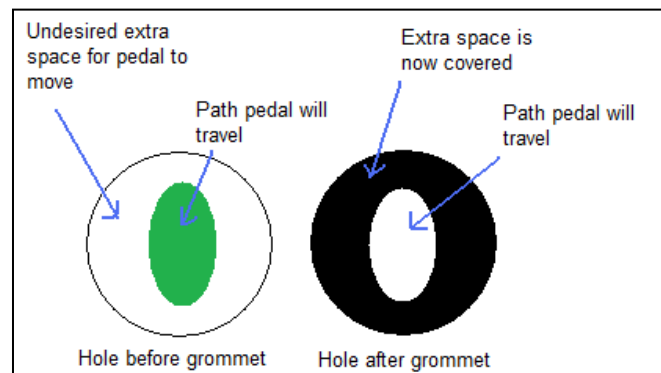


Figure 6 - Hole before and after grommet

2.8 Provide for adjustable clearance under the board (5)

Adjustable clearance under the board is necessary to account for varying rider weights, wheel sizes and trucks. Alternative methods for achieving this in the design were considered. Interlocking pipes with a clamp would resemble the system used to adjust the height of seat post of a bike. The interlocking pipes could also be adjusted with coinciding holes in the pipes. These could be fixed in place with a pin.

The interlocking pipe system was an idea, but was never fully developed. A threaded interface was chosen because it could be integrated into the existing shaft design easily. 0.5in of clearance was achieved with this system. This was enough adjustability to account for the wear of the pad but not the other varying factors.

2.9 Provide for normally off position (6)

During normal riding the brake must be set in a normally off position because it is desired that no braking should occur until activated by the rider. Several alternatives were considered to provide this functionality. One consideration was torsion springs attached around the pin and connected to the lever (Figure 7).

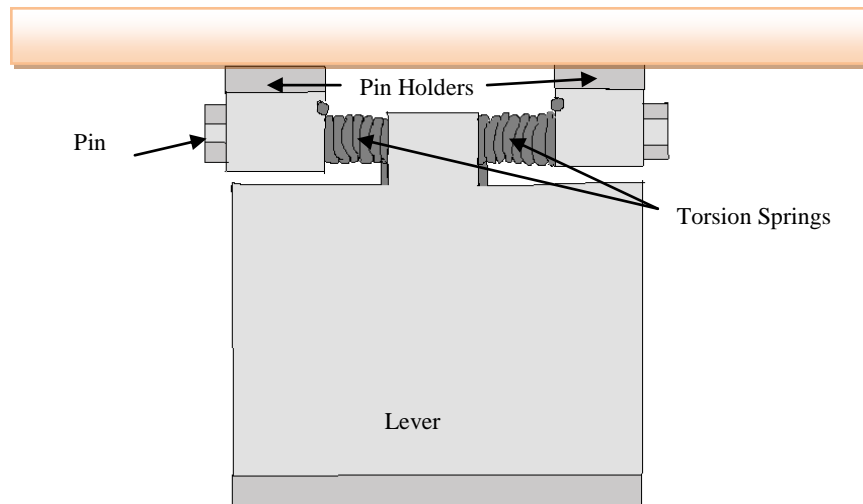


Figure 7 – Torsion spring return system (front view)

A cantilever spring that interacts between the underside of the board and the lever was also considered (Figure 8). A strip of metal attached to the lever would act as a cantilever spring and return mechanism.

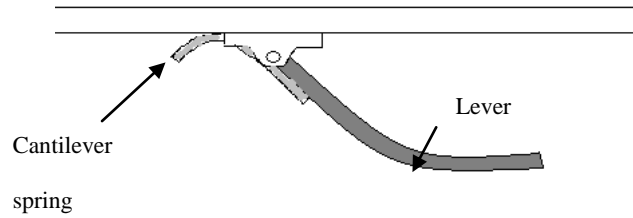


Figure 8 – Cantilever spring return system (side view)

Extension springs attached to the underside of the board were ruled out because they are unaesthetic, and would require a fixture to the underside of the board. Minimizing the amount of board modification was taken into consideration. The decision was made to use a conical compression spring that sits between the pedal and the board. A conical spring has a low compressed length and can keep the pedal at a lower height above the board in its uncompressed state. Calculations for the preload on the spring necessary to hold up the transmission and lever can be found in Appendix H.

3 Physical Integration and Finite Element Analysis

This section shows what the parts physically look like and how each FR is met through each component. Appendix B shows the decomposition of each of FR followed by figures pointing them out in the actual design. Figure 9 shows the assembly of the braking system with all the components attached and it should help visualize the purpose of each component when they are discussed in more detail later in this section.

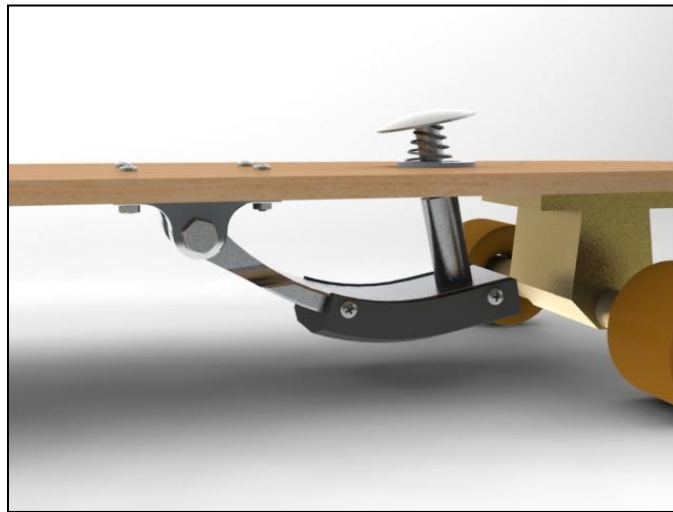


Figure 9 - Braking System Assembly

This section also contains the finite element analysis conducted prior to machining the major load bearing components of the system. These components were the pedal, shaft, pin holders, rubber pad and pin. Other components like the spring are also discussed in this section, although finite element analysis was not necessary. Components were constrained according to the mounting conditions and stresses were verified to ensure that no component exceeded the yield stress of the material. Deflections were observed to ensure the component did not deflect to an extent as to inhibit proper functionality. Unless otherwise specified, all the components are made of Aluminum 6061-T6. The yield strength for this material is 40 ksi. The reason the team

choose this material is because it is the most common metal used in the school because of its material properties and the relative low price.

3.1 Pedal

The pedal is the only component that the rider interacts directly with to activate the brake. The functional requirement that the pedal satisfies are to provide ease of activation by being able to be activated by sliding the foot and being able to be activated from all sides. In order to activate with sliding foot the pedal has a dome shape and is symmetric from all sides. Some other functional requirements satisfied by the pedal are to provide an upper limit for the spring and to transfer the loads to the transmission system, as illustrated in Figure 10.

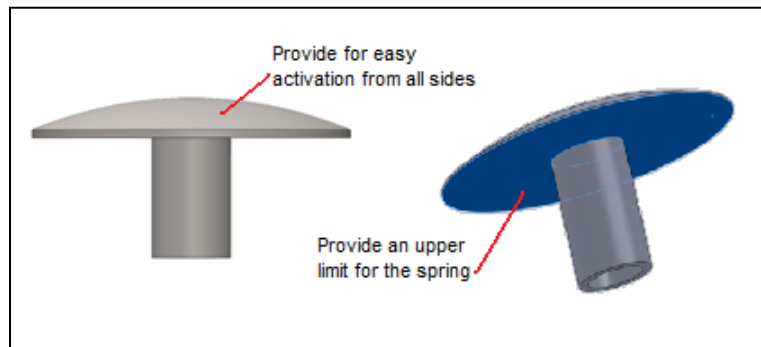


Figure 10 - Pedal FR's and DP's

Again, before machining this part finite element analysis was conducted in order to find the safety factor of the component. The team decided to design the pedal to be able to support the force of someone actually jumping on the pedal. This is not the correct way to use the pedal, but just in case a user decided to test the strength of the pedal it was designed to withstand high loads. Using a force plate from the Physics Department at WPI, we found the average force when landing was around 330 pounds of force, so this is the force we applied to the pedal. The safety factor was 6.4, meaning it could sustain the force of a user jumping on the pedal.

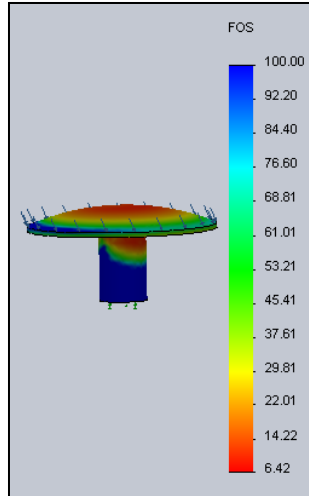


Figure 11 - Pedal FEA (Factor of Safety)

Mesh type	Solid Mesh
Element size	0.082928 in
Number of elements	7393
Number of nodes	12510
Min stress	2.8 psi
Max stress	6.213 ksi

Table 3 - Pedal FEA Summary

3.2 Spring

The spring's main function in the brake was to return it to an "off" position so it would deactivate once the rider wasn't stepping on it. This added control to the rider so he could activate and deactivate the brake at any time. It does this by resting between the pedal and the board (Figure 12), providing an upward force upon compression that will bring the pedal back up once there is no longer a stepping load. This slight resistance against the stepping force also grants control to the rider. This means that the brake isn't fully activated when the pedal is stepped on and the rider can decelerate as gradually as he needs. The spring constant of the spring was 7.81 lbf/in.



Figure 12 - Spring

3.3 Shaft

The shaft is the component that transfers the loads from the pedal down to the lever arm. It is connected to the pedal and the lever by two separate fasteners, a threaded stud and a machine screw (Figure 13). The attachment between the pedal and the shaft could have been achieved by a direct connection between the pedal and the shaft. This could be done using outer threads on the pedal which screw into the tapped hole in the shaft. This was not done because the machining of outer threads was more difficult and less repeatable than tapping inner threads on each side.



Figure 13 - Exploded Sub-assembly

The shaft also provides adjustable clearance between the pad and the ground using two locknuts between the machine screw and the shaft. The shaft can turn along the machine screw and be locked into position using the locknuts.

Plain carbon steel (Appendix F) was used for the shaft, the stud, and the machine screw. This material was used because it was easily available for use in the prototype, and can hold threads better than aluminum can. In terms of corrosion this material is not optimal, as steel will certainly corrode in a wet environment. The interface between the aluminum pedal and the steel stud will also introduce galvanic corrosion.

To ensure that the shaft and the fasteners could withstand the stepping loads placed on it during braking, FEA was performed on the assembly. A load of 200 lbs was placed on the top surfaced of the pedal at a slight angle to simulate a rider's weight being placed onto the brake. This is a higher load than will be experienced during braking, but the system should be able to withstand a rider standing on it without yielding. Stress concentrations appear in the threaded rod, and the minimum safety factor for the system was 2.57 as can be seen in Figure 14.

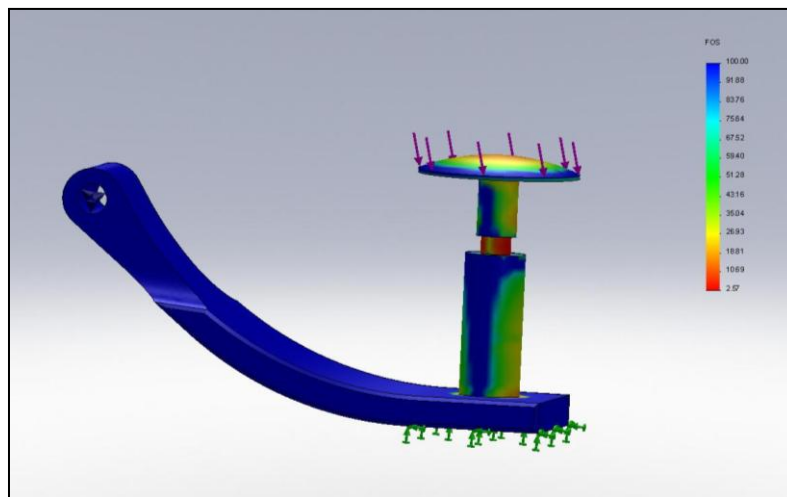


Figure 14 - FEA of assembly of pedal, shaft, and lever

Mesh type	Solid Mesh
Element size	0.15149 in
Number of elements	15612
Number of nodes	25595
Min stress	3.28 psi
Max stress	12.372 ksi

Table 4 - Shaft sub-assembly FEA summary

3.4 Lever arm

The lever is the rotating member that transfers the normal loads from the shaft to the rubber pad creating a friction load on the ground. At the point where the shaft transfer's stepping loads to the lever there is a hole in the lever for a bolt assuring connection in activation and return position. This member is securely connected to the rubber pad with side bolts so these friction loads get transferred to the board by means of a hinge mechanism. The curved shape of the lever provides an optimized contact surface between the rubber pad and the ground so when the brake is fully activated the flat surface of the pad is flush with the ground. The hole in the lever pivot point was given an accurate tolerance so that the bushings would fit tightly in those holes preventing sliding. Figure 15 below shows the lever and features that satisfy these functions.

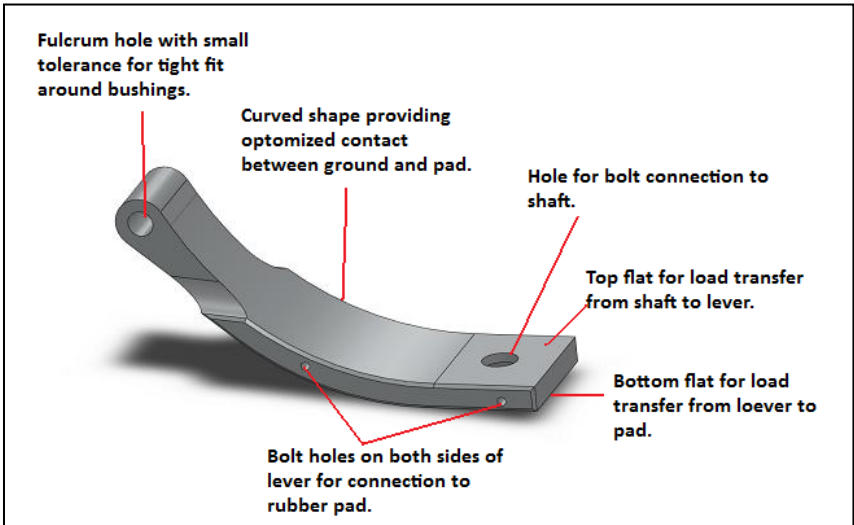


Figure 15: Lever with labeled features

Finite element analysis was performed on the lever to see how it would handle the stresses from the friction loads that would be created upon braking. 200lbs of force were applied to the surface where the shaft would be attached and 100lbs of force were applied to each of the holes where the bolts would be. The safety factor was 14.

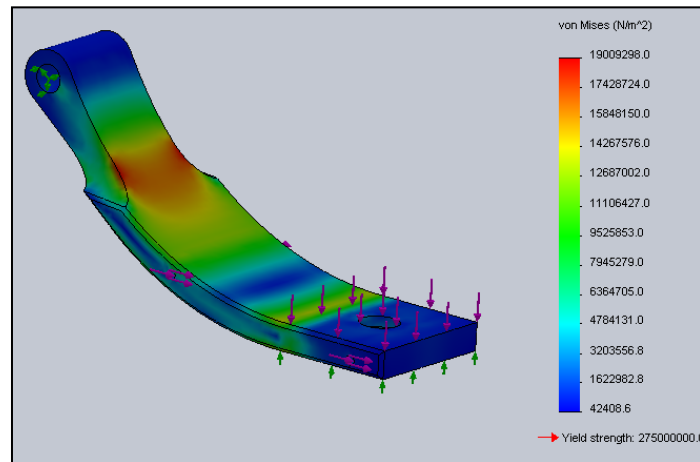


Figure 16 - Lever FEA

Mesh type	Solid Mesh
Element size	0.16902 in
Number of elements	9113
Number of nodes	15185
Min stress	6.51 psi
Max stress	2.757 ksi

Figure 17 - Lever FEA Summary

3.5 Rubber Pad

The rubber pad's functional requirements are to transfer load from rubber pad to lever, optimize contact surface between rubber pad and ground, reduce wear of rubber, provide removable interface, minimize the effects of inconsistent ground surface and provide consistent braking while turning. Since the lever and the rubber pad are directly connected, the functional requirements optimize contact surface and reduce wear of rubber are satisfied by the lever being curved and wider where the rubber pad is attached, respectively. The other functional requirements are met by the rubber pad's design. To transfer the load from the rubber pad to the

board and to provide a removable interface the rubber pad has 4 holes that attach it to the lever. In order to minimize the effects of inconsistent ground surface the rubber pad is curved so it can glide smoothly over little obstacles in the ground. To provide consistent braking while turning the rubber pad has 17 degree chamfers on the sides. Figure 18 below shows the rubber pad with it's functional requirements and design parameters that meet them.

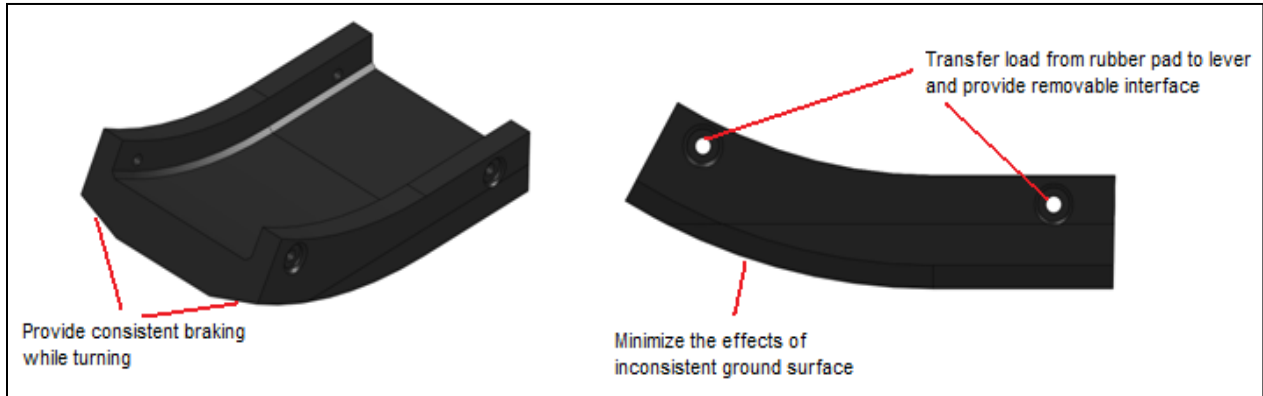


Figure 18 - Rubber Pad FR's and DP's

During the design of the rubber pad, it was necessary to know what size holes and how many will be necessary to make sure that the rubber wouldn't fail while it was being used. Using the SolidWorks finite element analysis feature, the team found that four holes of 0.1275in diameter (two on each side) would be sufficient to hold the rubber pad in place without it failing. The team applied a shear force of 100lbs to the bottom of the rubber pad while making the holes the restraints. The safety factor was found to be 2.08. Figure 19 and Table 5 below show the results.

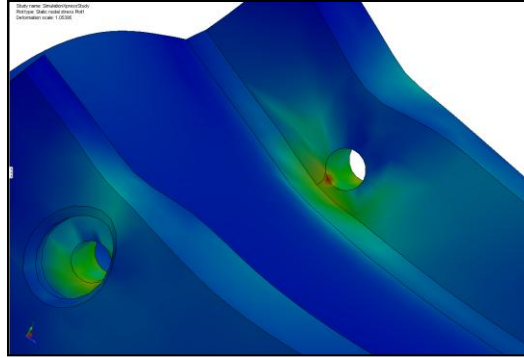


Figure 19 - Rubber Pad FEA

Mesh Type	Solid Mesh
Element Size	0.176 in
Number of elements	8715
Number of nodes	14321
Min Stress	3.46psi
Max Stress	1.022ksi

Table 5 - Rubber Pad FEA Summary

3.6 Pin Holder

There are two pin holders and their main function is to provide a hinge for the lever. Their other functional requirements are to transfer loads to the board, reduce stress concentrations and provide a tight fit for the pin. To transfer loads from the pin holder to the board two 0.19in diameter holes were drilled in order to attach each pin holder to the board with 10-32 fasteners. The locational clearance fit was accomplished by designing the hole for the pin with tight tolerances and stress concentrations were reduced by providing rounds of 0.5in diameter. Figure 20 below shows the design parameters that fulfill each of these functional requirements.

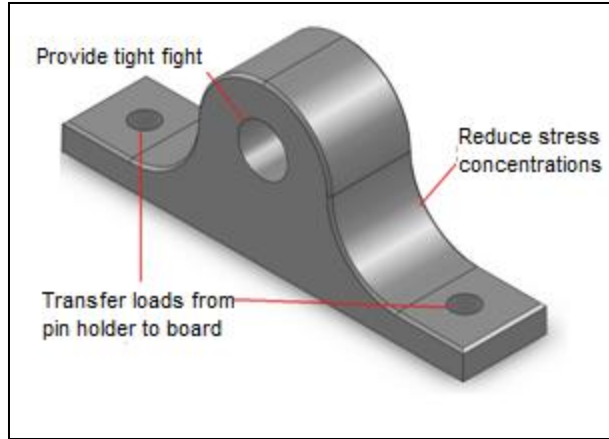


Figure 20 - Pin Holder FR's and DP's

To ensure the pin holders could sustain the loads without failure a finite element analysis was done in SolidWorks. The force used was 200lbs, which is 4 times higher than the maximum force the team calculated was needed to brake. The safety factor was found to be 5.76. Figure 21 and Table 6 below summarizes the results.

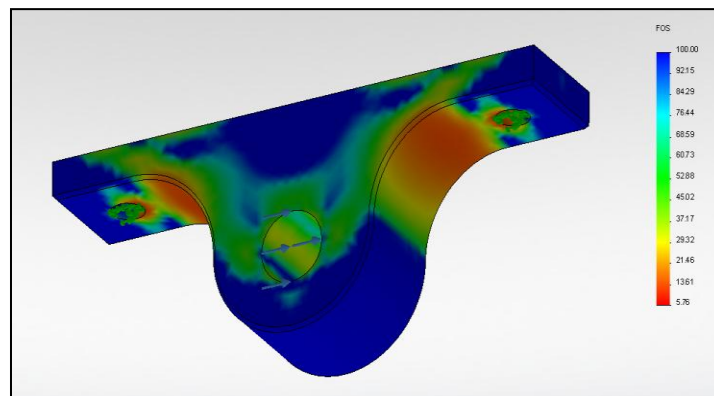


Figure 21 - Pin holder FEA

Mesh type	Solid Mesh
Element size	0.0972 in
Number of elements	7793
Number of nodes	12481
Min stress	0.069 psi
Max stress	932.28 psi

Table 6 – Pin Holder FEA Summary

3.7 Pin and nylon bushing

The function of the pin is to transfer loads from the lever to the pin holder. The pin also provides for rotation of the lever. A threaded shoulder bolt was used for the pin so that it could be prevented from moving axially. At one end the head of the shoulder bolt prevents axial translation, and at the other end a nut (not shown) is screwed on to the threaded end of the shoulder bolt. The material used was zinc plated steel (Appendix G).

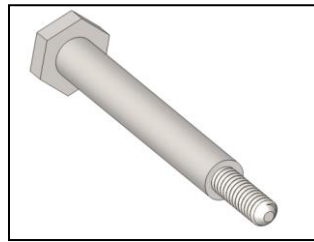


Figure 22 - Threaded shoulder bolt (pin)

The nylon bushings provide for a proper sliding interface between the pin and the pin holders. They also provide a barrier between the dissimilar metals of the pin and the pin holder which prevents galvanic corrosion. FEA was performed on the pin to ensure that it can handle the loads without yielding. Figure 23 and Table 7 show a summary of the results

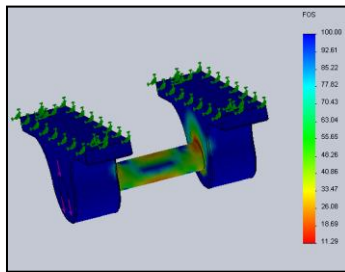


Figure 23 - Pin FEA

Mesh type	Solid Mesh
Element size	0.12832 in
Number of elements	8792
Number of nodes	14430
Min stress	.117 psi
Max stress	1.604 ksi

Table 7 - Pin FEA Summary

4 Prototype Production

4.1 Milling

In the production of our prototype two parts had to be milled and fixtured. Due to the complexities in shape of these parts to be milled, special fixtures needed to be designed and milled as well. Throughout this process there were several problems that occurred as foretold by the project advisor; most of which were solved, but some merely served as educational experiences.

4.1.1 Fixture process

Both the pin holders and the lever arm are symmetric about their central axis (Figure 24). Because of their complex shape once one side was machined, they needed special fixtures to hold the machined side while machining the other. This allowed the other side to be faced off or machined as a mirror image of the first side.

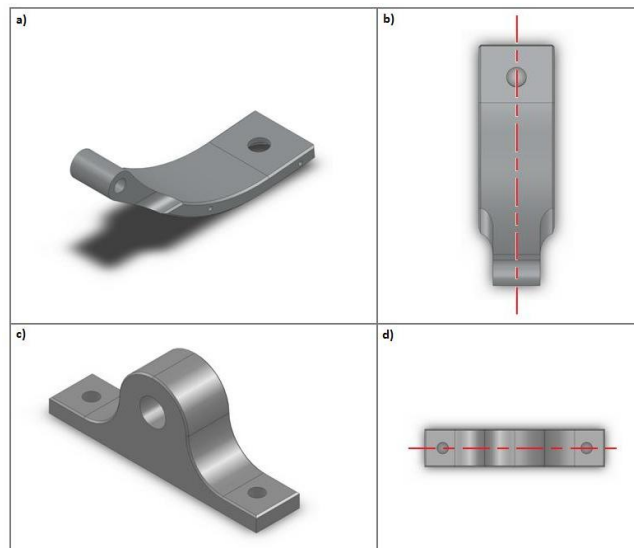


Figure 24: a) Isometric lever; b) top view lever showing axis of symmetry; c) isometric pin holder; d) top view pin holder showing axis of symmetry.

The pin holder had a flat bottom and a rounded top. Regular soft jaws were sufficient to fixture the part for machining the first side, but once that side was machined one of the soft jaws were machined to hold the round side of the part. In order to effectively fixture the rounded feature on the pin holder, there needed to be more than one point of contact in that fixture. This was accomplished by making a “V” indent on the soft jaw that would be on the rounded side (Figure 25).

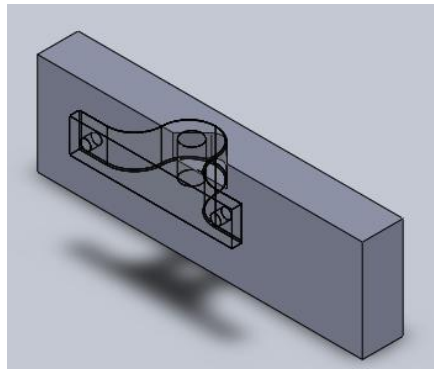


Figure 25: Machined soft jaw with transparent pin holder.

Because the lever had a more complex shape, a more complex fixture (Figure 26) had to be developed to hold it to machine the other side. With the way the lever is shaped it wasn't as simple as to design jaws that came in from positive and negative y-axis. There was a concern with the elastic deformation during machining that would prevent the mirror machining. To prevent this deflection, the fixture was designed to have a base that two vice grips would approach from the positive and negative y-directions and from the base a connected rod that goes through the pivot point of the lever with a tight fit. There is an extrusion from the base that interfaces with the top face of the lever and the vice grip acting as an extension of the vice grip to the work piece. The part of the base where the rod is located interfaces with both the positive and negative approaching vice grips. This fixture acts as a locator to assure the part is in the

correct position relative to the tool for machining. The vice grips come in from the positive and negative y-axis to apply force that keeps the part and fixture in position during machining.

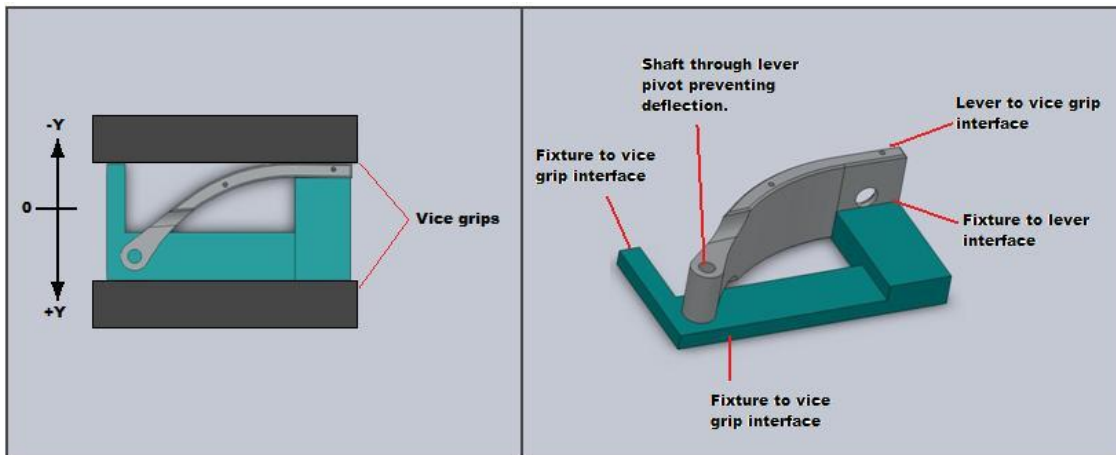


Figure 26 - (left) Orientation of vice grips relative to fixture device (right) Fixture and part with labeled interfaces

4.1.2 Problems

It was advised that the machining of the prototype be started as soon as possible before the project due date to ensure there was enough time to deal with machining problems if any arise. This was a good consideration because there were several issues that came up within the process of trying to manufacture the prototype such as machine time, tooling, error in stock measurement, and machining for desired tolerances.

4.1.2.1 *Reduce machining time*

When the first side of the lever arm was machined it was decided to have to the main shape of the lever machined using a contouring operation. The problem with this was that due to the shape of the lever and the stock used there was a lot of air machining and this made the machine run for over three hours just on that one side. To improve this process for the other side instead of using a contouring operation to create the main shape of the lever, a pocketing operation was used having the lever as an island and the outer edges of the stock as open edges

(Figure 27). This eliminated all the air machining and greatly reduced machining time to be around a half hour.

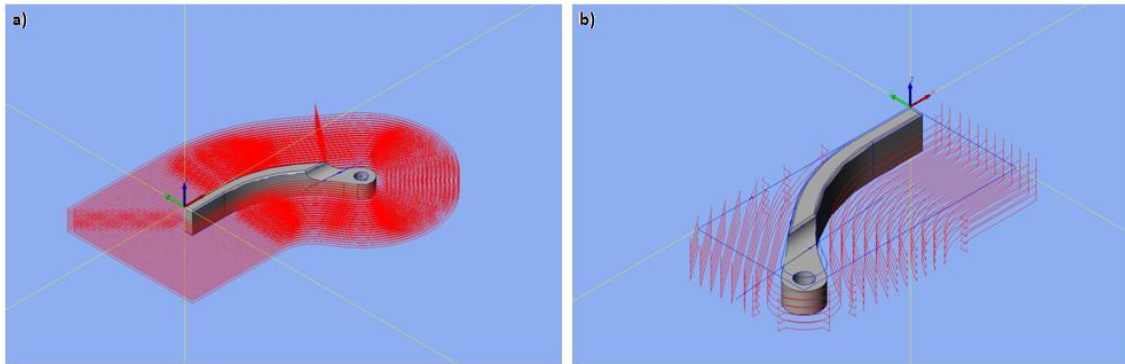


Figure 27: a) contouring first side showing unnecessary tool path; b) pocketing operation of second side of lever.

4.1.2.2 *Proper tooling for hole operations*

When machining the pin holders it was found that a chamfer mill may not be the best choice for drilling holes. This may sound obvious to a more experienced machinist, but being novices this wasn't immediately obvious. The first pin holder's hole was machined 0.75in deep using a 0.375in chamfer mill without any problems. Using the same tools and the same program, from ESPRIT, on the second part the chamfer mill plunged into and got stuck in the work piece. After some advice from experienced lab monitors the program was changed so the hole operation was spotted with the chamfer mill and drilled with a 0.375in drill bit instead.

4.1.2.3 *Error between stock size and model in machining*

When going from the modeled simulation of machining operations to actual machining for parts such as the pin holders and the fixture device for the lever arm there was an issue of extra material being left behind from some facing and contouring operations. After a facing operation on the pin holder and a contouring operation on the fixture device there was a thin

sheet of metal left over in an area where there was expected to be nothing. This may have been due to human error in measuring the stock for these parts because the stock wasn't faced on all sides assuring parallelism between opposite sides and perpendicularity between adjacent sides. These pieces of extra material were able to be pulled off without damaging any critical features. In the future, measuring of the stock piece should be done more accurately.

4.1.2.4 *Tolerances for holes*

After machining the pin holders the holes in the pin holders were observed to have a different fit on the pin than desired. The tolerance on these holes intended for a locational clearance fit so that the fit would be tight on the pin holders preventing motion of the pin, but still allow for hand assembly. There was an agreement between the group that this wouldn't be detrimental to the final product and due to the difficulty in getting machine time there wasn't another attempt to re-machine them. This acted as a lesson for machining the lever pivot point so that hole could have the desired tight tolerance. It was found that reaming was a more accurate machining process for tight tolerance holes. Knowing this, the lever pivot point was drilled with a 0.4844in drill and reamed with a 0.5in reamer. This resulted in a press fit for the nylon bushings in the lever pivot point.

4.2 Turning

Two of the components in the braking system were manufactured on a CNC lathe because of their cylindrical symmetry: the shaft and the pedal. Both operations were fairly simple, not requiring any special fixtures or tooling. However, the order of machining processes for the pedal was significant in order to ensure that it could be fixed properly at each step. The only significant issue encountered in the machining process was the use of a relatively long drill bit in the drilling of the hole in the pedal. Using a bit that is longer than necessary is undesirable

because it causes extra drill wander, which negatively affects tolerances. Since the hole drilled was going to be tapped, the tolerance on the diameter of the hole was not critical.

The pedal was turned using two machining processes, one for the stem, and one for the top surface. (Figure 28) The stem was machined first because once the stem feature was created it allowed for a simple fixture in a collet, while the outer rim of the top of the pedal would not offer enough surface area for a secure fixture.

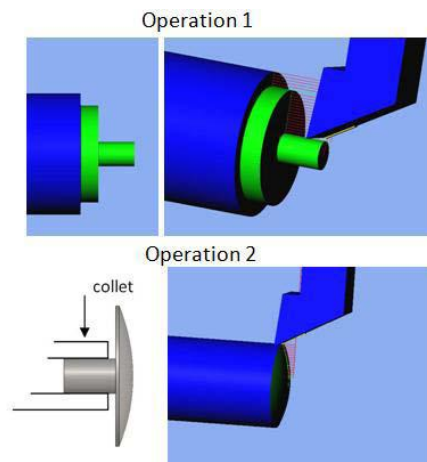


Figure 28 - Machining operations for pedal

4.3 Rubber Casting

4.3.1 Mold

The rubber material for the friction pad started as a liquid that needed to be casted, so a proper mold was necessary. The mold was designed using the rubber pad solid model and using the integrated molding tools in SolidWorks. The mold turned out to have intricate shapes not easy to machine, so the team decided to use the rapid prototyping machine. The rapid prototyping machine took a virtual design from SolidWorks and created thin horizontal cross sections built on top of one another until the prototype was complete. Figure 29 shows the top and the bottom of the mold after it was rapid prototyped.

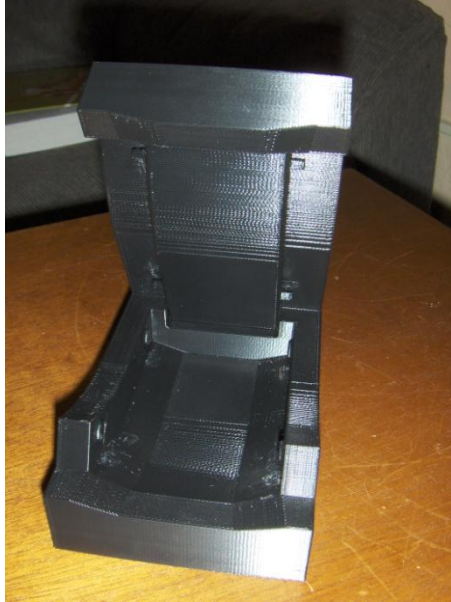


Figure 29 - Rapid prototyped mold

The team decided to use 60A liquid urethane for the rubber pad because of the material properties (Appendix D). Since the molds were made out of ABS plastic it was ensured that the urethane could cure at room temperature. Since we had no molding experience we asked for the help of Kenneth Stafford, a robotics' team advisor with experience molding the same urethane as our brake pad would be made of. He advised to add breathing holes to the mold and to pick a non critical surface of the mold to pour the rubber in because bubbles will form on the top of the mold. He has tried getting rid of the bubbles by using vibrations and other methods, but all methods failed to get rid of the bubbles completely.

4.3.2 Casting

4.3.2.1 Prerequisites:

Following Kenneth's advice the team had to find the best place to inject the urethane, how many injection holes were needed and their sizes. The team decided that the least critical part of the rubber pad was the surface that touched the lever, so the injection holes were placed

4.3.2.3 Procedure

1. Spray the silicon on the mold and make sure it is well lubricated
2. Spray silicon on the metal studs and put them into the holes inside the mold
3. Mix for 2 minutes maximum, because instructions said that the rubber would start curing in 10 minutes, so we figured that 8 minutes of injecting should be enough
4. Use the syringe to put the urethane mixture inside of the closed mold.
5. Leave it closed for about 8 hours, but it wouldn't be fully cured for at least a week.

4.3.3 Problems

As expected, the team ran into many problems during the casting process. First, the syringe was too small and the mixture was much denser than expected so it was very difficult to inject the mixture. In fact, the urethane started curing inside of the syringe so we couldn't use it anymore (Figure 31). When the syringe became useless, 10 minutes had already passed so all of the liquid urethane was already dried. When we opened the mold we noticed that we didn't accomplish much by injecting the urethane because it was pretty much empty inside.



Figure 31 - Dried rubber inside syringe

4.3.4 Casting (Second Try)

With our knowledge of the previously failed casting experiment the team decided to try the casting again but with a different technique. Instead of injected the liquid urethane, we decided to make a box the same size as the mold in order to fit the bottom side of the mold in it. The box was much taller than the mold because our strategy was to pour all the urethane into the box and then put the top of the mold on top and close it. This strategy was messy but it prevented

the mold from curing before we had the chance to pour it all in. As shown in Figure 32 the rubber pad casted very well, but in Figure 33 it can be seen that the casting wasn't perfect because the corners are missing. This corner was important because this is where the screws holes were suppose to be, but team decided that this cast was good enough and that we could work around that by making screws holes elsewhere.



Figure 32 - Rubber Pad casted



Figure 33 - Rubber Pad missing piece

4.4 General Assembly

To assemble the completed prototype (Figure 34) three sub-assemblies had to be assembled. These assemblies were the pedal-sub, the lever-shaft-pad-sub, and the board-sub.



Figure 34: Exploded assembly of brake system showing all parts without board

4.4.1 Lever-shaft-pad-sub

For the lever-shaft-pad-sub (Figure 35) the bushings were pressed into the lever pivot point. One of the bushings was cut ~0.25in shorter so both of them could fit. Once these bushings were pressed in place they were difficult to take out without defecting them. A machine bolt was screwed through the other hole of the lever, from the bottom, and a shaft on top of the lever screwed tightly. The pad was placed around the bottom of the lever so the curve of the lever screwed tightly. The pad was placed around the bottom of the lever so the curve of the pad followed the curve of the lever and was bolted on the sides.



Figure 35: Lever-shaft-pad-sub

4.4.2 Pedal-return-sub

To assemble the pedal-return-sub (Figure 36) the threaded bolt was tightly screwed through the stem of the pedal. The spring was placed around the stem of the pedal with the small diameter of the spring touching the bottom face of the pedal and the large diameter away from that face.



Figure 36: Pedal-return-sub

4.4.3 Board-sub

In order to make the holes in the board for the board-sub a positioning assembly needed to be built. To do this the pin holders were placed on both sides of the lever pivot point of the lever-shaft-pad-sub and the pin was put through the pin holders and fixed with a nut on the threaded end of the pin. This positioning assembly was placed on the bottom of the board near the back truck with the pin holders in front and lever in back. Once the positioning assembly was in place, the location of the 0.19in holes, for the fixture bolts, and a 1.25in hole, for the grommet, were marked and drilled. The 10-32 machine bolts and grommet were then put into place from the top completing the board-sub.



Figure 37: (left) position assembly placement; (right) board-sub

4.4.4 Final assembly

The pin holders were taken off the lever and put on the bolts under the board without nuts in place. This was done to keep the pin holders loose for proper placement of the lever-shaft-pad-sub, accounting for the curve about some boards' axis of motion. The lever-shaft-pad-sub was placed between the pin holders and pin was placed through the pin holders similar to Figure 37. Nuts were tightly applied to the bolts and threaded pin. The pedal-return-sub was then screwed into the top of the shaft from the top of the board so the board is between the shaft and return mechanism. Once the final assembly was complete the pedal was pressed a few times to test the brake motion before riding.

5 Testing and Analysis

Testing was performed to verify that the braking system meets its functional requirements and to measure its performance. The braking system was tested for normal ride-ability by several volunteers as well as the team members. Stopping distance testing was also carried out using the braking system and a foot braking method. Critical dimensions of components in the system were also measured to see how well they met the desired tolerances.

5.1.Functional Requirement testing

Once the board and braking system were assembled, each component was tested for functionality. A temporary machine screw was used for attaching the rubber pad because of the casting problems (section 4). Most of the components passed the functionality test, except the pin and the spring which were satisfactory because they performed their function with minor flaws. Two of the components failed, which made the braking unusable. Table 8 below shows the summary of the test.



Component	Result	Comments	Picture
Lever Arm	Passed		
Pin holders	Passed		
Pedal	Passed		
Nylon bushings	Passed		
Pin	Satisfactory	The thread doesn't go all the way through the pin holder.	
Spring	Satisfactory	Not stiff enough, goes in hole and wobbles.	
Shaft	Fail	Too long (when rider steps on board the brake pad touches the ground because of the deflection of the board) Slight Corrosion on threads.	
Rubber pad	Fail	Temporary attachment screw touched the ground before the pad.	

Table 8 – Initial functionality test results

In the figures in Table 8, the top of temporary screw can be seen before the test painted with the red marker and after the test with the marker scratched off from having contact with the ground. Also, the rubber pad can be noticed almost touching the ground with no rider on the board because the shaft was too long.

At this point testing the brake as a system was not possible until the two components that failed could pass the functionality test. A short term solution was identified in order to test the performance of the brake as a system, but the failed components will need to be iterated and redesigned.

5.1.1 Solution for testing braking function

Modifications were made to the prototype so that the braking functionality could be tested relatively quickly. The machine screw that the shaft attaches to was shortened, and the locknuts were removed, consequently removing the ability to adapt the clearance of the pad from the ground. The threaded rod that attaches the shaft to the pedal was lengthened. The temporary machine screw holding the pad was replaced by adding two additional holes on each side of the rubber pad, for a total of six screws.

5.1.2 Initial riding test results

During the initial riding test, the front surface of the brake pad ran into a bump on the ground. This can be fixed by bringing the surface of the pad higher on the lever, and tapering the part of the pad that doesn't contact the ground so that it ends flush with the lever surface. The spring rate was not high enough to provide comfortable control over the braking. The positioning of the pedal on the board affected normal riding because it was found to be a natural position for the rear foot to be placed during riding. At higher speeds the braking was found to be quite consistent, but at lower speeds it became less constant and more subject to jerkiness.

5.2.Normal riding test

We had several volunteers try the brake and give feedback on how it felt to ride the board with the brake, and the functionality of the brake. Some users reported that the brake is too sensitive (so did we) but we got used to it quickly. The main reasons for the high sensitivity can be attributed to a spring that is not stiff enough to provide proper resistance to the rider's weight. Also, the brake pad material is too soft, which causes sharp spikes in deceleration at lower speeds due to the pad catching on the road surface. Users could ride the board normally, but the presence of the pedal on the board surface was something that required a conscious effort to avoid. Because the longboard used for testing is relatively short, the pedal occupies a space that is a natural footing position. It is simple to adjust to a stance with the foot in front of the pedal, but this shortens the rider's stance, which decreases his/her stability. One of the major problems during testing was that different stances and different rider weights cause varying board flexes, which changes the clearance of the pad above the road. The pad was observed to hit the ground while going over large bumps and cracks in the ground. The variability in clearance based on rider weight and stance calls for a larger amount of adjustability than was originally designed for. This will be discussed further in chapter 6 in the iterations section.

5.3.Stopping distance testing

The stopping distance test was performed to compare our braking system with the foot braking method (Figure 38). Both braking methods were executed on the same hill and were analyzed based on stopping distance and stopping time.



Figure 38 - (left) braking with braking system, (right) braking with foot

5.1.3 Method

Markings were placed at 2 ft intervals along the road (see Figure 39) so that the position of the board could be determined from video footage. For the braking system, the team conducted 3 trials with the same user to get an initial velocity at the designated marking where the user would start braking. The initial velocity was taken as the average velocity over 6ft. The initial velocity averaged over the three trials was approximately **19.8 ft/sec**. For the foot braking test, the user started from the same place as in the braking system test, but started braking before getting to the designated marking as a precaution to prevent falling. The intention was to have identical initial velocities for all tests, but they ended up varying slightly.



Figure 39 - Markings along the road in the testing area

To obtain a position plot from the video, data was taken every 5 frames on the video and the position was recorded using the tape markings. The position of the board was recorded at each point to within a 0.5ft resolution based on the perspective and clarity of the video. Since the camera was fixed at the bottom of the hill, the markings were clearer as the rider passed the location of the camera; hence a 0.2ft resolution was available.

5.2 Results

With the data from the video, position vs. time plots were made in Excel (Figure 40). From these plots, fourth order polynomial regression lines were obtained (

Table 9) and plotted. These functions were then derived and plotted using MathCad to obtain velocity and acceleration functions of time.

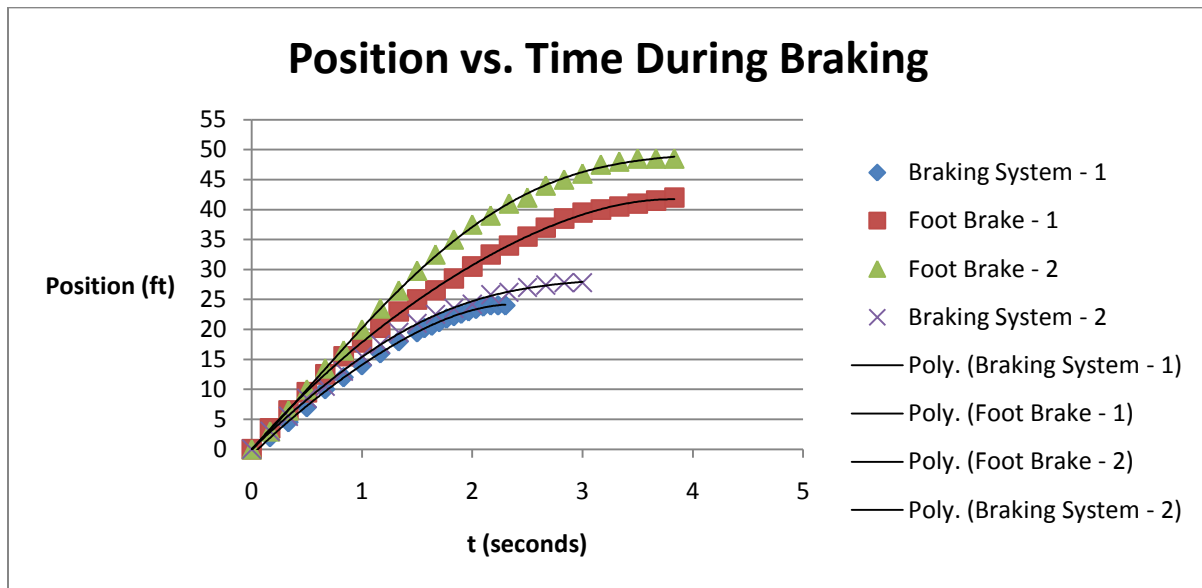


Figure 40 - Position vs. time plots for stopping distance test

Foot Brake - 1	$y = -0.0957x^4 + 0.6755x^3 - 3.8554x^2 + 21.129x - 0.0129$	$R^2 = 0.9997$
Foot Brake - 2	$y = 0.2366x^4 - 2.1318x^3 + 3.0077x^2 + 19.248x - 0.1588$	$R^2 = 0.9997$
Braking System - 1	$y = -0.3352x^4 + 1.0706x^3 - 3.8476x^2 + 18.203x - 1.0186$	$R^2 = 0.9997$
Braking System - 2	$y = 0.2104x^4 - 1.265x^3 - 0.7024x^2 + 17.112x + 0.038$	$R^2 = 0.9995$

Table 9 – Regression functions for position vs. time from stopping distance tests

The plotted regression functions are shown below for the data from Braking System – 1, and Foot Brake – 1. The position function predicted the experimental stopping distance with a very small error (.08%) and the initial velocity of **18.2 ft/sec** matches the experimental initial velocities within 8%. From the position functions in Figure 41, the difference in stopping distance can be seen between the foot braking test and the braking system test. The average stopping distance using foot braking was 39.2ft while with the braking system it was 26.7 ft. The stopping distance for the braking system was under 70% of that using foot braking.

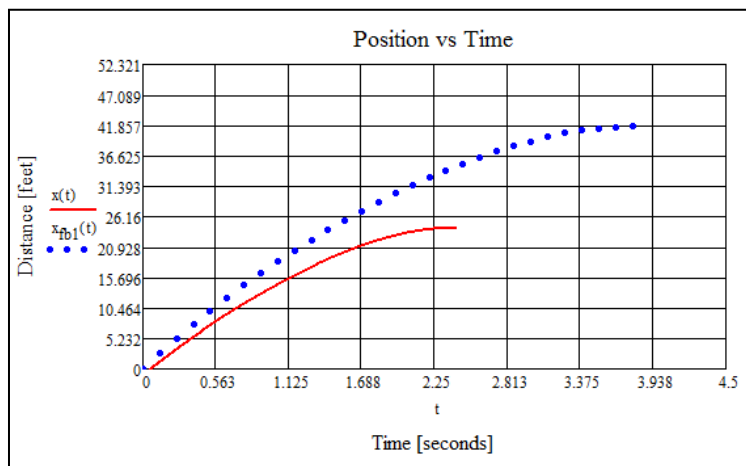


Figure 41 - Position vs. time during braking from curve fit.

Blue dotted line: foot braking Red line: braking system

Initial velocity for foot the braking test was higher than expected (see Figure 42). This could be due to a number of factors. Although the initial starting position was the same for each test, the two tests were performed on different days which could present different wind resistance conditions. The discrepancy could also be due to any small measurement error during analysis, because the derived functions inflate any errors in the position function.

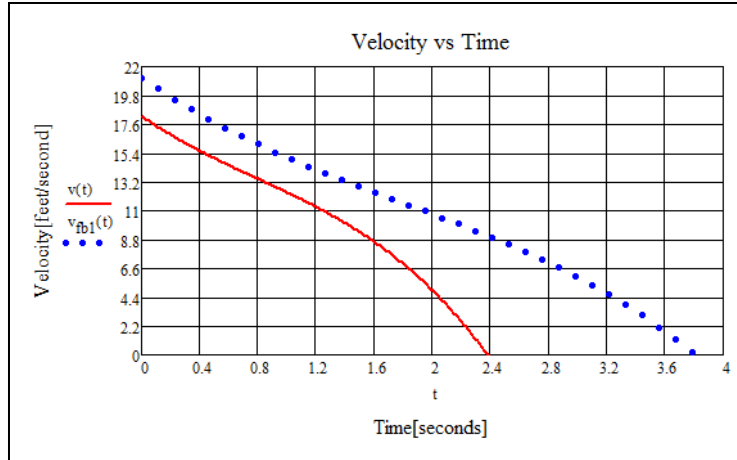


Figure 42 - Velocity vs. time during braking from curve fit

Blue dotted line: foot braking Red line: braking system

5.1 Tolerance testing

The design contains certain tolerances to achieve critical dimensions like fits between components. The actual dimensions were measured to verify that the desired tolerance was achieved. For the fit between the pin holders and the pin, a locational clearance fit was desired. This fit provided that the components would fit together snugly and stationary, and could be assembled and disassembled by hand easily. The actual fit between the two components was a clearance of 0.003in (see Table 10), which falls into class LC 9 (Lieu & Sorby, 2009). This ended up allowing free rotation of the pin in the pin holders. This fit was not as snug as desired because it allowed for rotation, but still was tight enough so that no rattling or undesired translation occurred. A fit that both allows easy assembly, and prevents rotation of the pin in the pin holders could be achieved with a tighter locational clearance fit, but was found to not be extremely critical, as the system performs satisfactorily as initially machined. It was difficult to find shoulder bolt pins with tight tolerances that are low in cost. However, a drilling and reaming operation could be used for the pin holder holes because on a CNC machine this does not significantly increase the machining time, and tightens the tolerance of the hole significantly.

Feature	Exact dimension (in)	Tolerance (in)	Actual dimension (in)	Measuring tolerance (in)
Pin holder hole 1	0.375	+0.006	0.376	+/- 0.001
Pin holder hole 2	0.375	+0.006	0.376	+/- 0.001
Lever pivot hole	0.5	+0.006		+/- 0.001
Pin diameter	0.375	-0.004	0.373	+/- 0.001
Bushing inner diameter			0.38	+/- 0.001
Bushing outer diameter				+/- 0.001

Table 10 - Nominal and measured sizes for critical dimensions

6 Iterations:

The initial riding and functional requirement testing brought about several design changes that future iterations of this prototype should include. While the prototype test was a success, several improvements could still be made. Future iterations of the design could fine tune certain aspects that were overlooked during the design of this prototype. Such iterations include the need to make the brake adaptable, improve the return mechanism, make it sleeker, reduce mass of the system, and improve design and material selection for the rubber pad.

After the braking system was assembled with the board, the first thing the team did was try to ride it normally. Once we stepped on the board, we noticed that the board wouldn't move because the board flexing caused the rubber pad to touch the ground. There are many factors that dictate how much clearance the rubber pad needs to have from the ground in order not to touch the ground in the "off" position, so the system has to be highly adaptable. These factors include the material that the board is comprised of, the rider's weight, the rider's stance on the board, and the maximum tilt of the board during turning. Although we tried to design an adaptable system our attempt came up short.

Another improvement that could be made is to have a better return mechanism. Although the spring fulfilled its function, the spring constant has to be higher in order to keep the brake from bouncing up and down and to provide more resistance when a load is applied. We also had trouble finding a conical spring with the same inner small diameter bigger than the diameter of the pedal rod. For this reason, future iterations need to find the conical spring with higher spring constant first and then design the pedal around that.

Aesthetic appeal is an important factor in longboarding equipment. Evidence of this is present in the various designs of boards as well as the artwork that many of these boards include.

Strongly addressing this need may make the design more marketable to the current longboarding population. Future iterations of the prototype should reflect this need.

The rubber used for the brake pad worked very well for testing purposes. The team did notice that the brake was wearing out a little faster than expected. Future work should be done to estimate the wear of the pad and find which rubber hardness would optimize braking performance and wear. The rubber used was 60A urethane, but because wear is inversely proportional to the hardness of the material, the harder the rubber the less it will wear. Also, some redesign of the shape of the rubber pad would be helpful in order to account for inconsistency in road surface.

When we had volunteers try out the braking system no instructions were given to them. The reason for this was to see if the system was intuitive. It turned out that everybody knew that stepping on the pedal would cause the braking system to activate, but we did notice the location of their feet was different for many subjects. The position of the pedal on the board makes the stance of the rider shorter and a little awkward because the board is relatively short and the pedal is where the rider would usually place their back foot. The activation system was designed so that the rider would place their back foot in front of the pedal and slide their heel back, but we noticed some riders felt more comfortable placing their foot behind the pedal and sliding their foot forward. Future research should find how wide the average longboarder stance is and use this as a lower limit to know the minimum length limit of the board for the pedal not to be intrusive. Although the pedal's shape allows the user to activate from any side, the pedal is leaning forward so it's easier to activate from the front. Future iterations should consider making the pedal equally accessible depending if the rider's foot is placed in the back or in front of the pedal.

All the components of the braking system were overdesigned and as a result of this several components are not optimized in mass, such as the lever and pin holders. All components had safety factors over 2, most being well over 2. This means that the thickness of the components could be reduced in order to reduce cost and weight. Using some high strength polymers could be a solution to reduce the weight of the shaft and pedal. The pin holders and the lever could be redesigned so they can also be smaller and weigh less. A more thorough material selection could be a solution for this.

Overall, the prototype the team designed and tested was more of a proof of concept. Now that we know it works, a lot of work could be done to optimize the components of the braking system.

7 Conclusion

The braking system fulfills its main functional requirement which is to provide the ability to control the speed of the board and its rider and the ability to make it attachable to existing boards. The braking system allowed for increased control and safety during riding that is currently not available on longboards. It also provided stability while braking and constant braking while turning.

After using the braking system on the board for a few months, the team considered using some of the ideas that were discarded at the beginning of the design process. One of the major changes would be where the friction is applied. As mentioned previously, one of the problems to applying friction to the ground is the uncontrollable variance on road surfaces. Some roads are very rocky and have cracks, while other roads are very smooth and this affects the ability to use the brake effectively. Now that the team figured this out experimentally, we believe applying friction to the wheels might be the safer and more controllable choice. Applying friction to the wheels has some negative attributes, like uneven wear of wheels, but our most important customer needs are safety and reliability and these could be negatively affected in the current prototype by uncontrolled factors.

Another consideration for future iterations is to have more specific limits to a “comfortable” riding stance. Some statistical data might be needed in order to find the average width of a rider’s stance. By having this data, future prototypes can provide a lower limit to the length of the board so that the activation system doesn’t interfere with the rider’s normal riding stance. Another consideration would be to look at previous patents and use one of the activation systems that this group discarded.

Overall, the team is satisfied by the performance of the prototype. As our testing and analysis section shows, at the same average initial velocity, our braking system stops the board and rider in a faster time and shorter distance when compared to foot braking. While the MQP team provided an excellent proof of concept, the design leaves much to be desired, as discussed in the previous sections.

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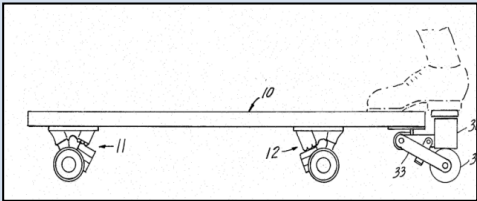
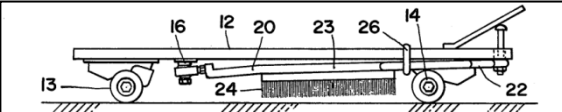
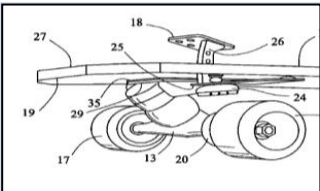
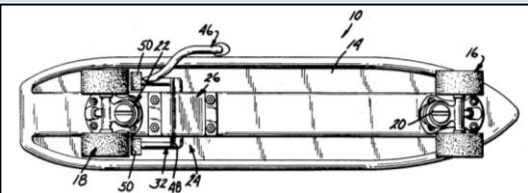
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9 Appendices

APPENDIX A – Existing Designs



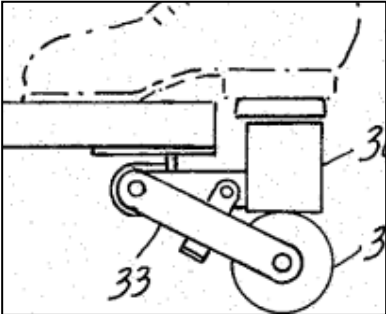
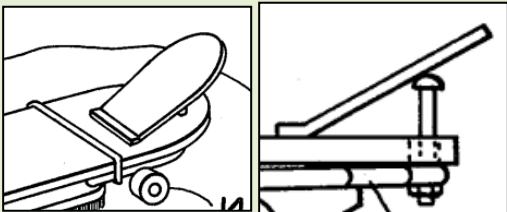
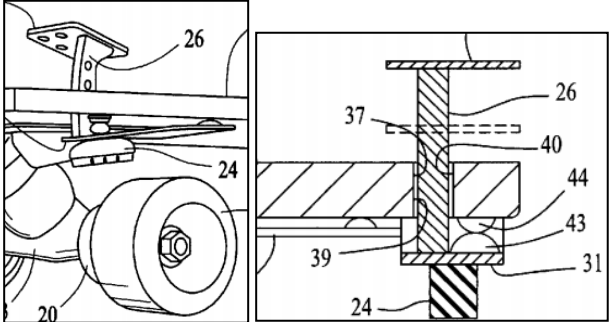
We looked at 6 existing designs, 4 patents, and 2 currently on the market. Below is a list of the designs with brief descriptions and pictures.

#	Name	Image
1	SkateBrake	
2	Pogo Brake	
3	5 th Wheel	
4	Brush	
5	Drum	
6	Side Lever	

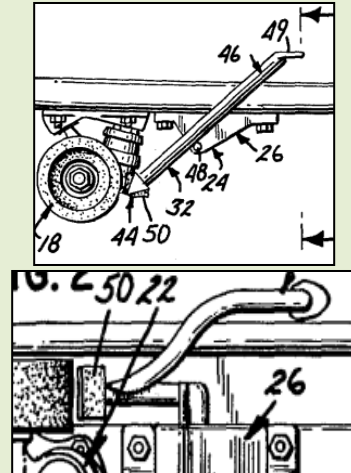
We will describe each existing brake design in more detail broken down by 5 different functional requirements of the braking system. These can be seen in the table below.

FR 1 Provide Controlled Activation of Brake



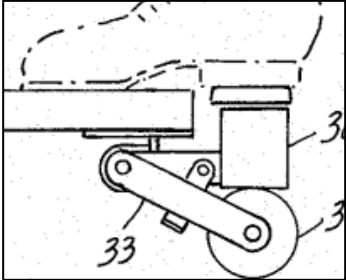
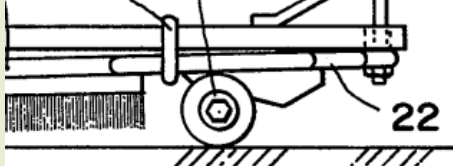
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#	Design Name	Design Parameter	Image
1	SkateBrake	- Hand lever attached to bowden cable	
2	Pogo Brake	- Plastic pedal attached to vertical shaft - Located in front of the rear trucks	
3	5 th wheel	- Pedal fixed to block - Hangs off back of the deck	
4	Brush	- Angled flat pedal sliding against vertical shaft	
5	Drum Brake	- Pedal attached to curved metal shaft	

- 6 Side Lever
- Foot activated lever off the side of the board
 - Returned by force from gravity



FR 2 Transmit energy from activation system to sliding friction system in a controlled manner

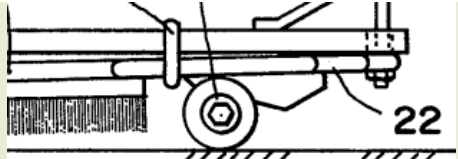
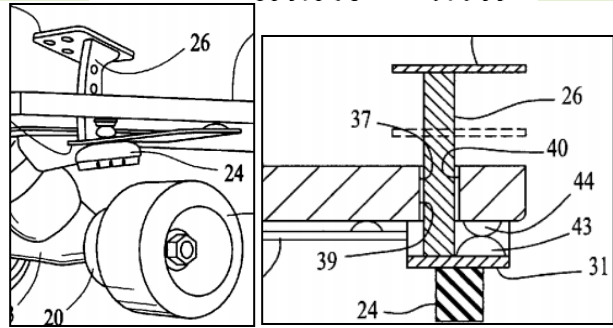
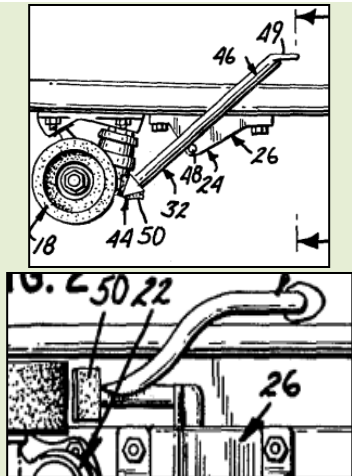
#	Design Name	Design Parameter	Image
1	Skate Brake	- Bowden cable pulls two levers (similar to bike brakes)	
2	Pogo Brake	- Vertical plastic shaft pushes on wooden cantilever	
3	5 th wheel	- Horizontal rotating shaft pinned under tail of the board pushes block against 5 th wheel	
4	Brush	- Pushes brush against ground	

5	Drum Brake	- Vertical metal shaft attached to brake pad	
6	Side Lever	<ul style="list-style-type: none"> - Metal lever pivots on rotating pin - Attached to brake pad at the opposite end of the pedal 	

FR 3 Provide friction interface with a controlled normal force

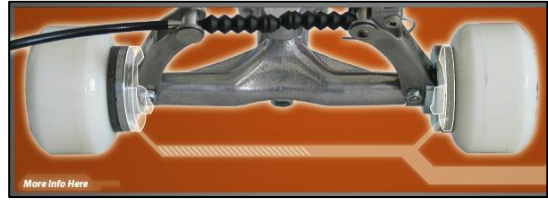

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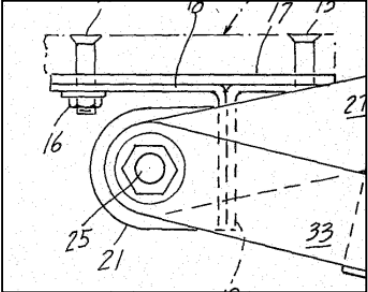
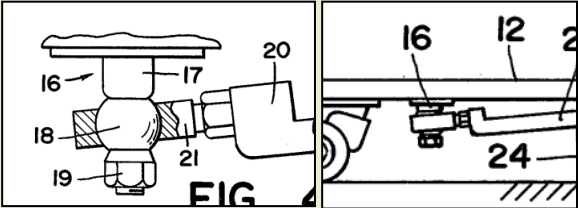
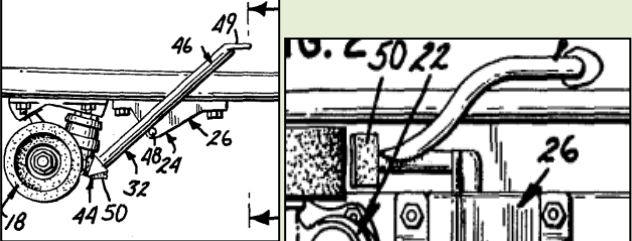
#	Design Name	Design Parameter	Image
1	SkateBrake	<ul style="list-style-type: none"> - The two levers press disc brake pads against inside of wheels 	
2	Pogo Brake	<ul style="list-style-type: none"> - Wooden Cantilever presses friction pad surface against ground 	
3	5 th wheel	<ul style="list-style-type: none"> - Horizontal rotating shaft pushes 5th wheel to ground, then the block presses against the wheel 	

4	Brush	-	
5	Drum Brake	- Vertical shaft pushes brake pad against drum surface	
6	Side Lever	- Lever pushes brake pads against the front surface of the rear wheels	

FR 4 Transfer Frictional Load to the Board (Attachment)


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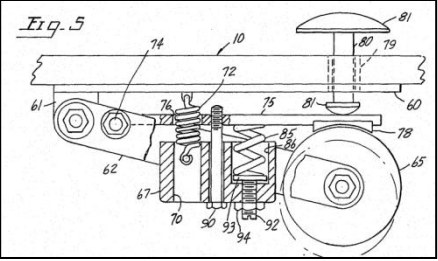
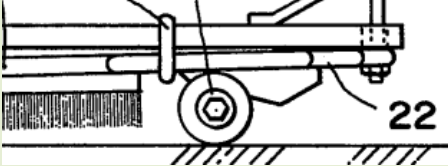
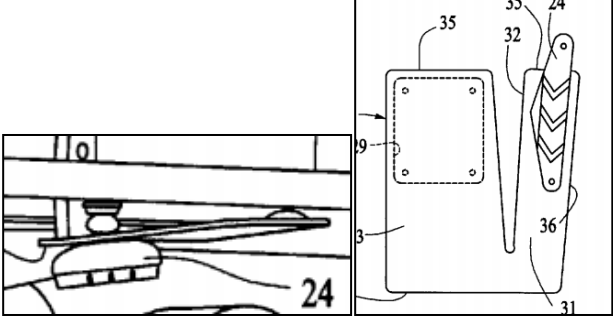
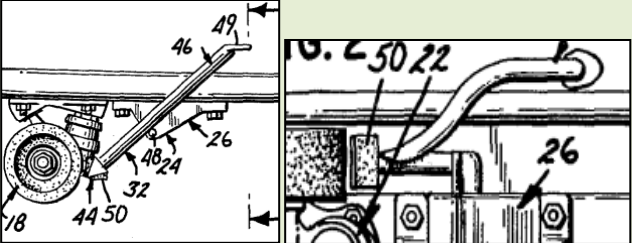
#	Design Name	Design Parameter	Image
1	SkateBrake	- Frictional load transferred through the wheels, which are pinned to the trucks	
2	Pogo Brake	- Frictional load transferred through wooden shaft to bolted plate under the deck - Attached with bolts to deck	

3	5 th wheel	- Frictional load transferred to bolted plate on deck	
4	Brush	- Shaft with brush on it is attached to a ball joint that is bolted to the deck	
5	Drum Brake	- Frictional load transferred through the wheels, which are pinned to the trucks	
6	Side Lever	- Frictional load transferred through the wheels, which are pinned to the trucks	

FR 5 Return braking system to original position

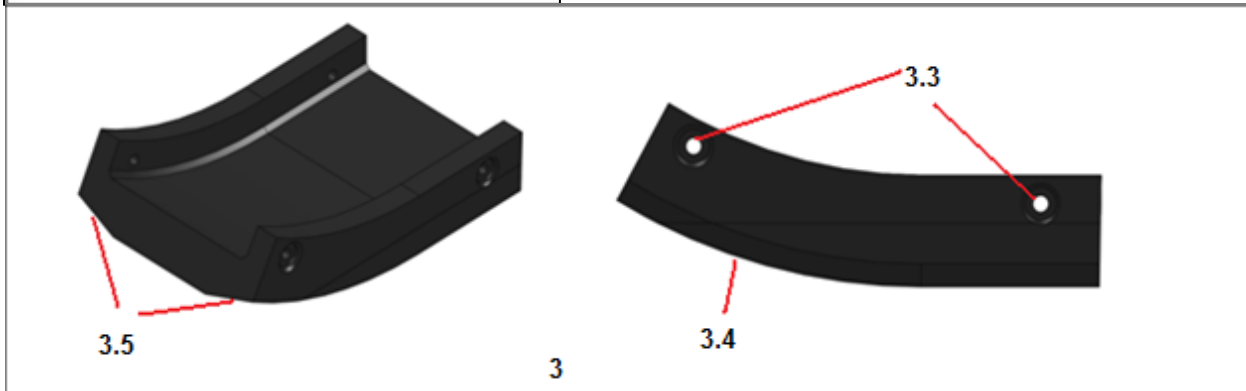
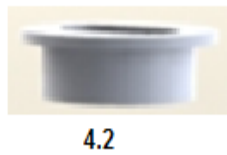
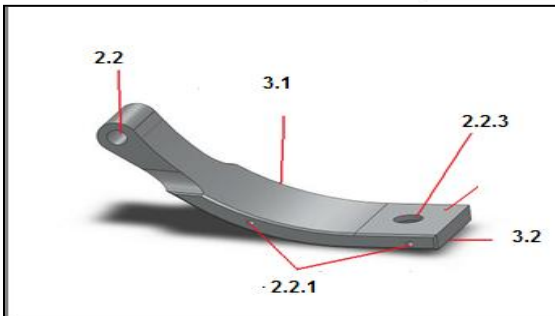
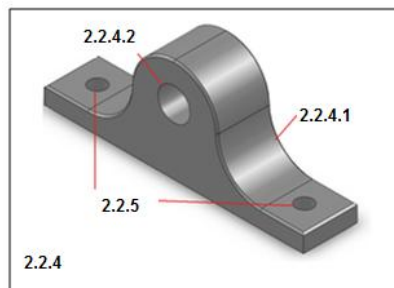
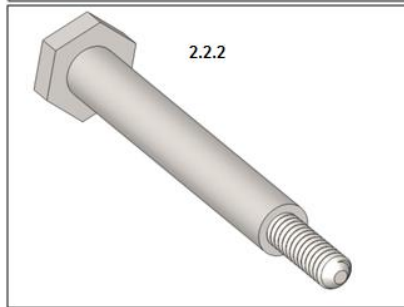
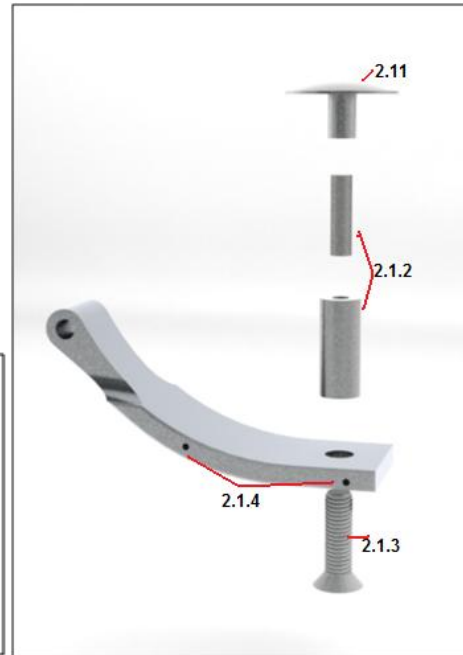
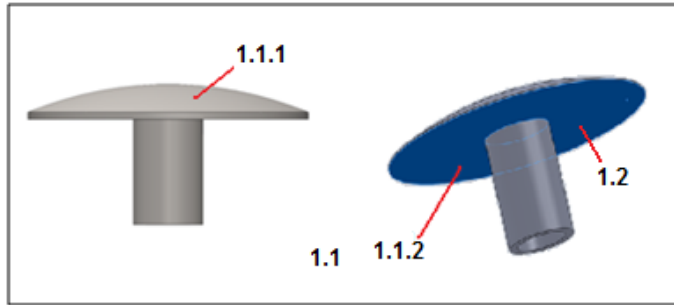
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#	Design Name	Design Parameter	Image
1	SkateBrake	- Spring in the hand lever applies a compressive force to the Bowden cable	

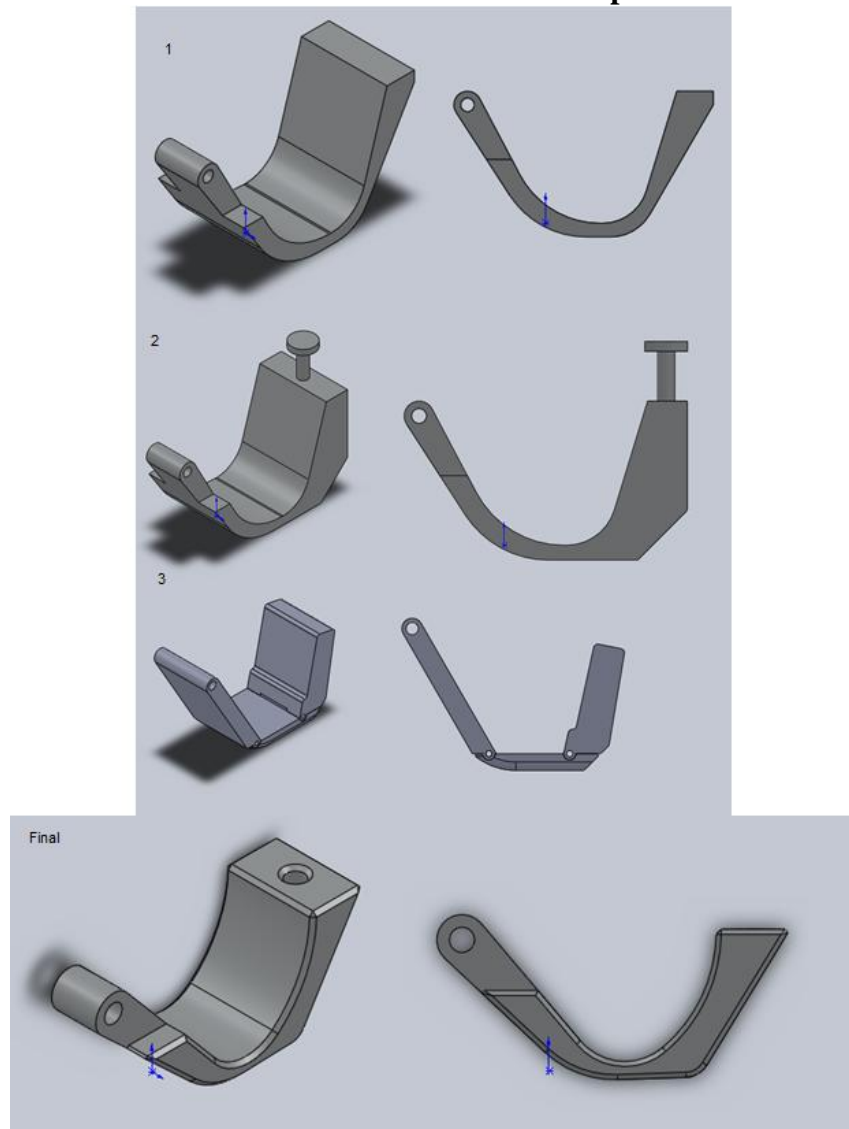
2	Pogo Brake	- Wooden Cantilever acts as a spring	
3	5 th wheel	- Vertically mounted spring attached to shaft pushes shaft back to initial position	
4	Brush	- Elastic band attached to the deck pulls the shaft back up	
5	Drum Brake	- Metal plate attached to deck and shaft acts as a cantilever spring	
6	Side Lever	- Larger moment on the front end of the lever causes return initial position	

Appendix B – Acclaro File screenshot with all FRs and DPs

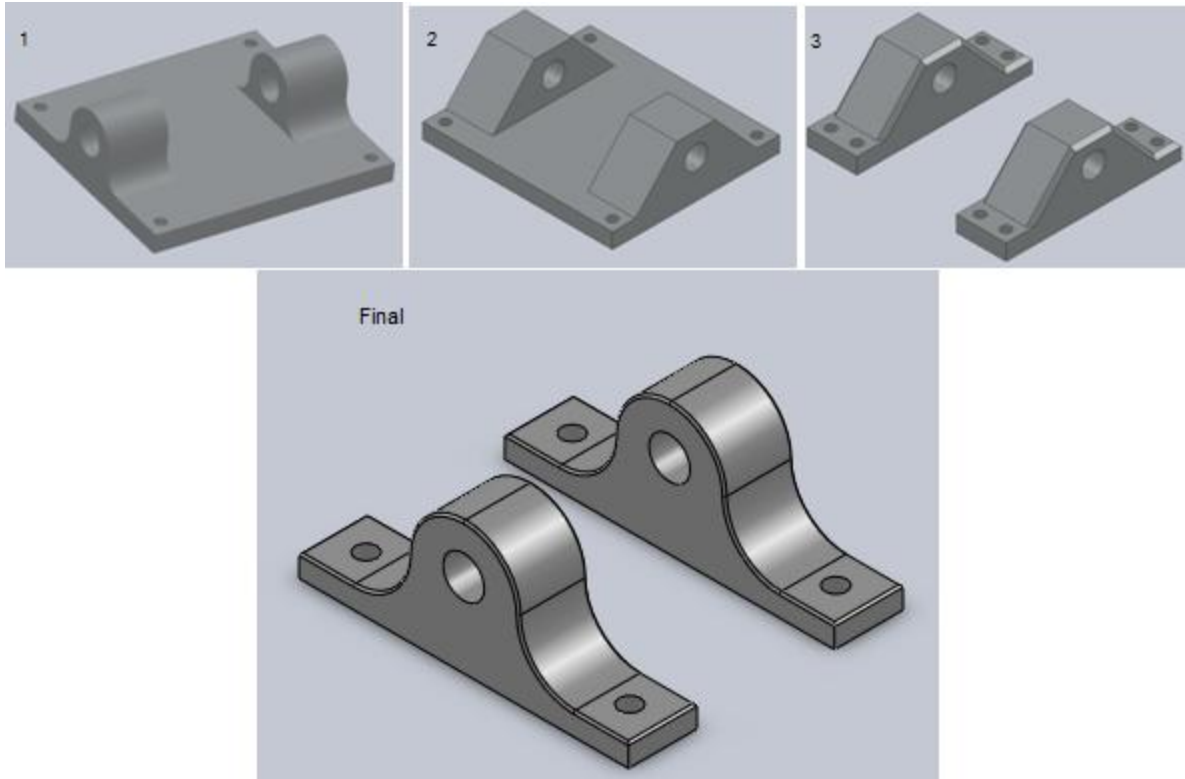
0	FR	Provide controlled deceleration	DP	Braking system
1	FR	Provide controlled activation	DP	Foot activated system
1.1	FR	Provide for ease of activation	DP	Pedal
1.1.1	FR	Provide for ability for activation with sliding foot	DP	Domed surface on pedal
1.1.2	FR	Provide for activation from all side	DP	Circular surface
1.2	FR	Provide resistance to pedal movement	DP	Spring
2	FR	Transfer Loads	DP	Mechanical system
2.1	FR	Transfer vertical loads from foot to sliding friction interface	DP	Activation and transmission system
2.1.1	FR	Transfer load from foot to pedal	DP	Top surface of pedal
2.1.2	FR	Transfer load from pedal to shaft	DP	Threaded shaft
2.1.3	FR	Transfer load from shaft to lever	DP	Machine screw
2.1.4	FR	Transfer load from lever to rubber pad	DP	Bolts on rubber pad to lever
2.2	FR	Transfer horizontal loads from sliding friction interface to board	DP	Hinged lever
2.2.1	FR	Transfer load from rubber pad to lever	DP	Bolts on pad to lever
2.2.2	FR	Transfer load from lever to pin holder	DP	Pin
2.2.3	FR	Transfer load from shaft to lever	DP	Pin
2.2.4	FR	Provide hinge for lever	DP	Pin holder
2.2.4.1	FR	Reduce stress concentrations around pin holder	DP	Rounds
2.2.4.2	FR	Provide for tight fit around pin in the pin holder	DP	Tolerance
2.2.4.3	FR	Provide for smooth sliding around pin in the lever fulcrum	DP	Nylon bushings
2.2.5	FR	Transfer load from pin holder to board	DP	Machine screws
3	FR	Optimize sliding friction interface	DP	Rubber pad
3.1	FR	Optimize contact surface between rubber pad and ground	DP	Curved lever
3.2	FR	Reduce wear of rubber	DP	Wide lever
3.3	FR	Provide removable interface	DP	Replaceable rubber pad
3.4	FR	Minimize the effects of inconsistent ground surface	DP	Curved rubber pad
3.5	FR	Provide consistent braking while turning	DP	Chamfer on sides of rubber pad
4	FR	Provide path from shaft to lever	DP	Hole on the board
4.1	FR	Optimize for stress concentration	DP	Hole centered on the board
4.2	FR	Reduce wobble	DP	Grommet
5	FR	Provide for adjustable clearance under the board	DP	Adjustable shaft height
6	FR	Provide for normally off position	DP	Spring



APPENDIX C – Iterations of lever arm and pin holder



The reason there are so many iterations to the lever arm is because we intended to place the activation system behind the trucks, but then we noticed we wouldn't have enough clearance of the ground, so the whole idea was eliminated.



The pin holder has many iterations because at first we didn't think of manufacturability or cost of materials. As we progressed through the iterations, it is obvious by the figure above that we tried to reduce the material wasted, facilitate the manufacturability and reduce stress concentrations.

APPENDIX D - Liquid Urethane material properties

Two-Part Casting Compounds

Capture intricate details when casting prototypes, molds, and linings with these easy-to-mix casting compounds. For release agents, see [page 2153](#).

Temperature Range After Cure	Working Time, min.	Cure Time @ Room Temp. (unless noted)	Color	Shrinkage per Inch	Hardness Shore	Tensile Strength, psi	Volume, cu. in.	Wt, lbs.		Each
Low-Viscosity Urethane — Flows smoothly into crevices to pick up fine details.										
-20° to +135° F	8-10	7 Days (Demold 2 hrs.)	White	0.001"	83D	5800	94	3.6	87075K57	\$62.17
			White	0.001"	83D	5800	374	14.4	87075K59	\$166.07
Solid Urethane — Cures quickly. Use for precision measuring, tracing, and making replicas for optical comparisons.										
32° to 180° F	5	1-2 Hours	Blu.-Gm.	0.0007"	85D-90D	9000	80	5	8690K1	\$60.98
32° to 180° F	5	1-2 Hours	Blu.-Gm.	0.0007"	85D-90D	9000	320	20	8690K2	\$158.88
Flexible Urethane — Offers high tensile strength, plus it's highly flexible, pliable, and water and abrasion resistant.										
-40° to +180° F	10-20	48 Hours	Black	0.0005"	20A	400	25	1	8644K51	\$34.88
-40° to +180° F	10-20	48 Hours	Black	0.0005"	20A	400	250	10	8644K52	\$225.58
-40° to +180° F	10-20	48 Hours	Black	0.0005"	40A	950	25	1	8644K53	\$34.88
-40° to +180° F	10-20	48 Hours	Black	0.0005"	40A	950	250	10	8644K54	\$225.58
-40° to +180° F	10-20	48 Hours	Black	0.0005"	60A	1250	25	1	8644K24	\$33.33
-40° to +180° F	10-20	48 Hours	Black	0.0005"	60A	1250	250	10	8644K26	\$217.22
-40° to +180° F	10-20	48 Hours	Black	0.0005"	80A	1725	6	0.25	8644K57	\$17.50
-40° to +180° F	10-20	48 Hours	Black	0.0005"	80A	1725	25	1	8644K11	\$31.24
-40° to +180° F	10-20	48 Hours	Black	0.0005"	80A	1725	250	10	8644K12	\$206.38
-40° to +180° F	10-20	48 Hours	Black	0.0005"	94A	3120	25	1	8644K18	\$33.33
-40° to +180° F	10-20	48 Hours	Black	0.0005"	94A	3120	250	10	8644K19	\$202.24
-40° to +180° F	10-20	48 Hours	Black	0.0005"	60D	3900	25	1	8644K55	\$34.88
-40° to +180° F	10-20	48 Hours	Black	0.0005"	60D	3900	250	10	8644K56	\$225.58
-40° to +180° F	10-15	12 Hr. @ 120° F	Clear	0.08"	80A	3250	25	1	8644K59	\$35.71
-40° to +180° F	10-15	12 Hr. @ 120° F	Clear	0.08"	75D	8110	25	1	8644K58	\$35.71

APPENDIX E – Aluminum 6061 T6 material properties

Property Name	Value	Units	Value Type
Elastic modulus	6.9e+010	N/m ²	Constant
Poisson's ratio	0.33	NA	Constant
Shear modulus	2.6e+010	N/m ²	Constant
Mass density	2700	kg/m ³	Constant
Tensile strength	3.1e+008	N/m ²	Constant
Yield strength	2.75e+008	N/m ²	Constant
Thermal expansion coefficient	2.4e-005	/Kelvin	Constant
Thermal conductivity	166.9	W/(m.K)	Constant
Specific heat	896	J/(kg.K)	Constant
Hardening factor (0.0-1.0; 0.0=isotropic; 1.0=kinematic)	0.85	NA	Constant

APPENDIX F – Low Carbon Steel

General properties

Density	487	-	493	lb/ft ³
Price	* 0.288	-	0.316	USD/lb

Mechanical properties

Young's modulus	29	-	31.2	10 ⁶ psi
Yield strength (elastic limit)	36.3	-	57.3	ksi
Tensile strength	50	-	84.1	ksi
Elongation	26	-	47	%
Hardness - Vickers	108	-	173	HV
Fatigue strength at 10 ⁷ cycles	* 29.4	-	42.5	ksi
Fracture toughness	* 37.3	-	74.6	ksi.in ^{1/2}

Thermal properties

Melting point	2.7e3	-	2.78e3	°F
Maximum service temperature	* 662	-	752	°F
Thermal conductor or insulator?	Good conductor			
Thermal conductivity	28.3	-	31.2	BTU.ft/h.ft ² .F
Specific heat capacity	0.11	-	0.121	BTU/lb.F
Thermal expansion coefficient	6.39	-	7.22	µstrain/°F

Electrical properties

Electrical conductor or insulator?	Good conductor			
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Optical properties

Transparency	Opaque			
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Eco properties

Embodied energy, primary production	3.14e3	-	3.79e3	kcal/lb
CO2 footprint, primary production	2.2	-	2.8	lb/lb
Recycle	✓			

Supporting information

Typical uses

Low carbon steels are used so widely that no list would be complete. Reinforcement of concrete, steel sections for construction, sheet for roofing, car body panels, cans and pressed sheet products give an idea of the scope.

APPENDIX G – Zinc Plated Steel

Same properties Low Carbon steel but with a coat of zinc to prevent corrosion

Supporting information

Design guidelines

Zinc is used as cladding and in galvanizing steel to improve corrosion resistance. Wrought zinc is available as strip, sheet, foil, plate, rod, wire and blanks for forging or extrusion. It is relatively soft (a strength of 60 - 120 MPa) but, because of its hexagonal structure, bends in rolled zinc sheet should be at right angles to the grain or rolling direction and should have a radius no less than the sheet thickness. Wrought zinc alloys are easily soldered and spot-welded. It can be polished, textured, plated or painted. When exposed to air, zinc develops a surface film of carbonate that is very protective; it is frequently left uncoated.

Technical notes

Wrought zinc is made by hot-rolling cast sheets, by extrusion or by drawing. Zinc foil is made by electroplating zinc on an aluminum drum and then stripping it off.

Typical uses

Galvanizing of steel and other protective plating; cladding, flashing and guttering of buildings; flashlight reflectors; radio shielding; gaskets; photo-engraving plates; kitchen counter-tops; electrodes for zinc-carbon batteries.

APPENDIX H – Calculations

static y forces

$$m_{\text{lever}} := .66\text{b} = 0.299\text{kg}$$

$$l_{\text{cm}} := 3.38\text{n} = 0.086\text{m}$$

$$l_{\text{lever}} := 5.22\text{n} = 0.133\text{m}$$

$$m_{\text{activation}} := .2118\text{kg}$$

$$m_{\text{lever}} + m_{\text{activation}} = 0.51\text{kg}$$

$$F_{\text{spring}} := \frac{m_{\text{lever}} \cdot g \cdot l_{\text{cm}}}{l_{\text{lever}}} + m_{\text{activation}} \cdot g = 3.98\text{N}$$

clearance during turning

$$c_{\text{wheel}} := 1.23\text{r}$$

$$.21187$$

$$w_{\text{board}} := 8\text{in}$$

$$\theta_{\text{turn}} := \text{atan}\left(\frac{c_{\text{wheel}}}{w_{\text{board}} \cdot .5}\right)$$

$$\theta_{\text{turn}} = 17.093\text{deg}$$

$$w_{\text{pad}} := 2\text{in}$$

$$c_{\text{pad}} := \tan(\theta_{\text{turn}}) \cdot w_{\text{pad}} \cdot .5 = 0.308\text{in}$$

spring constant (lbs/in)

$$th_{\text{pad}} := .5\text{in}$$

$$k_{\text{spring}} := 7.81 \frac{\text{lbf}}{\text{in}}$$

$$\text{clearance}_{\text{ground}} := 1\text{in} - th_{\text{pad}} = 0.5\text{in}$$

$$v := .52 \cdot 5 = 5$$

$$\text{preload} := \frac{F_{\text{spring}}}{k_{\text{spring}}} = 0.115\text{in}$$