Advanced Design of a Binding Plate to Reduce Anterior Cruciate Ligament Injury during Alpine Skiing

A Major Qualifying Project Proposal
submitted to the faculty of
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Abstract

The objective of this project is to reduce the incidence of Anterior Crucial Ligament (ACL) injury in skiing by designing, prototyping, and testing a plate between the ski and binding to filter out injurious loads that would otherwise be transmitted through the ski to the skier. While ski technology in the past five decades has adapted to protect the skier's foot, ankle, and tibia, the knee and ACL are still susceptible to injury. There are two types of ACL injuries; Boot-Induced Anterior Drawer (BIAD) and phantom foot. Axiomatic Design was used to design a ski binding plate to minimize BIAD ACL injuries. After the design was chosen, calculations, material selection, computer aided design (CAD) drawings, and Finite Element Analysis (FEA) were conducted. This project holds importance in both a societal and economic context.

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1. Introduction

1.1 Objective

The objective of this project was to reduce the chance of ACL injury in skiing by designing, prototyping, and testing a plate between the ski and binding that would filter out injurious loads that would otherwise be transmitted through the ski to the boot and thus prevent injury.

1.2 Rationale

This research project, which aimed to reduce ACL injury in skiing, holds importance in both a societal and economic context. While ski technology in the past five decades has adapted to protect the skier's foot, ankle, and tibia, the knee and ACL are still susceptible to injury. "Clearly if falls [today] generate the same amount of force as skiing falls in the 1970s, and the ankle and tibia are protected from those forces by modern boots and bindings, then the forces must be dissipated somewhere else...those forces are now dissipated in the knee (Hunter, 1999). A New York Times article on ACL injury references an American Journal of Sports Medicine study by Mr. Carl Ettlinger and Drs. Johnson and Sheally noting that, "Skiing overall is safer than it has ever been, with injuries on the slopes declining 55 percent since 1972, [however] ACL tears soared by 103 percent from 1972 to 2006, according to a study of more than 18,000 ski injuries at the Sugarbush Resort in Vermont (Pennington, 2008)."

It is estimated that "skiing-related ACL injuries may cost Americans up to $250 million annually (Pennington, 2008)." To put it in perspective, a skier who has suffered an ACL injury while skiing can expect "the cost of ACL injury including reconstruction and rehabilitation to be approximately $17,000 (Wilcox, 2012)." This figure does not take into account the costs that

come with hardship that will follow the skier over the next eight months of recovery. The success of this project could mean both a reduction in debilitating injury in the skiing community as well as a relief to medical costs stemming from ACL injury in skiers.

1.3 State of the Art

There are currently three types of injury preventing equipment – binding systems, boot systems, and plate systems. Commonly used binding systems provide for vertical release of the heel and lateral release of the toe, but do not allow for lateral release of the heel in the event of a BIAD or phantom foot scenario. The Kneebinding and Pivogy binding systems are two binding systems designed to improve upon the commonly used systems by providing release mechanisms in the event of a phantom foot scenario. The Kneebinding, pictured in **Error! Not a valid bookmark self-reference.** below, provides for lateral release of the heel with a pivot point at the toe, protecting the ACL from a phantom foot injury (Howell, 2004). However, the Kneebinding can only be mounted on "flat" skis (skis sold without a plate or binding system) or by using an adaptor.

Figure 1: Kneebinding (Kneebinding, Inc.)

The Pivogy binding system consists of a top and bottom plate, the top of which can pivot relative to the bottom in the event of a potentially injurious load to the ACL (Dodge, 2001). This in turn causes the binding to release, preventing ACL injury. A third binding system, the "Alpine Ski Binding Having Release Logic for Inhibiting Anterior Cruciate Ligament Injury," triggers a binding release when the lateral shear loads applied to the inside rear end of the ski surpass the predetermined injurious load level (Ettlinger & Dodge, 2009). Similarly to the Kneebinding and Pivogy binding system, this system prevents ACL injury by triggering binding release. Currently, there are no binding systems in production that prevent ACL injury without triggering a binding release.

The Lang RRS is the most successful boot based ACL injury prevention system. The Lang RRS features an adjustable release mechanism, which allows the back of the boot to displace when subjected to excessive force. While this design has been proven in independent laboratory testing to be effective, it is no longer in production (Benoit, et al., 2001).

The final type of system, ACL protecting plates, have been prototyped but have yet to be manufactured by a well-known binding or ski manufacturer. Two examples of these are the "Design and Prototyping of an Under-Binding Plate to Reduce ACL Injury" and "Design and Manufacture of a Binding to Reduce ACL Injuries in Alpine Skiing" (Austin, Ferland, & Seibold, 2011) (Miley, 2006). These plates are both Worcester Polytechnic Institute Major Qualifying Projects.

1.4 Approach

Products currently on the market only address phantom foot injuries. This project differs from the state of the art because it protects against BIAD injuries. Additionally, this project does not trigger a binding release as the injury prevention mechanism and allows the user to continue

skiing normally immediately following an injurious loading event. It also allows the toe to rise while the heel falls in response to a potentially injurious load, allowing greater displacement and minimizing the effect of potentially injurious loads. This approach also minimizes the height of the plate over the ski when compared to previous MQPs, and this mechanism complies with all International Ski Federation standards for combined plate, ski, and binding height. This project will design and prototype a plate to be placed between the ski and binding to prevent injurious loads from being transmitted from the ski to the boot.

During this project, Axiomatic Design will be used to design a ski binding plate to minimize ACL injuries. The type of ACL injury studied during the design process is the Boot-Induced Anterior Drawer (BIAD). Appropriate functional requirements (FR) and design parameters (DP) will be developed using axiomatic design. The FRs will be collectively exhaustive and mutually exclusive (CEME), meaning all of the functions combined will minimize ACL injury while skiing.

1.5 Methods

Axiomatic design is an engineering design method that utilizes axioms, or laws, that allow designers and engineers to analyze designs and make good decisions. Nam Suh, a former professor at MIT, outlined two design axioms to govern the engineering design process in the 1970s. These two axioms have come to define what does and does not constitute good design. The two axioms are as follows: (1) maximize independence and (2) minimize information (Suh, 2001).

The first axiom, to maximize independence, requires a design to be collectively exhaustive and mutually exclusive, thus decoupling the design. Decoupling all components in the design ensures that changing one component of the design does not affect the rest of the

design. Translating functional requirements (FRs) into design parameters (DPs) can help to ensure a decoupled design. Customer needs dictate the functional requirements and the design expectations. Once the designer forms functional requirements, he or she must formulate design parameters to meet the functional requirements. Christopher Brown, axiomatic design expert, outlined the types of coupling as follows: FR-FR coupling between functional requirements, FR-DP coupling between functional requirements and design parameters, and DP-DP coupling between the design parameters (Brown, 2006).

Designers consider the second axiom, to minimize information, when there are multiple designs that can satisfy the design requirements equally well. In this case, the design with the least information is the best design. Engineers can achieve the second axiom by choosing the design that allows for greatest probability of success due to greater simplicity. For example, axiom two would guide a designer in manufacturing to choose a design with less stringent tolerance requirements. The key to satisfying the second axiom is to allow for a larger target area, where the design will achieve desired functions but the chance for failure is less.

We utilized axiomatic design in the creation of our ski plate through Acclaro, the leading axiomatic design computer program. Through this program, a design decomposition with FRs and DPs can be created. Axiom one was satisfied by ensuring the omission of coupling in our design decomposition. Every component in our design serves a purpose of one of the FRs, and only one of the FRs. In addition, the design does not include extraneous features that serve no purpose in satisfying the functional requirements. Axiom two was not required since we settled upon one design and performed iterations moving forward, rather than choosing from multiple designs at the start of the design process.

After the design was chosen, we performed calculations, selected material, and created computer aided design (CAD) drawings. A finite element analysis (FEA) was performed using SolidWorks to determine if the design would withstand high loads. It also allowed the group to see where material could be added or removed to make the lightest, strongest model possible.

Manufacturing the chosen design began after the design and analysis was completed. This initial stage included reviewing our drawings for manufacturability, insertion of the design into a computer aided manufacturing (CAM) program, and a preliminary check with the lab staff. We machined the components to their desired specifications after the initial manufacturing stage was completed. The ski binding plate was assembled after machining was completed and testing was done to make sure the functional requirements were satisfied. If any FRs were not satisfied, redesign and additional manufacturing was done on the individual components that did not work.

2   Design Decomposition

Axiomatic design was used to formulate the best possible design alternative through the design decomposition outlined in section 1.4 above. Section 0 below details the functional requirements and their associated design parameters.
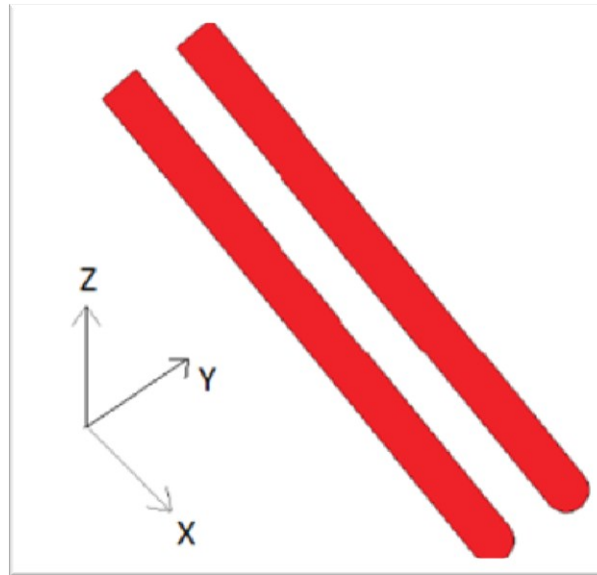
Functional Requirements and Design Parameters

The next step in the design process was to create Functional Requirements (FRs) and Design Parameters (DPs) from the FRs. Both FRs and DPs begin at a broad high level and become more specific at each sub-level. The FRs represents the functional need of the design whereas the DPs are the physical apparatuses that allow the FRs to function.

FR 0	Shield ACL from injurious loads during skiing	DP 0	Binding plate to shield ACL from injurious loads during skiing
FR 1	Transmit loads about the y-axis	DP 1	Mechanism to transmit loads about the y-axis
FR 2	Transmit loads about	DP 2	Mechanism to

	the x-axis		transmit loads about the x-axis
FR 3	Transmit loads about the z-axis	DP 3	Mechanism to transmit loads about the z-axis

FR 0 Shield ACL from injurious loads during skiing

The highest level for the design decomposition, or the primary functional requirement of the design, is to prevent ACL injury during skiing. As the highest functional requirement, all subsequent functional requirements will aim to accomplish this goal. Each subsequent functional requirement is known as a child to the higher-ranking functional requirement; the child requirements seek to fulfill the requirement of the parent. The coordinate system used in this design is featured in Figure 2 above.

DP 0 Binding plate to shield ACL from injurious loads

The highest design parameter represents the complete implementation of FR 0. All of the lower DPs combine to fulfill DP 0 and can be seen in Figure 3: Full Assembly. These lower design parameters combine to be the entire mechanism and are explained in detail below.
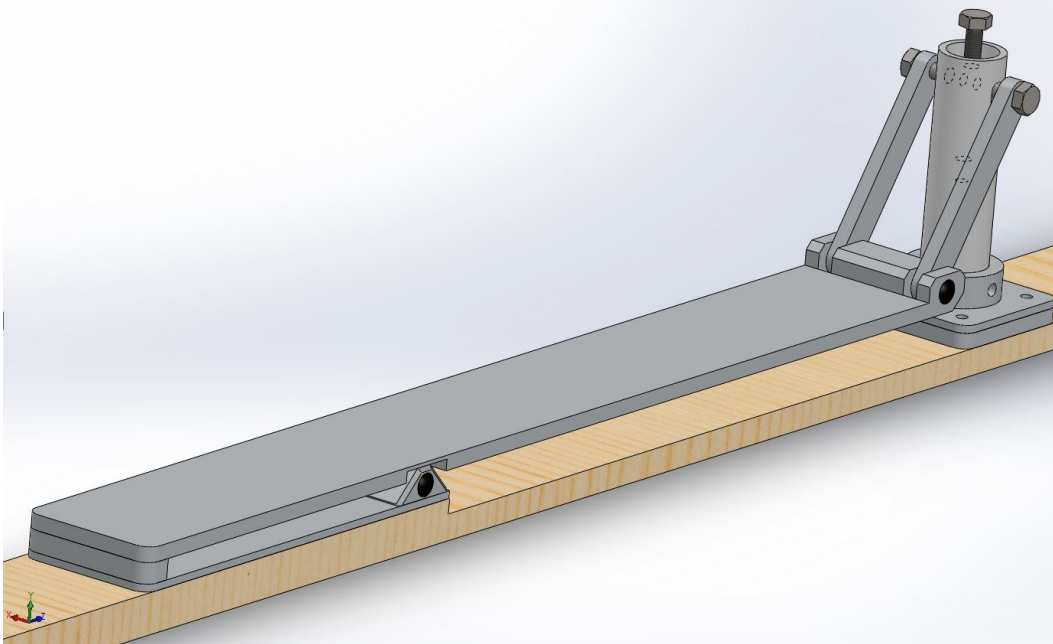
FR 1 Transmit loads about the y-axis

The first child functional requirement for the design is to transmit loads about the y-axis during skiing. The y-axis runs across the width of the ski, the axis about which forces causing BIAD injury are transmitted. The children of FR 1 can be seen in Table 1 below.

Table 1: FR 1 Children

FR 1.1	Transmit control loads about the y-axis to allow typical skiing conditions	DP 1.1	Mechanism to transmit control loads about the y-axis
FR 1.1.1	Provide lever arm perpendicular to y	DP 1.1.1	Rigid structures in the z-x plane
FR 1.1.1.1	Provide lever arm at toe	DP 1.1.1.1	Toe support

FR 1.1.1.2	Provide lever arm at heel	DP 1.1.1.2	Preloaded spring
FR 1.1.2	Provide interface perpendicular to y	DP 1.1.2	Plugs
FR 1.2	Filter BIAD ACL injury loads about the y-axis	DP 1.2	Mechanism to filter BIAD ACL injury loads about the y-axis
FR 1.2.1	Accept injurious load input	DP 1.2.1	Pin
FR 1.2.2	Transform injurious loads into non-injurious loads	DP 1.2.2	Spring system
FR 1.2.2.1	Adjust injurious load minimum based on skiers weight and style	DP 1.2.2.1	Bolt that adjusts the spring's preload
FR 1.2.2.2	Control spring motion	DP 1.2.2.2	Spring housing system
FR 1.2.3	Transmit the non-injurious loads	DP 1.2.3	Linkage system
FR 1.2.3.1	Convert between linear and rotational motion	DP 1.2.3.1	Pins and connector arm system

	Transmit torques to		Bolt connector and
FR 1.2.3.2	ski	DP 1.2.3.2	spring pusher system

DP 1 Mechanism to transmit loads about the y-axis

The mechanism that transmits loads about the y-axis has to transmit two types of loads, control and injurious loads. During control loads, this mechanism will allow for stability and the correct stiffness required during normal skiing conditions. When injurious loads are present the mechanism will absorb the high loads, protecting the skier.

FR 1.1 Transmit control loads about the y-axis to allow typical skiing conditions

During normal skiing conditions, a skier is secured to the ski through a binding which transmits control loads from the skier to the ski. Stiffness must be maintained about the y-axis during normal skiing to allow the skier to shift his or her weight backwards and forwards as the terrain demands.

DP 1.1 Mechanism to transmit control loads about the y-axis

This mechanism creates a solid platform between the ski and the ski boot. Thus it is used to maintain controlled movement in the y-direction and prevent injurious loads. In the design there is a rigid structure at the toe to prevent rotation in the positive y direction as well as transmitting loads at the toe area. At the heel there is a spring preloaded to a predetermined amount. When loads are under the preload, the spring will act as a rigid structure and transmit the control loads at the heel. These features are shown in Figure 4 below.
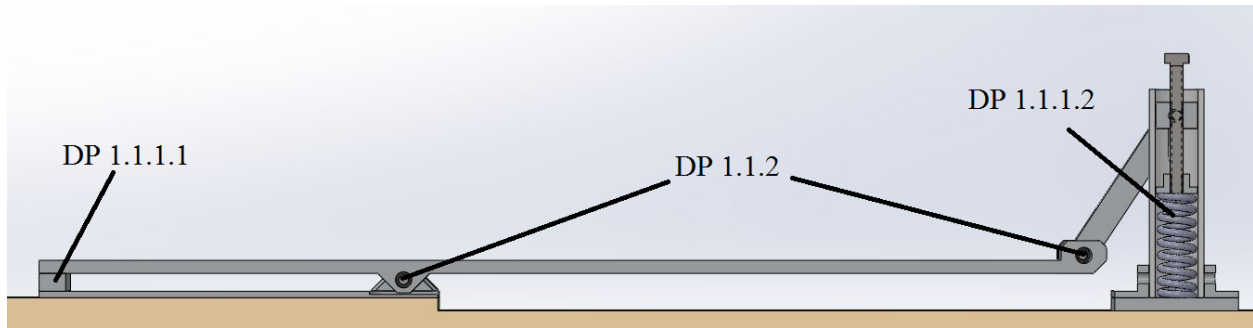
Figure 4: Design Parameters for DP 1.1

FR 1.2 Filter BIAD ACL injury loads about the y-axis

During BIAD ACL injury, it is necessary have rotation about the y-axis in the negative direction. This will allow the tibia to move with the femur, preventing ACL injury as discussed in Appendix A: Types of ACL Injuries Common to Skiing. Additionally, these high loads should be absorbed away from the skier to further reduce the risk of injury.

DP 1.2 Mechanism to filter BIAD ACL injury loads about the y-axis

The mechanism created to filter the injurious loads was a pin, spring and linkage system. Between the three devices, the high loads are transferred and stored and rotation is allowed.

FR 1.2.1 Accept injurious load input

When injurious loads occur, the plate must be allowed to rotate about the y-axis. This rotation will allow the toe to raise and heel to lower.

DP 1.2.1 Pin

During normal skiing conditions, the pin (Figure 5) helps to transmit the loads between the ski and the skier around the middle of the boot. However, when injurious loads are present the pin allows rotation of the plate.
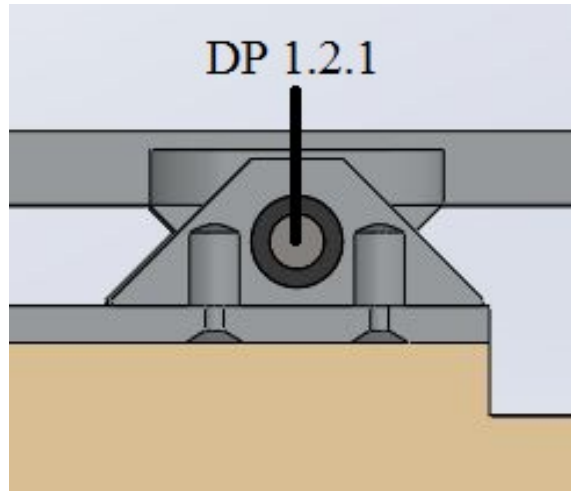
FR 1.2.2 Transform injurious loads into non-injurious loads

Injurious loads must be transformed into non-injurious loads to prevent harming the skier. This is done by storing the energy and releasing it in a controlled manor.

DP 1.2.2 Spring system behind the plate

The spring system behind the plate is used to control rotation about the y-axis and store the energy that could harm the skier. The spring preload is adjustable using a bolt. Allowing the preload to be adjusted is necessary because different skiers have different weights and abilities and require different preloads. Additionally, it is difficult to control rotary motion, therefore a spring housing system was created to translate the rotational motion into linear motion. With linear motion, the spring can properly store the injurious energy. These DPs are shown in Figure 6 below.
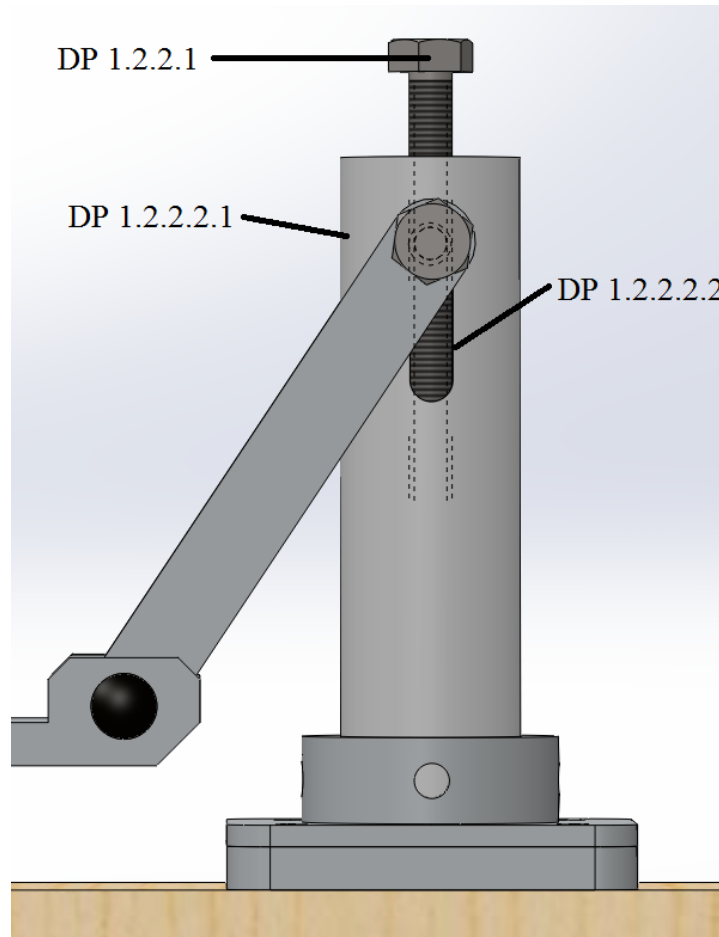
Figure 6: Spring System

FR 1.2.3 Transmit the non-injurious loads

A mechanism is needed to transmit loads back and forth between the ski, the skier and the spring. Additionally, it is necessary to convert the rotational motion of the plate to a linear motion to the spring.

DP 1.2.3 Linkage System

A linkage system was introduced to transmit the loads between the plate and the spring. The linkage was broken up into three separate parts, all shown in Figure 7 below. The pins and connector arms allow the rotary motion to be converted into linear motion. The pins sit in the slots on the spring housing so they will slide in the single axis. The connector arms attach and

transmit loads from the plate to the spring mechanism. There is a bolt connector and spring pusher system in the spring housing system. The bolt connector connects the pins to the bolt that displaces the spring. There is a threaded hole in the center of the bolt connector to allow the spring to be preloaded by screwing the bolt in or out. When loads are being transmitted through the linkage, these threads will cause the bolt to go up or down, displacing the spring.
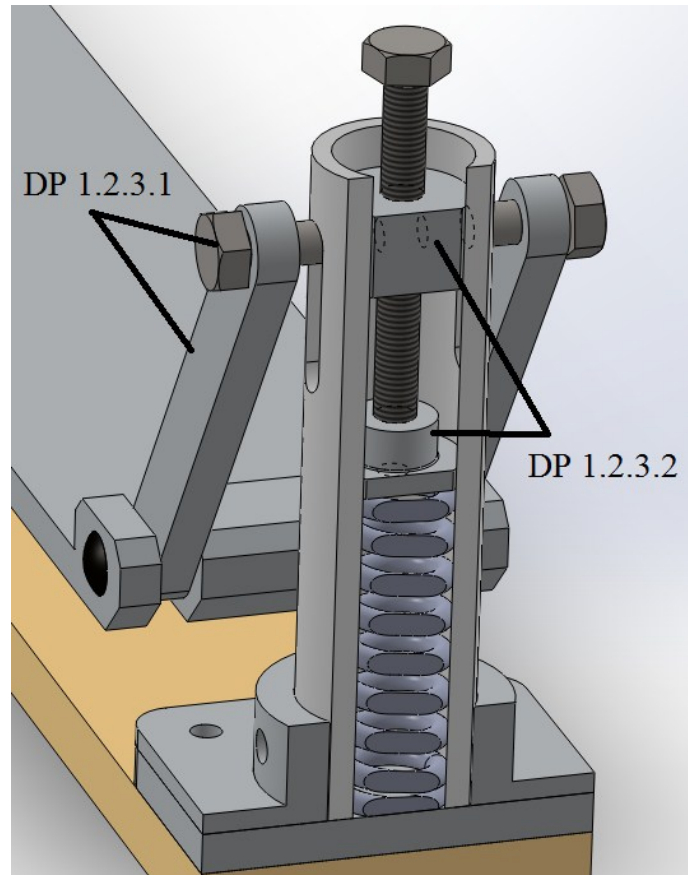
Figure 7: Cut out view of Linkage System

FR 2 Transmit loads about the x-axis

It is necessary to transmit loads about the x-axis because edging loads in normal skiing are transmitted about the x-axis. The mechanism must be able to transmit these normal edging loads to the ski. The children to FR 2 can be seen in Table 2 below.

FR 2.1	Provide lever arm perpendicular to x	DP 2.1	Cradle system
FR 2.2	Provide interface perpendicular to x	DP 2.2	Bottom cradle screws

DP 2 Mechanism to transmit loads about the x-axis

Normal control loads including edging, changing direction, and stopping, involve transferring loads about the x-axis and thus the plate must be able to rigidly transmit loads about the x-axis. A mechanism must be used to transfer the loads from the skier to the ski in this manner and is shown in Figure 8 below.
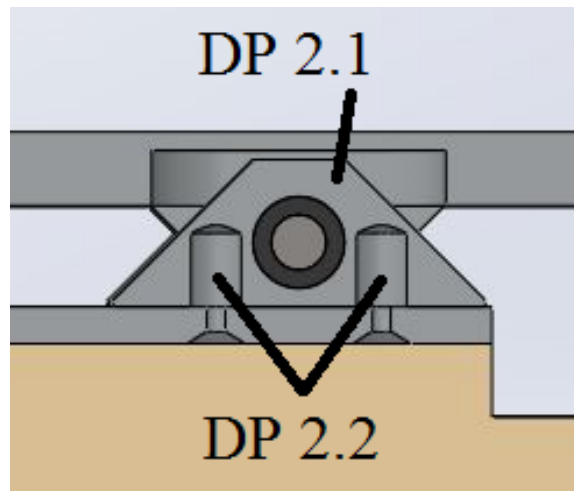

Figure 8: Cut out view of cradle system

FR 3 Transmit loads about the z-axis

Loading about the z-axis is present in normal edging movements. The mechanism must transmit loads about this axis as to not interfere with normal skiing.

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FR 3.1	Provide lever arm perpendicular to z	DP 3.1	Pin
FR 3.2	Provide interface perpendicular to z	DP 3.2	Toe support

DP 3 Mechanism to transmit loads about the z-axis

A mechanism is used to transmit loads about the z-axis maintains normal skiing conditions. Edging movements require loads to be transmitted about the z-axis to maintain normal skiing conditions. This mechanism (Figure 9 below) is used to transfer control loads from the skier to the ski.

DP 3.2   DP 3.1
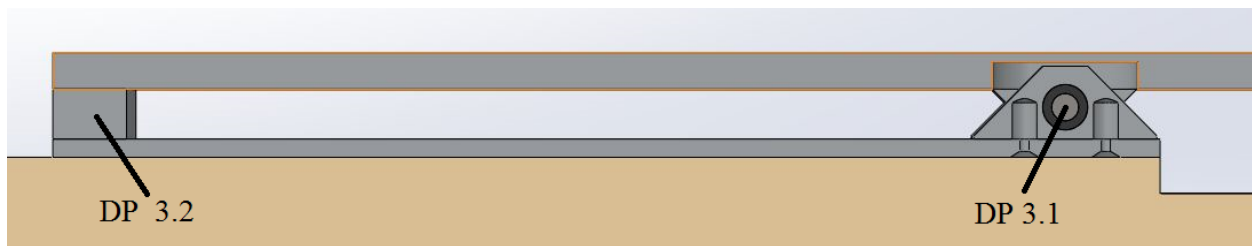
Figure 9: Design parameters for transmitting loads in the z-axis

Constraints

Understanding the constraints of a design is essential. The constraints include a list of what the device must conform to, defines the boundaries, can link several FR's, and can set limits for the design. (Suh 1990, 2001) For this project, the main constraints are to minimize friction, prevent snow from getting in, no sharp edges, and minimize cost. \

Minimizing friction is important for the ski binding plate to work correctly. Bushings were used to reduce friction at each pivot point. This bushing could not be metal because of corrosion and metal fragmentation. We decided to use nylon bushings because their coefficient of friction was the lowest of all bushings considered. Secondly, we used PVC pipe for the spring housing because it has sliding interfaces with the spring pusher and the bolt connector.

The PVC minimized frictional forces in comparison to aluminum. This first constraint links many FR's throughout the implementation.

The second constraint is the prevention of snow interfering with the top plate motion. It is important because normal skiing conditions include snow and ice. If snow or ice were to get into the ski binding plate, it would act as an abrasive could lead to failure. A plastic covering that will go around the opening between the bottom and top plate will fulfill this constraint. This constraint affects many FR's including the top and bottom plates.

The second constraint is to minimize sharp edges throughout the design. This is important for safety reasons because a ski could come off the skier's boot and cause injury to other skiers. Accordingly, chamfered edge is essential to the ski binding plate. This constraint links every part of the design because they all have external edges.

The prior history is the fourth constraint. Prior history limits the design to new ideas while creating a foundation for the project. Since there are ACL prevention devices on the market already, it was crucial to find an area that was lacking. This design is different from others because it can reset itself. This constraint links all the FR's and changes some FR's from other projects.

Cost is the final constraint. We had enough money in our budget to comfortably purchase all of our required materials and parts. We minimized shipping costs by purchasing items through the Mechanical Engineering Department. Budget Therefore, this constraint is imperative but was not highly essential to this project.

3 Physical Integration

3.1 Material Selection

Material selection was a key component in the design and testing of this prototype. We considered several materials before we made our selection. We evaluated several material properties, including yield strength, weight, and machinability. The final materials we evaluated were aluminum 6061-T6, grade 4 titanium, and aluminum 7075-T6, detailed in Table 3 below.

Table 3: Material Properties

Material	Yield Strength	Weight	Machinability	Relative Cost
Aluminum 6061-T6	8,000 psi	Lightweight	Easy to machine and weld	Inexpensive
Grade 4 Titanium	70,000 psi	Lightweight	Difficult to machine	Extremely Expensive (5 times the cost of Al 7075-T6)
Aluminum 7075-T6	63,000 psi	Lightweight	Easy to machine	Moderately Expensive

We used aluminum alloy 7075-T6 for the top plate because of its superior strength, machinability, and weight but did not use it for the rest of the prototype because of its cost. For the rest of the prototype we used aluminum alloy 6061-T6.

3.2 Spring Calculations

We utilized a spring system to allow for displacement upon the application of injurious loads on the ski to prevent them to be transmitted to the skier. The spring features a preload to minimize movement before the injurious threshold and transmit normal control loads. Once the

injurious threshold is reached, the spring will compress, allowing the skier's heel to rotate about the y-axis.

The chart below in Figure 10 demonstrates the relationship between load and displacement and how that relationship is altered with the addition of a spring system to provide additional displacement.
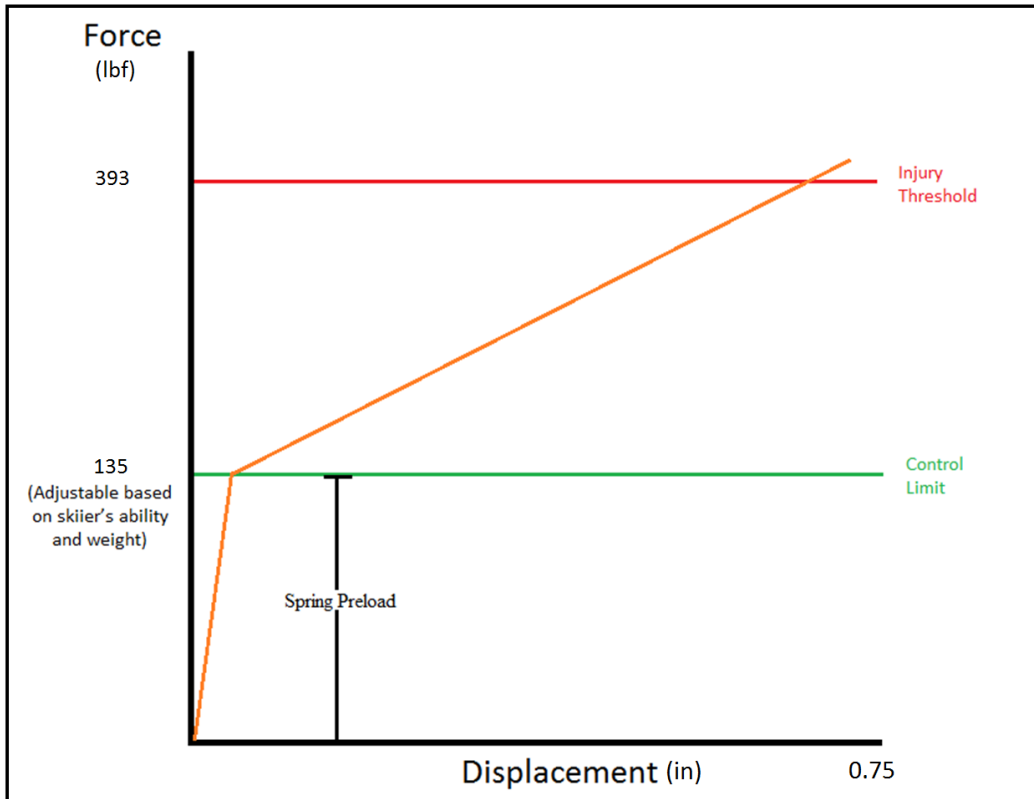
Figure 10: Force vs. Displacement

The line for normal skiing loads identifies the point at which loads exceed normal skiing conditions and begin to negatively affect the skier. This is addressed by adding a spring system to mitigate the loads beyond this point.

If no system were put in place, the load-displacement curve would continue straight upward once it reaches the normal skiing load limit cause the injury threshold to be reached

much more quickly. Allowing displacement at the heel with a spring system minimizes loads on the ACL and prevents the loads from reaching the injury threshold.

An integral part of choosing the correct springs for use in the system is calculating the required spring constant (k) value. In addition, we need to calculate the preload so the spring only compresses when injurious loads are present. A free body diagram illustrating the forces used to calculate these parameters is featured in Figure 11 below.
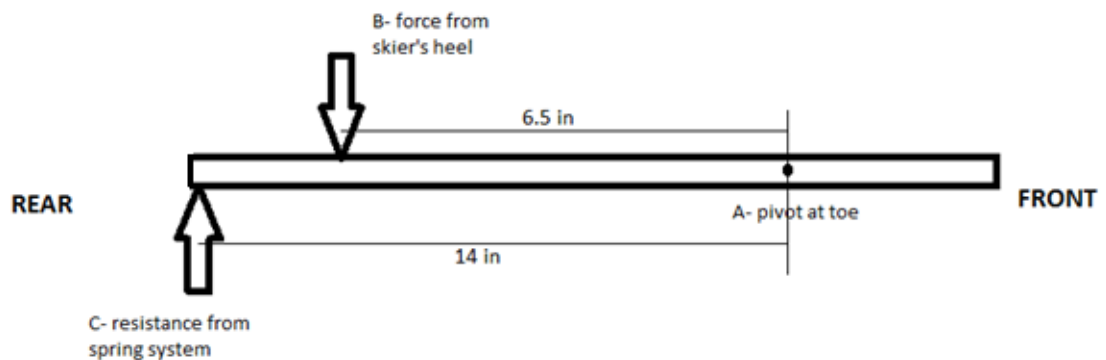
Figure 11: Forces present in system

With this diagram, and assuming 135 pounds force delivered at the heel, we calculated the required spring preload to be approximately 63 pounds force: .

$$M_A = 6.5 \ in(B) - 14 \ in(C)$$

$$0 = 6.5(135 \ lbf) - 14(C)$$

$$6.5(135) = 14(C)$$

$$C = 62.63 \ lbf$$

Knowing that injury to the ACL becomes pertinent at about 393 lbf, we can solve for the maximum load for the spring.

$$M_A = 6.5(B) - 14(C)$$

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$$0 = 6.5(393\ lbf) - 14(C)$$

$$6.5(393\ lbf) = 14(C)$$

$$C = 182.46\ lbf$$

This tells us that the maximum load for the spring should be set at about 183 pounds force; forces above this level will be expected to cause ACL injury.

With this, we now move on to calculating the spring constant required for the desired output by the spring. We used a displacement of 0.75 in to allow the heel maximum possible displacement. We calculated an ideal spring constant of 160 lbf/in:

$$k = \frac{Max\ load - Pre\ load}{Displacement}$$

$$k = \frac{183\ lbf - 63\ lbf}{0.75\ in}$$

$$k = 160\ lbf/in$$

In summation, we calculated that the spring should begin to displace at approximately 63 lbf and continue to displace until loads reach the injury threshold at approximately 183 lbf. The spring will displace approximately 0.75 in during this time and should have a spring constant of approximately 160 lbf/in.

3.3 Finite Element Analysis

A finite element analysis (FEA) was completed on all parts to determine whether each part would fail, and if so, where material needed to be added to prevent failure. We used SolidWorks Simulation Xpress Analysis Wizard for all FEA. We used FEA as an iterative process to improve our design and remove as much material as possible from each part to minimize the total weight of the plate. The FEA for all designed parts is included below.

The first part analyzed was the top plate, depicted in Figure 12 below. Two finite element analyses were conducted for the top plate – a maximum loading FEA and loading due to edging FEA. For the maximum loading FEA, a 183 lbf force was applied to the through holes at the end of the plate where it connects to the spring to simulate the upward force of the spring. A 382 lbf force was applied to the area at which the binding interfaces the plate to simulate the force applied by the skier. The von Mises stresses are shown in Figure 12 in pounds per square inch with a maximum von Mises stress of 38,328 psi, which is under the yield strength of Al 7075 T6 of 73244 psi, giving the part a factor of safety (FOS) of 1.9.
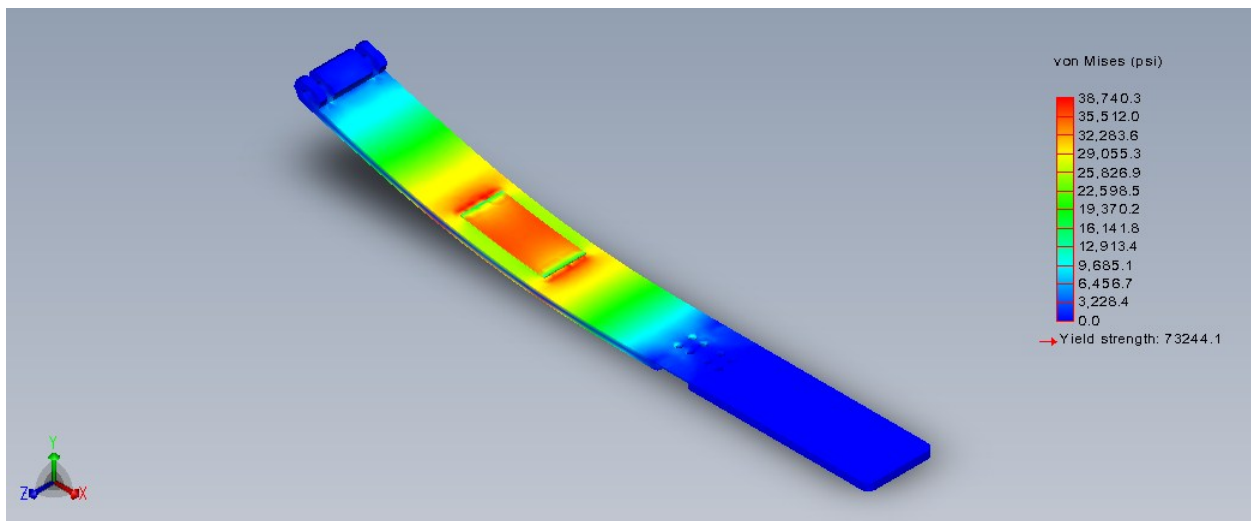

Figure 12: Top Plate Maximum Forces FEA

The top plate was then analyzed for edging loads as seen in Figure 13. The part was fixtured at the holes where the top plate and top plate cradles connect and again under the toe where the toe support interfaces with the top plate. A 224 lbf compressive force was applied to the toe and a 183 lbf compressive force was applied to the heel of the plate to simulate edging loads. The plate was fixed at the toe and at the linkage connectors to simulate normal skiing conditions. The part had an FOS of 2.4 under edging loads.

FEA for the top plate was a significant part of our design process. After completing several iterations of FEA for our top plate design without any success in bringing the FOS above 1, we were forced to consider different materials stronger than the aluminum 6061-T6 we had purchased. After materials research, we determined aluminum 7075-T6 would be sufficiently strong for our design.
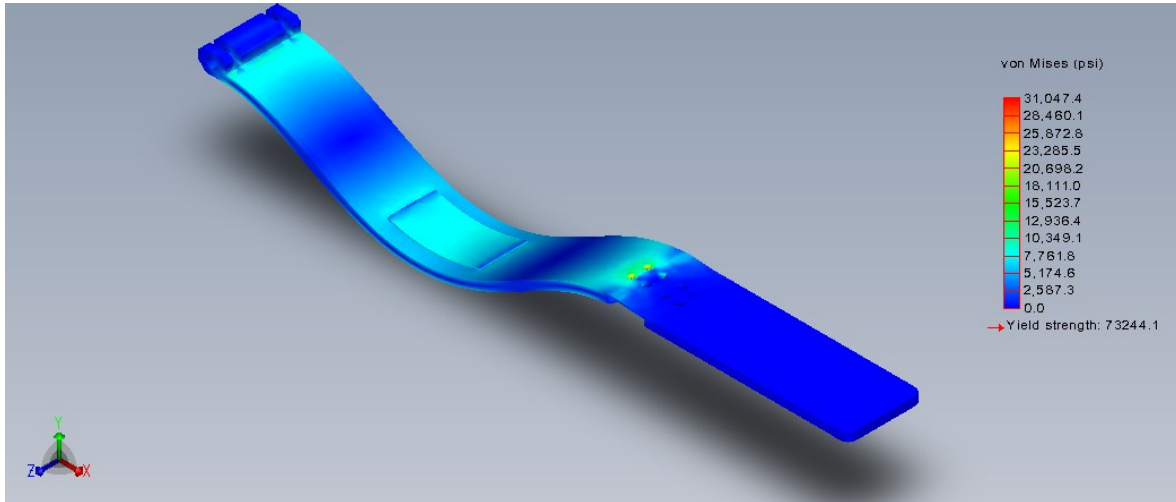
Figure 13: Top Plate Edging Loads

After we completed the FEA on the top plate, we performed analyses on each of the parts we we designed. The results of these finite element analyses can be found in Table 4 below. A detailed explanation of the analysis parameters and results can be found in

Appendix D: Additional Finite Element Analysis Results.

Part	Material	Yield Strength (psi)	Maximum von Mises Stress	Factor of Safety
Top Plate Cradle	Aluminum 7075-T6	73,200	3,694	29.2
Bottom Plate	Aluminum 6061-T6	8,000	2,943	2.7
Bottom Plate Cradle	Aluminum 6061-T6	8,000	1,376	5.8
Bottom Plate Toe Support	Aluminum 6061-T6	8,000	928	8.6
Spring Housing	PVC Rigid	5,130	1,546	3.3
Spring Pusher	Aluminum 6061-T6	8,000	5,572	1.4
Bolt Connectors	Aluminum 6061-T6	8,000	1,942	4.1
Housing-Ski Interface	Aluminum 6061-T6	8,000	2,915	2.7
Links	Aluminum 6061-T6	8,000	4,148	1.9

Table 4: Finite Element Analysis Results

4   Prototype Production

The next step after completing the CAD was finished was to machine the individual

parts. As stated before, the material that was chosen to for the prototype was aluminum 6061-T6.

All the parts besides the bearings, pins, top plate, and PVC tube were machined from this. The

top plate was machined out of aluminum 7075-T6 because it is a stronger material and could

withstand the stronger loads. The machining was completed in two ways; manual and computer

numerical control (CNC).

We used a lathe for the manual machining. We used the lathe by positioning circular

aluminum stock and drilling into it. We faced and shaped the stock, and drilled a hole through

the center of the stock.   We used the lathe to manufacture the spring pusher and the bolt

connector. Making these through manual machining allowed us to save time in machine programing and also save material.

We used CNC machines for the majority of the parts. CNC machining was preferable because it allowed us to perform multiple operations quickly. The first step to using the CNC machines was to program the machine to perform the correct operations in the correct order, which was accomplished by the CNC instructor. The top and bottom plates were the biggest CNC machined. This was done by centering the aluminum stock and creating an X, Y, and Z-axis. A probe was used to tell the computer program the exact position of the stock. Once the positioning and dimensions were set, the spindle was turned on and the CNC machining began. The bed of the CNC machine powered by automatic feed motors moved the stock into the needed position to be machined. The parts were made after several passes in the z direction with increased depth each time. Each part was deburred after machining to remove sharp edges and all external corners were rounded to improve the safety of the design.

After machining, we assembled the prototype. Starting with the parts that didn't need to be fastened to the ski, we assembled from the base up. We drilled holes into the top and bottom plates, so that we could use the original ski screws. Assembly was successful as all the parts fit together as designed.

5   Testing

The prototype was tested to determine if the top plate displaces when loads are applied to the heel and by how much. We completed this in two separate tests: the first preliminary test determined if the top plate displaces when loads are applied to it, and the second determined the relationship between the applied force and the displacement.

We applied varied dumbbells upon the heel portion of the mechanism as a means of providing preliminary assessment of our mechanism under load. Force values were dictated by the weight of the dumbbells, while an affixed ruler recorded corresponding displacement. An image of the preliminary test setup is featured below in Figure 14Figure 15.
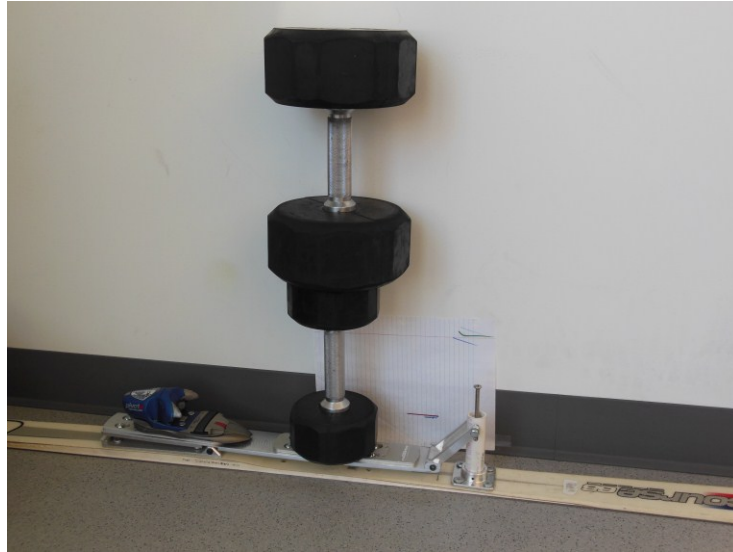
Figure 14: Preliminary Testing with Dumbbells

While this preliminary testing served well to demonstrate the overall operation of our mechanism under load, it was not sufficient to provide accurate numerical results. Thus, we set up a fixture to provide more precise load application.

Once we completed the preliminary testing, we performed a measured force-displacement test. We created a fixture to precisely control the application of force on the plate, as shown below in Figure 15Figure 15.

We constructed a yoke to control the direction of force, with a centered, threaded rod pressing down toward the heel portion of the plate. By inserting a force scale between the applied load and the plate, we can measure precise values of the applied force. We provided the downward load by screwing down on the center bolt that was positioned on the heel. Calipers positioned at the heel portion of the plate provide precise displacement measurements. We used the calipers to measure the displacement provided at the heel of the plate and compared it to the applied force.

We started by applying a load of 10 lbf by screwing down on the bolt until the force scale read 10lbf. We increased the load incrementally by 10lbf until we recorded displacement values up to a load of 200 lbf. We then constructed force-displacement graphs using this data to demonstrate the overall operation of our spring system.

Once we completed testing, we tabulated and analyzed the results. The graph displayed below in Figure 16 demonstrates the results obtained from our force-displacement testing.
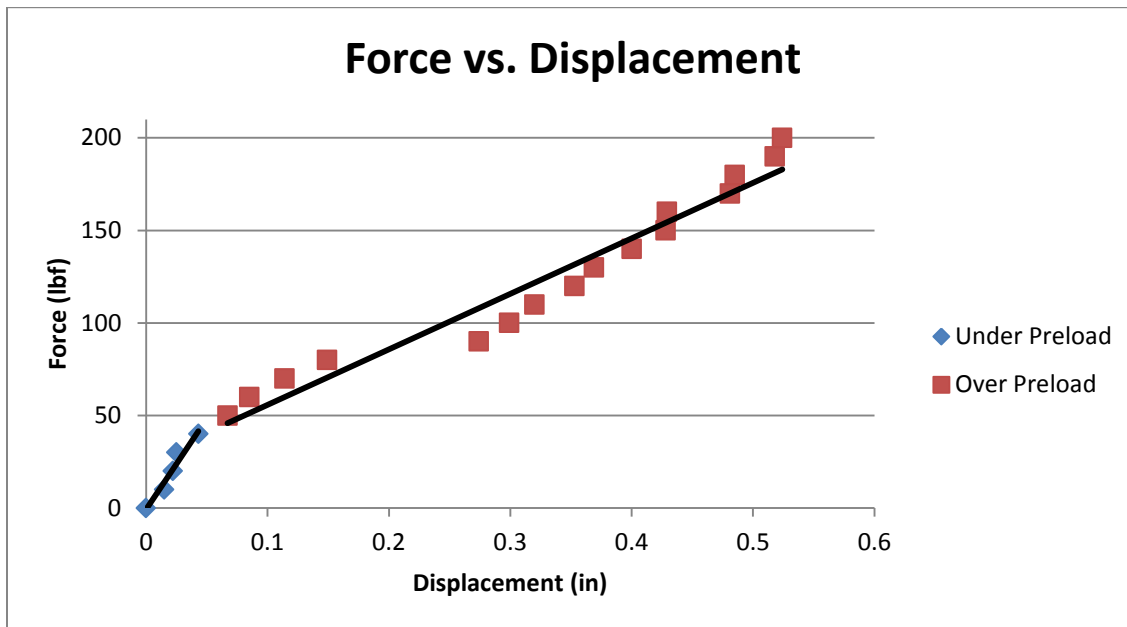
Figure 16: Testing Results

The results demonstrate that our plate behaves as expected it to: it displaced minimally until the loads reached the preload, and then it displaced linearly at a different rate after the preload. This graph closely mirrors the ideal spring graph shown in Section **Error! Reference source not found.**: Spring Calculations. At 200 lbf, the largest load we applied, the associated displacement was just over 0.5 inches. These tests results are consistent with our decomposition and our prototype can be considered a successful reduction to practice of our design.

6   Iteration

Overall, the prototype that was designed and machined functioned as expected. However in retrospect, there are changes that should and will be made to improve the prototype. Making these changes will help to reduce ACL injuries more effectively.

This design performed well and testing showed that the prototype could withstand the correct conditions however there are future improvements that could make this design better. Many of these improvements were thought of in hindsight to make machining easier and the design and assembly can be simplified.

6.1   Bushings

In future work, we would prefer to machine our own bushings rather than buy premade ones. First off, the source that sold the Nylon bushings did not specify the inner diameter tolerances. This prevented us from understanding what sliding fit tolerance was present. If we were to machine our own bushing, we would be able to obtain the desired sliding fit for the bin. This would take some of the undesirable play out of the system.

Although Nylon is ideal for friction and corrosion purposes, it was not reliable for minimizing perceptible play. This is because polymers are generally soft, so when dealing with high loads, the plastic displaces even under compressive loads. In order to better deal with these displacements, in future models we would like to use brass or some other stiffer bushing. Between the changing of the material and determining our own tolerances, the rotational motion about the z-axis would be considerably less than that of it currently is.

6.2   Tolerance between Cradles

It was brought to our attention that the probe on the machine we used to create the cradles was broken. This caused our dimensions to be over thirty thousandths off. This was noticeable in many aspects of our assembly and testing. Visually, the cradle is slightly angled which even more noticeable when we tried to put the pin into its proper place. The pin should have been a slide fit through the bushings; however, we had to use considerable force to get the pin through

both cradles and the top plate pivot. In addition to the pin not sliding in properly, this problem could be the reason why there seemed to excess movement about the z-axis.

6.3   Slot Design

During the assembly process it became clear that some force must be applied to the spring to connect the bolts to the bolt connector. This required several people to complete and complicated the assembly process. Increasing the height of the housing slots would allow the spring subassembly to be built without applying force to the spring. The spring preload can then be applied using the bolt as designed.

6.4   Housing Material

During testing it was noticeable that the PVC piping did not fail, however it did bend at loads less than the preload. This bending in the spring housing created unwanted displacement in the top plate. In a future product, we would like to make the spring housing out of aluminum. This would create a more rigid structure, so the housing can complete its proper function of limiting spring motion to a single axis. The only noticeable downside of creating the part out of aluminum is it will be heavier than that of the PVC. Aluminum will be a better option for safety and functional reasons than that of its PVC counterpart.

6.5   Top Plate Material

For prototyping purposes, we made the top plate out of aluminum 6061-T6. After extensive FEA on the different loading conditions, we determined that the Al 6061-T6 would not be stiff enough or strong enough to withstand the bending moments. Instead we would like to construct the top plate out of aluminum 7075-T6. This alloy is considerably stiffer and stronger. For the most part, the yield strength and Brinell Hardness of Al 7075-T6 is roughly double that

of Al 6061-T6. Having these mechanical properties will limit the bending displacement noticed in testing and will be much safer for the rider without considerable weight difference. The Al 7075-T6 properties are comparable to that of titanium, but the aluminum is considerably cheaper.

7   Discussion

The spring system displaces at the heel and at the toe as designed and thus is a successful ACL prevention mechanism. The spring stores the energy from the loads as demonstrated in our testing. This energy has the potential for causing ACL injury. When our design was loaded with 200 lbf, the displacement was consistent with our calculated values. The proper displacement of the mechanism under load demonstrates that ACL injury can be avoided because the spring will absorb the injurious loads and allow the skier to regain their balance and continue skiing.

Axiomatic design was an appropriate choice of a design method and allowed us to break our objective down into smaller, manageable sections. We were able to precisely define our functional requirements and chose appropriate design parameters. We were also able to compare design parameter alternatives by determining how well each DP fulfilled its FR. Through axiomatic design, we were able to create a simple design that accomplished our objectives

While the design decomposition was effective, it did take several months to accomplish and was the single most time consuming section of our project. We focused on rewording and reorganizing our decomposition long after we had begun machining. While this produced a high quality decomposition, it was not necessary once our design had been completed.

The constraints in the project were determined through axiomatic design. They limited the design of the project in many ways but also helped to define and regulate alterations in the design process. Eliminating sharp edges and minimizing friction were the most critical

constraints. Eliminating the sharp edges is very important for the safety of the skier and other skiers in the event of a ski pre-release. Minimizing friction helps reduce wear on components and improve life of the mechanism. Overall, the constraints were important throughout the design process.

This design impacts the ski industry and skiers globally by helping to prevent BIAD ACL injury. As stated earlier, $250 million is spent annually on ACL injuries, creating both an economic and societal problem. Skiers that tear their ACLs not only spend money but also lose potential to live their normal lives. This design will help to decrease the number of BIAD ACL injuries, thus addressing these problems.

8   Conclusions

This project successfully designed, created, and tested a ski binding plate to reduce the incidence of Boot Induced Anterior Drawer, one of the common types of ACL injury. The plate reduces the chance of injury by providing displacement at the heel and toe when injurious loads are transmitted through the ski. It also reduces the chance of injury by storing injurious loads in the spring and releasing the loads in a controlled manner. This project utilized axiomatic design to decompose our design into functional requirements (FRs) and design parameters (DPs). The FRs and DPs were then used to create a computer-aided design (CAD) model of our mechanism. A prototype was machined using the CAD models and assembled upon a ski. The plate was force-displacement tested to confirm the plate would displace at the proper force. The mechanism behaves as expected and we identified several ways to improve the design. Results of testing show our ski binding plate has potential in reducing the incidence of ACL injury in skiing.

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Appendix A: Types of ACL Injuries Common to Skiing

The most common injury to alpine skiers is a partial or complete tear of the ACL (Webster & Brown, 1996). There are two main modes of injury among recreational skiers: the Boot-Induced Anterior Drawer (BIAD) and phantom foot injury. BIAD injuries occur when a skier loses balance backwards and the majority of his or her weight moves behind the heel. The force is then transmitted up through the plates, bindings, and boots, causing an anterior drawer of the tibia relative to the femur, which results in a potentially harmful load on the ACL (Webster & Brown, 1996).

Phantom foot injuries occur when the skier is out of balance and leaning back with his hips below his knees. The phantom foot profile has six parts: 1) skier is off balance to the rear, 2) all the skier's weight is on the inside edge of the downhill ski tail, 3) the skier's uphill ski is not weighted, 4) the skier's hips are below his or her knees, 5) the skier's upper body is facing the downhill ski, and 6) the skier's uphill arm is back (Ettlinger, Johnson, & Shealy, 1995). When the inside edge of the downhill ski engages the snow surface, it causes the knee to rotate internally, tearing the ACL (Hame, Oakes, & Markolf, 2002).

Appendix B: Engineering Drawings

Top Plate
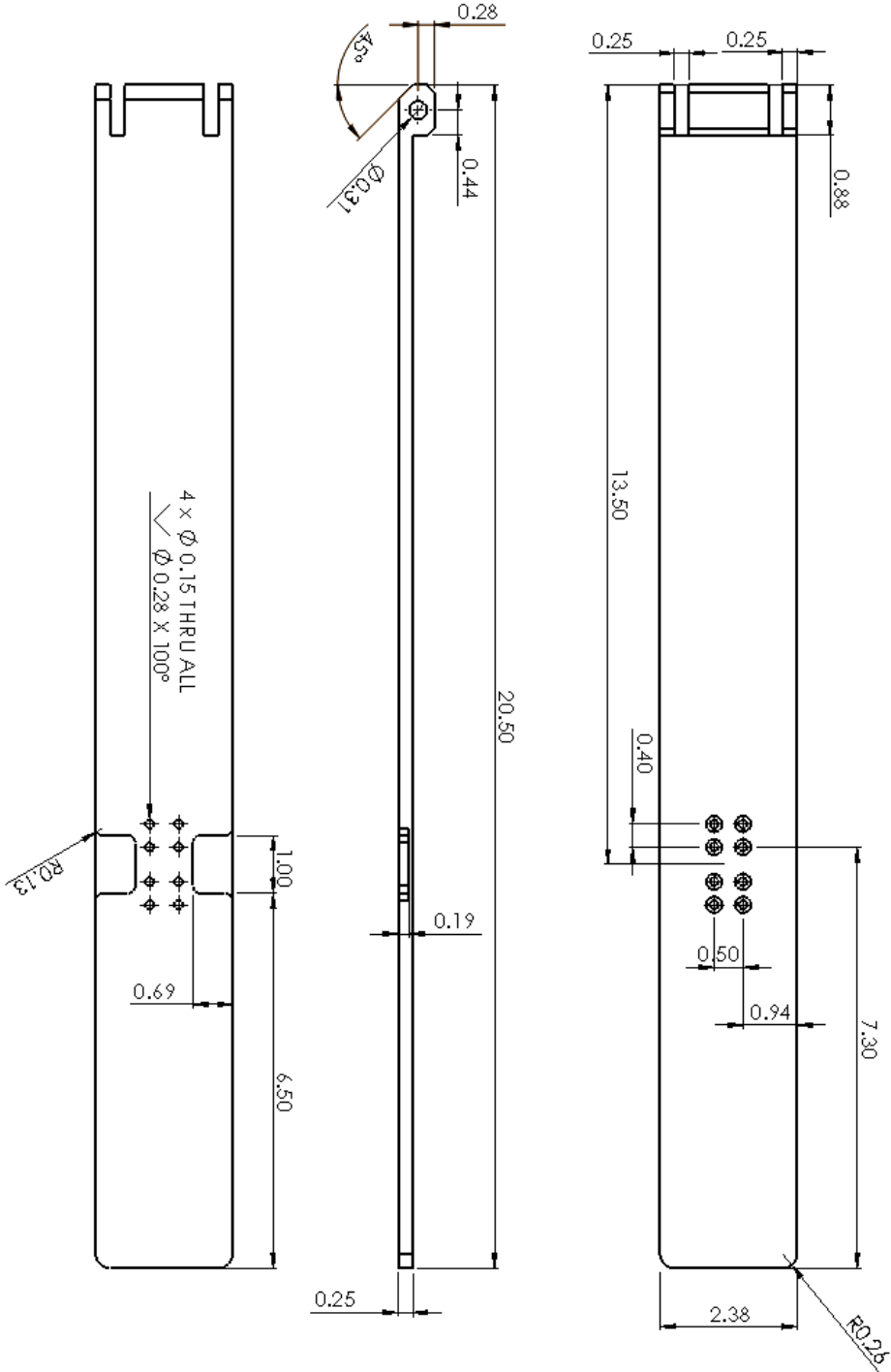
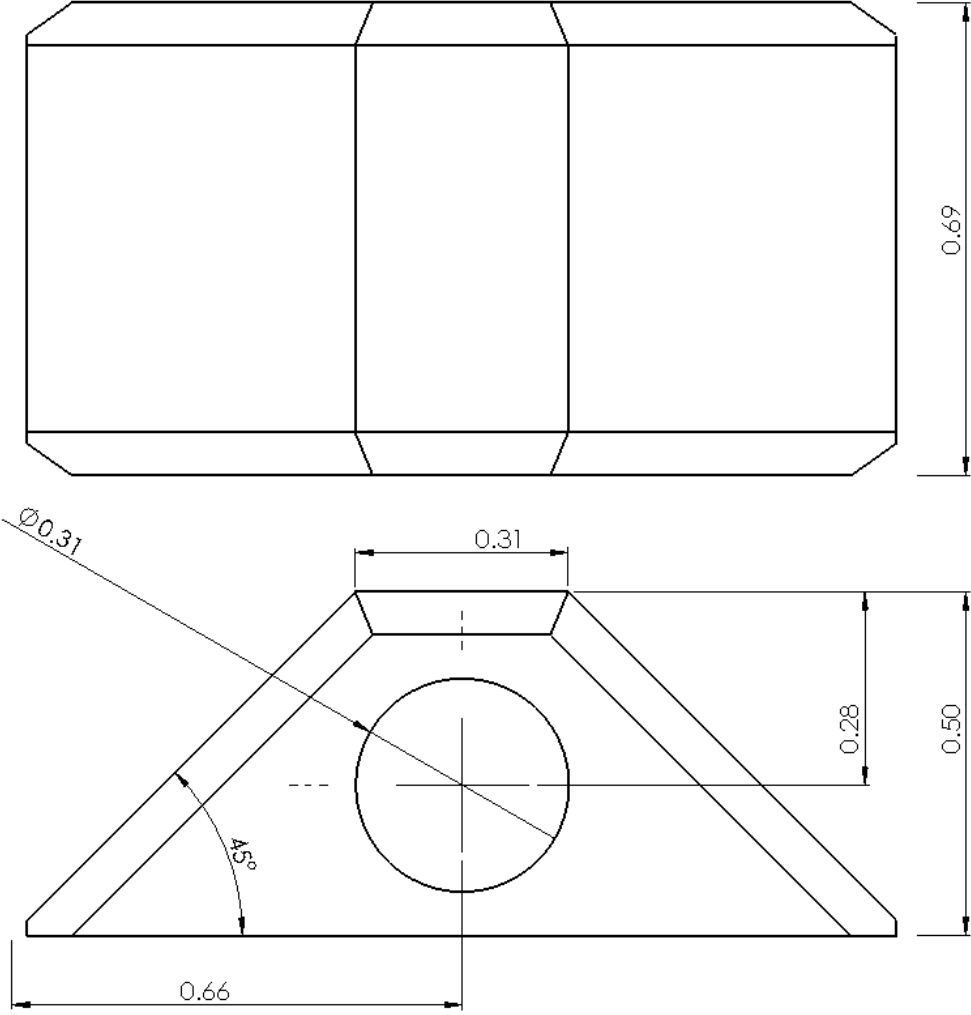## Top Plate Cradle
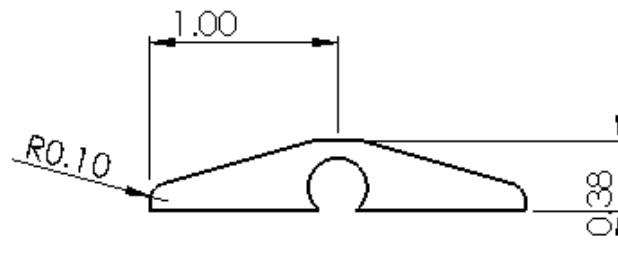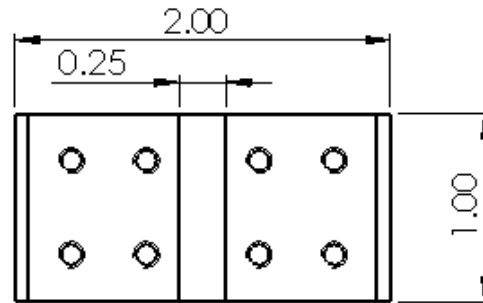
4 × ∅ 0.11 THRU ALL
6-32 UNC THRU ALL

4 × ∅ 0.11 THRU ALL
6-32 UNC THRU ALL

Bottom Plate

2.38

0.69

1.00

0.06

1.31

7.66

0.13

4 × ⌀ 0.13 THRU ALL
⌀ 0.23 × 100°

2 × ⌀ 0.13 THRU ALL
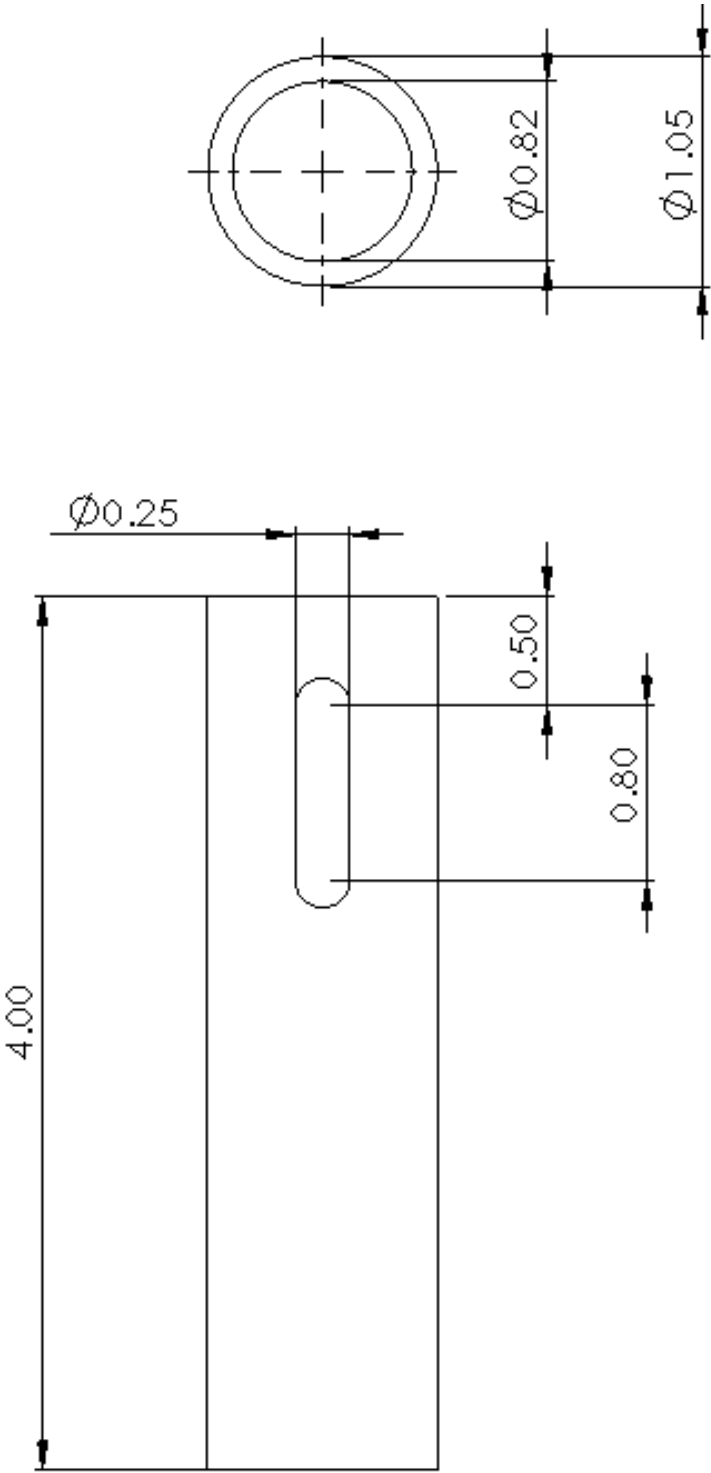⌀ 0.23 × 100°

R0.26
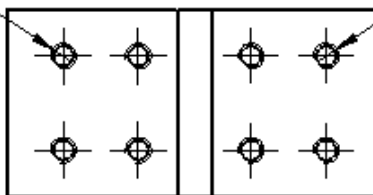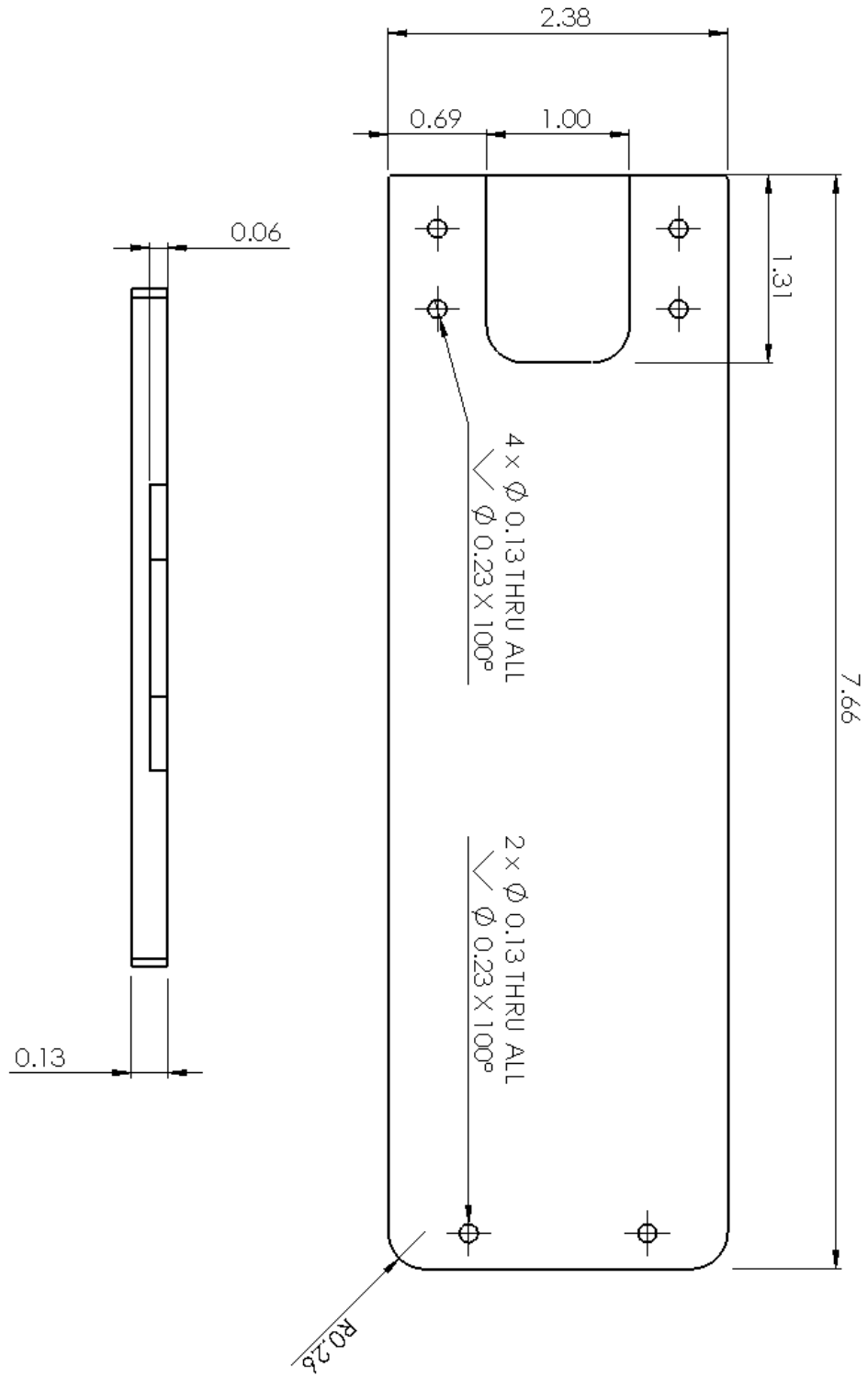
Bottom Plate Cradle

Toe Support

0.25

R0.26
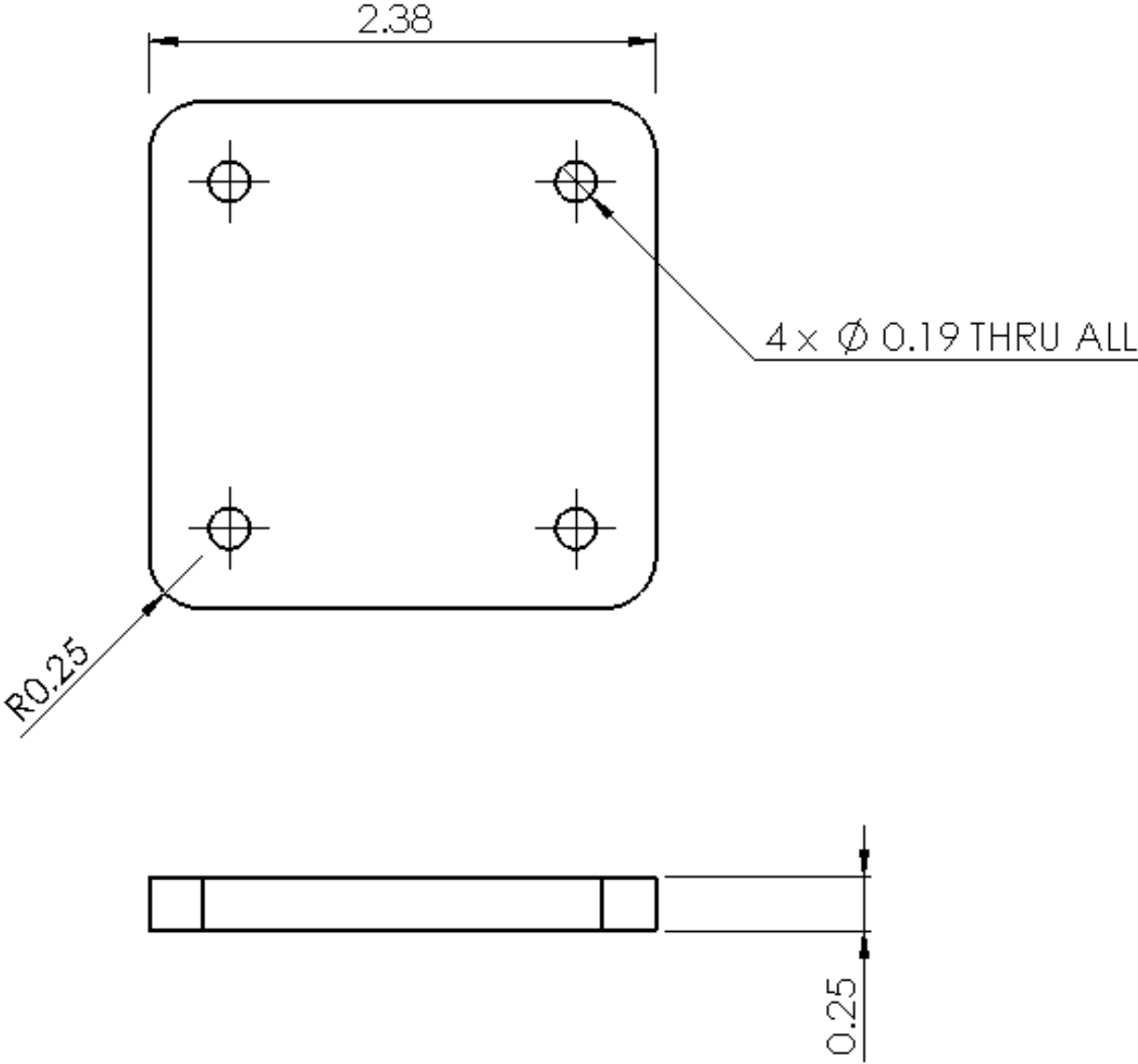
2.38

0.34
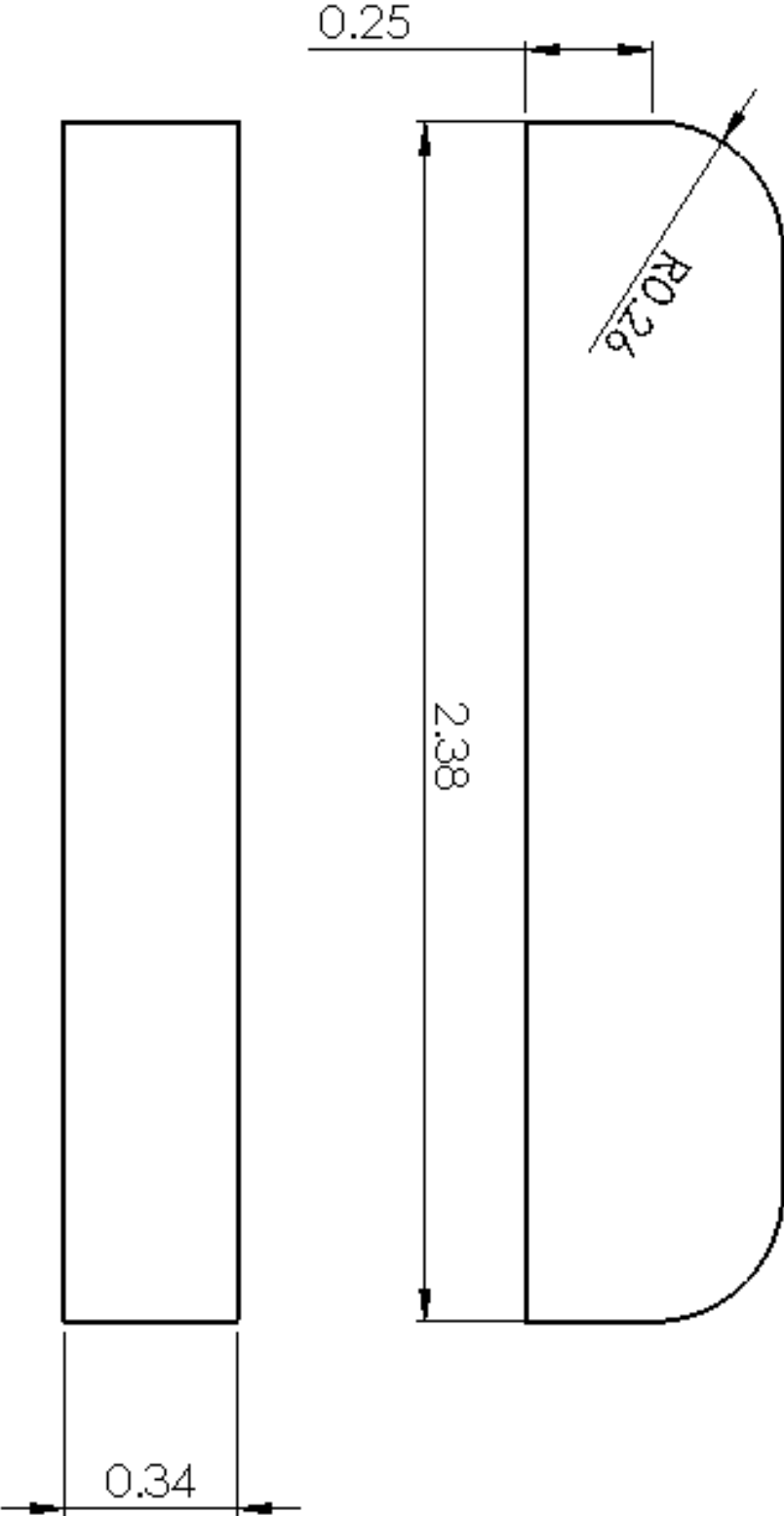
Ski-Housing Interface
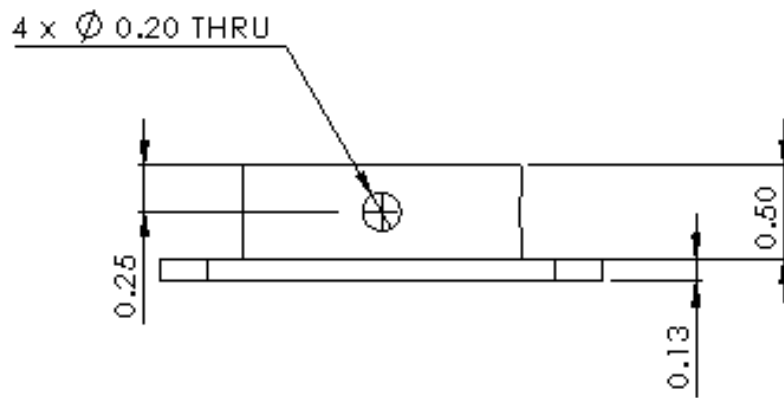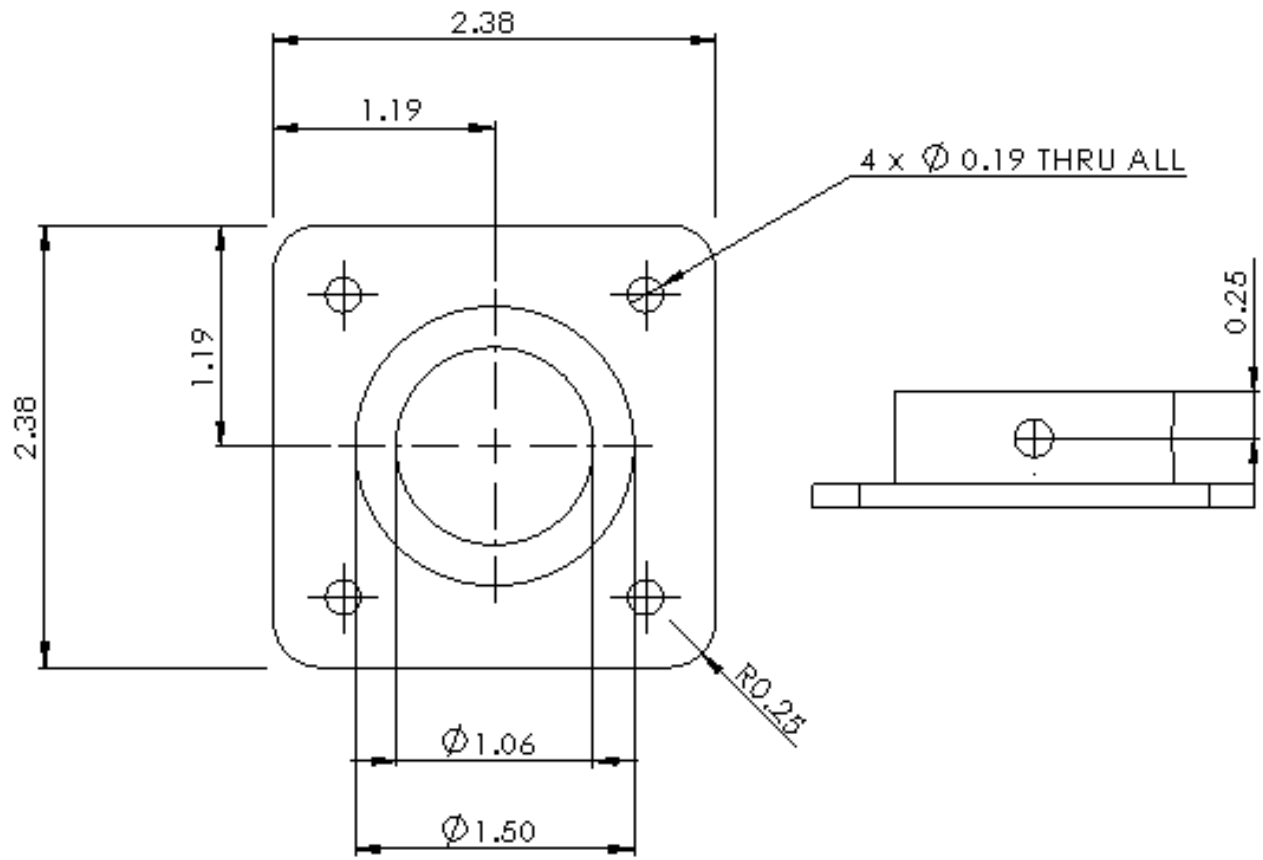
Spring Housing

Spring Pusher

Ø0.80

Ø0.25

Ø0.50

0.25

0.13

Bolt Connector

Link

⌀ 0.26 THRU ALL

R0.25

3.22

0.25

0.50

⌀ 0.31 THRU ALL

Ski Adaptor

2.38

4 × Ø 0.19 THRU ALL

R0.25

0.25
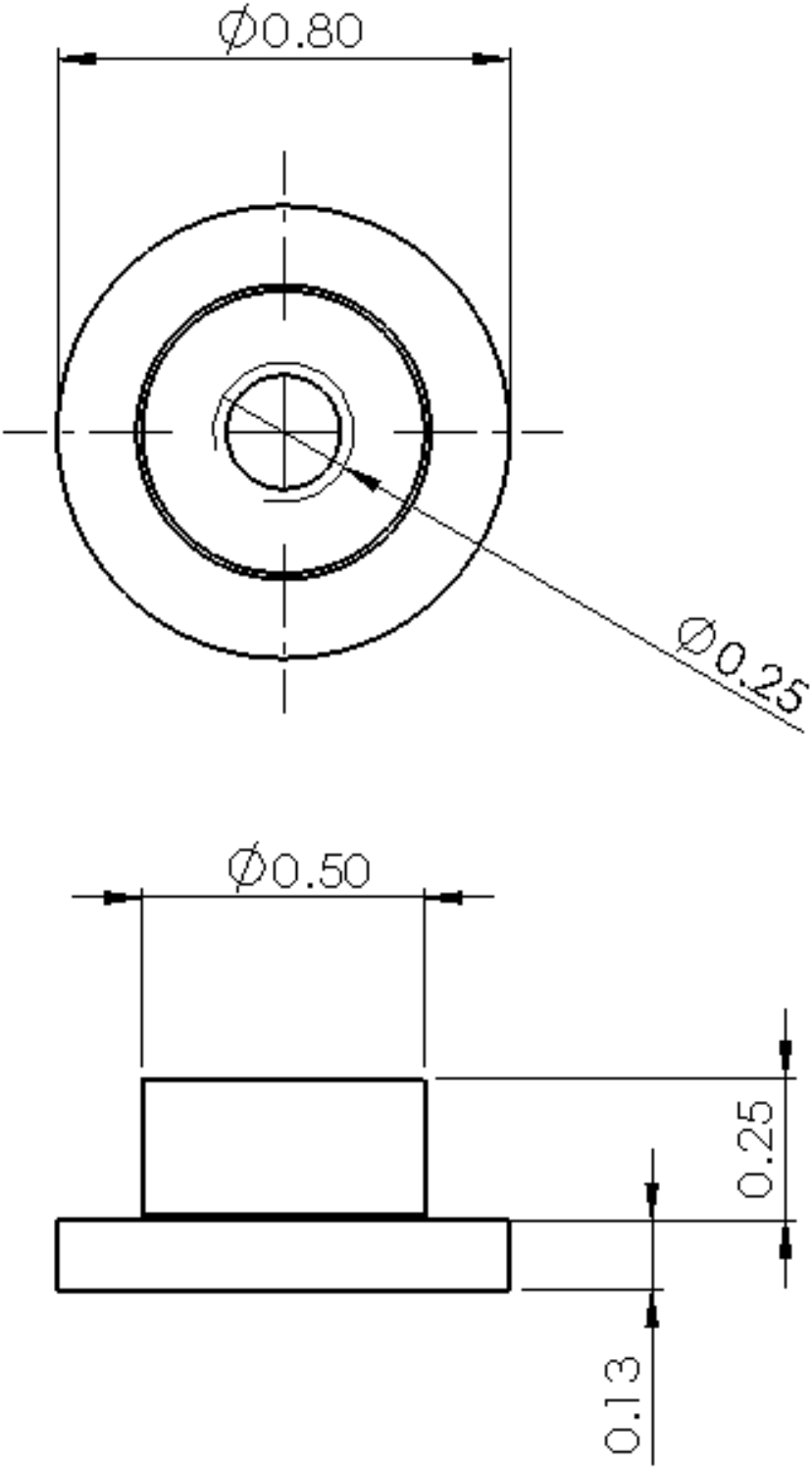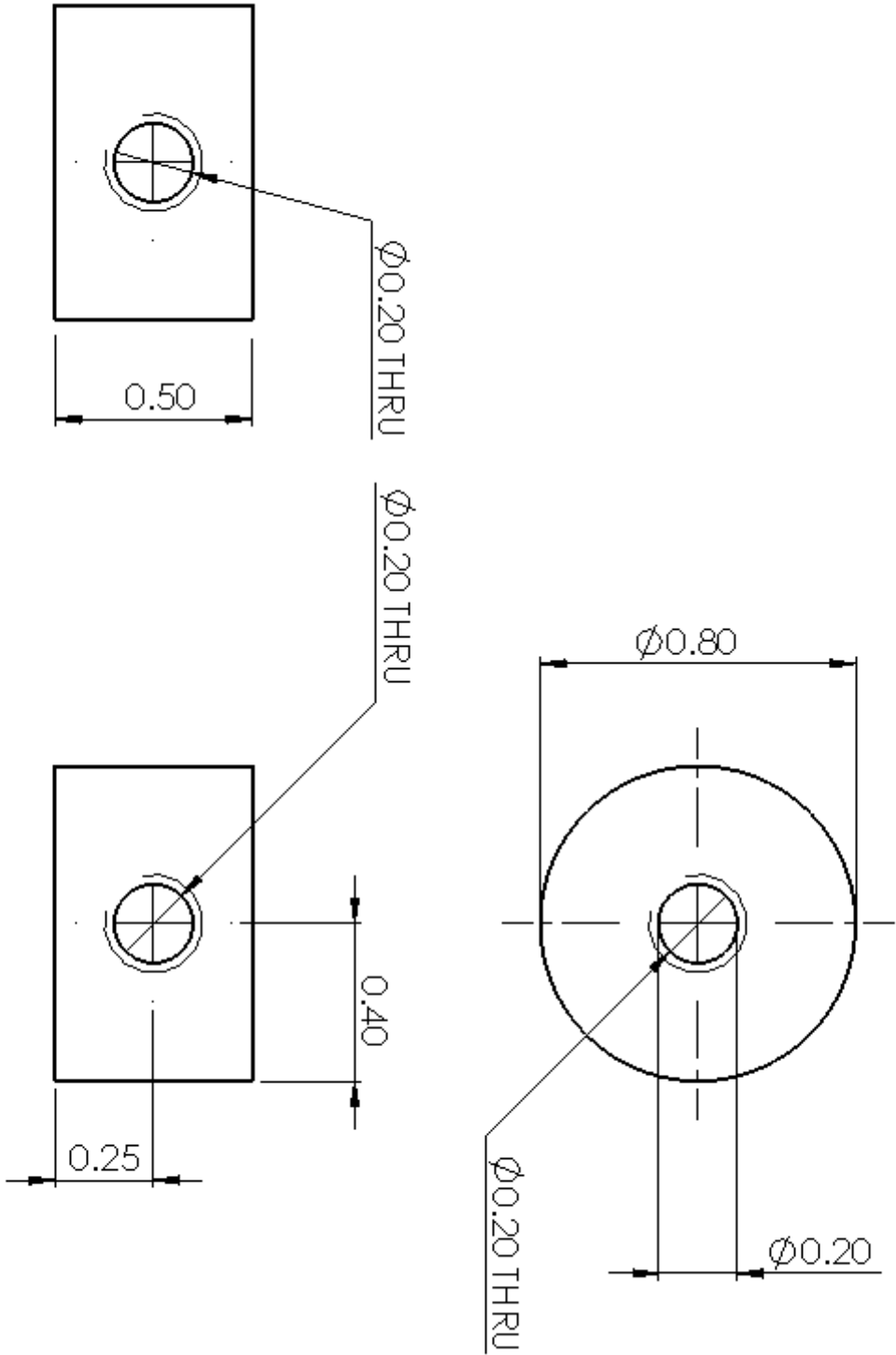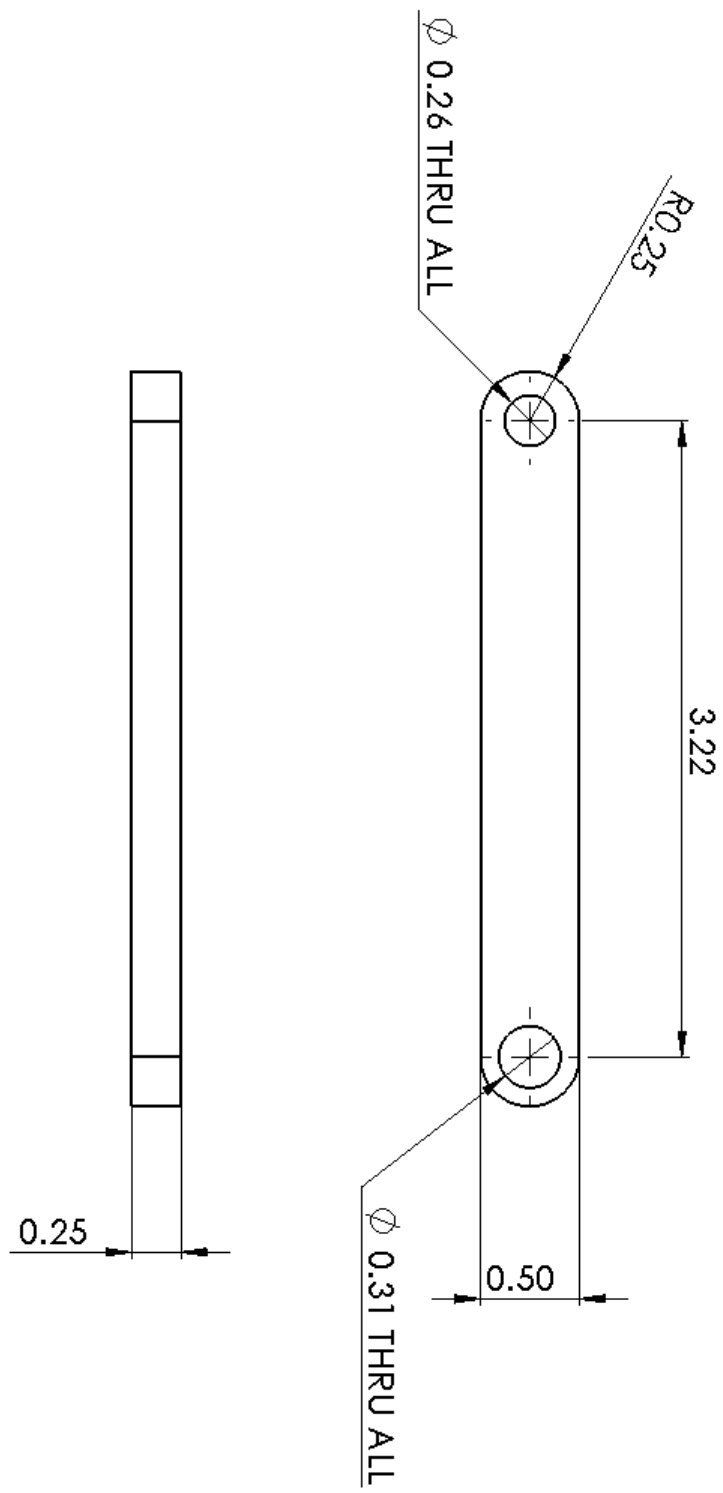
Appendix C: Friction and Tolerancing

Friction Between Materials

Kinetic friction is the type of friction where two surfaces are moving along each other. Coefficient of friction is a dimensionless measure of the ratio of friction between two surfaces, depending upon the two materials in contact.

We examined the coefficient of friction values between sliding parts of our mechanism so that we may make recommendations as to better design decisions in future iterations.

Tolerancing

Running and Sliding Fits (RC)

The tolerances for running and sliding fits are split into nine classes. The range of the classes for running and sliding fits range from the tight tolerances of the *close sliding fits* (RC1) to the greater variation allowed of the *loose running fits* (RC9) (Oberg, 2008). For the bearing and shaft interface of our design, we chose the RC 7 class. This class is the *free running fit* which is intended for an application where accuracy is not essential. There are barely any loads axially on the shaft so we are not worried about the shaft running out of the hole. We have plugs to prevent the shaft from coming out and snow from entering the hole. Our product will be exposed to large temperature variations and the RC 7 class allows for differences in thermal expansion coefficients. Relative to some other applications our product will be exposed to temperatures that are below freezing and can reach upwards of 100°F.

The interface of the hole of the bearing and the shaft is nominally 3/16 of an inch. Therefore, according to the Machinery's Handbook, the minimum clearance of the shaft and bearing should be 0.0012 and the maximum clearance should be 0.0031 inches. The hole should

be between its nominal size of 3/16 and 3/16 + 0.0012. The shaft should be between 3/16 –

0.0012 and 3/16 - 0.0019. This is the desired dimensions and tolerances for the bearing shaft

interface.

Force Fits (FN)

The tolerances for force fits are categorized into five classes. The range of these force fits

are from *light drive fits* (FN 1) which requires light assembly pressures, to *force fits* (FN 5) that

require high stresses, shrink fits or expansion fit (Oberg, 2008). The portion of our project that

utilizes the force fit is the interface between the holes and the bearings. For this application we

chose the *light drive fit* (FN 1). FN 1 requires light assembly pressures and produces a more or

less permanent assembly. This class is for thin sections, which our bearing and walls of the hole

get fairly thin.

The size of the holes that we have for force fits is 5/16 of an inch. According to the ANSI

Standard Force and Shrink Fits table, Class FN 1 interference for our bearing and hole should be

between 0.0001 and 0.00075 inches (Oberg, 2008). The dimension and tolerance for hole should

be between 5/16 and 5/16 + 0.0004 of an inch. The bearing should be between 5/16 + 0.0005 and

5/16 + 0.00075 inches. These are the desired dimensions and tolerances of our hole and bearing

interface.

Appendix D: Additional Finite Element Analysis Results

After completing a finite element analysis on the top plate as described in Section X above, we analyzed was the top plate cradle as seen in **Error! Reference source not found.** below. The top plate cradle was fixtured at the holes where it attaches to the top plate and a tensile force of 243 lbf was applied to the pin hole. The part had a maximum von Mises stress at approximately 3,694 psi, giving the part an FOS of 29.2.
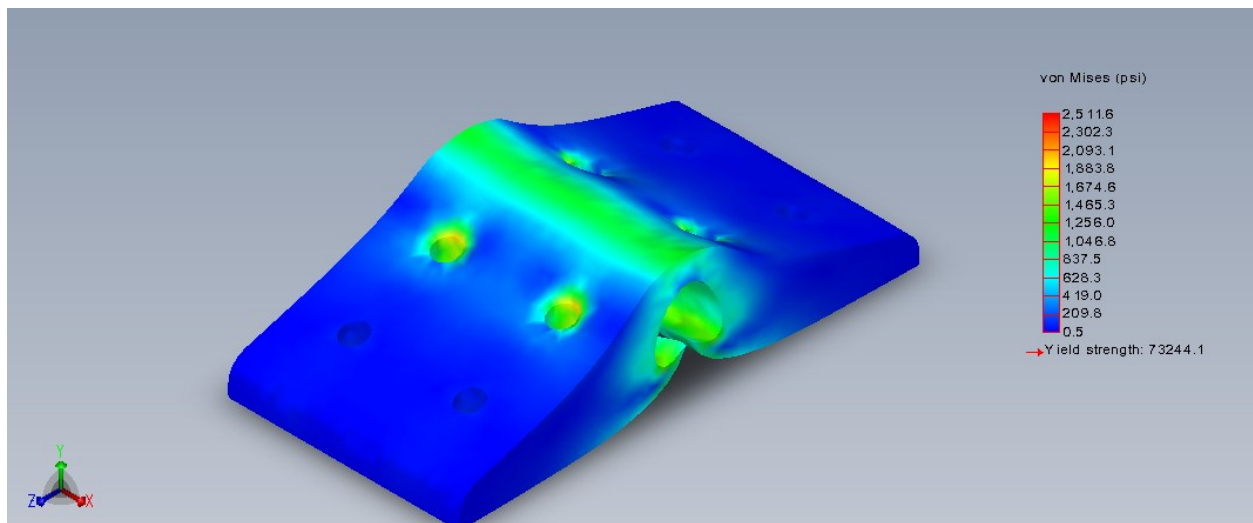

Figure 17: Top Plate Cradle FEA

Figure 18 depicts the FEA for the bottom plate, which had an FOS of approximately 2.7. The bottom of the plate was fixture and a total tensile force of 245 lbf was applied to the screw holes where the bottom plate cradle connects to the bottom plate, representing the maximum loading. The analysis was run with aluminum alloy 6061-T6 as the material. The maximum von Mises stress shown below are approximately 2,943 psi with a yield strength of 7,999 psi.
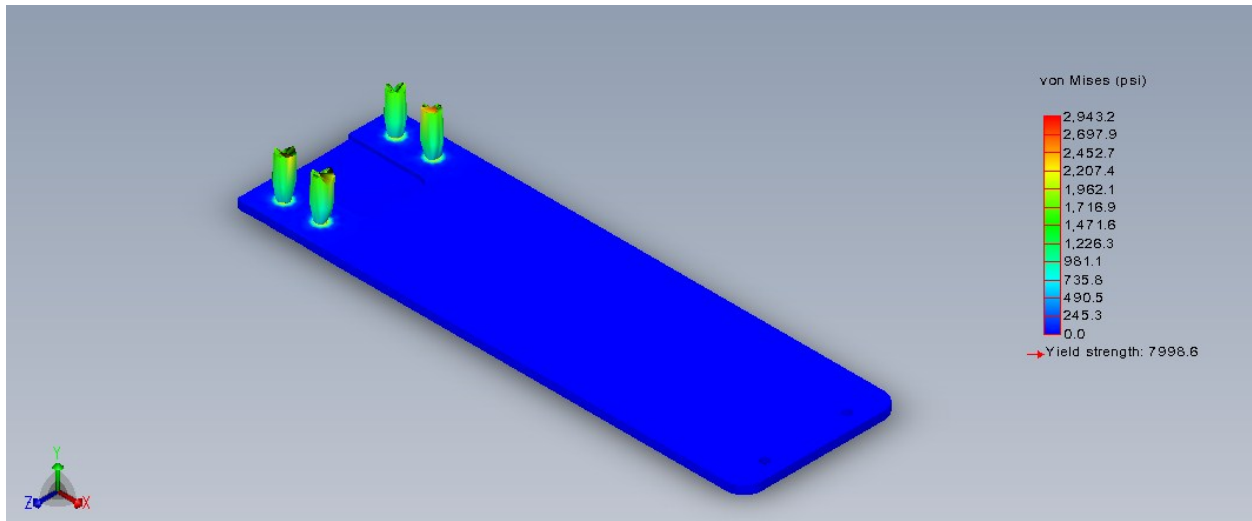
Figure 18: Bottom Plate FEA

We next ran a finite element analysis on the bottom plate cradle as shown in Figure 19 using Al 6061-T6 alloy as a material. The part was fixture at the screw holes where the bottom plate and cradles interface and a tensile load of 127 lbf was applied to the pin hole. The maximum von Mises stress for the max loads was approximately 1,376 psi and the FOS for this part was 5.8.
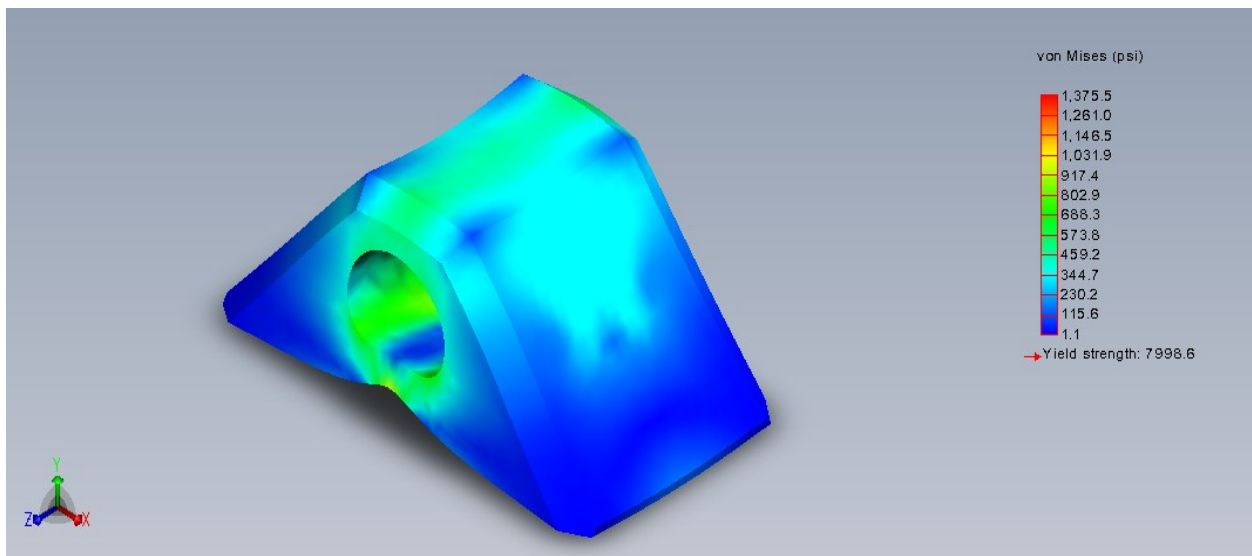

Figure 19: Bottom Plate Cradle FEA

The bottom plate toe support was the next part analyzed as shown in Figure 20 below.

The part was fixtured at the screw holes where the toe support connects to the bottom plate and a

compressive force of 112 lbf was applied to a corner to simulate normal edging loads

(Yoneyama, Kagawa, Okamoto, & Sawada, 2000).   The maximum von Mises stresses for this

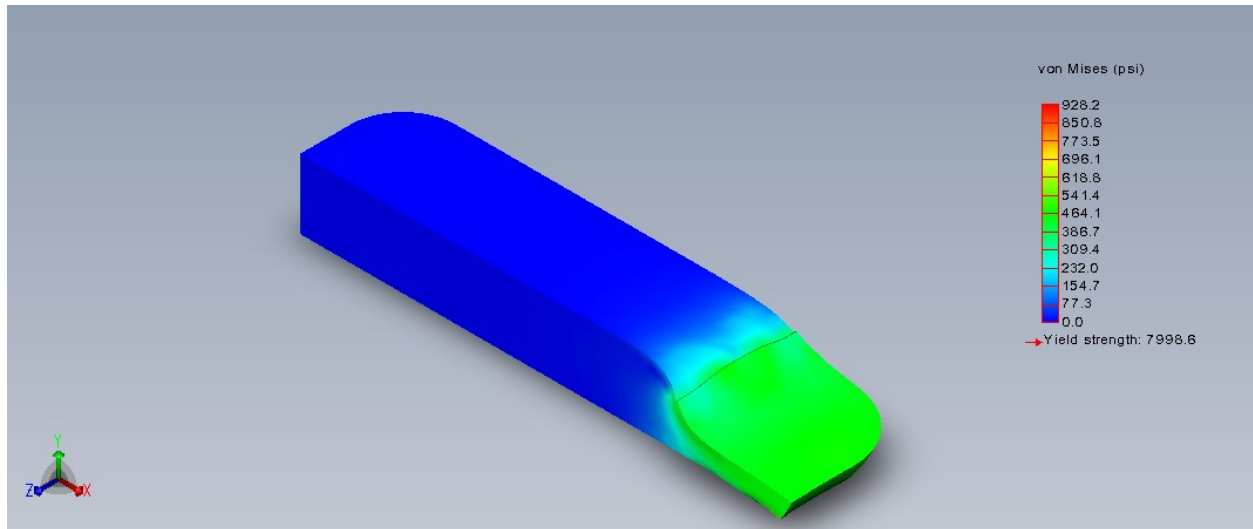part was 928 psi and the lowest FOS for this part was 8.6.

Figure 20: Toe support FEA

We then performed an FEA on the spring housing as depicted in Figure 21. The part was

fixtured on the bottom edge and a total tensile force of 63 lbf was applied to the slots,

representative of the maximum loading on this part. The maximum von Mises stress was found

to be approximately 1,546 psi, well under the yield stress of PVC Rigid of 5,130 psi. The lowest
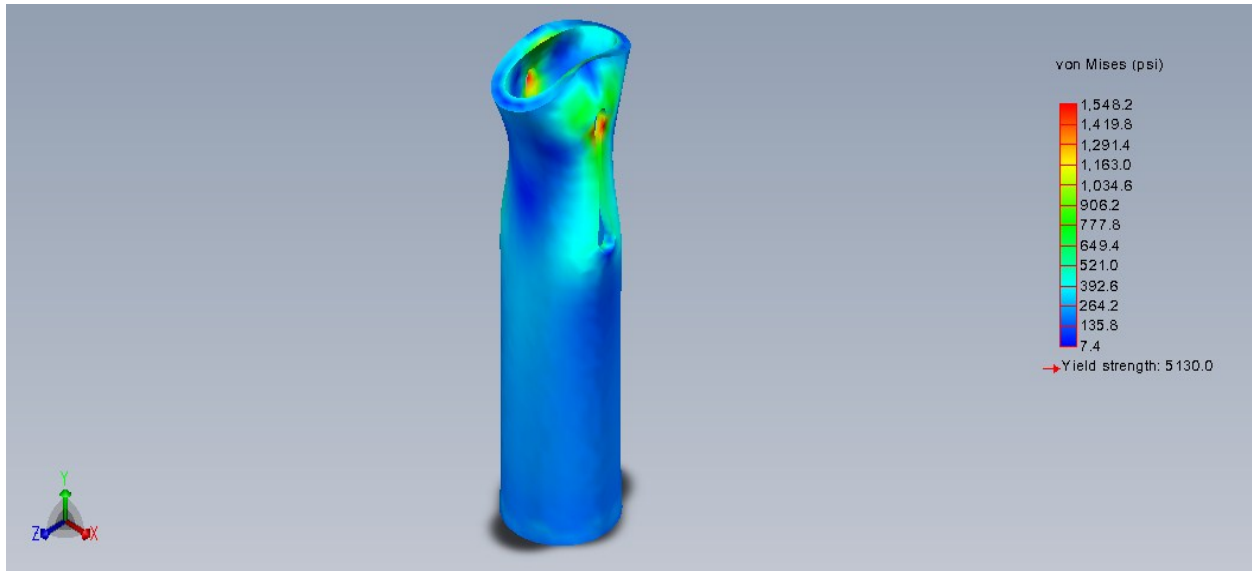
FOS found was approximately 3.3.

Figure 21: Spring Housing FEA

The next part analyzed was the spring pusher, illustrated in Figure 22 below. The part was fixtured along the bolt hole and a 183 lbf compressive force was applied to the spring interface to simulate the maximum force on the part. The maximum von Mises stress on the part was found to be approximately 5,572 psi and the lowest FOS on this part was found to be 1.4. If testing indicates the FOS of this part needs to be increased, an increased radius between the spring interface and the bolt interface will increase the FOS.
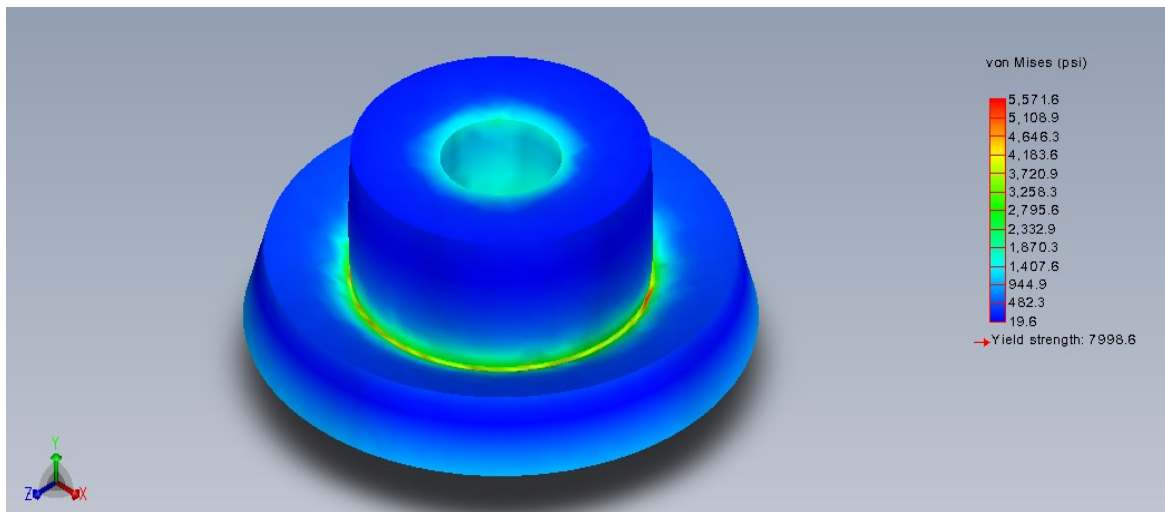

Figure 22: Spring Pusher FEA

We next completed a finite element analysis on the bolt connectors, shown in Figure 23. The part was fixtured along the connector holes and a tensile force of 63 lbf was applied to the bolt hole. The part had minimum FOS of 4.1 with maximum von Mises stresses of 1,942 psi.
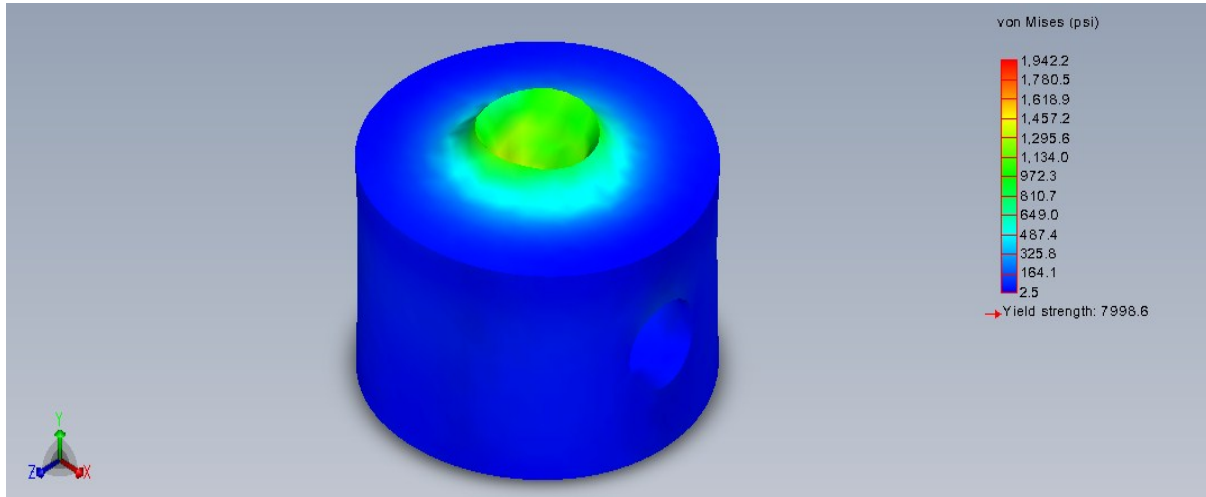

Figure 23: Bolt Connector FEA

The next part analyzed was the housing-ski interface, illustrated in Figure 24. The part was fixtured at the holes where the interface connects to the ski and a 63 lbf tensile force was applied to the holes at which the interface connects to the housing. The maximum von Mises stress on this part was approximately 2,915 psi.
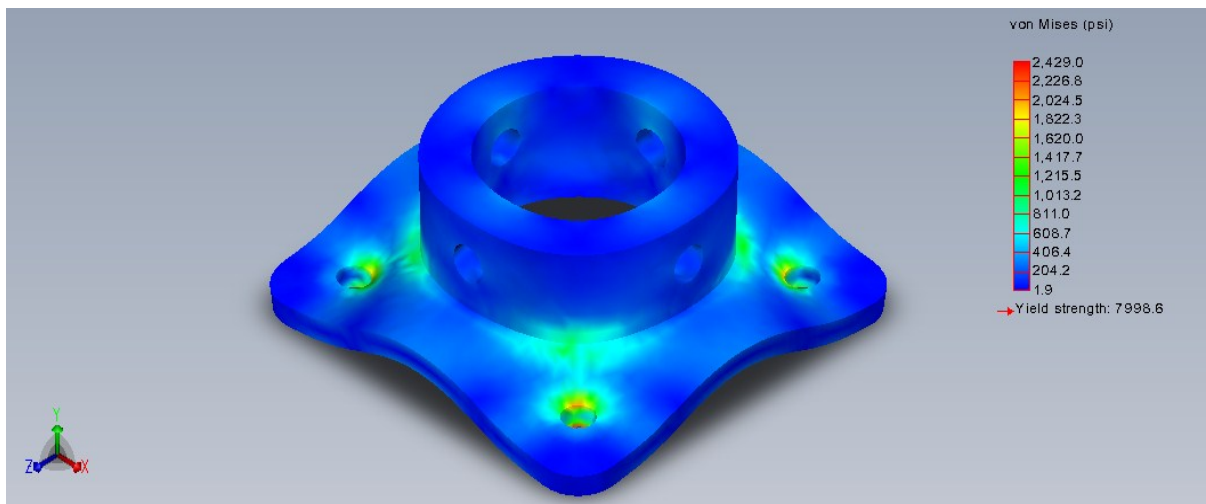

Figure 24: Housing-Spring Interface

The last part we performed an FEA on was the links, depicted in Figure 25. The links were made of Al 6061-T6 alloy. The pin hole where the link attaches to the top place was fixtured and a tensile force of 183 lbf was applied to the hole where the like attaches to the bolt connectors. The maximum von Mises stress applied to this part was approximately 4,148 psi with a FOS of 1.9.
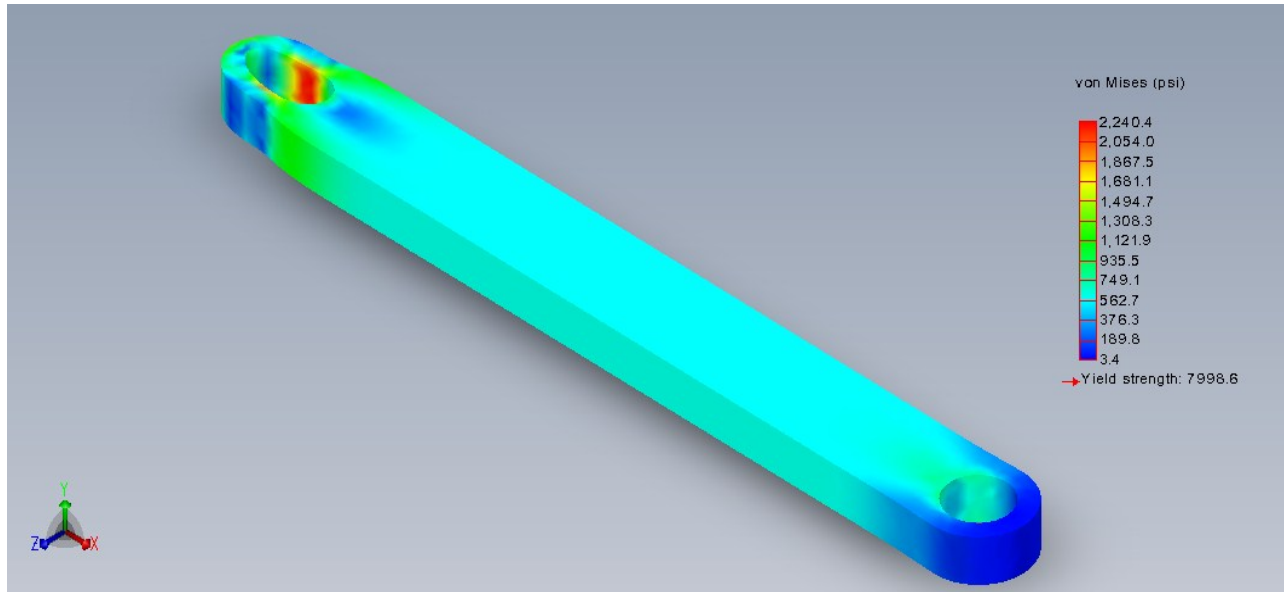

Figure 25: Link FEA