Design of Binding Plate to Provide High-Performance, Injury Free Skiing

A Major Qualifying Project Report:

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

Submitted by:

Nathan Braun

Date: May 1, 2014

Professor Christopher A. Brown, Advisor

Abstract

Injuries to the anterior cruciate ligament (ACL) are the most prevalent injury in the sport of alpine skiing. Prevention of ACL injuries is one of the biggest issues facing the alpine skiing industry today. Many skiers who experience an ACL injury will retire from the sport, and those who do return are more likely to experience the injury again. ACL injuries cost patients upwards of $250 million a year. Typical alpine ski bindings are good at preventing some injuries, but they do not target the mechanisms of ACL injuries. This project aims to solve the issue by adding a binding mounting plate between the binding and the ski targeting the most common mechanism of ACL injury, known as Phantom Foot, which is attributed to ACL strain due to inward Valgus rotation. Utilizing the axiomatic design process, the solution to preventing Phantom Foot was determined to be a pivot point about the toe, allowing dampened lateral displacement at the heel of the boot. This project analyzed several potential designs to absorb the injurious forces during the phantom foot scenario in an attempt to determine the most effective design.

Contents

1. Introduction

1.1.Objective

The objective of this project is to design a ski binding plate that will reduce or prevent ACL injuries occurring as a result of the mechanisms involving valgus loading through internal rotation of the tibia. This device would be marketed to both recreational skiers and competitive ski racers.

1.2.Rationale

Since the introduction of the releasable ski binding some six decades ago, a remarkable decrease in skiing injuries has been observed; from1972 to 2006, the overall number of skiing injuries decreased by 55 percent. Lower-extremity, equipment-related (LEER) injuries such as shear and spiral fractures of the tibia used to be a large problem for skiers; the two degrees of release featured in the modern ski bindings have made these injuries a rare occurrence (Pennington, 2008).

Although the improvements in boot and binding design helped to decrease the number of equipment related injuries, the industry began to see a massive increase in knee injuries, especially injuries to the ACL; between 1972 and 2006, a 103 percent increase in ACL tears has been observed (Pennington, 2008). ACL injuries are now the most prevalent injury in alpine skiing, accounting for about 20% of all skiing injuries (Shealy, Ettlinger, & Johnson, 2003). The number of annual ACL injuries is around 20,000, which costs up to $250 million a year (Pennington, 2008). These injury trends are not limited to recreational skiers; an FIS injury survey on FIS alpine ski racers during the 2006-2013 seasons displayed knee injuries to be the most prevalent injury, ahead of hand/wrist injuries and head/facial injuries. Knee injuries made up 38 percent of all reported injuries; hand /wrist injuries were hardly a close second place, amounting to fewer than 13 percent of all injuries. By creating a device that can effectively reduce the occurrence of ACL injuries, the financial impact of these injuries to the sport of skiing can be reduced significantly.

The majority of ACL injuries occur when there is some sort of internal or external tibial rotation combined with a valgus load. There are currently three recognized mechanisms of ACL injury commonly experienced by skiers attributed to Combined Valgus, Inward Rotation (CVIR). When a skier’s body position is back weighted during CVIR, they increase the likelihood of an ACL tear.

The main mechanism of ACL injury in World cup alpine skiing, “Slip Catch,” is a situation that occurs when a skier attempts to compensate for a loss of pressure on the outside ski in a turn. The skier extends the outer knee to regain contact with the snow, at which point the inside edge of the ski catches and abruptly forces the knee into CVIR. (Bere, et al., 2011). Figures 2 and 4 in the Bere et al. article are excellent examples of this phenomenon.

The “Dynamic Snowplow” mechanism was observed in World cup downhill athletes, when the skier is placing much of their pressure on the outside ski. The inside ski begins to drift out from underneath the athlete’s center of mass, forcing the legs into a split position. The inside ski rolls from outside to inside edge, catching on the snow surface, and forcing CVIR. Both slip-catch and dynamic snowplow have only been observed in competitive ski racing (Bere, et al., 2011).

Recreational skiers typically experience the mechanism known as “Phantom Foot.” This occurs when the skier’s is in a deeply flexed, back-weighted position, with the hips below the knees, typically with the uphill arm behind the back. The skiers weight is concentrated onto the inside edge of the outside ski, and the tail of the ski acts as a lever opposed to the human foot and forces the knee to undergo CVIR (Ettlinger, Johnson, & Shealy, A Method to Help Reduce the Risk of Serious Knee Sprains Incurred in Alpine Skiing, 1995).

The majority of ACL injuries in both competitive and recreational skiing are caused by one of these three mechanisms involving inward tibial rotation, combined with valgus loading. By designing the proposed device specifically to minimize or absorb the effect of this rotation, injuries to the ACL due to these mechanisms can be avoided. Furthermore, the percentage of ACL injuries is equivalently represented in the competitive ski-racing community. Therefore, such a device should be designed to meet the demands of competitive ski racers, as well as recreational skiers.

1.3.State Of the Art

Modern ski bindings work well for certain areas of injury prevention by providing an upward release at the heel and a lateral release at the toe, but the majority of them do nothing to prevent ACL strains or tears. There are many different devices aimed at reducing ACL injury in recreational skiers; none of these devices are used by competitive ski racers due to a general notion that they will not meet performance demands, and often would not be permissible due to the equipment regulations of alpine skiing competition. These devices include bindings, binding plates, and specialized ski designs.

The Pivogy binding system was one of the industry's first attempts to combat the high rate of ACL injuries that were being reported. Designed to drastically reduce the torque experienced by the knee in a backwards twisting fall, the Pivogy binding allowed the boot to be release laterally under conditions of internal rotation. The Pivogy binding was not very popular; consumers loved the idea of ACL protection, but the binding was heavy and notoriously prone to breakage (Dodge, 2001). Several years later, Carl Ettlinger partnered with David Dodge to design the Alpine Ski Binding Having Release Logic for Inhibiting Anterior Cruciate Ligament Injury. This design could also be regarded as a binding-plate system; there was a pivoting plate system underneath the toe piece of the binding. A force on the rear half of the inside edge of the ski, referred to in Ettlinger's notes as the third quadrant, would be the only condition under which the pivot would be able to move. Once the binding had pivoted, the boot slid out of the toe piece as in a conventional binding. This design was never produced commercially (Ettlinger & Dodge, 2009).

FIG. 10A

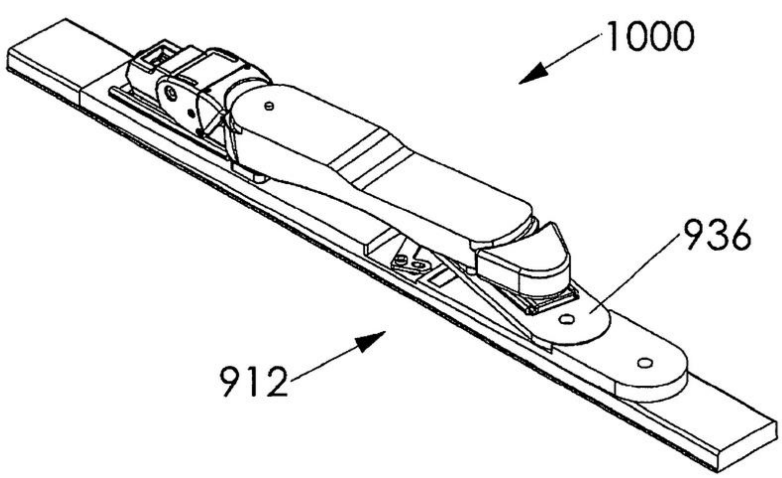

Figure 1: Alpine Ski Binding Having Release Logic for Inhibiting Anterior Cruciate Ligament Injury (Ettlinger & Dodge, 2009)

The Kneebinding fundamentally functions the same way as the Pivogy binding. The design however is much more refined. The heelpiece uses lateral release cams to allow lateral release under injurious loads, and a force vector decoupling mechanism to limit heelpiece rotation and redirect non lateral forces. This decouples the lateral heel release mechanism from the vertical release mechanism (Howell R. J., 2004). Kneebinding claims its customers to have had no ACL injuries on their equipment, and that their binding is safer than conventional bindings.

Figure 2: Kneebinding Carbon Model (Kneebinding, Inc.)

Rick Howell, the inventor of the Kneebinding, is currently testing and developing another binding to help prevent ACL injuries as a product for his own company. The Howell Ski Binding is similar in function to the Kneebinding; featuring an extra mode of lateral release at the heel. The Howell ski binding also aims to lower ACL strain by featuring an 18mm stand height and a zero degree ramp angle to provide a neutral body position. The Howell binding aims to improve upon existing binding technologies not only in injury prevention, but by maximizing performance as well. A major concern among advanced skiers, and even more so ski racers, is the possibility of inadvertent release; skiers at higher ability levels almost unanimously adjust their equipment's retention settings above manufacturer recommendations, increasing the work to release to a point that may exceed their injury threshold. Despite this, inadvertent release can cause a loss of control and has the potential to cause far greater injury or even death, thus many skiers choose to risk injury in favor of a pre-release. The Howell binding utilizes the axiomatic design approach in its engineering to decouple retention and release, which serves to minimize the likelihood of inadvertent release at lower retention settings than other bindings (Howell R. , 2014). If Howell's claims regarding his product are true, this would be the first ACL injury reduction system that could be marketed to competitive ski racers.

Several prototypes of binding plate systems have been designed by WPI students to protect against ACL injury. These designs mostly aim to mitigate ACL injuries due to the Boot-Induced Anterior Drawer (BIAD) mechanism, which occurs when a skier lands off a jump in a back weighted position. One

MQP group, the “Design and Manufacture of a Binding to Reduce ACL Injuries in Alpine Skiing”, created a plate to prevent BIAD injuries as well as Phantom Foot injuries. Their prototype features a bi-directional joint underneath the toe piece of the binding that allows for both vertical and lateral displacement at the heel, as well as a system to absorb injurious loads (Austin, Ferland, & Seibold, 2011).

Figure 3: The physical integration of the ACL injury reducing binding plate MQP (Austin, Ferland, & Seibold, 2011).

Axiomatic design was mentioned earlier as the strategy used by Howell in his development of the Howell binding. This method of engineering design was also used in his designs for the knee binding, as well as many of the MQP projects designing ACL injury-preventing ski equipment. The term “decoupling” has been mentioned several times in this section, and is the primary objective of the axiomatic design process. This strategy gets its name due to its use of two design axioms to direct the crucial engineering decisions, ensuring an efficient high quality product. Axiom one in to maintain the independence of the functional requirements (FR’s); a fully decoupled design has an independent solution, or design parameter (DP), for each functional requirement. This ensures that no mechanism in the design is trying to perform more than one task at once, simplifying individual mechanisms and decreasing the chance of malfunction. Axiom two is to minimize the amount of information in the design. Within the bounds of possible design solutions for Axiom one, the simplest solution has the greatest probability to be successful, and therefore is the preferred choice (Suh, 2001).

Figure 4: A look at the mechanism of the ACL injury reducing binding plate (Austin, Ferland, & Seibold, 2011)**. It can be seen that the mechanisms to absorb BIAD loads has been decoupled from the mechanism to absorb phantom foot loads.**

1.4.Approach

This design aims to address ACL Injuries through a much different approach than many current systems. This design moves away from the approach that binding systems use, which is to release the ski in an injurious situation. A releasable binding is designed to displace a small amount until it reaches a set force, and is adjusted using DIN settings. Once this threshold is reached, the binding separates from the boot. The issue with this system is that there is a range between the skier ability and the injury threshold in which the binding is adjusted to release. If the release occurs below the injury threshold but within the skier ability range, then an inadvertent release occurs. By providing additional displacement, the system may absorb forces over a larger distance, increasing the work to release over that of the releasable binding alone. Once the injurious situation has passed, the user will be able to resume skiing normally.

Maximizing skier control is a principle behind many of the other binding plate MQPs; by absorbing dangerous loads, rather than releasing in response to them, the skier will remain in contact with their equipment throughout the potentially injurious situation. The "Design and Manufacture of a Binding to Reduce ACL Injuries in Alpine Skiing" MQP group proposed a pivoting joints about the toe to combat phantom foot and BIAD loads. The main issue with the design was the size; the regulations for alpine ski racing dictate that the distance between the base of the ski and the sole of the boot may not exceed 50 millimeters, a distance which is visibly surpassed by that design.

As the objective of *this* project is to design a device that can offer a level of performance that will be acceptable to both recreational and competitive skiers, it will have to offer improvements where the other devices in the state of the art have fallen short. Several devices offer lateral displacement at the heel, which has proven to be effective at reducing ACL injuries due to CVIR. As the study involving World cup ski racers revealed, injuries involving CVIR are more prevalent than BIAD; out of 20 observed cases, 13 ACL injuries resulted from CVIR, and only four from BIAD (Bere, et al., 2011). Despite this, racers seem unwilling to use knee-friendly bindings due to the fears of inadvertent release. It is clear that a displacing binding plate is the ideal choice; it offers ACL protection without the increased risk of inadvertent release. It is also clear that if this plate was to be marketed to ski racers, it must be as close to regulation height as possible. Lastly, this design must not negatively affect the performance of the ski or interfere with the skier in any way

Taking these points into account, it was decided that the proposed design be a low-profile, laterally displacing binding plate that allows the ski to flex freely. It will also be adjustable; it must be useable by beginners and racers, over a wide range of weight for both men and women. The final design was created based upon this criteria utilizing axiomatic design, and was modeled in 3D using SolidWorks to allow for visualization and finite element analysis.

2. Design Decomposition and Constraints

The most basic functional requirement of this design is to provide high performance, injury free skiing. This is the customer need that the project aims to fill at the highest level, and is called FR0. FR0 then gets decomposed into several upper level requirements that describe what the design is supposed to with higher detail. Those FRs are then decomposed as needed to the most detailed level so that each describes a specific function. Once the FRs have been established to both collectively exhaustive and mutually exclusive, each one is assigned a design parameter. The proposed device to best fulfill FR0 is an under binding plate, which will be DP0. At higher levels, DPs mainly describe the systems for their associated FRs; at the lowest level they describe specific parts or devices. If there are further traits that are desired, but do not necessarily qualify as independent FRs, then they are listed as constraints. In this design, the plate must as close to or within the FIS equipment regulations; specifically the width and height. Some other constraints would be weight and compatibility with other products. They are not vital to the design of the plate as a whole, but they are things that should be taken into consideration throughout the design process, as they can affect performance and can be important factors to a consumer. Once completed, the design should be reevaluated to ensure it fulfills both axioms; checking to make sure each FR is fulfilled by its own specific DP confirms independence and eliminates coupling, and minimizing the information content warrants simple designs and ease of variation (Suh, 2001).

2.1.Functional Requirements

To reiterate, the first functional requirement of this design, FR0, is to provide high performance injury free skiing. The next level of FRs under FR0 is the children, and can be decomposed into three main groups. The subsequent children of these groups have been decomposed until they were accepted to be collectively exhaustive and mutually exclusive.

FR1: Transmit Control Loads

The most important component of skiing is control. It is essential that any interface between the boot and the ski fully transfers the forces and moments that a skier generates when attempting to turn or stop. Likewise, a skier must be able to register feedback from the snow surface to gauge their level of grip and control. Since this design would feature multiple contact surfaces between the boot and the ski surface, it is essential control loads are conserved between each component. This FR is decomposed into three child features.

FR1.1: Transmit Loads from Binding to Plate

The binding is the first thing in contact with the skier's boot, and thus transfers the initial input forces from the skier. The binding is also responsible for the transmission of feedback forces to the skier's boot. Since this project does not attempt to engineer a binding, the direct transmission of loads between the boot and binding is left up to the binding manufacturer. This project is however, concerned with the transmission of forces between the binding and the top surface of the plate. Loads must be transmitted across the vertical, transversal, and longitudinal planes (as shown in the full decomposition as FR1.1.1, FR1.1.2, and FR1.1.3).

FR1.2: Transmit Loads within Plate

Just as it is essential to transmit loads between the binding and plate, the transmission of forces and moments within the plate itself must be well controlled. Since the design will feature a top and bottom plate connected only by a pivot connection underneath the toe, it is essential that the connection between the plate sections on the vertical access be addressed directly.

FR1.3: Transmit Loads from Plate to Ski

The interface between the plate and the ski is just as important as any of the sections on load transmission, and it is specified that moments must be transferred across the axes mentioned earlier. However, there are more FR's that deal with the plate-ski interface under different parent sections. Therefore, this section is left rather ambiguous.

FR2: Filter Injurious Loads

The next important task this design must accomplish, after transmitting control loads, is to provide injury-free skiing. This section of the decomposition is the most complex, since the most complex systems and parts are those used in the injury prevention system. It should be noted that earlier decompositions featured additional children for filtering BIAD injuries and tibial plateau fractures; later it was decided against integrating these requirements into the design due to their complexity and effect on the overall product size. However, much work was put into the design of those features, as will be mentioned in the discussion.

FR2.1: Filter Potentially Injurious CVIR Loads

As mentioned earlier, there are three major mechanisms of ACL injury associated with CVIR. It was also mentioned that the majority of ACL injuries occurs in part to one of those mechanisms. The two main requirements of a device that is designed to protect against this kind of injury is the ability to absorb the CVIR loads (FR2.1.1), and something to return the system to its original state (FR2.1.2). The absorption of CVIR loads can further be decomposed into the requirements of allowing lateral displacement (FR2.1.1.1), and the resistance to lateral displacement (FR2.1.1.2). Each one of those FRs is further decomposed to the point that they are collectively exhaustive and mutually exclusive. The full decomposition of FR2.1.1 can be seen in the figure below.

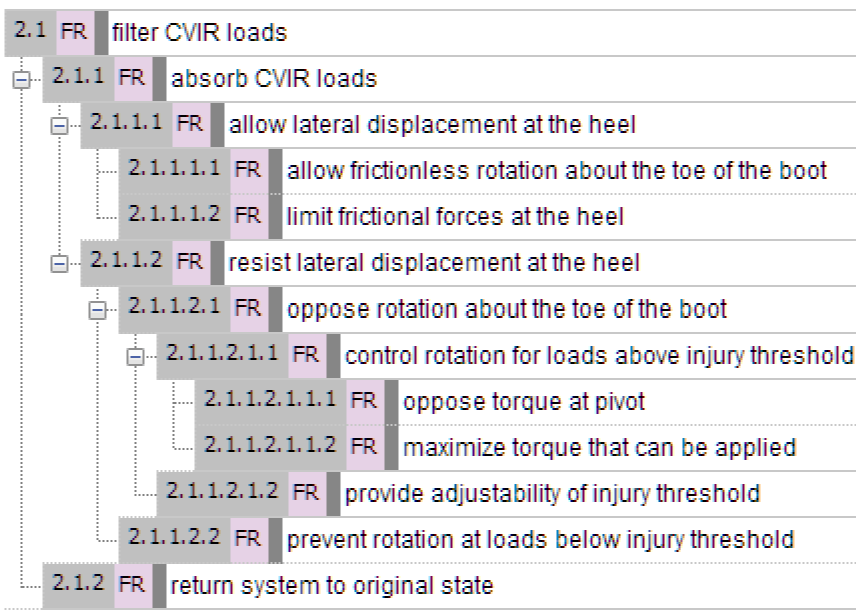

Figure 5: Decomposition of FR2.1.1

FR2.2: Filter Loads Leading to Lower Leg Fractures

Lower leg fractures, although no longer as common thanks to the modern ski binding, are still a safety concern that must be addressed by the design. This functional requirement has no children, as a ski binding can be used as the associated design parameter, which fulfills the requirement without further elaboration.

FR3: Limit Interferences with the Act of Skiing

In order to provide truly high performance skiing, the system must do more than just transfer control loads and prevent injuries. It must be designed in a way that removes the possibility of negative interferences with the act of skiing.

The prevention of inadvertent release (FR3.1) must be considered. There have been studies regarding the various mechanisms of inadvertent release, which can be grouped into three main categories. The prevention of IR due to the bow effect (FR3.1.1) is significant, as it was identified in a video study of college ski-racers to be a common situation across a range of skier abilities (Horgan, et al., 2013). The bow effect often occurs when the ski, under deep flexion due to a mogul or hole in a race course, changes the distance between the toe and heel binding components. When the flexion is suddenly relieved and goes into deep camber, the boot is then no longer securely held by the binding and is released (Brown & Ettlinger, 1985). The same study identified IR as a result of chatter or vibration (FR3.1.2) as another commonly experienced IR mechanism (Horgan, et al., 2013). As large vibrations are transmitted through the ski, they repeatedly change the boot/binding clearance until the binding can no longer keep up with the change, at which point the skier loses their ski. These situations were observed in situations where the skier was not placing the majority of their pressure on the ski. As a result, it can be observed that ski flex and the binding must be decoupled. The prevention of IR as a result of laterally releasable bindings at the heel was also considered in the design (FR3.1.3). Any mode of release in a binding is subject to some chance of pre-release, so the lateral release mechanism in ACL protecting ski bindings was not overlooked.

As it was identified that the flex of the ski and the binding must be decoupled to prevent IR, it is also imperative that the system does not interfere with the natural flex of the ski (FR3.2). By decoupling the flex of the ski from the plate, it ensures that there will be a minimal effect on the skier's ability to carve.

2.2.Design Parameters

Once it has been satisfied that all the functional requirements are collectively exhaustive and mutually exclusive, the next step is to assign a design parameter to each one. DPs follow the same model as FRs; at high levels they are basic and tend to be more exact, but as they progress down the decomposition they become more specific. DPs are the description of how an object will look or behave. For this project DP0, the highest level design parameter, has been assigned as an ACL injury preventing binding plate.

DP1: System to Transfer Control Loads

The transmission of control loads was decided to be one of the most crucial design components. The highest level DP for that function was established to be a system to transfer the control loads. The FRs were decomposed to ensure this system would be collectively exhaustive and mutually exclusive, and each FR was assigned a DP to fulfill the function. The full decomposition for FR1 can be seen in the figure below.

1	FR	Transmit control loads	DP	system to transfer control loads
1.1	FR	transmit loads from binding to plate	DP	system to attach binding to plate
1.1.1	FR	transmit moments across the vertical axis	DP	Binding mounting screws
1.1.2	FR	transmit moments about the transverse axis	DP	Torque = force * length
1.1.3	FR	transmit moments about the longitudal axis	DP	Torque = force * width
1.2	FR	transmit loads within plate	DP	system to transfer loads within binding
1.2.1	FR	transmit moments across the vertical axis	DP	twisting motion through the shaft
1.2.2	FR	transmit moments about the transverse axis	DP	intergration between plate components
1.2.3	FR	transmit moments about the longitudal axis	DP	contact surfaces transfer moments and limit motion
1.3	FR	transmit loads from plate to ski	DP	system to attach plate to ski
1.3.1	FR	transmit moments across the vertical axis	DP	Plate mounting screws
1.3.2	FR	transmit moments about the transverse axis	DP	moments transfered to ski through base of plate
1.3.3	FR	transmit moments about the longitudal axis	DP	Base of the plate transfers torque directly

Figure 6: The fully expanded decomposition for FR1/DP1

DP1.1 System to Attach Binding to Plate

To attach a binding to a binding plate typically involves five or eight screws, depending on the design of the binding. The top of the plate features a series of predrilled holes, shown in the figure below, for mounting bindings featuring an eight screw design. This pattern was selected arbitrarily to give a visual representation to how a binding would integrate with the plate; the commercial product would likely be offered as either a blank top plate or as different pre-drilled configurations to accommodate various bindings.

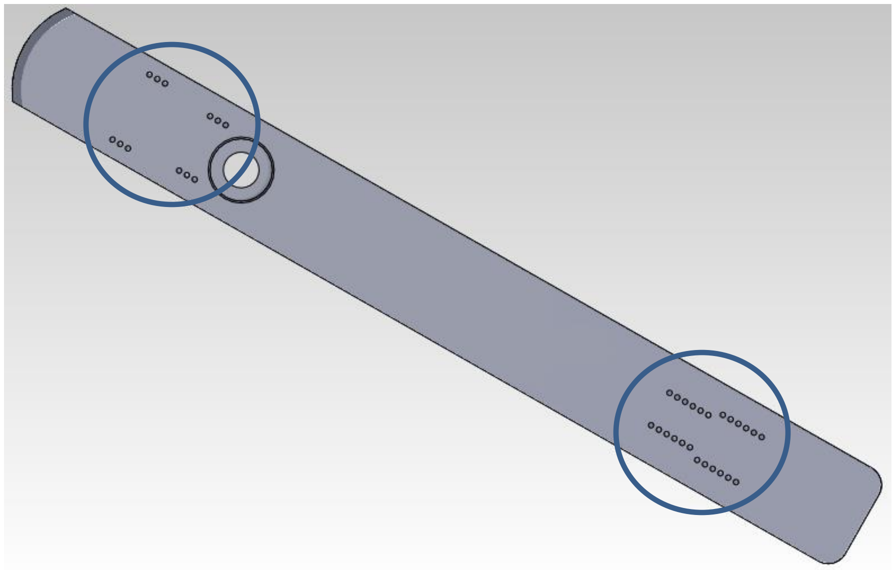

Figure 7: DP1.1-Top view of the upper plate section showing a possible mounting hole configuration.

It should also be noted that there are many more mounting locations for the heelpiece of the binding than the toe piece. As the pivot location is intended to be approximately located underneath the anti-friction device on the toe piece, the mounting location for that binding component is fairly restricted. As the plate would be marketed towards a wide demographic of skiers, there should be flexibility to accommodate a range of boot sole lengths; this is accomplished through the wide range of possible mounting locations for the heelpiece. It should further be noted that since the toe piece is intended to be mounted in a specific location, as recently mentioned, it may be best for a consumer version to be offered without pre-drilling and instead be prepared by a ski shop for the individual customer.

DP1.2 System to Transfer Loads within the Plate

The importance of this feature to the performance of the design as a whole is emphasized in the FR section. To properly transmit loads through the binding, it is essential that the integration between the two main plate components have close tolerances to minimize play in the binding. Furthermore, the integration must be sturdy enough to handle the forces and moments that it will endure. The transmission of loads on the various loads is preserved by a variety of features; this includes the robustly designed pivot system and flat surfaces where the plate components are in contact. Some examples are shown in the figures below.

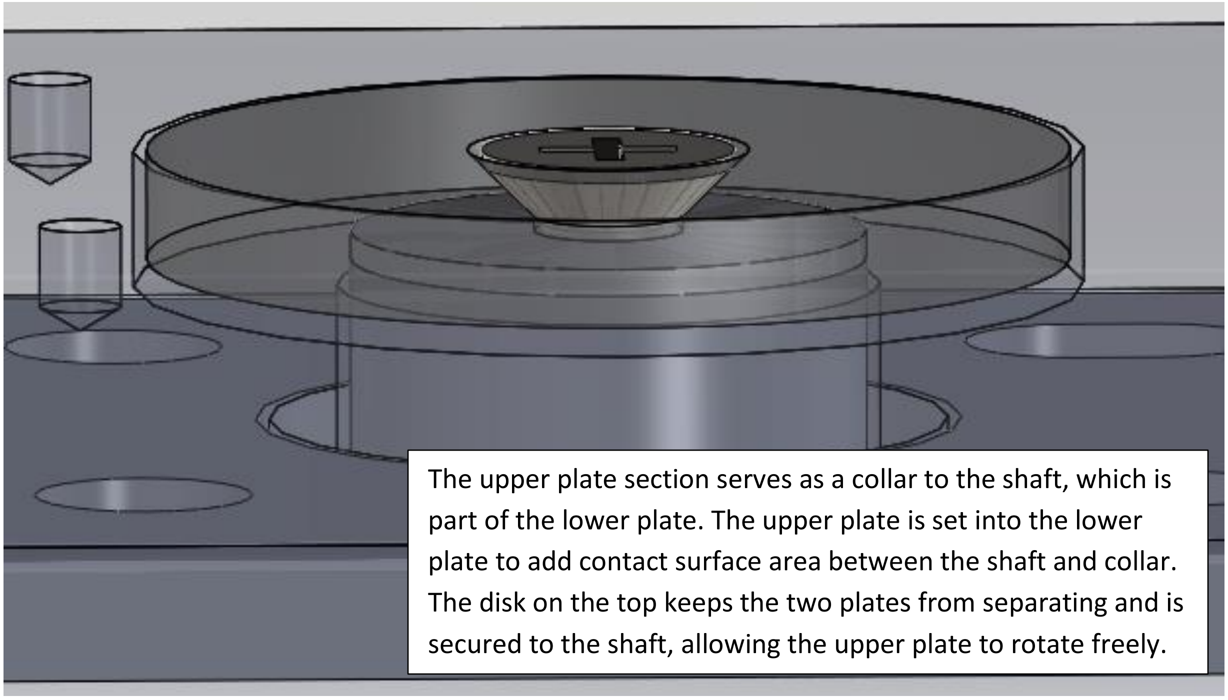

Figure 8: DP1.2.1-The plate sections are integrated in a way to maximize the contact surface area and are held together by a cap screwed into the bottom plate section, allowing the top plate section the freedom to rotate.

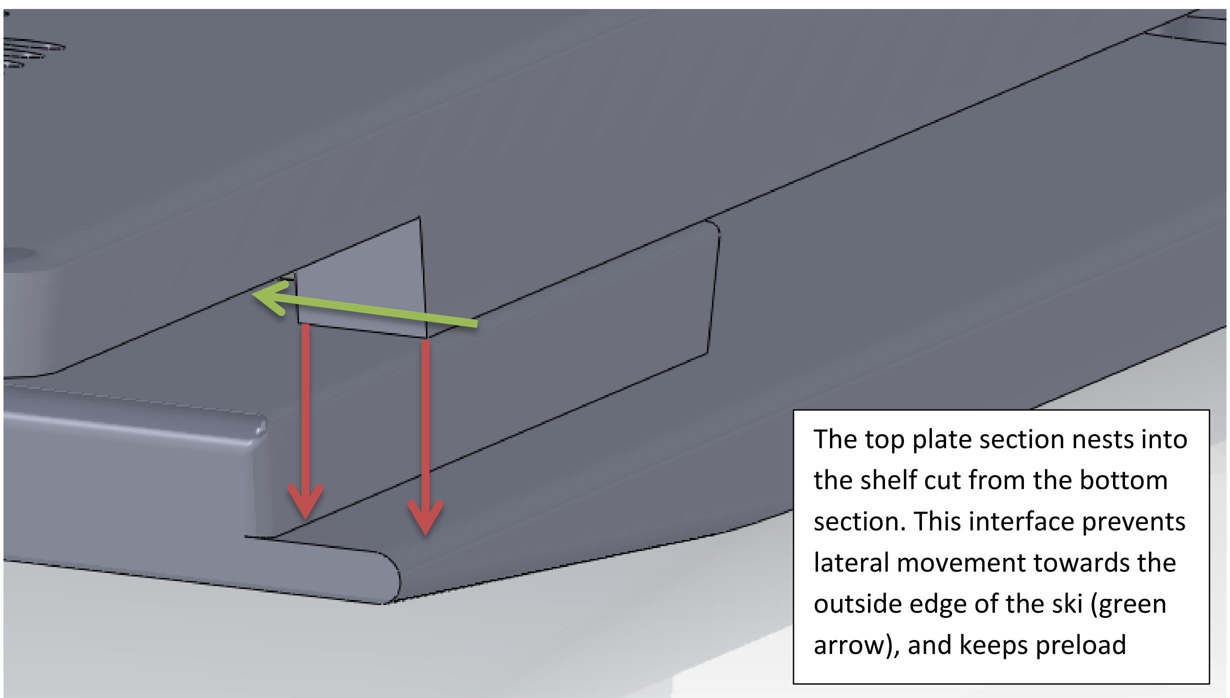

Figure 9: DP1.2.2/3-These interlocking shelves located near the rear of the plate oppose moments about the vertical axis due to control loads as well as the load of the absorption system; the plate may only rotate inward, and only when injurious loads are present

DP1.3: System to Attach Plate to Ski

The transfer of loads between the plate system and the ski is similar in principle as the binding/plate interface and the interface between plates. The plate will be mounted in a manner that ensures it remains in the proper location on the ski via the mounting screws, and control loads will be transferred to the ski through the face to face contact between the bottoms of the plate and the ski. As mentioned in the FR section, this particular interface has multiple functional requirements to fill, and there is another design parameter discussed later in this section.

DP2: System to Filter Injurious Loads

In order to filter injurious loads, a system to filter these loads must be established. As this FR has two child functional requirements, it is necessary for there to be two higher level children as design parameters; a system to prevent injurious loads to the ACL, and a system to prevent lower leg fractures.

DP2.1 System to Filter CVIR Loads

A system to filter CVIR loads is the most innovative component of this design. Many of the other concepts are well recognized in the skiing industry and require little detail. Even the concepts at the highest levels of this section in the decomposition are not alien to the field of ACL injury reduction. The significant innovative concepts in this design lie within the lower level design parameters. The full decomposition for this section is shown in the figure below. As can be seen in the decomposition, the major component used to absorb the injurious forces is reliant on a custom cantilever spring set between the two plates; as the upper plate rotates around the toe pivot, the spring is flexed, providing absorption for potentially injurious forces.

This project experimented with several different spring types; once the cantilever version was accepted as the best solution, the design was optimized. After experimenting with several different shapes, a design featuring a slot cut down the middle of the beam performed most desirably.

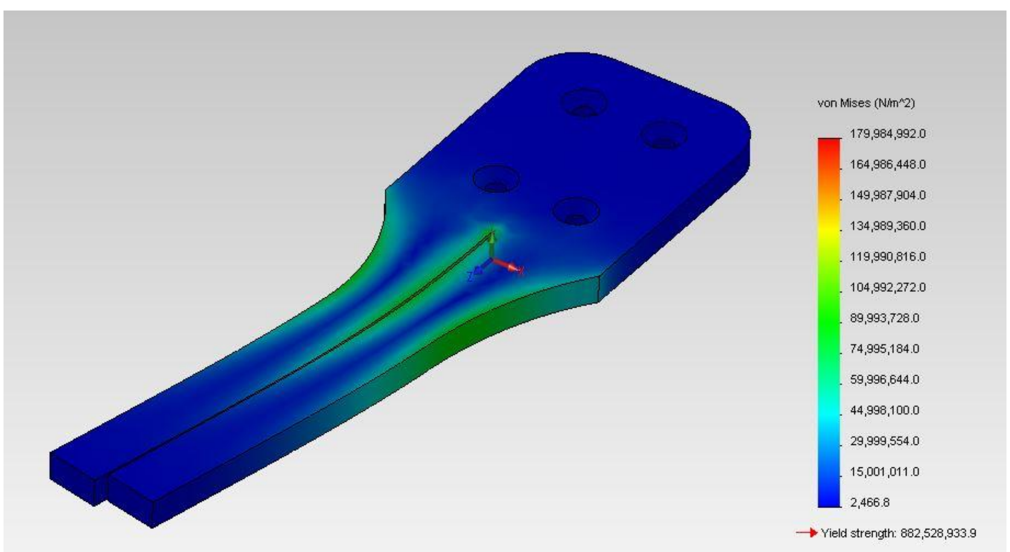

Figure 10: Final spring design & FEA simulation.

2.1	FR	filter CVIR loads	DP	system to filter CVIR loads
2.1.1	FR	absorb CVIR loads	DP	Apsorption system
2.1.1.1	FR	allow lateral displacement at the heel	DP	system to allow displacement at the heel
2.1.1.1.1	FR	allow frictionless rotation about the toe of the boot	DP	bearing
2.1.1.1.2	FR	limit frictional forces at the heel	DP	friction reduction at plate-to-plate interface
2.1.1.2	FR	resist lateral displacement at the heel	DP	system to resist lateral displacement
2.1.1.2.1	FR	oppose rotation about the toe of the boot	DP	system to provide resistance to rotation
2.1.1.2.1.1	FR	control rotation for loads above injury threshold	DP	system to provide opposing torque
2.1.1.2.1.1.1	FR	oppose torque at pivot	DP	cantilever spring system
2.1.1.2.1.1.2	FR	maximize torque that can be applied	DP	torque=F*d; increase d
2.1.1.2.1.2	FR	provide adjustability of injury threshold	DP	preload adjustment
2.1.1.2.2	FR	prevent rotation at loads below injury threshold	DP	system does not displace at loads below injury threshold
2.1.2	FR	return system to original state	DP	constant opposing force provided by absorption system

Figure 11: Fully expanded decomposition of FR/DP2.1

DP2.2 Ski Binding

The modern ski binding, whether a knee-friendly design or not, is extremely effective at preventing lower leg fractures. Since a binding is a complete system that can be easily integrated into this design, it is listed as a DP. By utilizing an existing system, it eliminates the need to design additional components or systems to fulfill the functional requirement to prevent lower leg fractures.

DP3: System to Prevent Interference with Skiing

The corresponding DP for FR3.1 is described as a system to prevent inadvertent release. DP3.1 decomposes into three children, each to combat the mechanism of inadvertent release identified in their corresponding FR. FR3.1.1 was to prevent the bow effect. The proposed DP3.1.1 to fulfill that function is to decouple the binding mounting surface from the flex of the ski. So long as the surface that the binding is mounted to does not flex when the ski does, this mechanism of inadvertent release will not be an issue. For FR3.1.2, which was to prevent inadvertent release due to chatter of vibration, the proposed DP3.1.2 is a rigid binding mounting surface. A rigid binding mounding surface will not respond to the effects of chatter, keeping the binding at exactly the right place to best retain the ski boot.

The third mechanism of inadvertent release is described in FR3.1.3. The solution to preventing an inadvertent release in a laterally releasing binding is covered in the approach, but the reason behind the engineering terminology is best understood through visualization. The current work to release a binding, specifically in the lateral direction at the heel, can be seen in the figure below represented by the green section. The peak of that section (circled in red) represents the point at which the binding will release. So long that the peak falls between the ski ability and the injury threshold, the skier will be theoretically protected from injury and safe from inadvertent release. Unfortunately, under certain circumstances, injury or inadvertent release is still possible. A sudden shock can trigger a release when the skier was not at any particular risk, and a gradual rotation can result in an injury without the binding responding at all. Furthermore, as the skier ability level increases, the adjustment window grows narrower, and becomes extremely difficult to set correctly. Due to this, many expert and competitive skiers have their bindings adjusted to a setting above the injury threshold. By having an under binding plate that releases laterally, more work can be transmitted without an injury occurring. If the threat of injury still exists at the end of the allowable displacement, the binding will still be able to release normally (green circle). This also allows skiers to leave their bindings set to safer DIN settings. In conclusion, the associated DP for preventing inadvertent release in laterally releasing bindings is DP3.1.3-increased work to release.

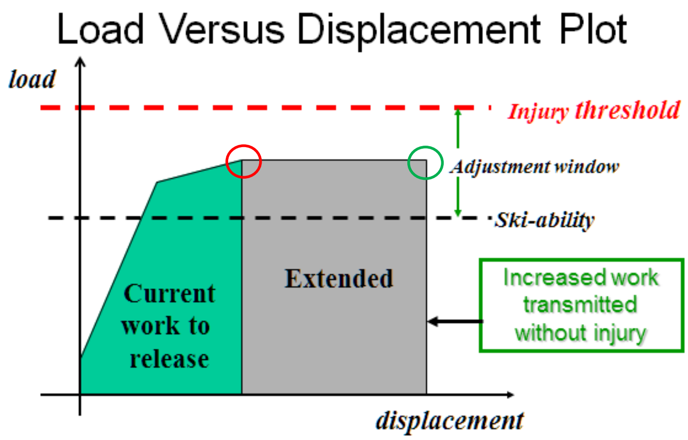

Figure 12: DP3.1.3-This graph depicts how the current work required to cause a binding to release, specifically a laterally releasing binding in the context of this section, can be greatly increased by allowing more displacement.

FR3.2 was to allow the ski to flex naturally. In order to ensure this function, it was established that the plate must be free floating on the ski. The DP3.2 is a floating plate design. This was achieved by having the plate attached in a centralized location at the front of the plate. The plate is attached by a series of four screws, two of which sit in slotted countersunk holes to ensure the least amount of interference with the flex of the ski; their location in relation to the toe pivot is shown in the figure below. The two front screws hold the plate in the desired location, while the back two give additional longitudinal stability and vertical pressure.

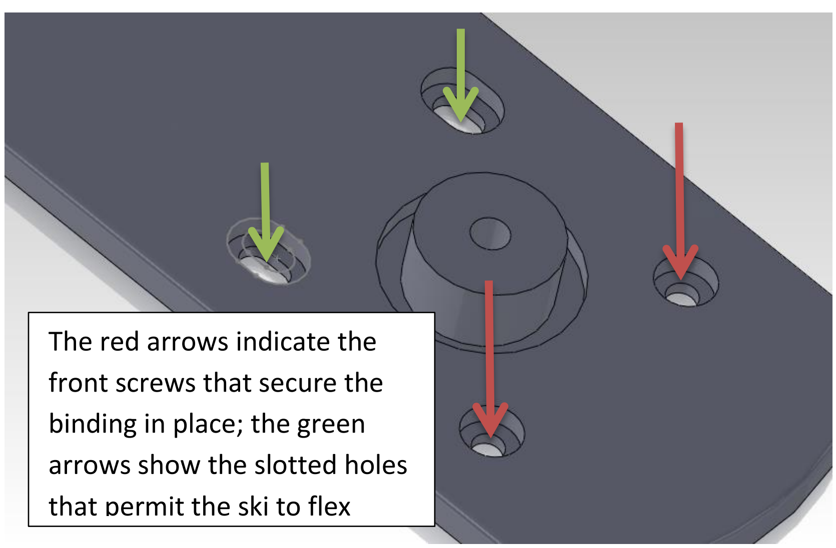

Figure 13: DP3.2-The countersunk holes indicate screw locations; the slotted holes allow the ski to flex freely.

2.3. Constraints

There are three constraints that were considered in the design of this project; the need to meet FIS equipment regulations, weight, and compatibility with other products. Constraints represent customer needs that do not require design. The intended customer base for this device is skiers across all skill levels, so it must be marketable to the most critical demographic out of the entire group; expert skiers and racers. Racers abiding by FIS rules are restricted to a 50mm overall stack height and a maximum ski width underfoot of 63mm in the slalom disciplines. In response to this, the width of the binding plate is 60mm, and the height was minimized at 15mm. It is difficult to establish whether the height would fall within these specifications, and would have to be addressed prior to a prototype. Weight is another important consideration made by ski racers, as race skis are often heavier than recreational skis to begin with. The minimalist design of this plate is ideal for keeping the product lightweight; however it is important that weight is not reduced at the expense of structural integrity. A product based on this design would have to go through much material testing to ensure the best material selection for the body of the plate. Compatibility with other products, specifically race bindings, is important as well. As pointed out in the section for DP1.1, the holes in this model are only for cosmetic purposes, and it would be recommended that a serious skier have a binding mounted professionally to their personal specifications.

4. Physical Integration

The physical integration of a project deals with the function of the design as a whole, and analyzes different components of a design as they interact with the other components. The physical integration of this project dealt with issues such as material selection and loading in relation to the various components. Much of the overall design of device was decided based upon the function of the individual components as they would be integrated.

4.1.Design

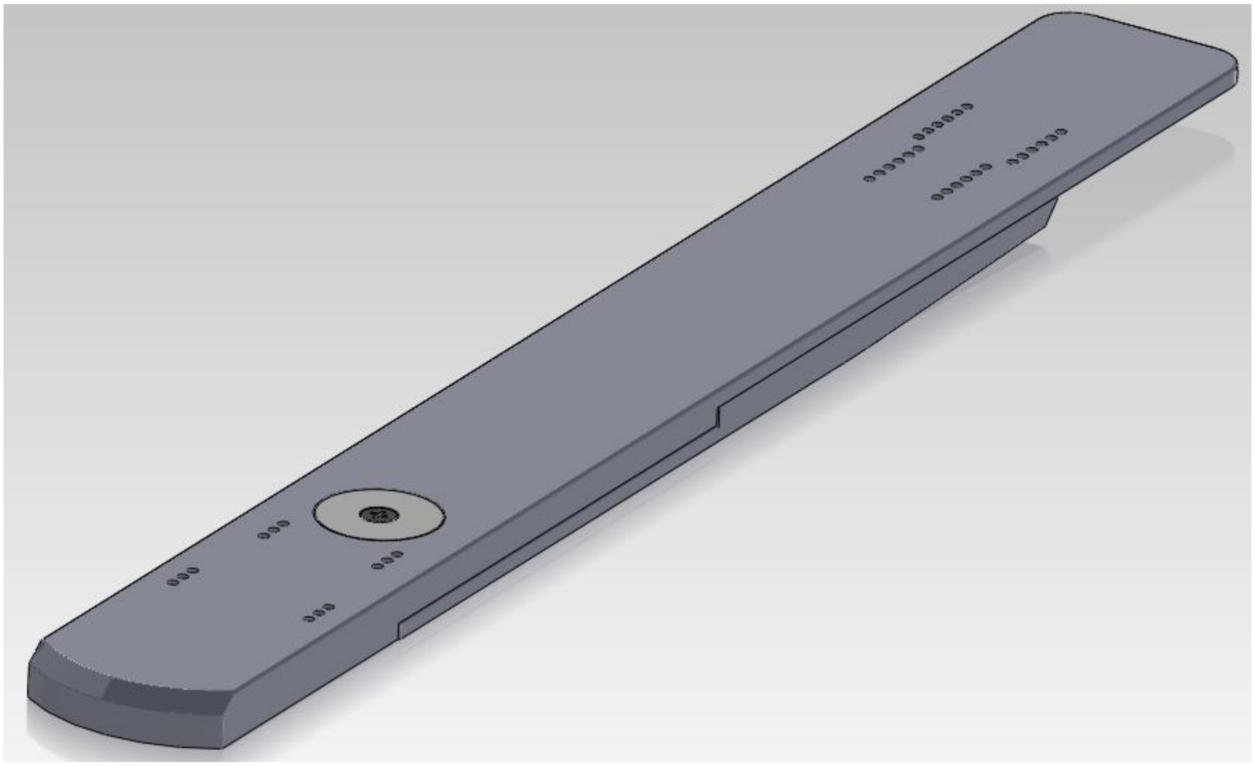

Figure 14: DP0-The fully assembled design for an ACL injury reducing binding plate

Although the axiomatic design process was useful at the preliminary stages of the project, much of the design of individual components had to be performed simultaneously. The design process actually began with the top plate section. Many of the dimensions for this part were already known or could be determined easily; the width was decided upon based on FIS regulations, as was the height. The length was easy to approximate as well, as it had to accommodate a large ski binding as well as a boot of maximum sole length. Once the general shape had been established, the lower plate section was easily designed around it, taking into account the need for a rotational interface between the two sections. At the same time, the cantilever spring was designed to fit in between the two main components. How the spring would be mounted into the bottom plate influenced the design of that plate greatly, as did the way it would interact with the top plate.

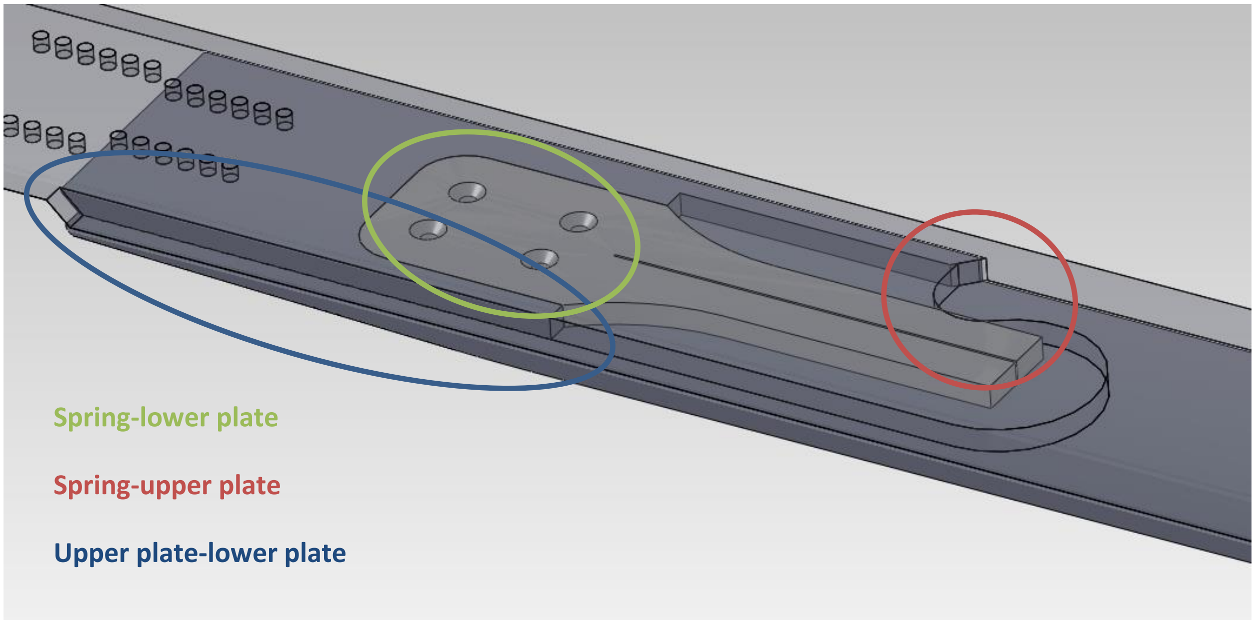

Figure 15: This image shows different levels of physical integration that had to be designed simultaneously.

4.2.Material Selection

The initial materials selected for the main plate components was aluminum. Aluminum's machinability, strength, and relatively light weight were important to consider. For an early prototype it would make an excellent material. It is also important to consider various plastics for a potential material for the main plate components. The typical riser plates used by racers are made of strong composite plastic to keep weight down; however, there are no plates on the market that function like the design proposed in this project. Furthermore, this design features very thin sections in certain areas of the main plate components, so materials must be strong enough not to shear at those locations. There is also the issue of keeping friction between plate components low. As a result, research must be performed to determine the ideal material selection. Aside from aluminum and composite plastic, combinations of the two could be considered, as well as low friction coatings on contact surfaces.

6. Discussion

The objective of this project to design a high performance binding plate to effectively protect against ACL injury was a success. It was crucial that the final product be marketable to skiers of all ability levels. With that goal as a benchmark, the best approach was determined to be designing a device that could be used by competitive alpine ski racers. As ACL injury trends in recreational skiing is reflected in ski racing, it is obvious that skill does not reduce the likelihood of an ACL tear. Modern bindings designed to protect against ACL injuries are completely absent in the ski racing demographic, which indicates two things; there is large consumer need that needs to be filled which provides an excellent marketing opportunity, as well as a chance to decrease the financial impact of these injuries on the skiing industry.

This design reduces the chance of injury by providing lateral displacement at the heel, which has proven in state of the art technologies to be effective at preventing these kinds of injuries. By providing dampened resistance to these loads, this design aims to maximize the potential that a skier will not only avoid an ACL tear, but possibly be able to ski away from the incident without having even known that they were at risk of an injury. The axiomatic design process ensured that each distinct functional requirement that this project hoped to achieve was satisfied with its own exclusive design parameter. Using this decomposition allowed for CAD models to be designed to provide a visual representation of the proposed design and allowed for easy modification of individual design parameters. This software further provided the ability to perform finite element analyses on load bearing components to ensure they would perform as expected and free from malfunction.

Extensive research had to be performed on the mechanisms of ACL injury in skiing to identify the specific issues to address in this design. The decision to abandon the BIAD portion of the design was a difficult decision to make, but the evidence in the ski racing community shows that the majority of ACL injuries occur due to slip-catch and dynamic snowplow; both mechanisms have been identified as involving combined valgus, internal rotation loading. This trend is reflected in recreational skiers, where phantom foot ACL injuries are the most common mechanism. Additionally, extensive research on the state of the art products and technologies had to be performed in order to determine the current methods being used to combat ACL injury so that they could be improved upon.

This project also analyzed multiple alternative methods to performing the same functions, including various hydraulic and mechanical systems to absorb injurious loads. Original designs were working with the possibility of integrating a system to prevent ACL injuries due to the boot-induced anterior drawer mechanism. One of the earliest designs was actually two custom rotary hydraulic cylinders, one each for CVIR and BIAD injury prevention, respectively. These designs made it all the way to the 3D modeling phase, including the integration of the entire assembly (image of the assembly in the appendix). They were eventually rejected due to the complexity of manufacturing that would be involved. The next designs involved conventional hydraulic cylinders with rack and pinions, but these too were rejected. Once the focus of the project shifted to a mechanical approach to DP2.1, another design made it all the way to the assembly stage. A system utilizing two disks that compressed a series of springs was used to absorb the loads (shown in the appendix). This idea was also rejected due to size and the complexity. This project served as an excellent example of the various stages and challenges that must be met through the course of any innovative design project.

This project has successfully utilized the axiomatic method to design a high performance riser plate to protect against ACL strain as a result of inward tibial rotation and valgus loading. By going step by step and deciding each specific function that was desired of the project, it ensured that all bases were covered. As the project progressed through the year, the design decomposition was edited and rewritten many times. Earlier iterations were more ambiguous, ensuring that multiple design solutions could be considered before making final decisions. Axiomatic design also helped in avoiding unnecessary components and components that were overly complex. Early designs intended to cover broader FRs were later discarded when analyzed through further decomposition; in a way, axiomatic design was used in parallel with intuitive brainstorming. It laid out the problem, and then an idea was created and analyzed based on axiomatic principles to determine how viable the idea would be.

This design method carried over into the 3D modeling. Models were generated at the early stages of a design concept to help visualize the function of a proposed system design. Modeling was performed simultaneously on multiple components to ensure seamless integration in assemblies.

Some issues still remaining with this project resulted as a lack of manpower on the most part. Being that this was a solo MQP, the much of the design decomposition was designed individually, as was the rest of the project. This led to a lack of thorough FEA testing and proper material optimization. A prototype of the design would be necessary for further development of the project to test durability and application. One potential flaw in the design that would need to be tested is the small number of screws attaching the plate to the ski. This is a potential location for failure, and as it is in an especially important part of control load transmission, should be investigated further.

7. Conclusion

- This project successfully designed a high performance system to reduce ACL injury as a result of CVIR loading.
- Extended research was performed in the field of ACL injury mechanisms and the state of the art protection technology.
- Various systems utilizing different hydraulic and mechanical systems were designed and evaluated as potential solutions to functional requirements.
- A 3D model was produced and tested using CAD and FEA software.
- The axiomatic design approach proved to be an excellent way to organize the project at the beginning to establish the most vital functions.
- Brainstorming using intuitive mechanical reasoning accompanied by continuous modification of the design decomposition proved most affective once an idea had been established
- Generating CAD models was performed simultaneously to ensure seamless interaction between components.
- Issues remaining are the need to optimize product materials, improve the plate to ski mounting interface, and to build and test a prototype.

8. References

Austin, R. D., Ferland, B. T., & Seibold, D. W. (2011). *Design and Prototype of an Under-Binding Plate to Reduce ACL Injury.* Worcester, MA: Worcester Polytechnic Institue.

Bere, T., Florenes, T. W., Krosshaug, T., Koga, H., Nordsletten, L., Irving, C., . . . Bahr, R. (2011). Events Leading to Anterior Cruciate Ligament Injury in World Cup Alpine Skiing: a Systematic Video Analysis of 20 Cases. *British Journal of Sports Medicine, 45*(16), 1294-1302. doi:10.1177/0363546511405147

Bere, T., Steenstrup, S., & Bahr, R. (2013). *FIS Injury Surveillance System.* Oslo: Oslo Sports Trauma Research Center.

Brown, C. A., & Ettlinger, C. F. (1985). A Method for Improvement of Retention Characteristics in Alpine Ski Bindings. In R. J. Johnson, & C. D. Mote (Ed.), *Skiing Trauma and Safety: Fifth International Symposium, ASTM STP 860* (pp. 224-237). Philadelphia: American Society for Testing and Materials.

Dodge. (2001). *Patent No. 7086662.* United States of America.

Ettlinger, C. F., & Dodge, D. J. (2009). *Patent No. 7762572 B2.* United States of America.

Ettlinger, C. F., Johnson, R. J., & Shealy, J. E. (1995). A Method to Help Reduce the Risk of Serious Knee Sprains Incurred in Alpine Skiing. *The American Journal of Sports Medicine, 23*(5), 530-537.

Horgan, M., O'Brien, P., Holman, N., Lagassey, J., Braun, N., & Butler, M. (2013). *Web Based Snow-Sport Injury Reduction.* Worcester, MA: Worcester Polytechnic Institute.

Howell, R. (2014). New Howell ski bindings= Confidence. Stowe, VT, USA. Retrieved from Howell Ski Bindings: http://www.howellskibindings.com/

Howell, R. J. (2004). *Patent No. 7318598.* United States of America.

Kneebinding, Inc. (n.d.). Retrieved April 27, 2014, from www.kneebinding.com

Pennington, B. (2008, December 26). Avoiding the Dreaded Knee 'Pop'. *The New York Times*, p. D4(L).

Shealy, J. E., Ettlinger, C. F., & Johnson, R. J. (2003). What Do We Know About Ski Injury Research that Relates Binding Function to Knee and Lower Leg Injuries? *Skiing Trauma and Safety: Fourteenth Volume, ASTM STP*, 36-52.

Suh, N. (2001). *Axiomatic Design: Advances and Applications.* Oxford University Press.

9. Appendices

Decomposition

#	FR	DP
0	provide high performance, injury free skiing	binding plate
1	Transmit control loads	system to transfer control loads
1.1	transmit loads from binding to plate	system to attach binding to plate
1.1.1	transmit moments across the vertical axis	Binding mounting screws
1.1.2	transmit moments about the transverse axis	Torque = force * length
1.1.3	transmit moments about the longitudal axis	Torque = force * width
1.2	transmit loads within plate	system to transfer loads within binding
1.2.1	transmit moments across the vertical axis	twisting motion through the shaft
1.2.2	transmit moments about the transverse axis	intergration between plate components
1.2.3	transmit moments about the longitudal axis	contact surfaces transfer moments and limit motion
1.3	transmit loads from plate to ski	system to attach plate to ski
1.3.1	transmit moments across the vertical axis	Plate mounting screws
1.3.2	transmit moments about the transverse axis	moments transfered to ski through base of plate
1.3.3	transmit moments about the longitudal axis	Base of the plate transfers torque directly
2	Filter injurious loads	system to to filter injurious loads
2.1	filter CVIR loads	system to filter CVIR loads
2.1.1	absorb CVIR loads	Apsorption system
2.1.1.1	allow lateral displacement at the heel	system to allow displacement at the heel
2.1.1.1.1	allow frictionless rotation about the toe of the boot	bearing
2.1.1.1.2	limit frictional forces at the heel	friction reduction at plate-to-plate interface
2.1.1.2	resist lateral displacement at the heel	system to resist lateral displacement
2.1.1.2.1	oppose rotation about the toe of the boot	system to provide resistance to rotation
2.1.1.2.1.1	control rotation for loads above injury threshold	system to provide opposing torque
2.1.1.2.1.1.1	oppose torque at pivot	cantilever spring system
2.1.1.2.1.1.2	maximize torque that can be applied	torque=F*d; increase d
2.1.1.2.1.2	provide adjustability of injury threshold	preload adjustment
2.1.1.2.2	prevent rotation at loads below injury threshold	system does not displace at loads below injury threshold
2.1.2	return system to original state	constant opposing force provided by absorption system
2.2	filter lower leg fractures	ski binding
3	Limit Interferences with the Act of Skiing	system to prevent interference with skiing
3.1	prevent Inadvertent release	system to prevent inadvertent release
3.1.1	prevent IR due to bow effect	binding mounting surface decoupled from ski flex
3.1.2	prevent IR due to chatter/vibration	rigid binding mounting surface
3.1.3	prevent IR in laterally-releasable bindings	increased work to release
3.2	allow the ski to flex naturally	floating plate design

Figure 16: Fully Expanded Design Decomposition

Technical Drawings

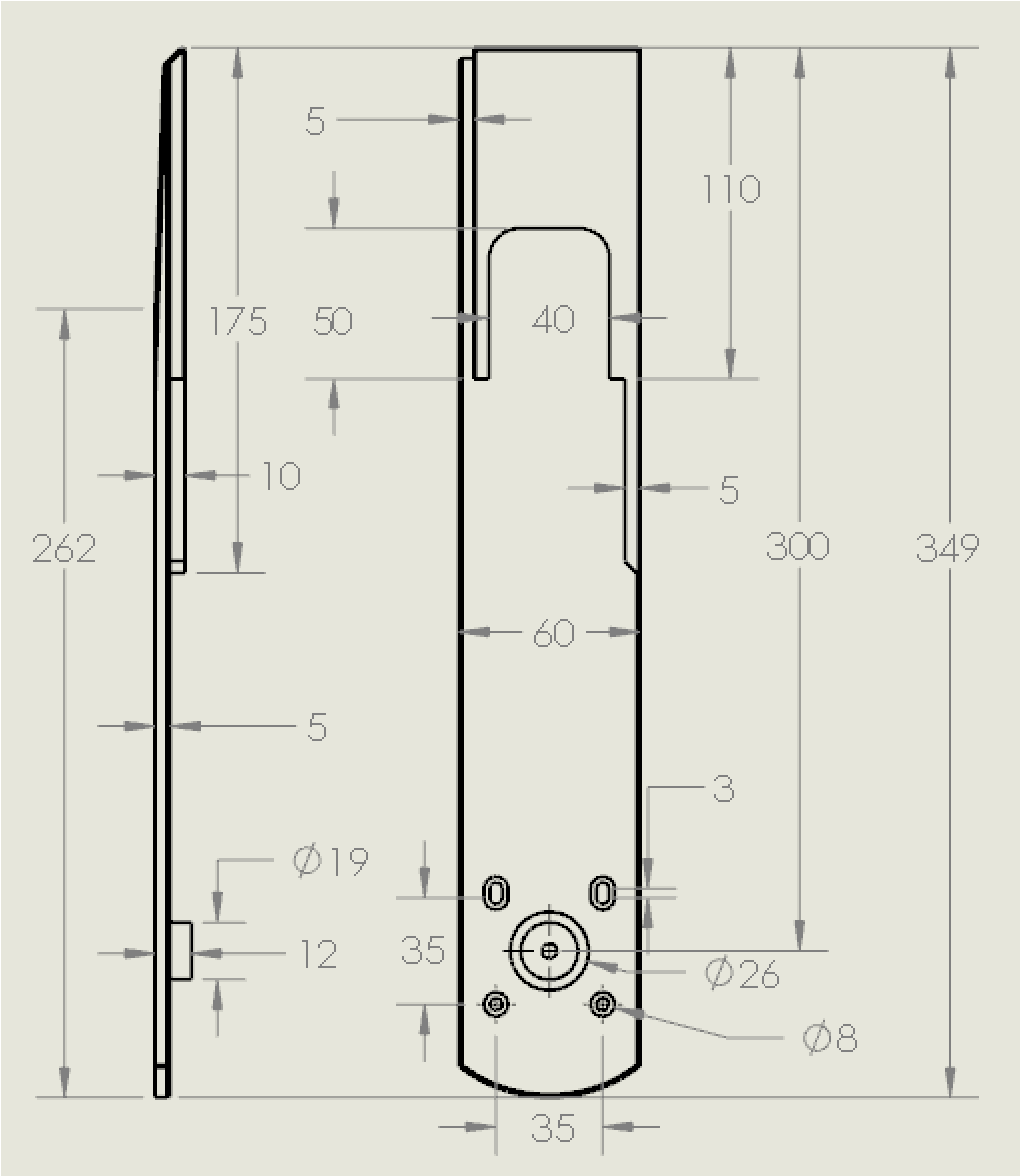

Figure 17: Sketch of Base Plate

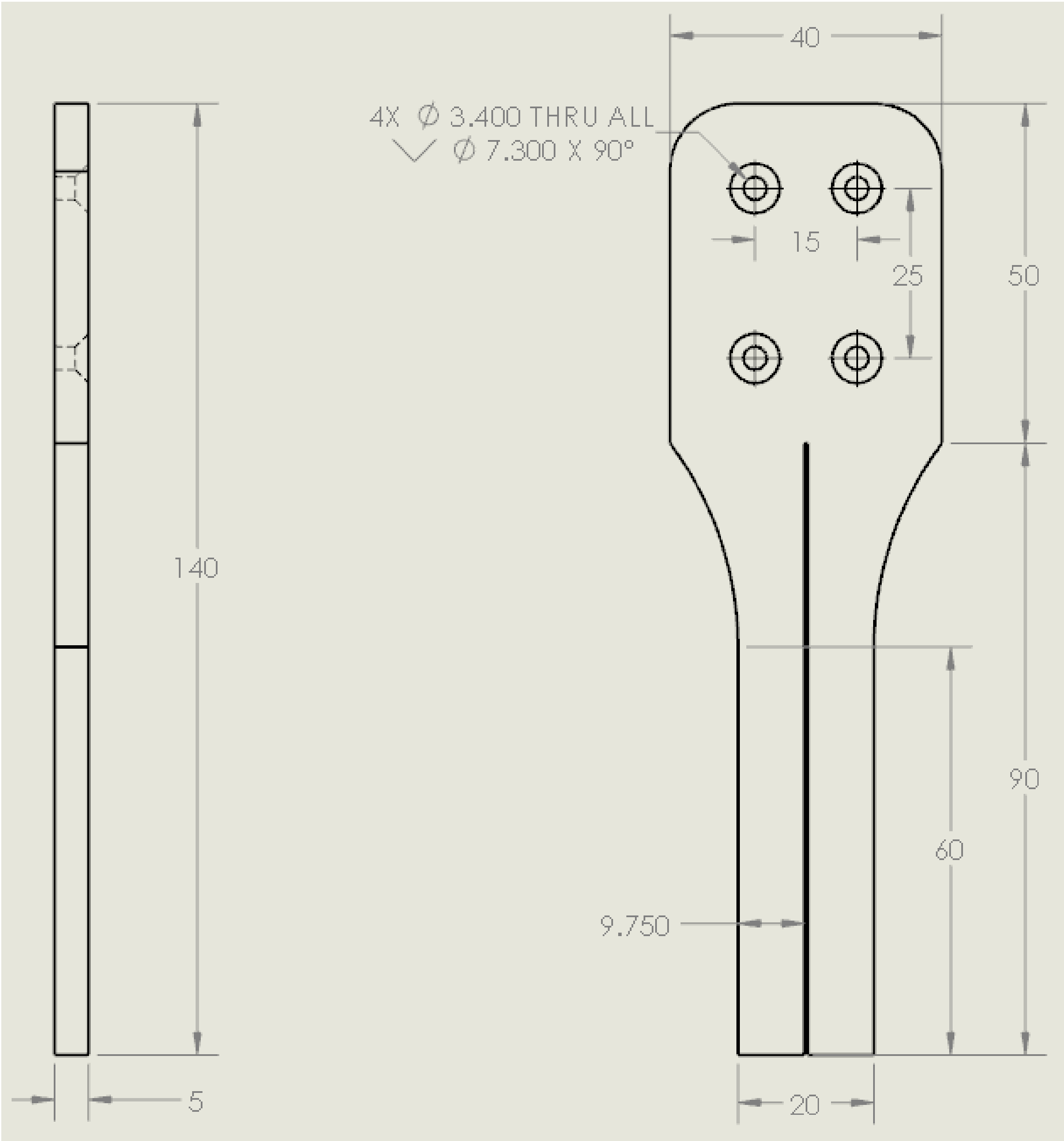

Figure 18: Sketch of Cantilever Spring

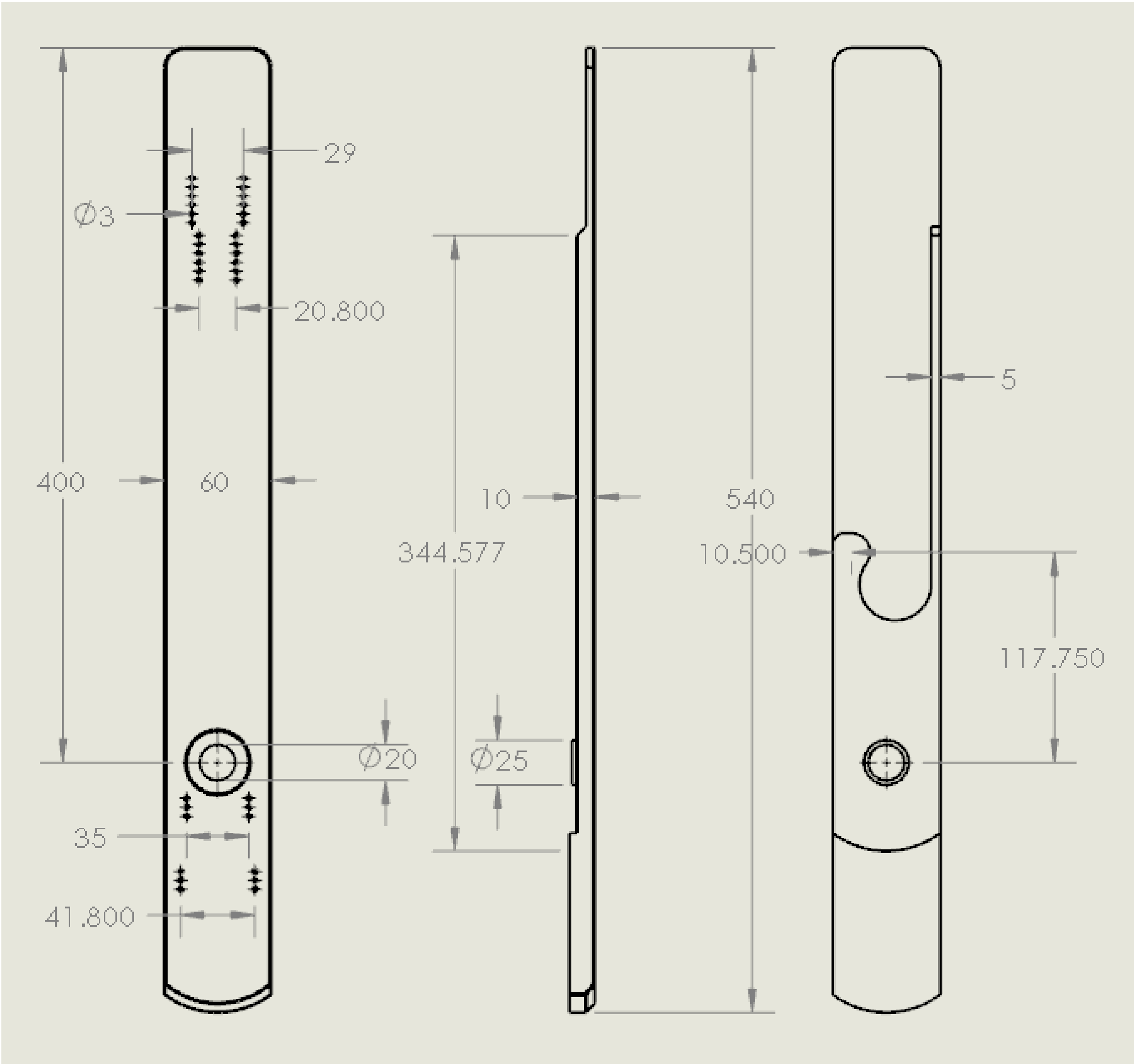

Figure 19: Sketch of Top plate

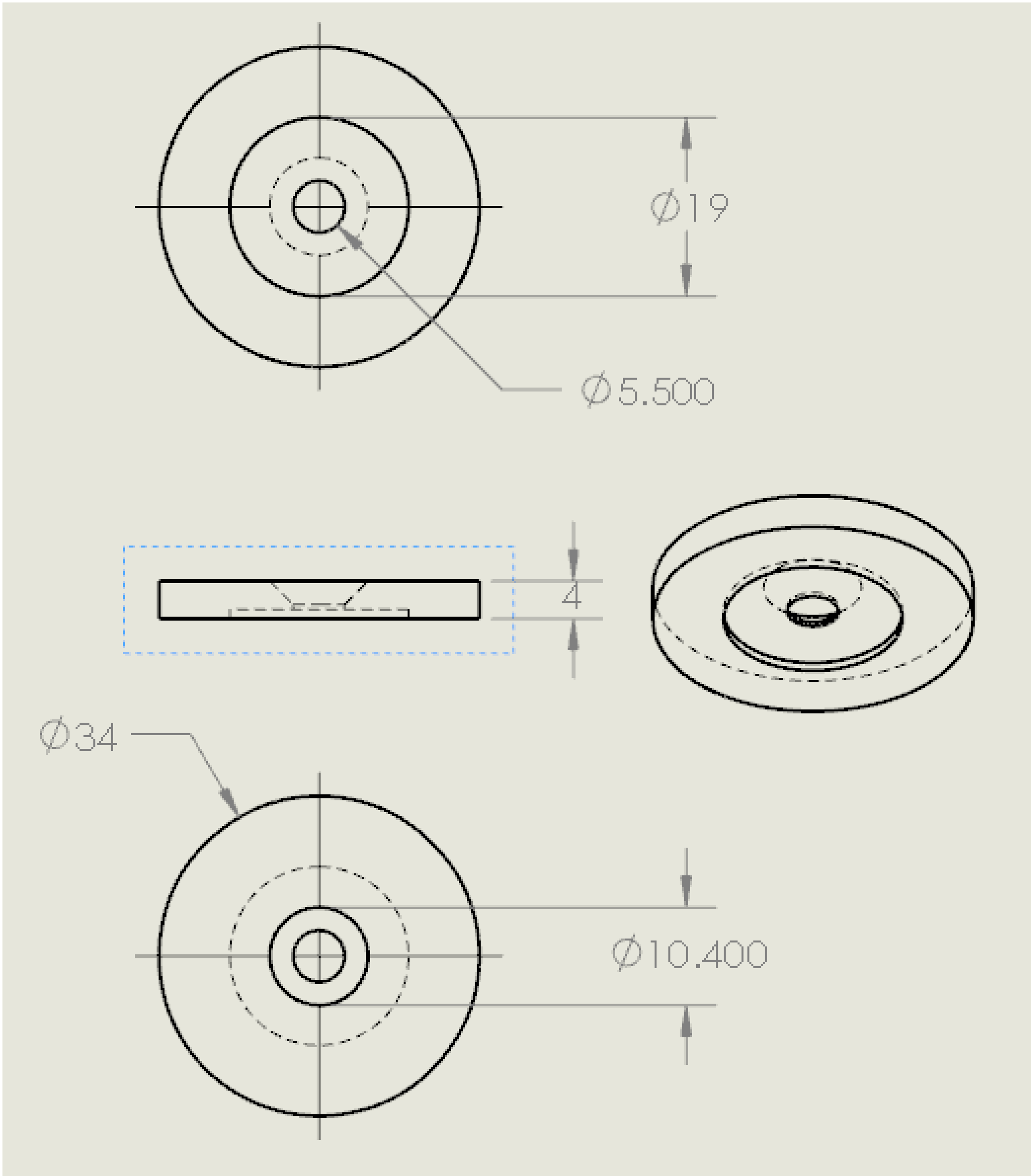

Figure 20: Sketch of Pivot Cap

Data on Ski Injury Statistics

Table 1: FIS Injury Statistics for Alpine Skiers (Reported through seasons 2006-2013) (Bere, Steenstrup, & Bahr, 2013).

Location of Injury	Number of Injuries	Percent of Overall Injuries
Head/Face	66	9.95%
Neck, cervical Spine	7	1.06%
Shoulder, Clavicle	44	6.64%
Upper Limb	9	1.36%
Hand, Wrist	84	12.67%
Torso	18	2.71%
Lower back, pelvis	58	8.75%
Hip, Groin	13	1.96%
Thigh	16	2.41%
Knee	252	38.01%
Lower Leg, Achilles	60	9.05%
Ankle, Foot	36	5.43%
Total	663	100.00%

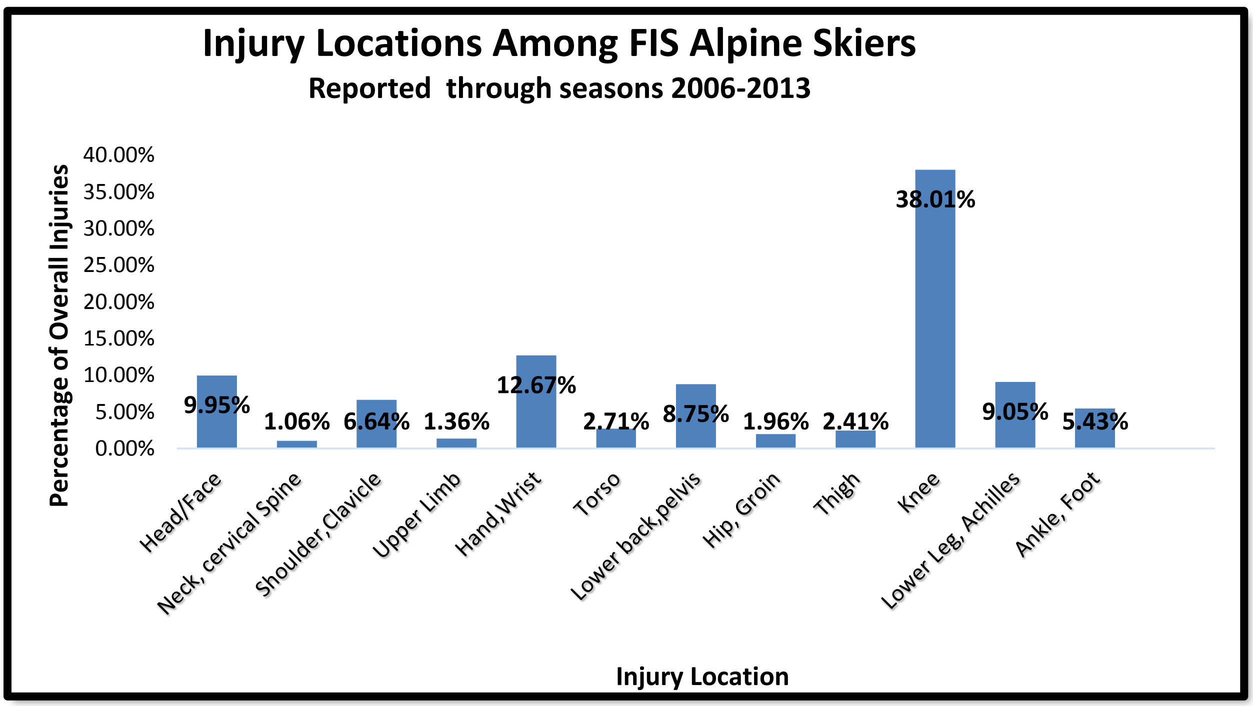

Figure 21: Graph is based on data collected during the seasons 2006-2013 by the FIS Injury Surveillance System. All data is based on injury reports by athletes of the Alpine discipline only. Associated tables can be found in the Appendix.

Old Designs

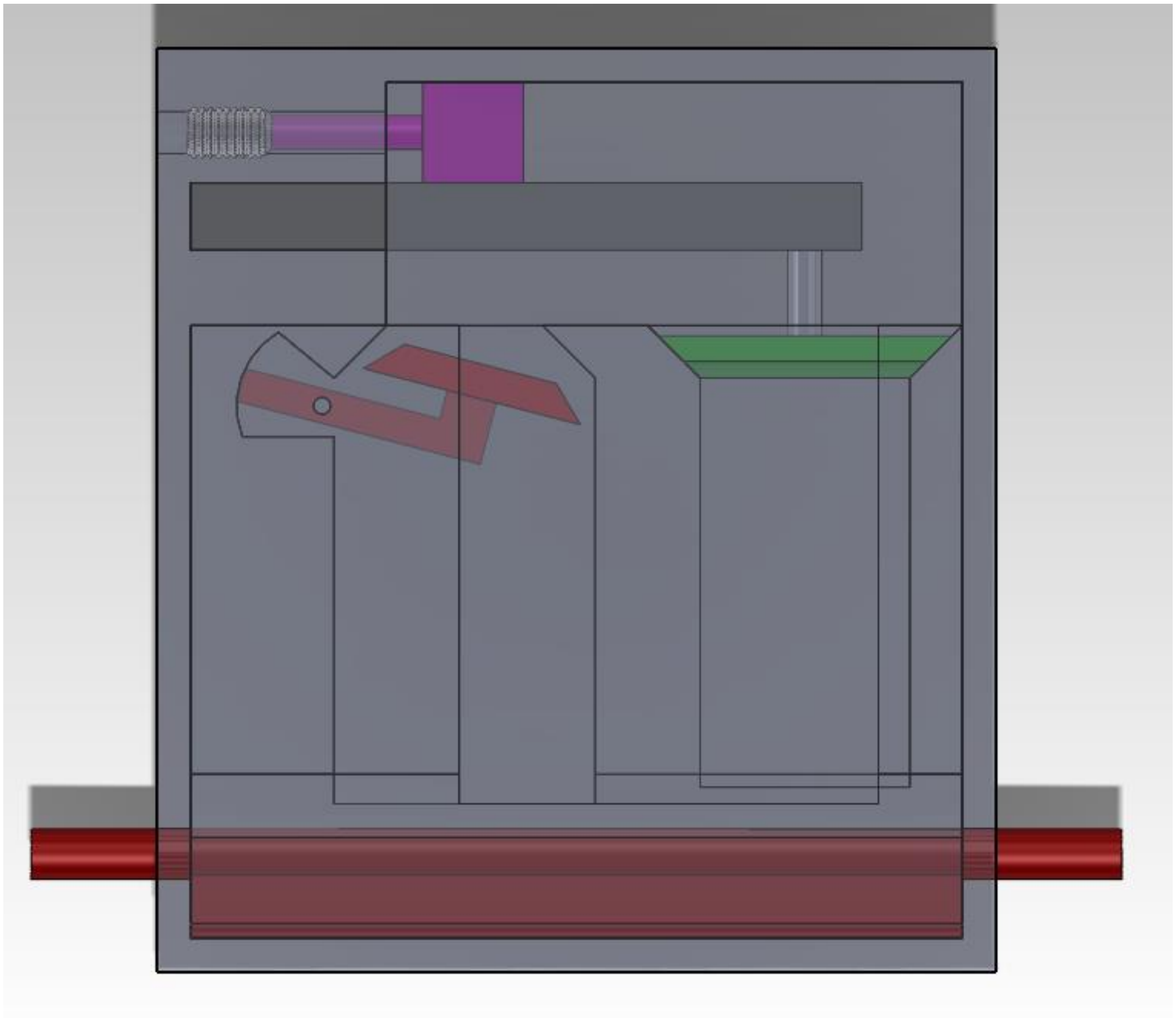

Figure 22: Original design for a BIAD prevention-Hydraulic Constant Rotary Force Absorber. Rejected due to a flaw in concept and complexity to manufacture.

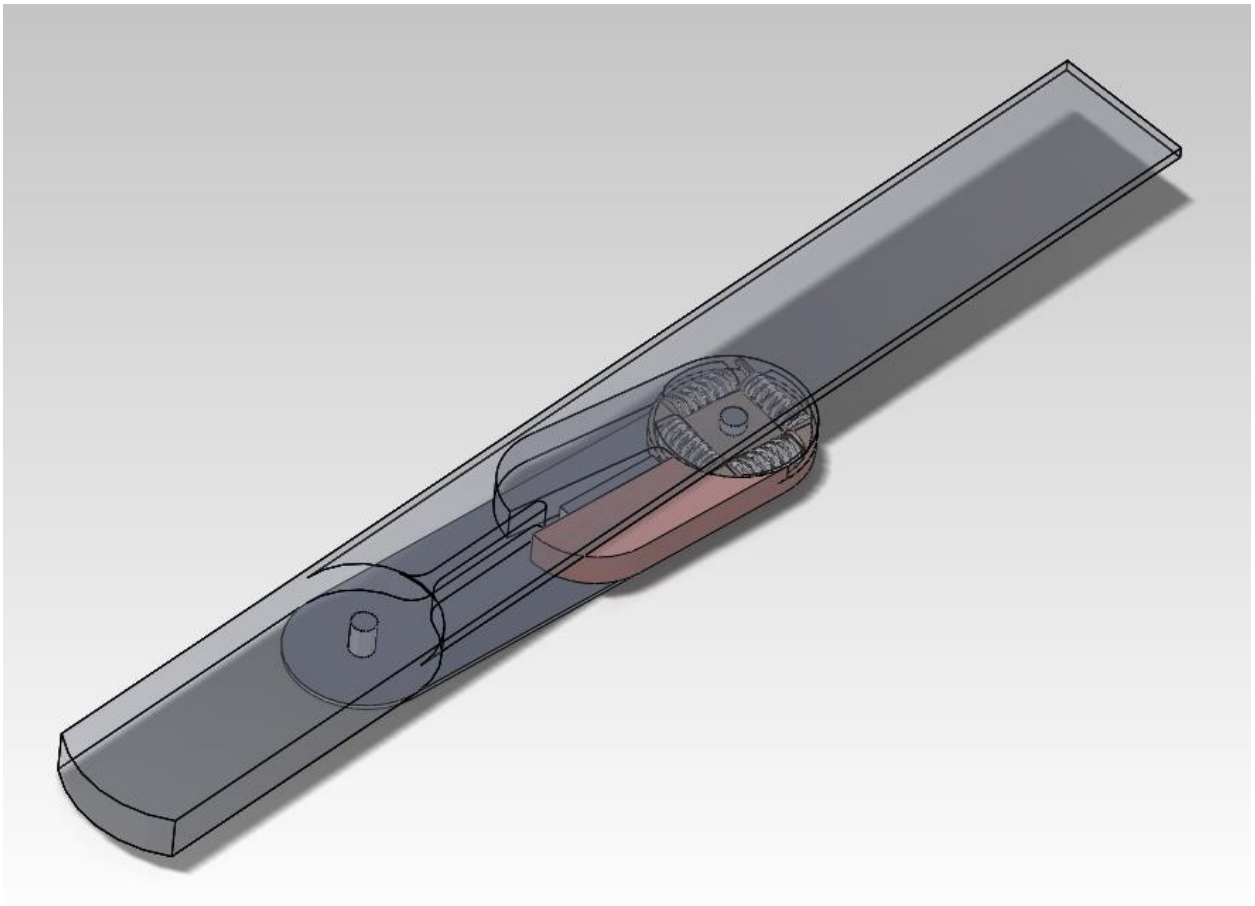

Figure 23: Older design for DP2.1- Dual spring plate mechanism. Rejected due to complexity and size.

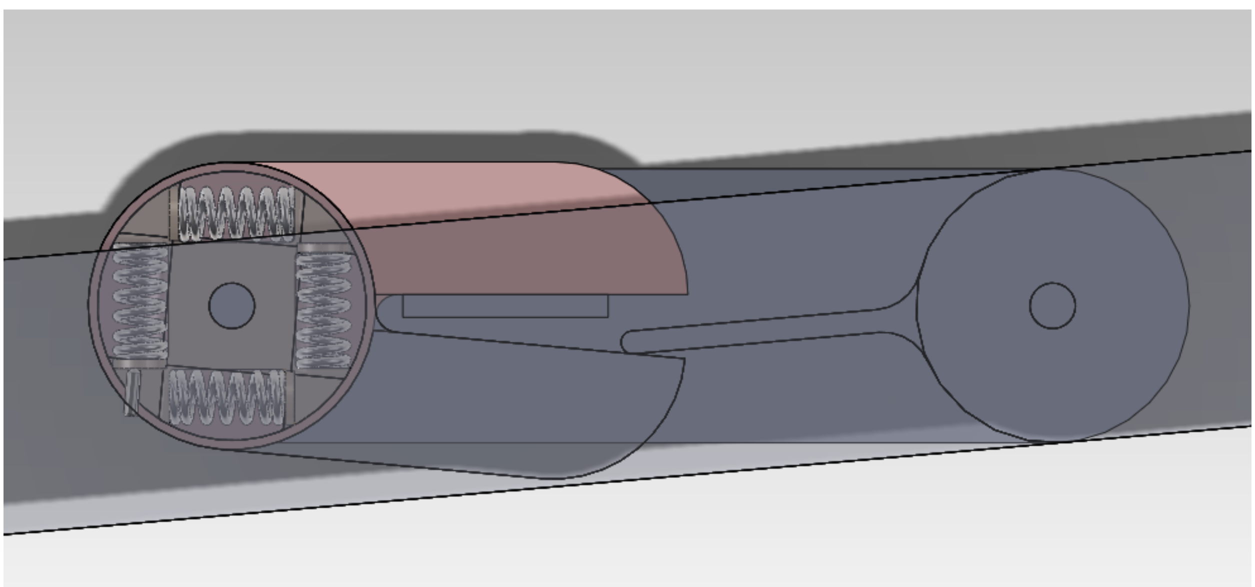

Figure 24: Closer look at the Dual spring plate mechanism; allowed for bi-directional ACL protection-offers the option to swap skis, potential to prevent external rotation injuries as well.