Multi-Mode Load-Limiting and Absorptive Ski Binding

A Major Qualifying Project
Submitted to the Faculty of
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Abstract

This project aimed to design a ski binding that could reduce the risk of common injuries. In doing so, this project addressed the lack of displacement mechanisms in current ski bindings and the issue of inadvertent release. Through the use of axiomatic design, it was determined that in order to prevent these injuries, lateral and vertical response mechanisms at the toe and heel were required. Additionally, this allowed displacement to occur internally—rather than between boot and binding—reducing inadvertent release.

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1 Introduction

1.1 Objective

The objective of this project is to design an improved ski binding that reduces the risk of injury to the anterior cruciate ligament (ACL) and the tibia, as well as to reduce the chance of inadvertent release (IR). This is to be accomplished by displacement in the binding to limit the loads that are transmitted into the leg through the boot-binding interface.

1.2 Rationale

1.2.1 Market Analysis

If accepted, this new level of control and injury prevention could present a new international standard for skiing. According to Snowsports Industry America, the United States had roughly 16.5 million downhill, alpine, or freeskiers participate in the 2014-2015 season, totaling 53.6 million visits (SnowSports Industries, 2015). Around $900 million was spent on snow sports equipment in the U.S. alone with roughly $49 million attributed to the sale of alpine ski bindings in 2014 (SnowSports Industries, 2017).

1.2.2 Ski Injuries

With over 53 million ski visits per year, and given the inherent risk of the sport, it is inevitable that injury can occur while skiing. One study looked at all Emergency Room visits for skiing related injuries that occurred in the United States in 2014. The researchers concluded that 42 of 1,000,000 skiers are injured each year, with the highest injury rates in the knee and lower leg (DeFroda et al., 2016). Our goal was to address some of the most common injuries that occur that are not actively prevented by bindings currently on the market. For this project, we looked specifically into the injuries that occur in the anterior cruciate ligament (ACL) and the tibia.

Knee Injury

Injuries to the knee alone account for 47% of injuries that occur each year, with 33%

attributed to knee sprain, strain, or laceration (DeFroda et al., 2016). The knee has four main ligaments that help to stabilize the knee; these are the anterior, posterior, medial, and lateral cruciate ligaments (ACL, PCL, MCL, and LCL, respectively). While all four contribute to knee stabilization, the ACL provides the greatest amount of support, and therefore is the most important to protect.

One common way the ACL is injured is through Boot Induced Anterior Drawer (BIAD). This can occur if the tail of the ski contacts the slope first, creating a moment behind the ski boot. This forces the boot to accelerate downwards at the front, creating tension between the tibia and femur, which can cause a sprain or laceration.

ACL injury may also occur due to Combined Valgus Inward Rotation (CVIR). In this event, the knee bends unnaturally towards the body midline, applying injurious tension to both the ACL and MCL. This event can occur when the ski edge gets caught in the snow during a turn. This forces the ski into a direction that is different than the direction of the inertia of the skier, resulting in an unnatural position of the knee.

Lower Leg Injury

Injury to the lower leg accounts for 22% of yearly ski injuries. While the lower leg contains both the tibia and fibula, injuries occur more often to the tibia as it is responsible for handling the majority of forces experienced. For the purpose of this project we focused only on fracture of the lower leg, which accounts for 15% of injuries reported (DeFroda et al., 2016).

Two common tibial fractures that may occur during skiing are spiral and tibial plateau fractures. Spiral fractures can occur when a large moment is applied to either the front or tail of the ski about the axis of the tibia. This creates an internal torque due to the distal end of the tibia rotating faster than the proximal end, causing the bone to fracture. Tibial plateau fractures occur when a large compressive force is applied, squeezing the tibia between the femur and the ankle. This force, if large enough, can cause fracture along the condyles of the tibia at the knee.

1.2.3 Inadvertent Release

Inadvertent Release (IR) is defined as any event where the binding releases from the boot when not intended. One way IR occurs is when the binding experiences a force that surpasses the release threshold although the skier is still in control. This is most often seen with professional skiers as they demand the most from their equipment, experiencing the most extreme forces. It is common for World Cup skiers to crank up the settings passed recommended values to ensure the binding never accidentally releases. Because the binding will no longer release, the risk of ACL and lower leg injury is dramatically increased, a risk these racers are willing to take.

Another cause of IR is an event called chatter-out. Bumps and impacts that occur along the length of the ski cause vibrations and ski flex. If the amplitude of this modal flexion is high enough, movement can occur at the boot-binding interface. The surface area at this interface is small; with enough ski flex, the binding can completely separate from the boot resulting in IR without triggered release of the binding.

This project will address IR by both reducing the chance of release while the skier still has control as well as eliminate the possibility of displacement at the boot-binding interface.

1.3 State of the Art

Binding Design

Over the years, skiing has greatly increased in popularity and new technology has been developed in order to provide safer equipment for the user. Many designs have been created to address different types of issues to increase safety. Several of these patents have been explored to see where there may be safety gaps that could be improved by our new binding.

The first patent that was studied was a safety binding that releases from the heel at a specified pressure. The design uses a spring mechanism that is located in the heel clamp. When the clamp is engaged by the boot, the spring is compressed. When the specified pressure is met, the clamp releases (Hans, 1967). This design is similar to many of the mechanisms found in current ski bindings.

A second patent was studied that aimed to reduce the risk of ACL injury by allowing lateral release at the heel. In most current bindings, lateral release is addressed at the toe while vertical release is at the heel. This patent added a secondary release in the heel to allow the boot to come out either vertically or laterally. This extra release option can reduce the risk of injury during a fall because it allows more ways for the boot to separate from the binding (Howell, 2004).

A third noteworthy patent was developed that was a binding with two plates, one on top of the other. The top and bottom plates are able to rotate in relation to each other during laterally loading. If the load is large enough, the binding releases, reducing the chance of injury to the ACL (Dodge, 2006).

The Design Gap

Some previous bindings have focused on reducing injury to the the ACL or reducing vertical load transmission, but there are no designs that address both issues simultaneously. In these designs, displacement usually occurs at the boot-binding interface, which may lead to IR. Our design is aimed at addressing all of these issues by allowing for displacement within the binding in both the vertical and lateral directions to filter injurious loads as well as limit the chance of IR.

1.4 Approach

1.4.1 Allow for multi-directional binding displacement

To achieve the desired objectives of this project, our binding will allow for displacement in the x-, y-, and z-axes of the ski binding. These axes will be referenced for the remainder of the report in accordance with FIS standards. The x-axis is along the length of the ski, the y-axis is across the width of the ski, and the z-axis is perpendicular to the ski surface. Displacement along all axes will be able to occur independently and allowed to fully recover to its neutral position to reduce forces transmitted to the boot, and therefore reduce the chance of injury.

1.4.2 Axiomatic Design

Nam Suh, a former professor at MIT, developed the concept of Axiomatic Design (AD) to allow engineers to solve a given problem through standardized decision making. Axiomatic Design is governed by two fundamental axioms, or laws. The first is to maximize independence and the second is to minimize information.

Fundamental Axioms

The first axiom is aimed at maximizing independence of the design elements. First, Customer Needs (CNs) are establish to see what the customer wants in order to achieve a successful design. These CNs are then translated into corresponding Functional Requirements (FRs). FRs are elements of the design necessary to fulfill the established CNs. Each FR is then paired with a Design Parameter (DP) which is created by the engineer to allow a specific design element to fulfill its associated FR. Together, these FR-DP pairs are created throughout the entirety of the design to ensure every FR is accounted for, and therefore every CN is fulfilled.

Through this process, the design is considered Collectively Exclusive and Mutually Exclusive (CEME). Since every DP is paired with only one FR, all FR-DP pairs are independent from each other ensuring that the effect of one pair does not affect any other pair. This decoupling ensures that one FR does not affect any others and ensures that a DP is not completing the function of multiple FRs.

The second axiom states that information should be minimized. Similar to the concept of Occam's razor, this axiom states that the option that is the simplest while completing the desired effect is usually the best solution. By reducing the required information needed to function, there is a lower chance of failure in the system. This relates to decoupling of FR-DP pairs because it ensures that every DP only serves one specific function (Suh, 2001).

Advantages of Axiomatic Design

There are several advantages of using AD over other general design processes. The main advantage is that it minimizes the need for excessive design iterations. If the design is decomposed to the full extent of the AD axioms, the final design should be the best solution to the problem at hand. While more time is spent in the decomposition process with AD, it saves time overall by eliminating the need to create completely new design concepts.

To carry out the design portion of this project, we used the Acclaro program to decompose the binding into its FR-DP pairs. This program allows for visualization of how each DP fulfills a specific FR as well as ensures all parent FR are fully covered by its children FRs. The software also allows for the elements to be displayed in matrix form to ensure independence of all design components.

1.5 Methods

1.5.1 Acclaro

The design decomposition was completed with the use of the computer program Acclaro. Acclaro is the leading software for AD. This program allows for visualization of how each DP fulfills a specific FR as well as ensures all parent FR are fully covered by its children FRs to maintain a design that is CEME by analyzing the FR-DP pairs. Lastly, Acclaro can create a matrix comparing every FR and DP to ensure independence of all pairs, satisfying Axiom 1.

1.5.2 SolidWorks

The use of 3D modeling software will be used to visualize the binding design by creating solid models. The software we will use for this product will be SolidWorks as it allows for easy visual representation of the design in both model and drawing formats. Since this project stresses the use of modular, adjustable systems, both specific parts and the assembly as a whole can be modified to achieve the desired effects of the binding.

2 Design Process

2.1 Constraints

Throughout the duration of this project, we must consider the constraints that are imposed to ensure the binding meets all needs and regulations to be a sufficient alpine ski binding. These include international ski regulations, customer needs, and constraints assigned to create this binding in our allotted time frame.

Standard Ski Requirements

To be considered an acceptable and marketable ski binding, this design must comply with all international regulations related to alpine ski bindings set by the International Ski Federation:

- Binding may not exceed width of ski, 65mm
- Distance between bottom of boot surface and top of ski surface may not exceed 50mm
- Must be compatible to hold ski boots already on the market at toe and heel
- Must be compatible to mount on skis already on the market at pre-specified locations (International Ski Federation, 2016)

Customer Needs

Customer needs are an important factor to the success of the ski binding. If the binding does not satisfy what the customer want, it is not considered a successful design:

- Binding must not inhibit the ability of the skier to effectively transit control inputs from the boot to the ski to properly navigate down the slopes
- Must be reasonably priced and in a competitive price bracket as compared to other conventional binding already on the market
- Must be aesthetically pleasing and fashionable

As this project is aimed as a proof of concept, our goal is to prove that an effective binding can be designed while reducing the chance of ACL and lower leg injury. As such, we are initially less concerned with binding aesthetics, and can be addressed in later design iterations.

Project constraints

This design project has a strict timeline and budget and therefore we must consider several other design constraints:

- Must be completed through the use of Axiomatic Design
- Project must be completed in 21 weeks, or three academic terms
- Minimize need for custom parts by using off-the-shelf components when possible

We will model our design using Aluminum 6061 as this is a cheap and readily accessible material that can be used for proof of concept prototyping. Afterwards, custom components and improved materials can be substituted to improve performance and overall aesthetics of the binding.

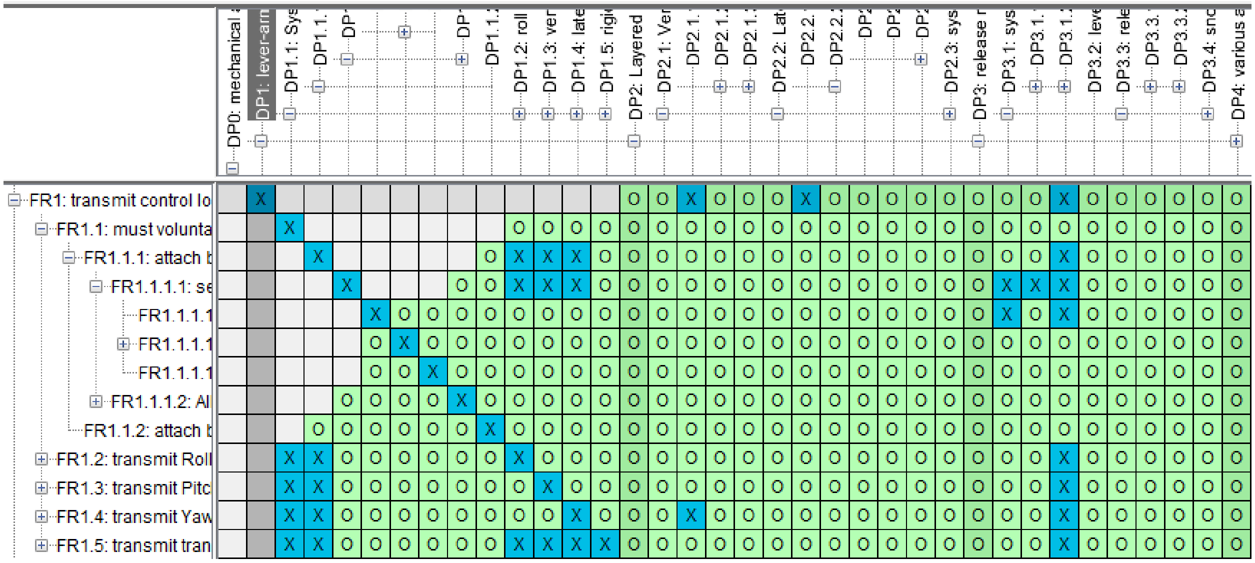
Self-Assigned Constraints

Lastly, our group set several additional constraints for the project in order to further define necessary FRs and DPs:

- Binding will only use mechanical components, no electronics
- Boot will be clamped at toe and heel independently
- Toe/heel clamps will only be in two possible states, fully closed or fully open
- Toe/heel clamps will not be location of binding displacement
- Release must not be triggered by ski chatter/flex

2.2 Design Matrix

In order to ensure that axiomatic design is followed one must confirm that there is no coupling. As expressed earlier in section 1.4.2 coupling is when a single physical component (design parameter) effects multiple functional requirements. To check for coupling the program Acclaro will generate a design matrix. A design matrix is a FR by DP grid that allows the user to check for coupling. Figure 1 below is an image of the design matrix for section one of the Acclaro file.



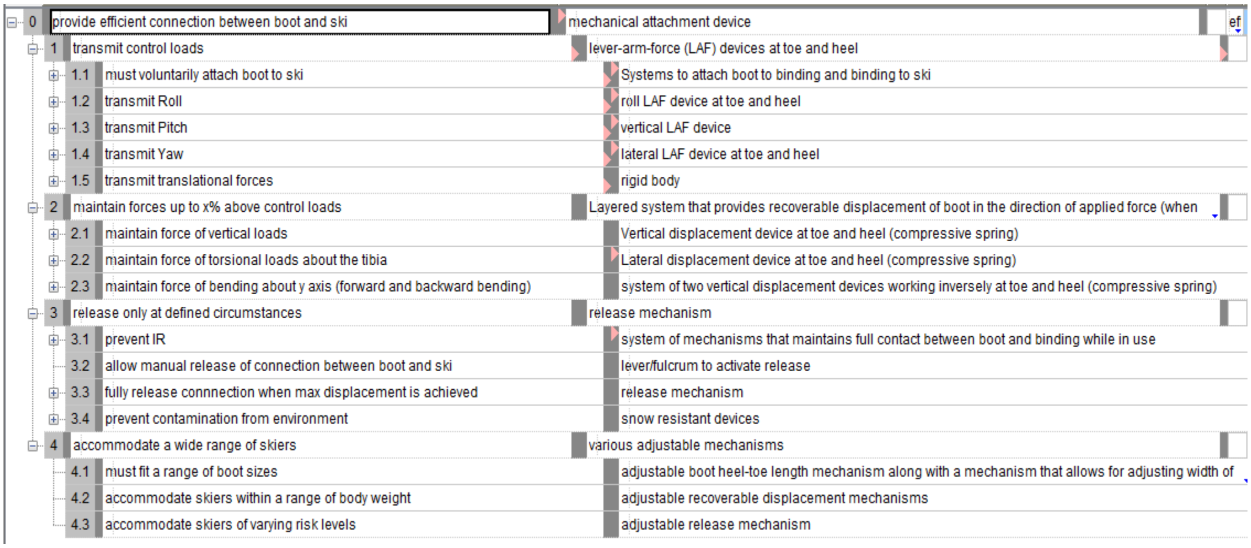
	DP0: mechanical	DP1: lever-arm	DP1.1: Sys	DP1.1.	DP				DP	DP1.1.	DP1.2: roll	DP1.3: ver	DP1.4: late	DP1.5: rigi	DP2: Layered	DP2.1: Ver	DP2.1.	DP2.1.	DP2.1.	DP2.2: Lat	DP2.2.	DP2.2.	DP2	DP2	DP2	DP2.3: sys	DP3: release	DP3.1: sys	DP3.1.	DP3.1.	DP3.2: leve	DP3.3: rele	DP3.3.	DP3.3.	DP3.4: snc	DP4: various
FR1: transmit control lo		X													O	O	X	O	O	O	X	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
FR1.1: must volunta			X								O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.1.1: attach				X						O	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
FR1.1.1.1: se					X				O	O	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	X	X	O	O	O	O	O	O
FR1.1.1.1						X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	X	O	O	O	O	O	O
FR1.1.1.1						O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.1.1.1						O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.1.1.2: Al					O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.1.2: attach				O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.2: transmit Roll			X	X	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
FR1.3: transmit Pitc			X	X	O	O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
FR1.4: transmit Yaw			X	X	O	O	O	O	O	O	O	O	X	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O
FR1.5: transmit tran			X	X	O	O	O	O	O	O	X	X	X	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	O

Figure 1: Design Matrix showing the independence of FR-DP pairs in FR 1

Note that every square is filled with either a green O or a blue X. A blue X indicates that the DP has some effect on the function of the FR. A green O indicates that there is no connection between the two. In a perfectly decoupled system the entire grid would be green Os with a single diagonal line of blue Xs running from top left to bottom right. The Acclaro file for this project do have some partial coupling as can be seen in the image above. This is largely do to the clamp. While transmitting different types of loads (roll, pitch, yaw, and translational) are all different functional requirements they all start by being transmitted through the same physical component. While this is not perfectly decoupled it was deemed acceptable since such a situation is unavoidable. What is not seen here is the third possibility which is a red X. A red X indicates complete coupling where two FRs both depend on each others DP. Complete coupling is an unacceptable violation of the first axiom of axiomatic design and was completely avoided in this project.

2.3 FRs and DPs

Using Axiomatic Design process several FRs were developed. For each FR there was an associated DP that guided the decomposition to a final physical solution. Figure 2 below is a screenshot of the Acclaro file used in this project, followed by a table showing only the highest level FR-DP pairs. For a full list see Appendix B. After the table, each pair is explained in more detail including images of the physical components. Note: At the highest level DPs are very large and vague, at lowest level they clarify specific parts.



0	provide efficient connection between boot and ski	mechanical attachment device	ef
1	transmit control loads	lever-arm-force (LAF) devices at toe and heel	
1.1	must voluntarily attach boot to ski	Systems to attach boot to binding and binding to ski	
1.2	transmit Roll	roll LAF device at toe and heel	
1.3	transmit Pitch	vertical LAF device	
1.4	transmit Yaw	lateral LAF device at toe and heel	
1.5	transmit translational forces	rigid body	
2	maintain forces up to x% above control loads	Layered system that provides recoverable displacement of boot in the direction of applied force (when	
2.1	maintain force of vertical loads	Vertical displacement device at toe and heel (compressive spring)	
2.2	maintain force of torsional loads about the tibia	Lateral displacement device at toe and heel (compressive spring)	
2.3	maintain force of bending about y axis (forward and backward bending)	system of two vertical displacement devices working inversely at toe and heel (compressive spring)	
3	release only at defined circumstances	release mechanism	
3.1	prevent IR	system of mechanisms that maintains full contact between boot and binding while in use	
3.2	allow manual release of connection between boot and ski	lever/fulcrum to activate release	
3.3	fully release connnection when max displacement is achieved	release mechanism	
3.4	prevent contamination from environment	snow resistant devices	
4	accommodate a wide range of skiers	various adjustable mechanisms	
4.1	must fit a range of boot sizes	adjustable boot heel-toe length mechanism along with a mechanism that allows for adjusting width of	
4.2	accommodate skiers within a range of body weight	adjustable recoverable displacement mechanisms	
4.3	accommodate skiers of varying risk levels	adjustable release mechanism	

Figure 2: Acclaro decomposition of top level FRs

The top level FRs each have a physical module that allows for the completion of the function. (Low level FRs are satisfied by the individual parts.) The following are FRs 1.1 through 4.3 and a brief explanation on how that FR is physically satisfied in the system.

FR 1: Transmit Control Loads

1.1 Must voluntarily attach boot to ski: This FR is met by having a lever that would allow the user to self-engage the clamps.

1.2 Transmit Roll: This FR is met by having moments about the x-axis transmitted through the toe and heel clamps. The clamps in turn applied the moment the rod that extends through the vertical tower to the lateral response that applies the roll across the surface of the ski allowing for maximum control.

1.3 Transmit Pitch: This FR is met by transmitting moments about the y-axis at the toe and heel through the clamp to the vertical rod and to the lateral displacement device. The moments act on the surface of the ski at the extreme x-axis of the binding allowing for maximum control of pitch.

1.4 Transmit Yaw: This FR is met by transmitting moments about the z-axis at the toe and heel through the clamp to the vertical rod and to the lateral displacement device. The moments act on the surface of the ski at the extreme x-axis of the binding allowing for maximum control of the yaw.

This diagram shows the components used in FRs 1.2-1.4, these could not be completely decoupled since all the control moments need to be transmitted through the boot-binding interface (the clamp), however all the functions can be done independently of one another.

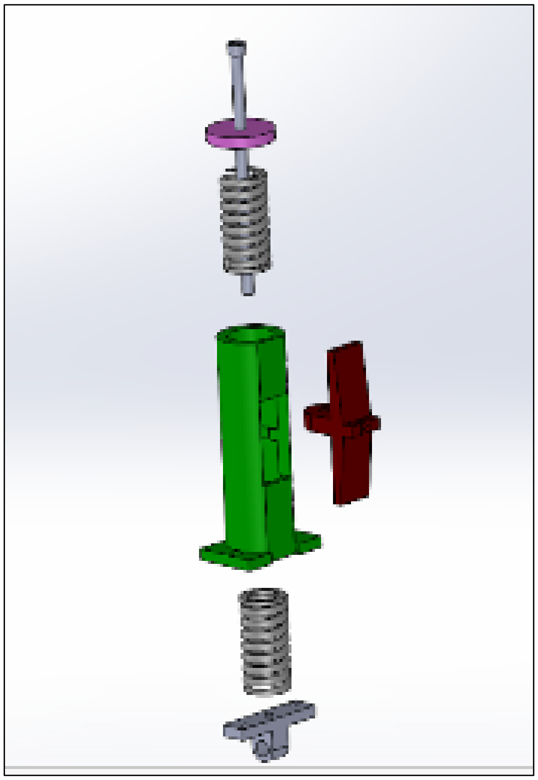


Figure 3: Exploded view of vertical displacement slider

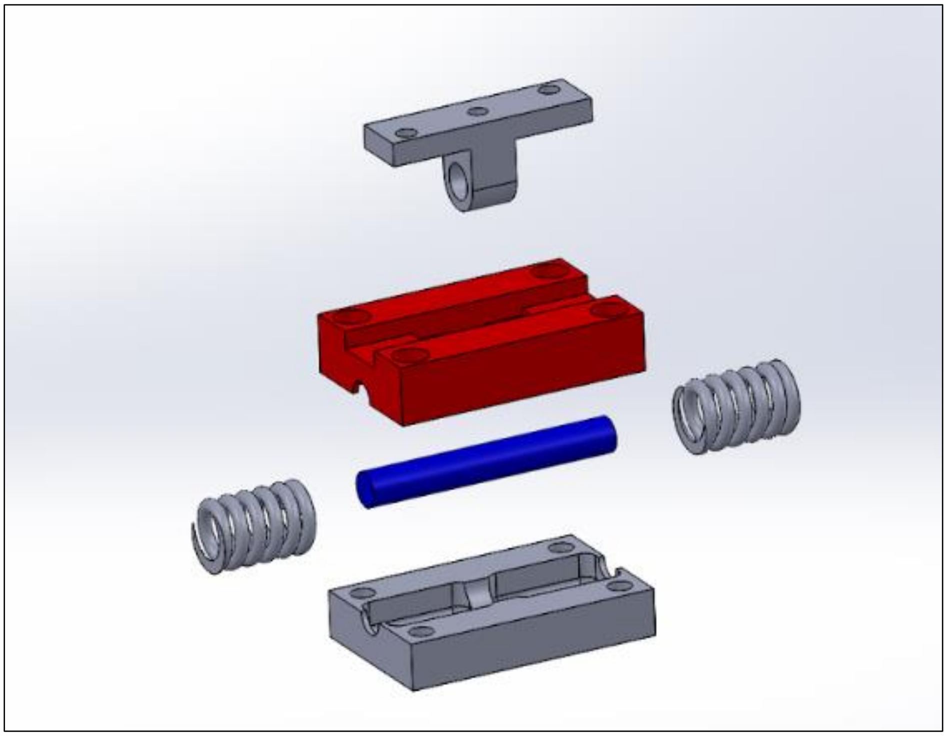


Figure 4: Exploded view of lateral displacement slider

1.5 Transmit Translational Forces: This FR is met by transmitting translational forces about all axes at the toe and heel through the clamp to the vertical rod and to the lateral displacement device. The moments act on the surface of the ski at the extremes of all axes of the binding allowing for maximum control of the translational forces.

FR 2: Maintain Forces up to X-above control load

2.1 Maintain Force of Vertical Loads: This FR is met by using preloaded springs and a vertical slider that ride along a vertical rod at both the heel and toe. The preload of the springs allows for forces to be applied without displacement until the user approaches the injurious threshold. At this point a traditional ski binding would release. The project binding, however, will begin to displace if the load continues to increase. This displacement increases the time the impulse is applied to the limb thus decreasing the amplitude of the load.

2.2 Maintain Force of Torsional Loads about the Tibia: This FR is met by using preloaded springs and a horizontal slider that ride along a vertical rod at both the heel and toe. The preload of the springs allows for forces to be applied without displacement until the user approaches the injurious threshold. At this point a traditional ski binding would release. The project binding however will begin to displace if the load continues to increase. This displacement increases the time the impulse is applied to the limb thus decreasing the amplitude of the load.

2.3 Maintain Force of Bending about the Y-axis: This FR is met by using preloaded springs and a vertical slider that ride along a vertical rod at both the heel and toe. The preload of the springs allows for forces to be applied without displacement until the user approaches the injurious threshold. At this point a traditional ski binding would release. The project binding however will begin to displace if the load continues to increase. This displacement increases the time the impulse is applied to the limb, thus decreasing the amplitude of the load. The decoupling of the toe and heel response mechanisms, allows for the angle between the boot and the ski to change reducing the risk of injury due to sudden bending. This motion is shown below in Figure 5.

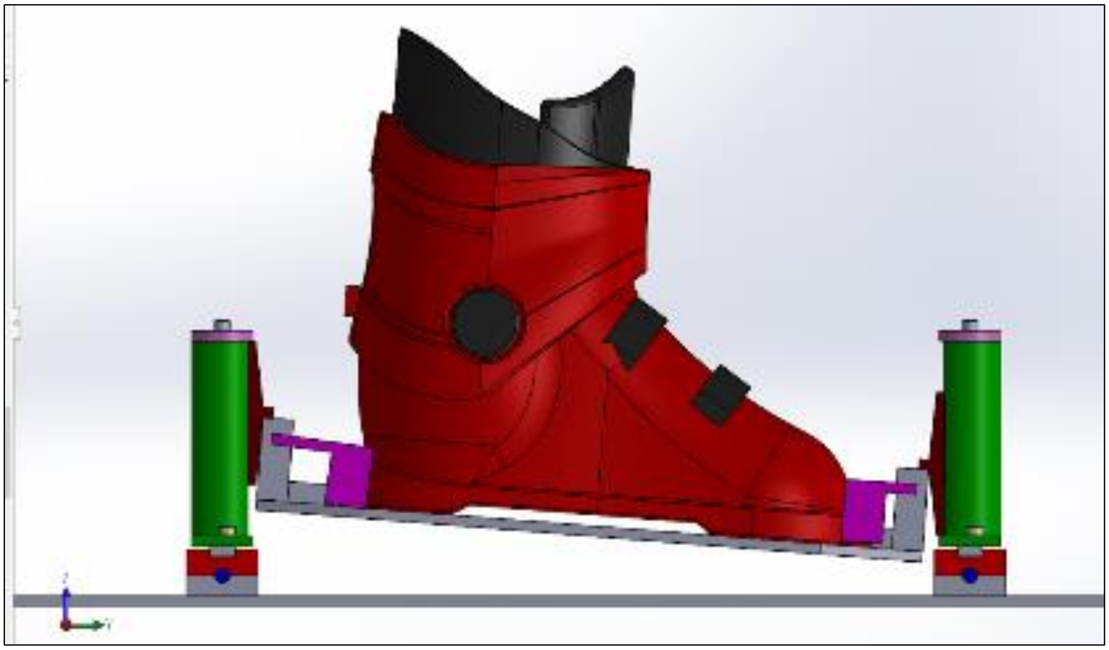


Figure 5: Response to forward or backward bending

FR 3: Release only at defined circumstances

3.1 Prevent IR: This FR is satisfied by preventing IR due to chatter and preventing IR due to a poor boot binding interface. The boot binding interface has been improved by having a clamp that rigidly attaches to the toe and the heel of the boot. Unlike traditional bindings displacement occurs within the binding not at the boot binding interface this ensures that the boot is always securely clamped. Chatter out is prevented by rigidly attaching the front tower to the ski and allowing the rear tower to ride along a slider. This allows for the ski to flex freely beneath the binding without affecting the relationship between the boot and the binding. This motion is shown below in Figure 6.

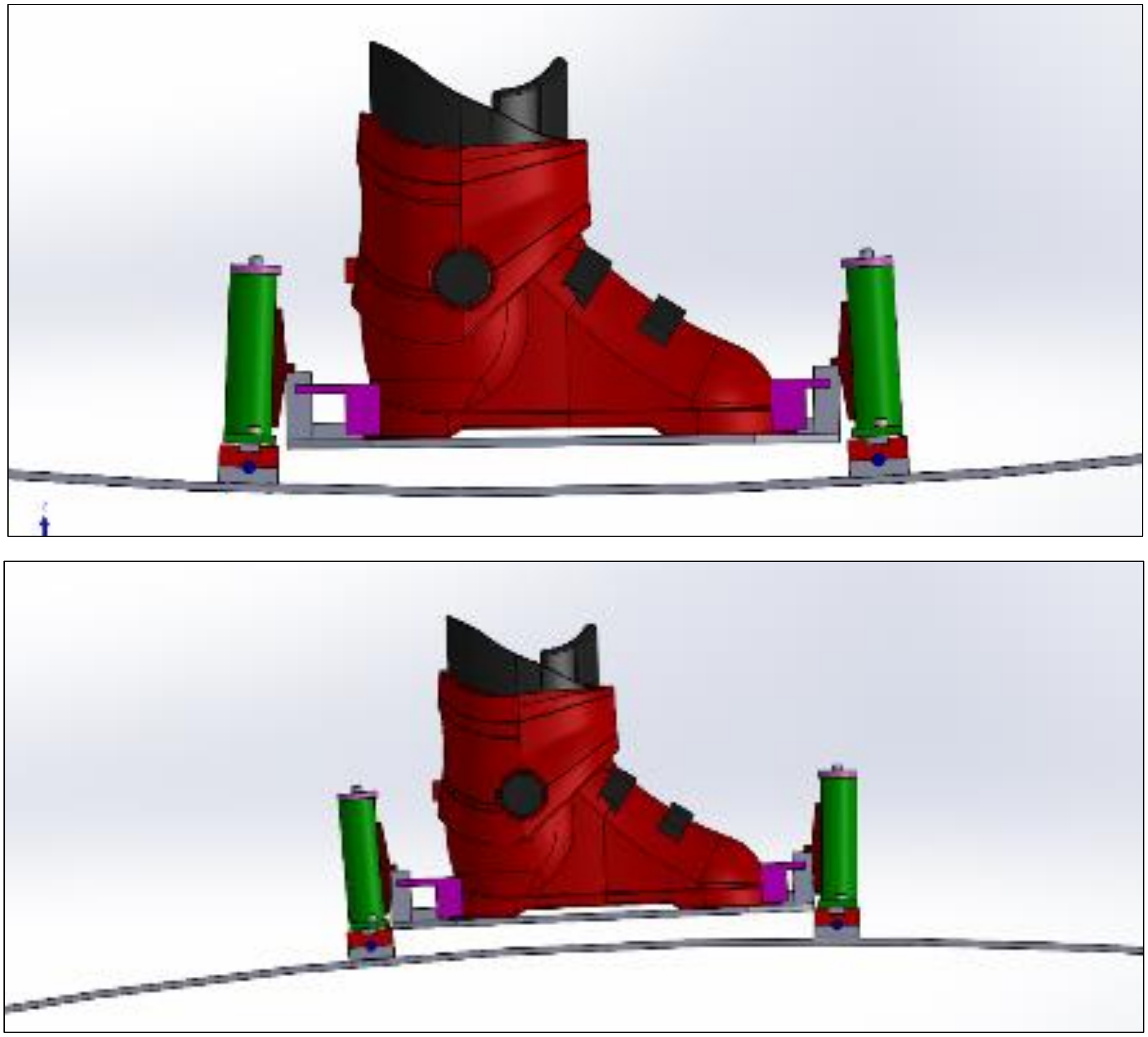


Figure 6: Binding response to upward or downward bending of ski

3.2 Allow for manual release: This FR is met by having a lever that allows the user to manually trigger the release.

3.3 Fully release connection when max displacement is achieved: This FR is met be having spring loaded clamps. In the final design the ski binding has only two stages fully close and fully open. There will be a communication device between the two release mechanisms that will trigger one if the other has been triggered. This ensures that when release is triggered user is fully removed from the ski and that there exists no condition where the user is only partially connected.

3.4 Prevent contamination from the environment: This FR was achieved by adding a casing to the lateral and vertical response system as well as dimensioning the sliders in such a way that snow and other particles cannot enter the response mechanism. The images in Figure 7 below show the vertical response mechanism. In this example the tower (left) has an open slit of 1.925 inches allowing the vertical slider (right) to move freely outside the tower. The vertical slider in either extreme (fully up or down) provides 1.9375 inches of cover ensuring that the internal mechanism remain unexposed to the elements.

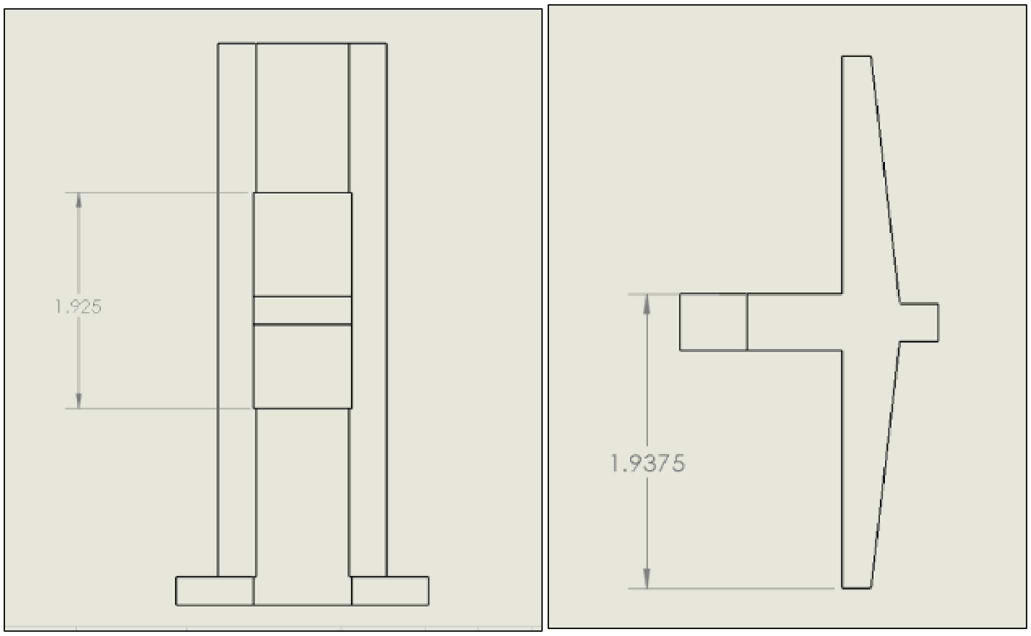


Figure 7: Dimensions showing at maximum displacement complete coverage of internal mechanisms from environment

3 Results

3.1 Final Design

The project resulted in eight unique claims that separate this design from others on the market as well as show that the objective of this project was achieved. Sections 3.1.1 through 3.1.8 explain each claim in detail.

3.1.1 Vertical Displacement

Provides vertical displacement, between the boot and ski, below injury thresholds, to reduce the risk of tibial plateau and ACL injuries due to BIAD (Boot Induced Anterior Drawer).

The binding provides a maximum of 50mm of vertical displacement as is the maximum allowed by the International Ski Federation. This displacement can occur either upwards or downwards, and can move independently at both the toe and heel, to prevent different injuries as shown below in Figures 8 through 11.

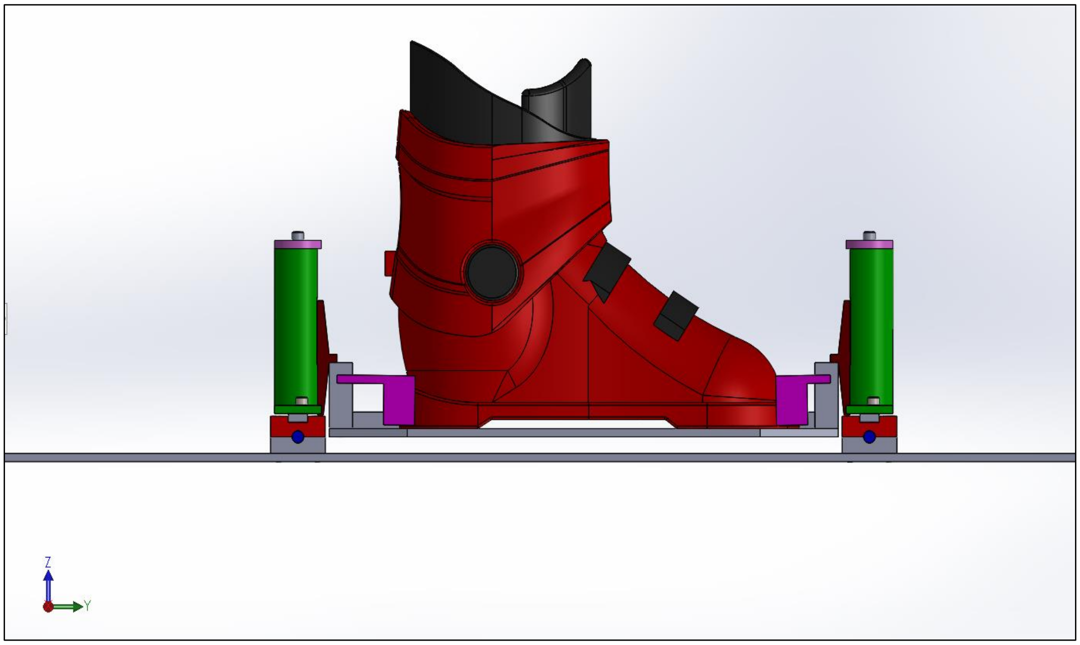


Figure 8: Maximum downward displacement

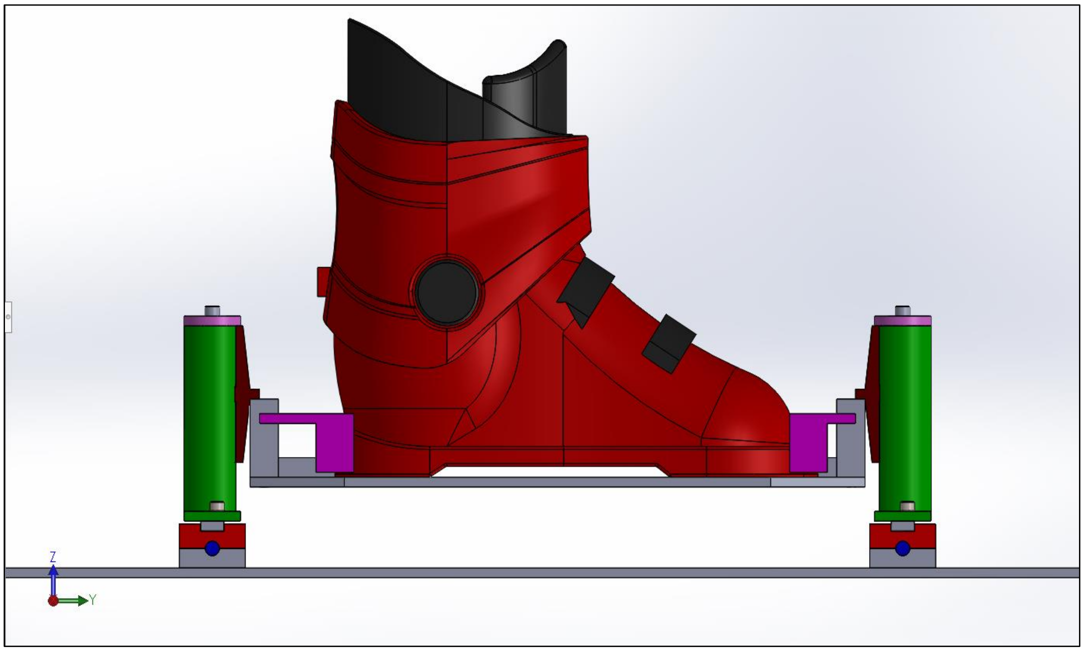


Figure 9: Maximum upward displacement

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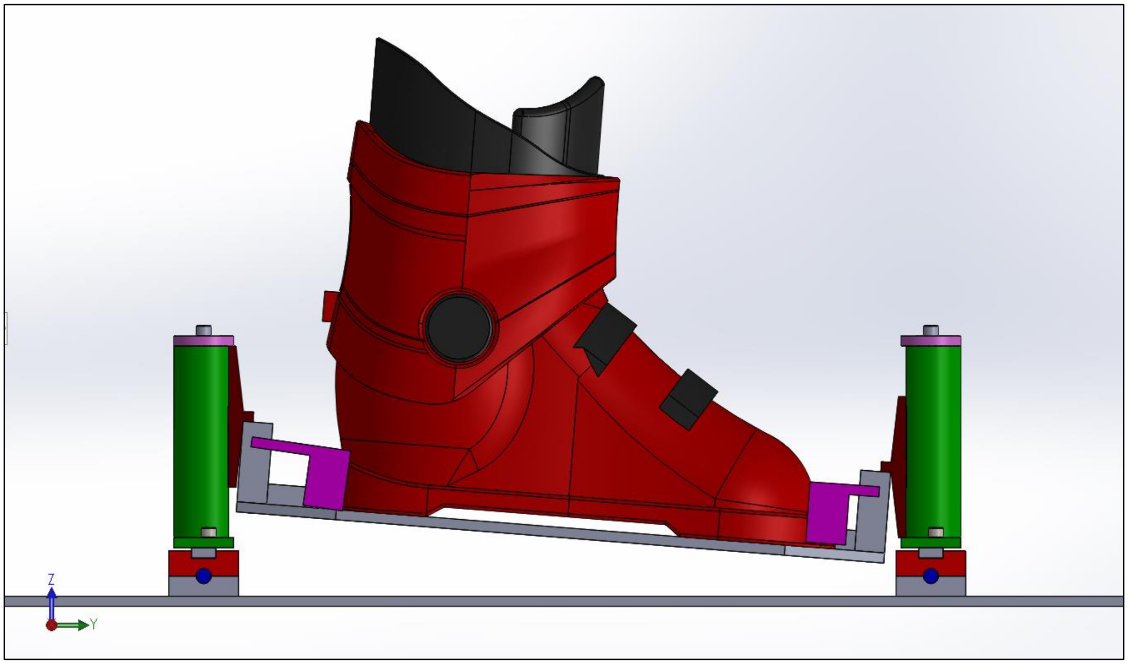

Figure 10: The response to forward bending showing the independence of the vertical responses at the toe and the heel

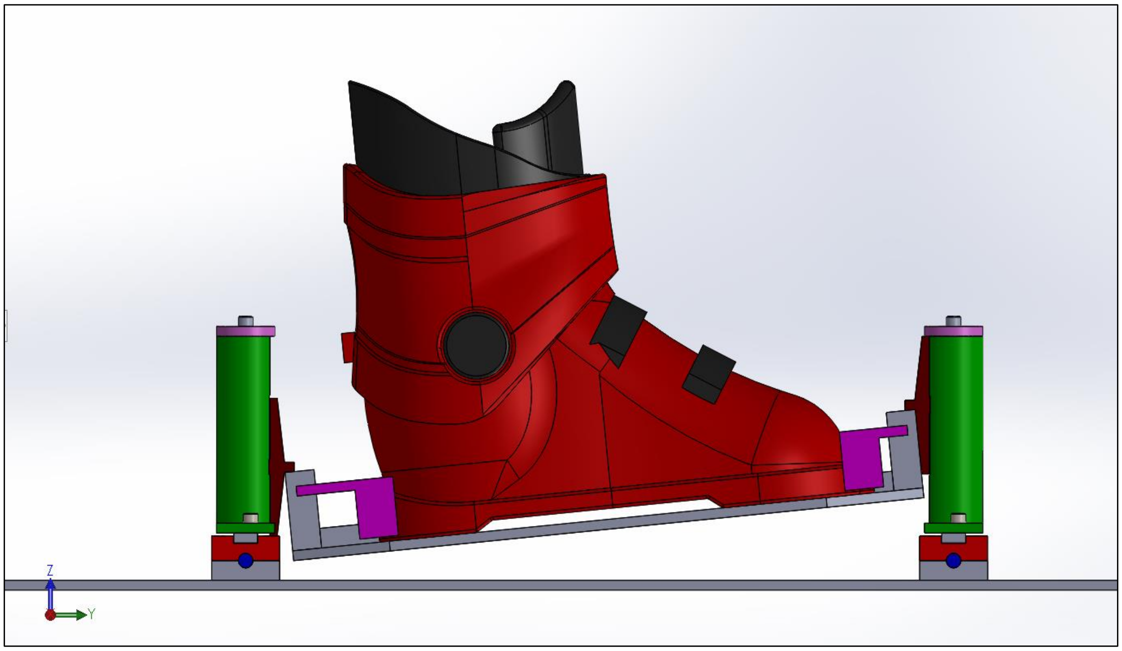

Figure 11: The response to BIAD conditions again showing the independence of the vertical responses at the toe and the heel

3.1.2 Lateral Displacement

Provides absorptive lateral displacement, between the boot and ski, at both the heel and toe, below injury thresholds, to reduce the risk of ACL injuries by CVIR (Combined Valgus Inward Rotation) and reduce the risk of inadvertent release.

The binding provides a maximum of 12.8mm of horizontal displacement limited by the size of the ski and the compression ability of the selected springs. The springs were selected as to match current DINN settings for an average size male and would release at a maximum torque of 31.6 Nm. This displacement can occur either to the left or right, and can move independently at both the toe and heel, to prevent different injuries as shown below in Figure 12.

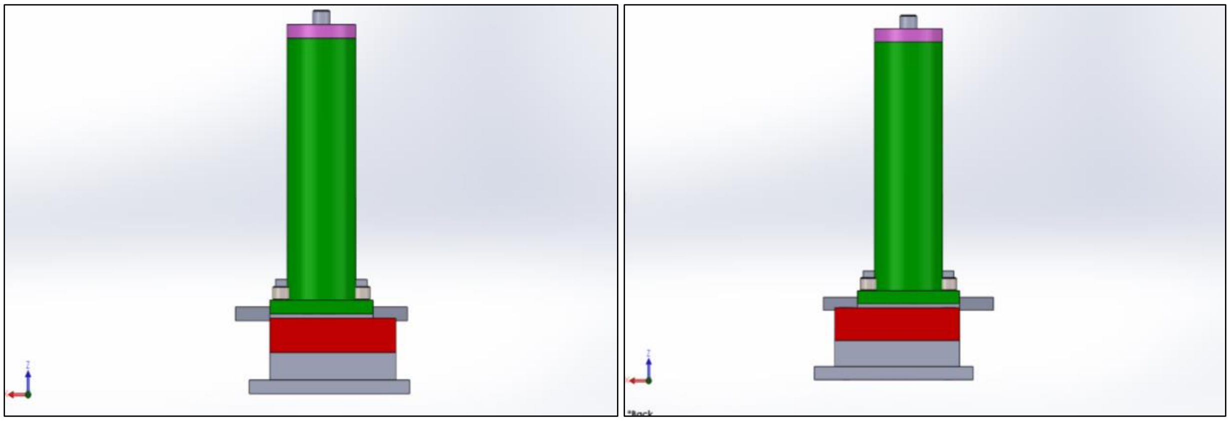

Figure 12: The maximum displacement to the left and right of the ski (shown from heel)

.

3.1.3 Internal Binding Displacement

Provides relative displacement between the boot and the ski in the binding under protected interfaces rather than at the boot-binding interfaces that are subject to contamination.

In traditional ski bindings displacement occurs at the boot binding interface, this couples the displacement for injury prevention with the actual binding of boot to ski. In the project binding the boot is securely clamped to a plate and any injury preventing displacement occurs within the binding itself.

3.1.4 Stages of Displacement

Provides 4 stages of adjustable load displacement relationships:

1) High frequency, low amplitude absorption for fatigue reduction

2) High fidelity load transmission for control at moderate and low frequencies

3) Displacement with near constant load below injury threshold and above normal control loads

4) Release at a threshold of displacement and recover displacement below the threshold

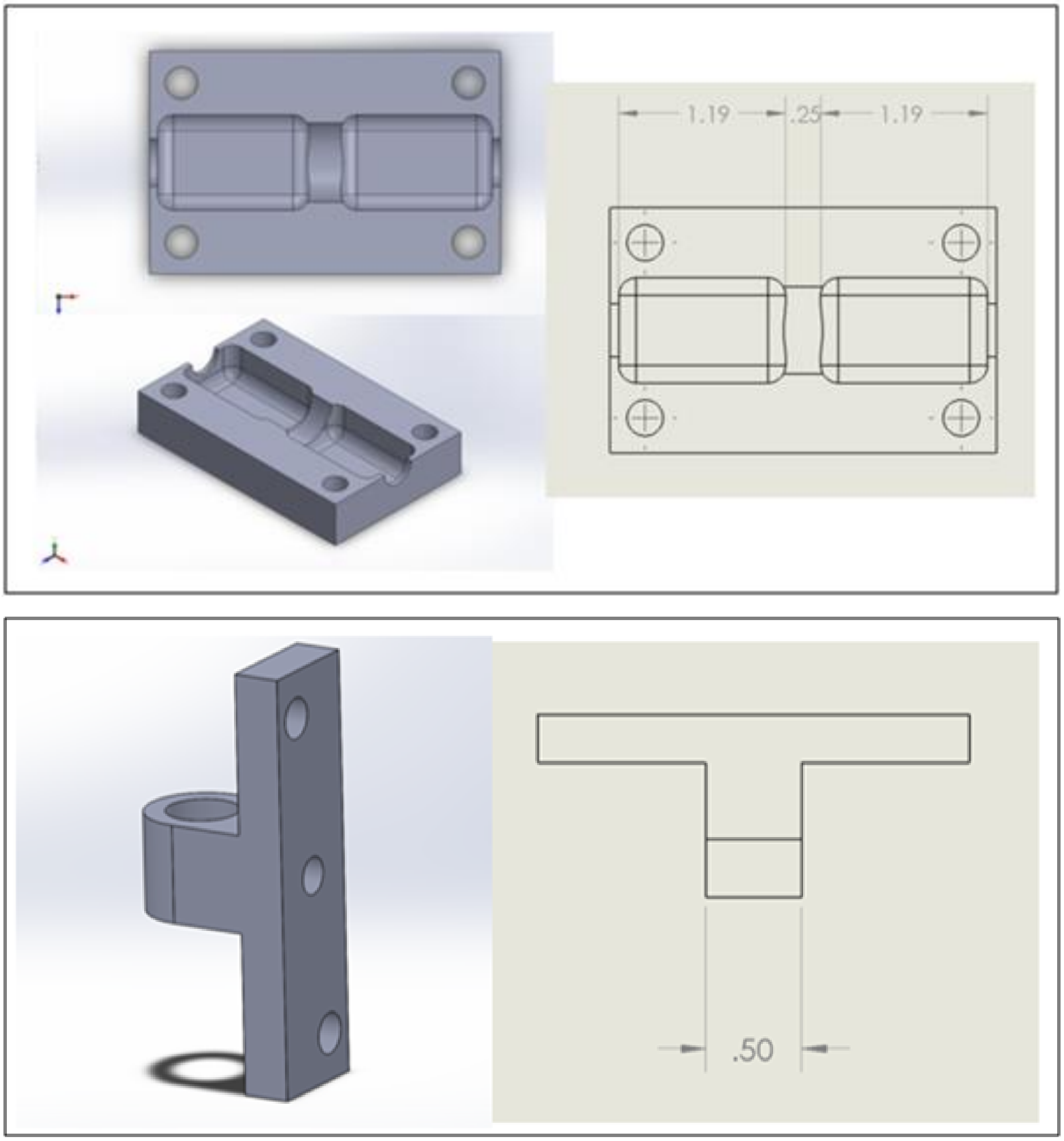

Figure 13: Lateral displacement components to show 4 stages of load transmission

The four stages are achieved by the way the springs and slider fit into the casing, as seen in Figure 13. The cylindrical hollows in the casing would each house a preloaded spring. This and the size of the slide allow for the four stages.

The ring of the slider is 0.50 inches, while the stopper in the casing is only 0.25 inches this allows for both springs act against one another allowing the slider to move freely side to side while the slider is located in the center of the casing. This is the first stage of response and absorbs light vibration, limiting fatigue to the muscles. The second stage of response is when a large enough load forces the slider 0.25 inches to the left or the right. Once this is achieved, one of the springs will make contact with the casing causing the slider to be acting against the preloaded spring creating a rigid body system. This would allow for the user to have complete control while executing turns and other movements. The third stage occurs when the load exerted on the slider exceeds the preload of the spring. In this case the load has exceeded the acceptable force and the spring begins to compress allowing for displacement, maintaining the load transmitted to the user below the injurious threshold. Finally, the fourth stage occurs at the end of the incident that caused displacement. If the load ceases prior to the binding achieving maximum displacement then the spring returns the slider to the center position. If the load lasts long enough for the binding to completely displace then the release is triggered to prevent injury. In Figure 14, the chart shows the stages and their relation to load and displacement.

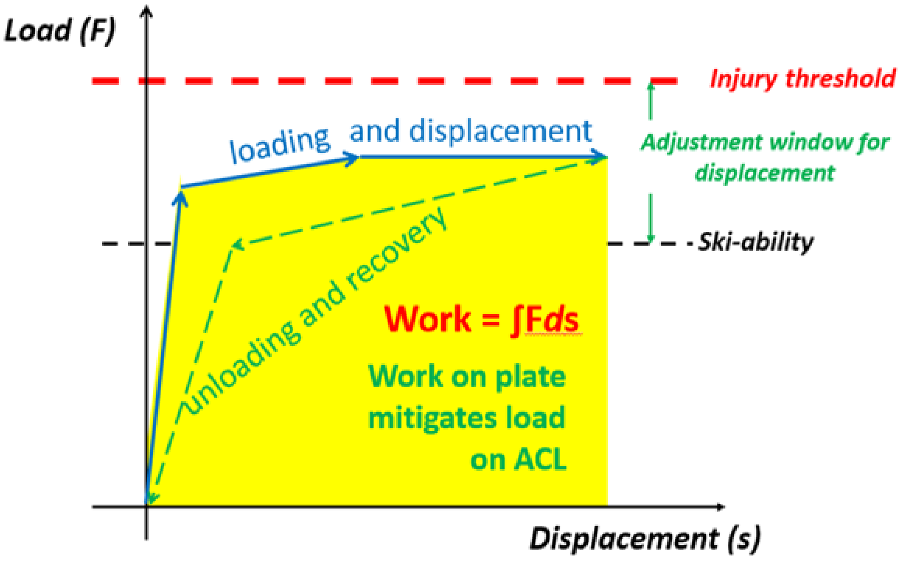

Figure 14: Graph showing that increasing displacement reduces load transmitted to skier

Stage one is not shown and only affects small loads. Stage two is the nearly vertical line. This is where the ski acts as a rigid body and the skier exerts the most control. Stage three is the loading displacement. This occurs beyond the ideal control loads and before the injurious threshold this lessens the chance of injury and allows for the user to recover from a high load event. This stage has less control than the second stage. The fourth stage either triggers the release (not shown). If at any stage the load completes, the slider returns to original position, shown by the unloading and recovery line.

3.1.5 Simultaneous Vertical and Lateral Response

Decouples directional displacement, allowing for simultaneous response to vertical and horizontal loads in addition to accommodating bending of the ski.

Just as the binding separates the toe and heel response, it also separates the vertical and horizontal responses. This allows for vertical displacement regardless of the current position of the lateral response and vice versa. As shown in Figures 15 and 16, the boot can exist at both the vertical and lateral extremes, and any lesser amount of displacement, simultaneously.

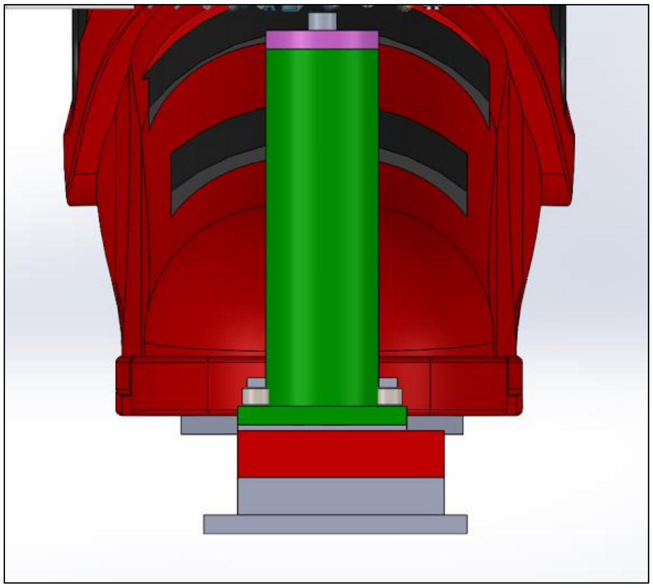

Figure 15: Front of boot at lower and right hand (from boot orientation) extreme displacement

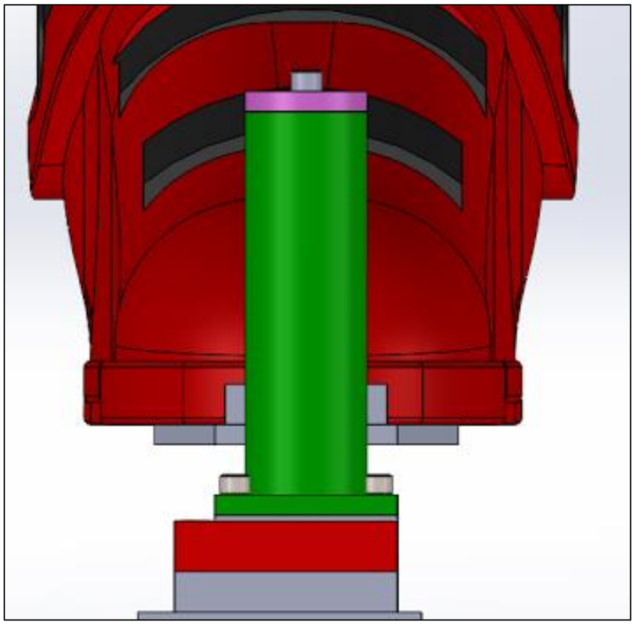

Figure 16: Front of boot at upper and left hand (from boot orientation) extreme displacement

3.1.6 Accommodate Ski Flex

Accommodates ski flex by allowing displacement between binding and ski along the ski, while gripping toe and heel of boot firmly to prevent inadvertent release due to chatter-out.

A common reason for inadvertent release is due to the ski flexing at a higher frequency than the binding can react to. The source of this problem no longer exists due to decoupling the displacement from the binding interface as shown below. Notice that the boot interface does not change with the ski flex.

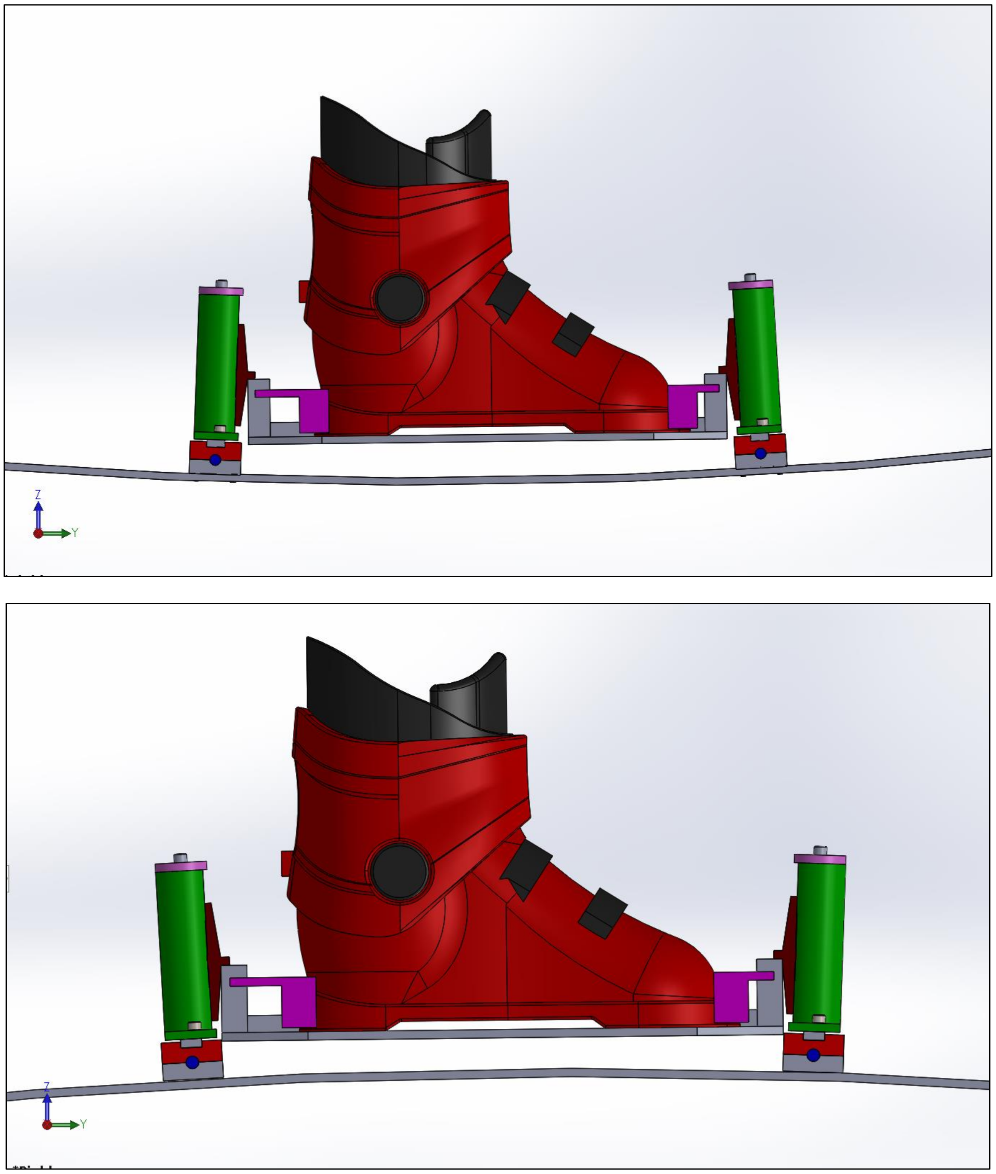

Figure 17: Binding response due to downward or upward ski flex

3.1.7 Two States of Boot Clamp

Provides two states, maintaining a firm grip on the boot at the toe and heel until release conditions are met.

In traditional bindings, due to the coupling of the displacement response and the binding interface, the amount of contact in the boot binding interface varies. In the project binding, due to the decoupling of the displacement response and the binding interface, the amount of contact in the boot binding interface remains constant until release conditions are met as shown in Figures 18 and 19.

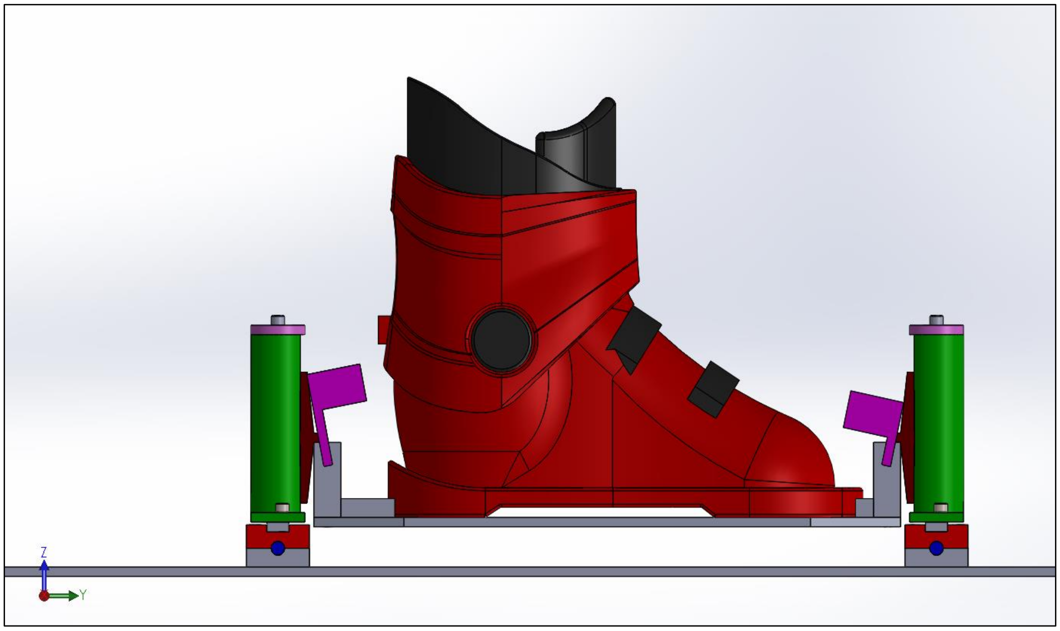

Figure 18: Binding in open clamp configuration

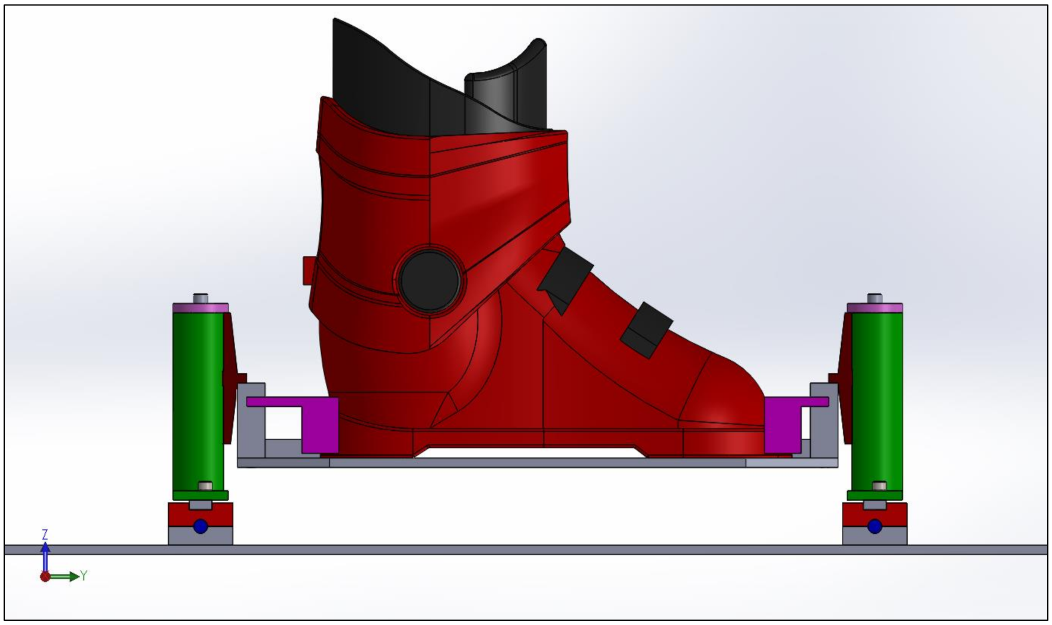

Figure 19: Binding in closed clamp configuration

3.1.8 Adjustability

Provides adjustable conditions for displacement that will trigger release while also providing separate adjustment for maximum loads.

By changing the springs within the binding one can choose custom settings that will match their height, weight, age, or skill level to allow for the desired displacement and release conditions. By increasing the pre-load applied to the springs the user can increase the control phase of the ski while maintaining release conditions. Finally the plate includes an adjustment system that will allow for an efficient fit of the boot to the system.

3.2 Additional Designs

In addition to the primary design, a hydraulic and a pneumatic adaptation was explored. This section presents the design along with calculations to verify the feasibility of each system as a response mechanism. Both the hydraulic adaptation and the pneumatic adaptation are the same in principle to the final design presented in this report in that it maintains nearly all of the FR-DP relationships outlined in section 2.3. Essentially, this design attempts to achieve the same functions as the spring displacement mechanisms through hydraulic or pneumatic displacement.

3.2.1 Overview

The design works by using a system of two bodies containing fluid. The system consists of a primary piston cylinder that can displace gas or liquid into a connected auxiliary chamber via a relief valve. When the set control threshold is breached, the relief valve opens to allow fluid to flow into the auxiliary chamber. This then allows the primary piston to displace, ultimately providing displacement in the binding. It is important to note that this means the primary piston has little to no displacement until control loads are exceeded. This allows the user to input loads that translate directly to the ski, allowing for the maximum control. When an event where control loads are exceeded is over, a one-way check valve allows fluid to flow back into the original chamber. Additionally, low k-value springs aid in the recovery of the system. A diagram demonstrating this key concept can be seen below in Figure 20.

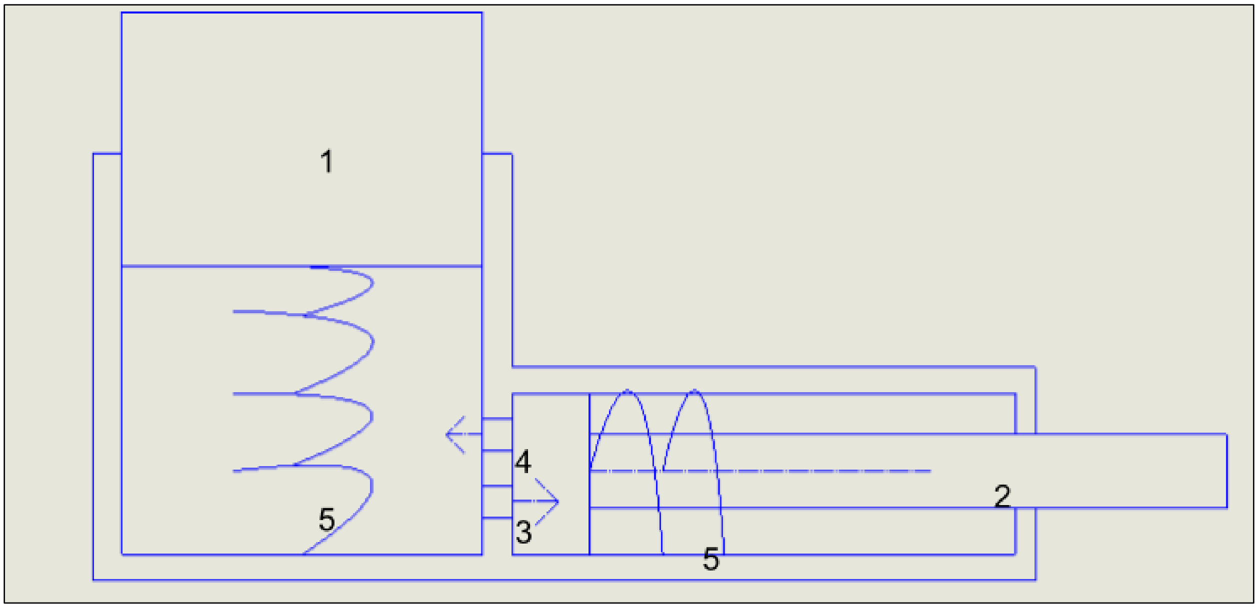

Figure 20: Diagram of piston displacement mechanism

1. Primary Piston- where the loads are applied
2. Secondary Chamber- where fluid is displaced
3. Direct Acting Relief Valve- allows fluid to flow from primary chamber to secondary chamber only after a preset pressure is reached.
4. One-Way Check Valve- allows fluid to return to the primary chamber when the pressure in the secondary chamber exceeds that of the primary chamber.
5. Return Mechanisms- weak springs that have little to effect on the compression of the primary piston but aid in the recovery of the system after the load is removed.

In Figures 21 and 22 below, an example of an integrated design is presented. The figures show the lateral response mechanism but it is important to note that the piston-cylinder design could also be integrated for the vertical displacement device with similar ease.

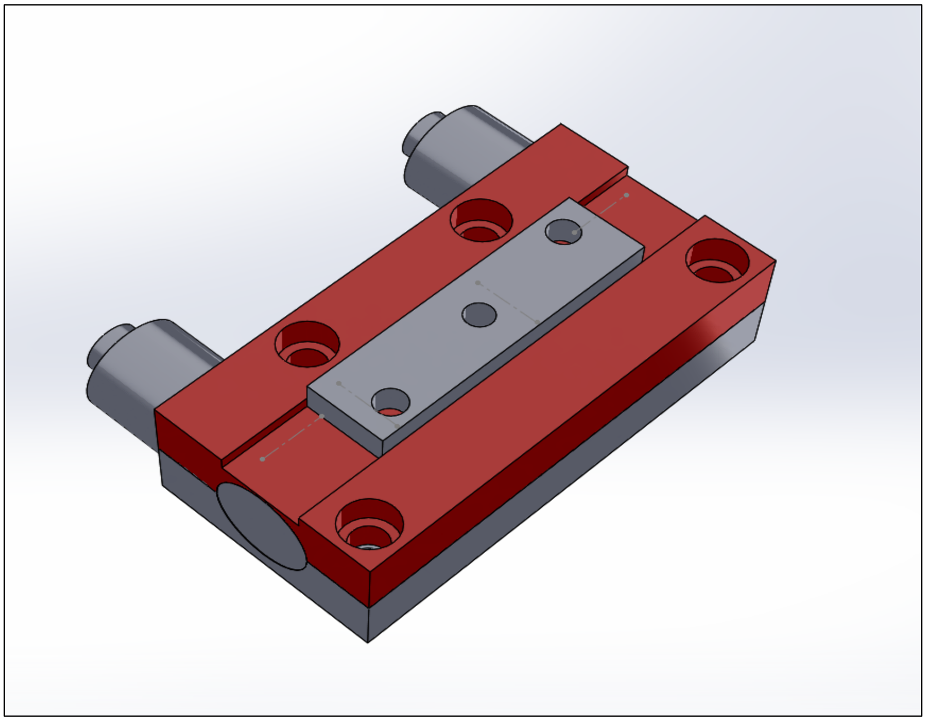

Figure 21: Lateral response piston mechanism

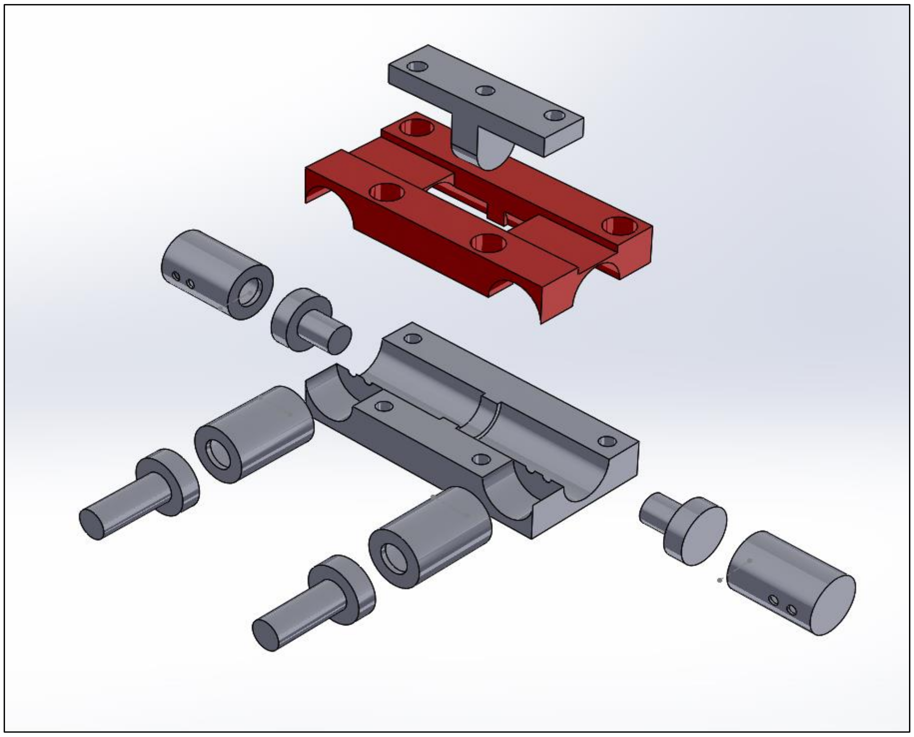

Figure 22: Exploded view of lateral response piston mechanism

Because this design mostly followed the FR-DP relationships for the the primary design, the pistons and chambers were easily integrated with the original design's parts and dimensions. The preloaded springs used in the primary design are simply swapped out in the design above. This design could then house either oil (hydraulic) or air (pneumatic). This means that structurally, the design is the same. The primary differences lies in the way in which an incompressible fluid (hydraulic oil) versus a compressible fluid (air) reacts to load being placed on it. Additionally, the two differ in viscosity as well as their specific heat. The significance and calculations of each of these differences can be found in the following sections.

3.2.2 Hydraulic Analysis

The hydraulic adaptation of this design uses an incompressible liquid in the piston chambers. Because hydraulic fluid cannot be compressed, there is no displacement of the primary piston when loads are within the control range. While a lack of displacement would maximize the ski's responsiveness to an input load from the skier, one downside to this is that this means the binding lacks absorption. Without the ability to absorb repetitive, small vibrations, the onset of muscle fatigue is catalyzed. As discussed in section 1.2.2, this increases the risk of injury. After control loads are exceeded, the binding would then have a direct relationship between load and displacement. The simplified associated load versus displacement graph can be seen below in Figure 23.

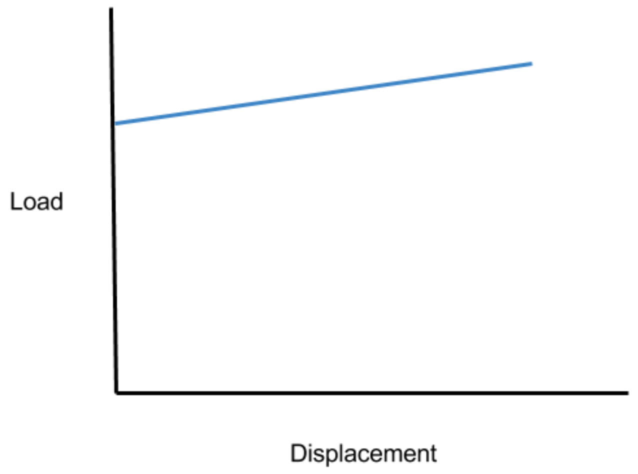

Figure 23: A basic load vs. displacement curve for the hydraulic (incompressible fluid) application

Flow Rate Calculations

In this section, calculations were presented that are needed to verify hydraulic oil could flow through the relief valve at a high enough rate to allow the binding to displace when sufficiently high loads.

Based on Poiseuille’s Law, the volume flow rate, F is given by the equation:

$$F = (\Delta P r^4)/8(\square L)$$

Where $\Delta P$is the pressure difference between both sides, r is the radius of the opening, ▯is the viscosity, and L is the length of the pipe.

Because our project was theory based, the precise threshold for control loads and injurious loads were not determined. Therefore, several estimates were made regarding the appropriate values and the calculations made in this section rely on the accuracy of those estimates. These can be found in Appendix E. Additionally, the relief valve seat might result in non laminar flow through the valve. If this is the case, a more in-depth analysis of the flow rate is necessary. Because of this, it is recommended that a future MPQ further investigate both the actual control and injurious load levels and the flow through the valves. From there, more precise calculations could be made to verify the viability of a hydraulic response mechanism.

Thermal Calculations

In this section, formulas were presented that are needed to verify that the selected ISO Grade 10 hydraulic oil could operate at various temperatures ranging from -33^{o} C to 32^{o} C. Based on background research, the viscosity of hydraulic oil increases exponentially as temperatures decrease. This is a significant concern and it is recommended further analysis be performed regarding the viability of a hydraulic based design. This can be seen below in Figure 24.

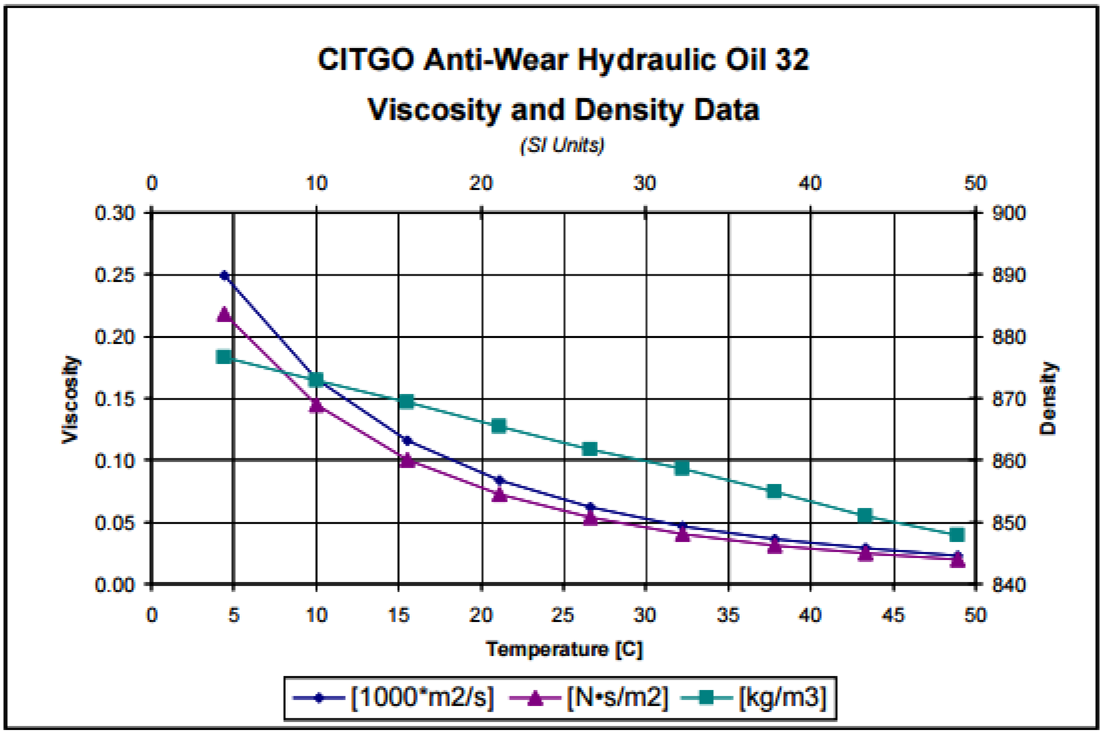

Figure 24: A graph demonstrating how viscosity and density are affected by the temperature

3.2.3 Pneumatic Analysis

The pneumatic adaptation of this design uses a compressible gas in the piston chambers. Because this gas can be compressed, there is displacement of the primary piston during the control phase. This displacement is kept relatively low so that control of the ski can be maintained while also offering some absorption. The simplified associated load versus displacement graph can be seen below in Figure 25.

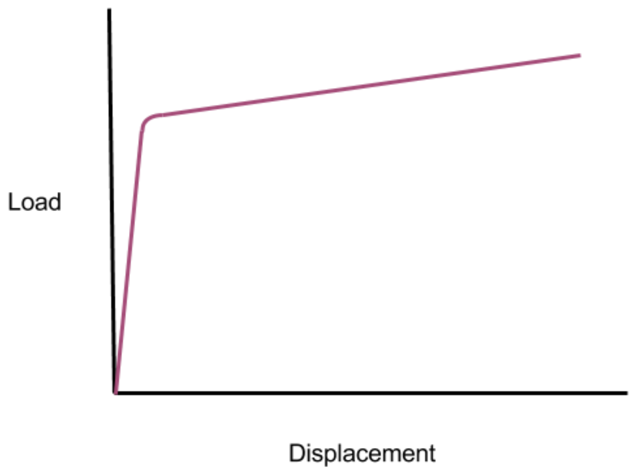

Figure 25: A basic load vs. displacement curve for the pneumatic application

The advantages of the pneumatic application are clear:

- the control phase displacement allows for absorption
- the fluid flow rate is not of concern
- the air pressure within the chamber can be adjusted even if environmental factors affect it.

3.2.5 Concepts to be Explored

Further analysis on the real-world application of these designs is necessary. This section discuss possible avenues of research. First, the leaking of gas or liquid would pose as significant issue to the performance and proper operation of the binding. Additionally, the concept of using the force a skier's body exerts on the ski while skiing to re-pressurize the system was discussed. The binding would then stop pressurization after the desired pressure is reached. In conclusion, much work is still to be done in order to bring these designs to production. However, the key takeaway from these analyses is that the hydraulic and especially the pneumatic applications are workable.

4 Thoughts and Reflections

4.1 Project Challenges

4.1.1 The Axiomatic Approach to Design

Understanding Axiomatic Design (AD) turned out to be both simple and complex at the same time. The primary to axioms were simple and quite useful in the process of working on this MQP. Axiom 1 states that functions should be decoupled. This really drove a lot of the thought process and changed the way that we approached the problem. It forced a need to understand the problem on a much more basic level. While certain things (like the clamp discussed in matrix section of this report) could not be decoupled, a lot of things could. The decoupling creates two major unique features in our final designs. The first feature is that if one part fails most of the functions will continue to work. If, for example, the horizontal response at the toe becomes packed or blocked in some way the binding can still respond vertically, rotate about the toes, and respond to flex in the ski. The second is that the binding can now respond to many more types of impact than a conventional binding. Axiom 2 states that the system should be kept as simple as possible. This one is a little more familiar to standard engineering thought, the less moving parts the less chances for failure. This concept helped us a great deal particularly in the selection process discussed later in the discussion.

While understanding the axioms of AD was rather simple and really useful, the full and rigorous application of AD was a different story. Using Acclaro, we had to take a high level functional requirement (FR) and break it down into simpler FRs that added up the original (process described in more detail in the Acclaro section of the report). This process seems simple but proved to be a large challenge to do without thinking ahead to a final product. Internally we all knew that we needed a release, but could we just say that a release was needed? No, we could not, we needed an FR, well what FR do we need to have so that we get a release. All these thoughts and questions would come up and then someone would point out that we aren’t being axiomatic and we would have to go back to the FR and trust that a release would come in naturally. Even this was probably not the purest of axiomatic processes since we should have (in theory) not even assumed that a release was needed. However, such a high level of axiomatic reasoning is still something we haven’t perfected. Aside from this, there are a few notable mistakes that we made that wasted hours of our time. They will be listed under small headers now describing the problem and how to address it.

4.1.2 Upper Level DP-Lower Level FR Interaction

It took us weeks of debating about the Acclaro and reviewing videos to finally discover one simple fact: high level Design Parameters (DPs) can affect low level FRs. At first we thought that it was a very linear process, take your high level FR0 and break it down till it is in its simplest components then begin to fill in the appropriate DPs after the fact. This simply doesn’t work as advertised. The DP created as a result of an FR can give guidance and requirements to the children of the FR. This little bit of back and forth in the thought process allowed us to generate a more detailed and accurate Acclaro in one weekend than we had achieved in the past month.

4.1.3 DP-DP Coupling

One problem that we had a lot of trouble with was the dimensions of objects. We were able to get all of the Acclaro down to specific parts that completed specific tasks to fulfill the needs of the FRs however, the size of these objects was an issue. An example of this is that we were able to define the need for a cord to trigger a release. However, the length of this cord depends on the height of the vertical and horizontal release; the placement on the vertical release, in turn, depended on the ratio of downward and upward response desired. Additionally, the size of both the vertical and horizontal release depended on materials, but materials depended on strength and deflection, which in turn depends on size. Such circular and interconnected dependency on dimensioning and materials was difficult to represent in Acclaro and we could not find a way for the FRs to tell us what to select. If a wide, weak spring provided the same effect as a narrow, strong spring, there seemed no way to use the FRs to select between the two. For this we ended up having to resort to a weighted decision matrix.

4.2 Weighted Decision Matrix

To resolve the issue of circular dependency of dimensions and materials, we used a weighted decision matrix. To create the decision matrix we took major criteria and weighted them on a 0-20 scale. We set the most important thing to a weight of 20 and made everything else a percent of that based on how we thought the importance matched up. For example dependability (safety and lifecycle) was our most important criteria so we gave that a weight of 20, manufacturability we valued at only half of that so we gave that a weight of 10. Total criteria and weights were, dependability (20), ease of use (12), manufacturing (10), compatibility (8), and cost (1). In addition to this, we had two pass/fail criteria which were 1) meets FRs, and 2) durability. If it didn't meet the FR or would break after a few impacts then the design was an instant fail regardless of how it would have scored in the other criteria. The grading matrix and results can be found in Appendix C.

5 Conclusion

ACL and Tibial plateau injuries can be incredibly serious, requiring invasive surgery and long rehabilitation times. Current ski bindings do not do enough to reduce the risk of these injuries. During the duration of this project Axiomatic Design was used to create a binding which allows for lateral and vertical displacement at both the toe and heel simultaneously. The binding also addresses and solves the very dangerous problem of inadvertent release. Our team makes the following eight claims about the binding in order to successfully fulfill the desired project objectives:

1. Provides vertical displacement, between the boot and ski, below injury thresholds, to reduce the risk of tibial plateau and ACL injuries due to BIAD (Boot Induced Anterior Drawer).
2. Provides absorptive lateral displacement, between the boot and ski, at both the heel and toe, below injury thresholds, to reduce the risk of ACL injuries by CVIR (Combined Valgus Inward Rotation) and reduce the risk of inadvertent release.
3. Provides relative displacement between the boot and the ski in the binding under protected interfaces rather than at the boot-binding interfaces that are subject to contamination.
4. Provides 4 stages of adjustable load displacement relationships:
    1) High frequency, low amplitude absorption for fatigue reduction
    2) High fidelity load transmission for control at moderate and low frequencies

    3) Displacement with near constant load below injury threshold and above normal control loads
    4) Release at a threshold of displacement and recover displacement below the threshold

5. Decouples directional displacement, allowing for simultaneous response to vertical and horizontal loads in addition to accommodating bending of the ski.
6. Accommodates ski flex by allowing displacement between binding and ski along the ski, while gripping toe and heel of boot firmly to prevent inadvertent release due to chatter-out.
7. Provides two states, maintaining a firm grip on the boot at the toe and heel until release conditions are met.
8. Provides adjustable conditions for displacement that will trigger release while also providing separate adjustment for maximum loads.

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Appendix A: Figure Analysis

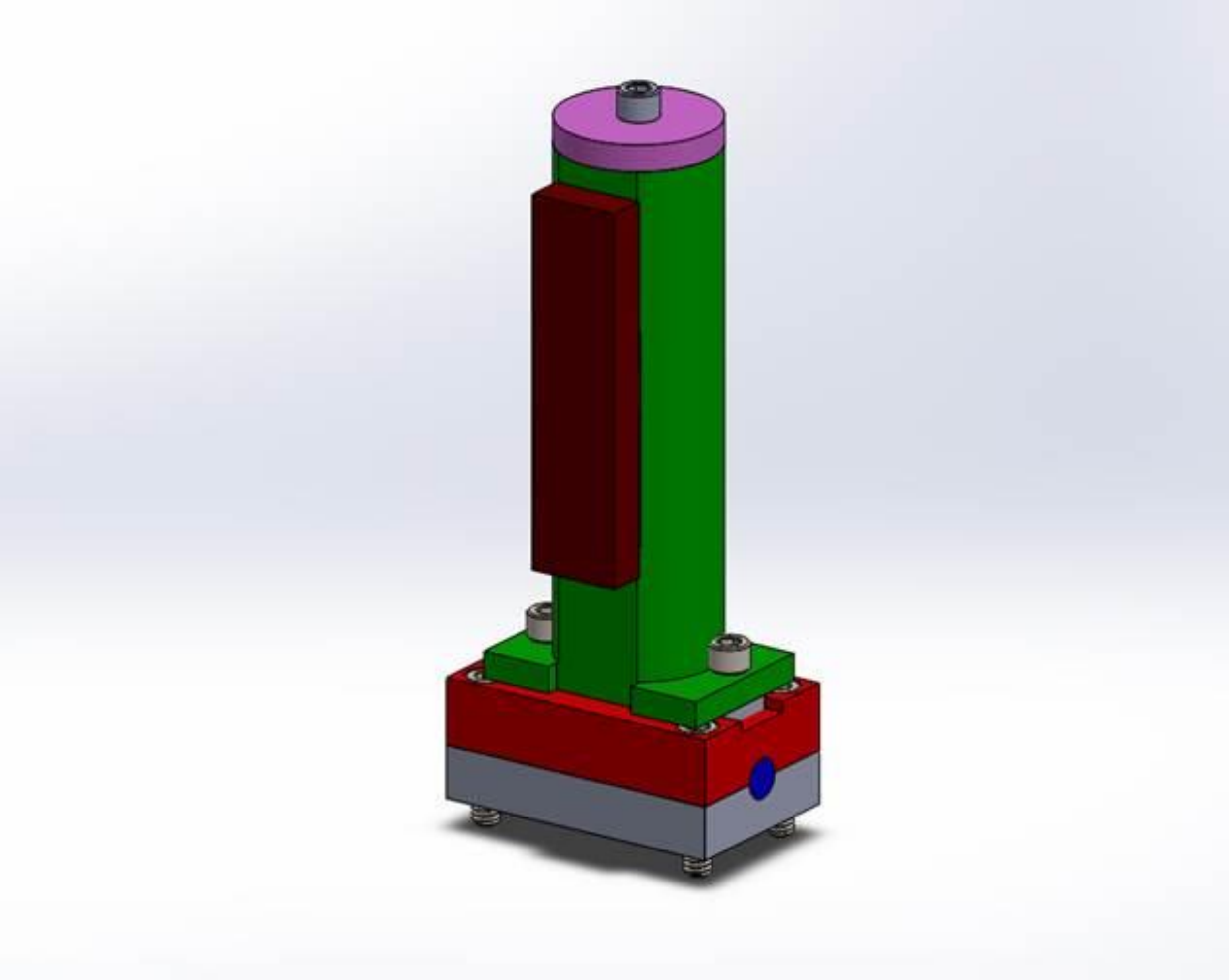


Figure 1: Neutral State of Response Tower

This is the binding response tower that allows for the vertical and horizontal displacement of the boot with respect to the ski. The response tower is also responsible for triggering the release. The dark red piece is where the boot binding interface would connect. The blue shaft holds springs in place and guides displacement left to right. The 4 screws running though the red and grey plates attach to the ski. The two through the green plate attach to a slider that rides along the blue rod. The Grey rod in the center of the purple plate extends through the design to a plate at the base. This rod holds the vertical springs in place, assists in guiding the vertical motion, and (in junction with the plate) assists in transferring control moments through the system.

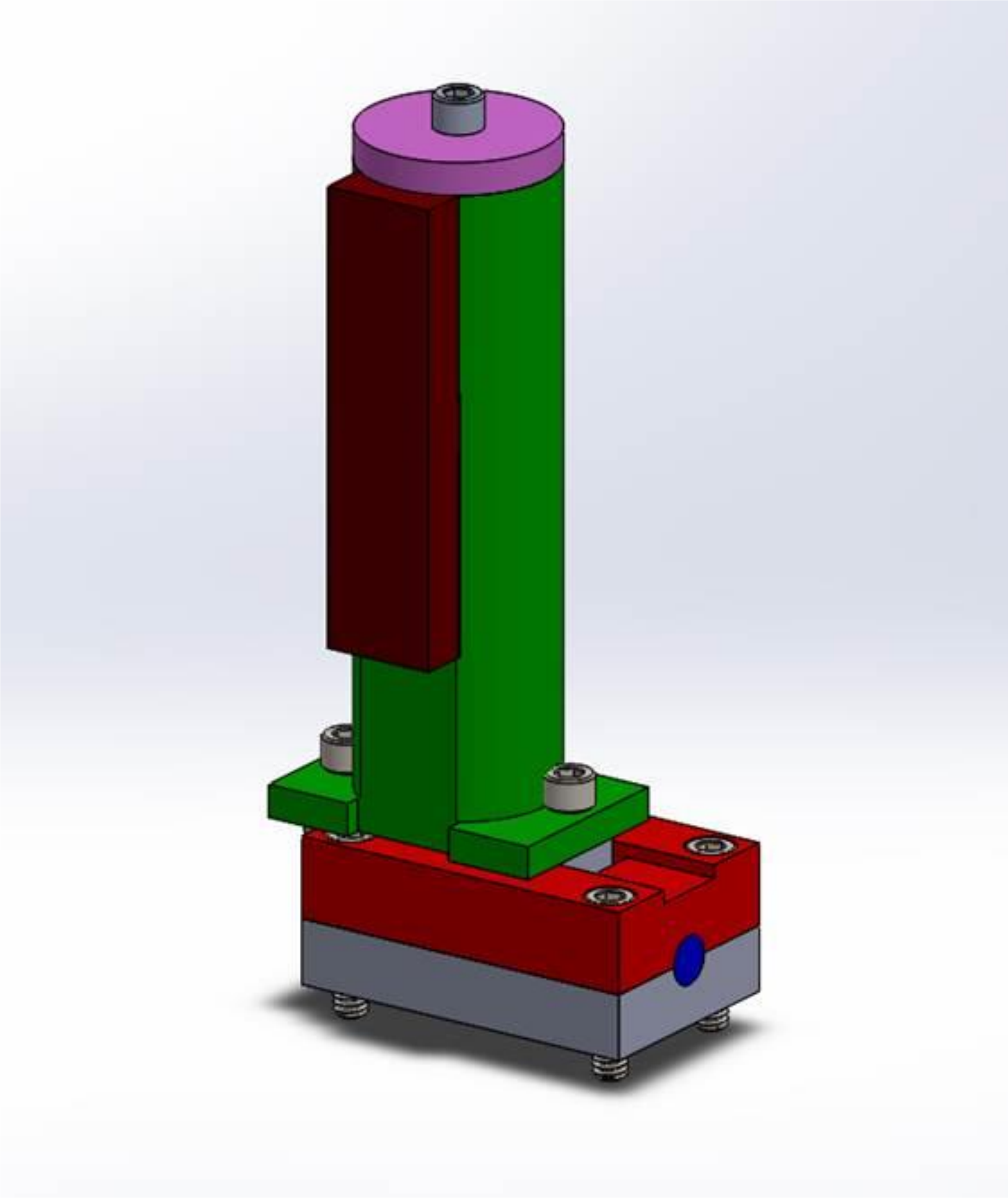


Figure 2: Extreme response to the left and up

In this photo, the binding has been shifted all to the extreme in the left x-direction and the positive z- direction. Reaching either extreme would trigger a release.

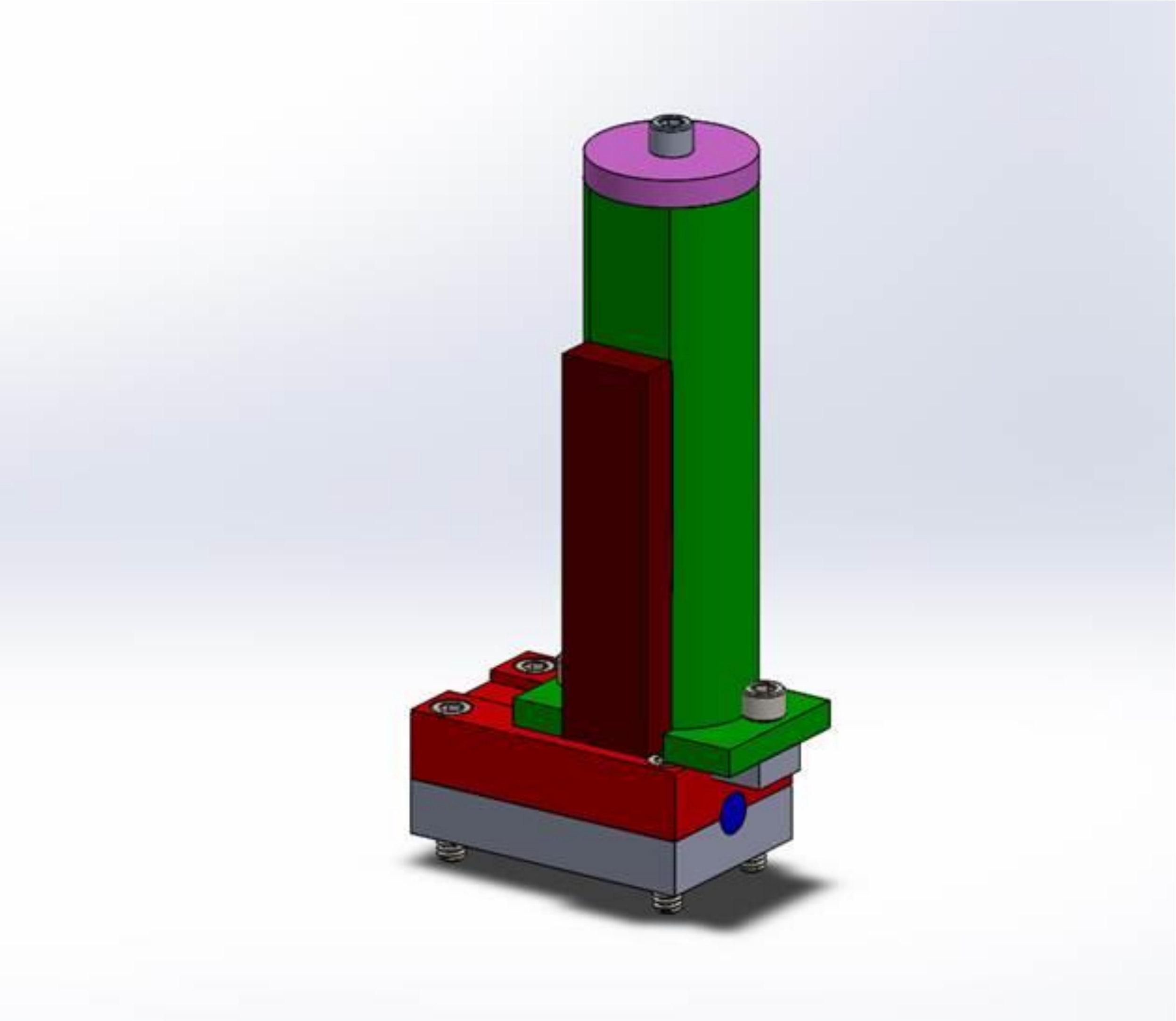


Figure 3: Extreme response to the right and down

In this photo, the device has been shifted to the opposite extremes. The horizontal displacement would trigger a release, vertical would not.

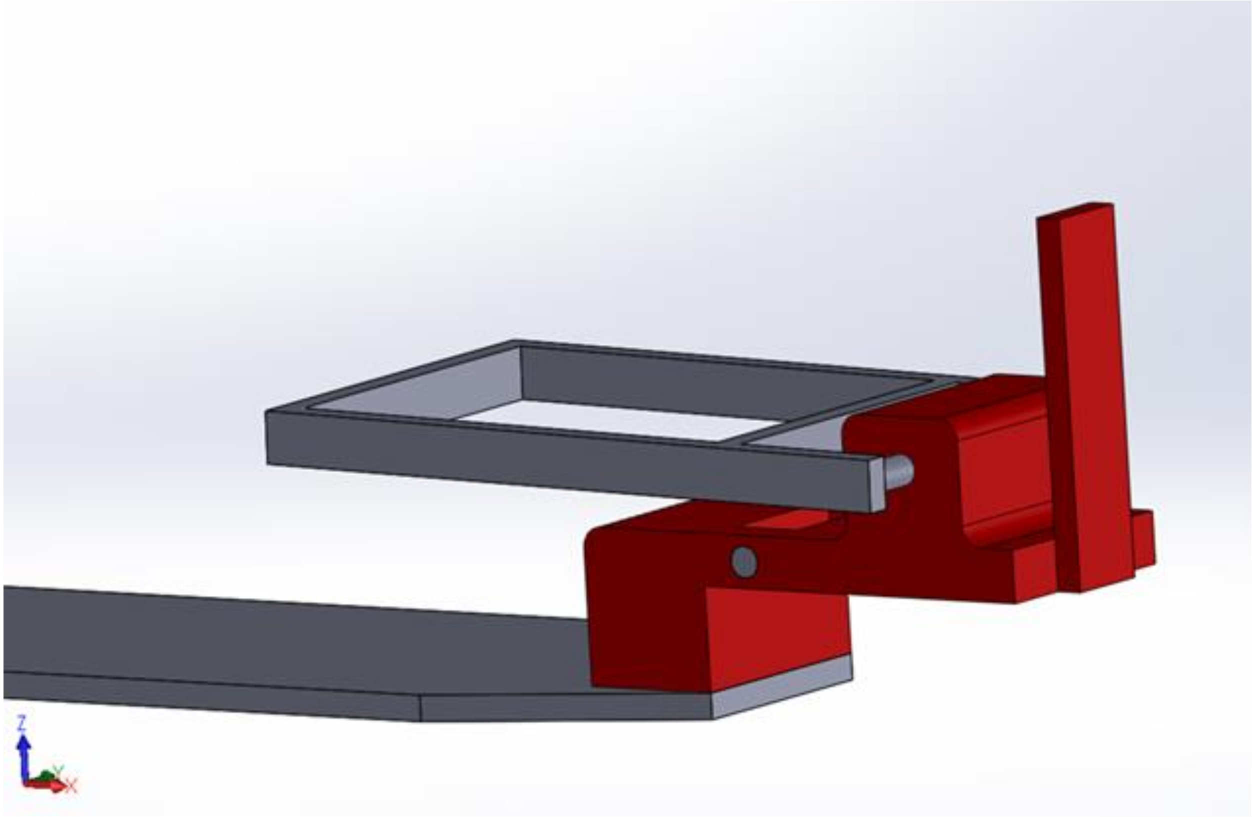
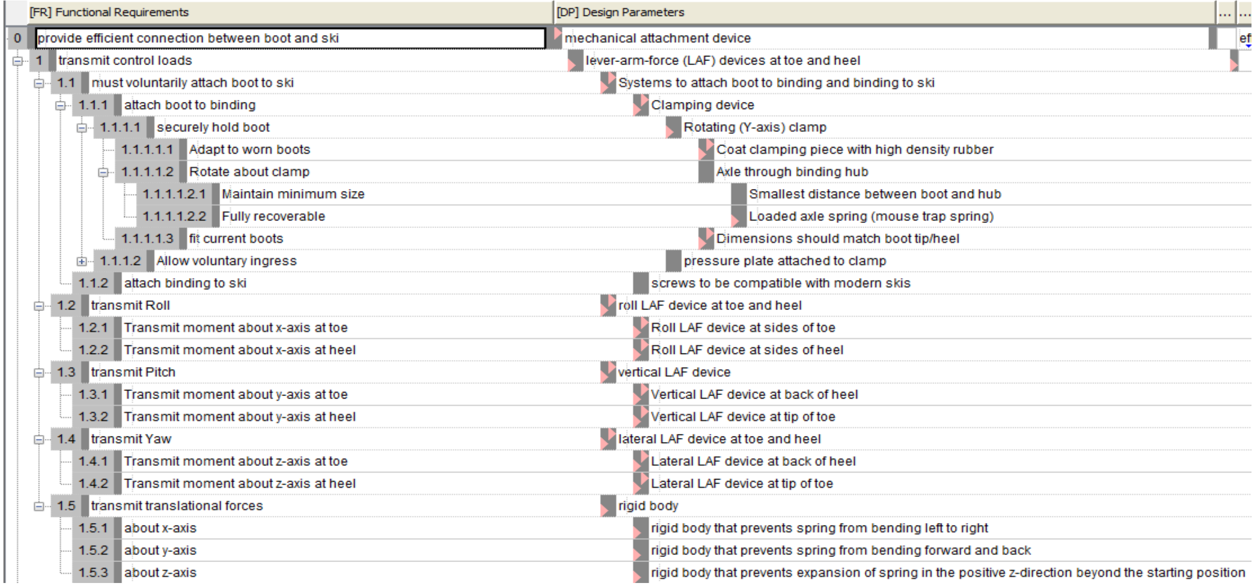


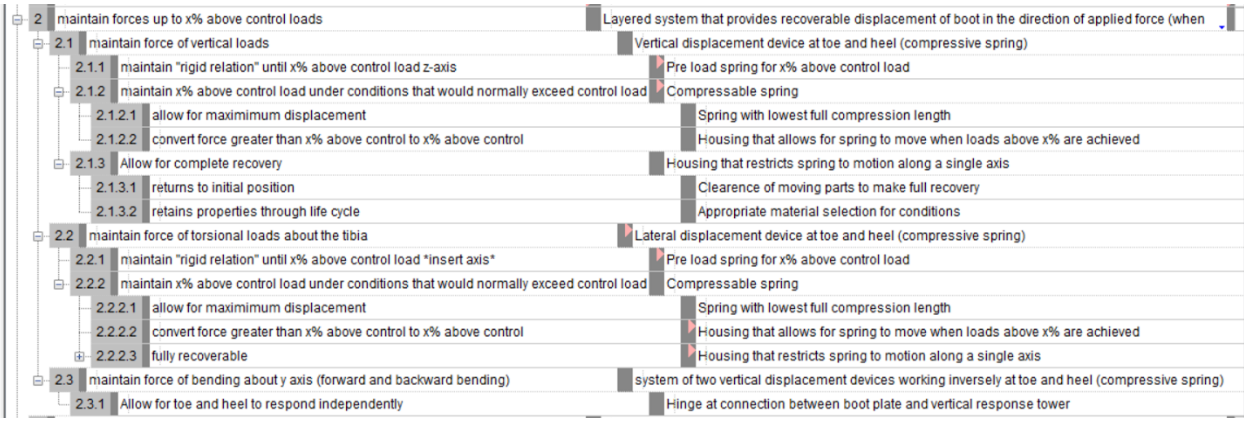
Figure 4: Location of response tower to rest of binding

The vertical red bar is the same as the dark red bar from the response tower. The Boot would be clamped between the plate and the grey bar (will be form fitting, this is rough model).

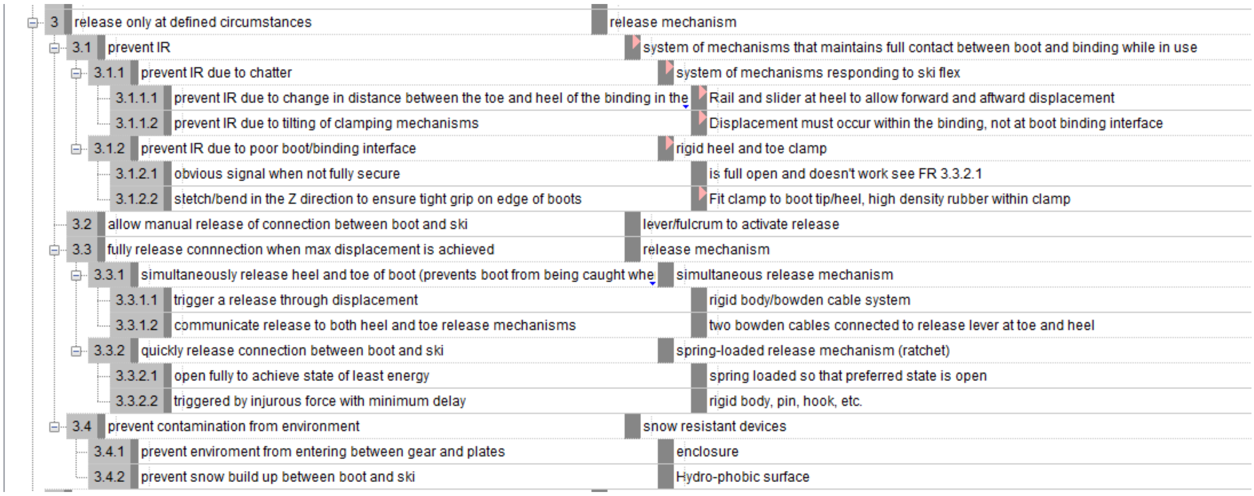
Appendix B: Full Acclaro Decomposition



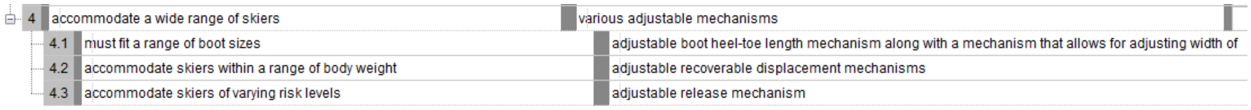
	[FR] Functional Requirements	[DP] Design Parameters	...	...
0	provide efficient connection between boot and ski	mechanical attachment device		ef
1	transmit control loads	lever-arm-force (LAF) devices at toe and heel		
1.1	must voluntarily attach boot to ski	Systems to attach boot to binding and binding to ski		
1.1.1	attach boot to binding	Clamping device		
1.1.1.1	securely hold boot	Rotating (Y-axis) clamp		
1.1.1.1.1	Adapt to worn boots	Coat clamping piece with high density rubber		
1.1.1.1.2	Rotate about clamp	Axle through binding hub		
1.1.1.1.2.1	Maintain minimum size	Smallest distance between boot and hub		
1.1.1.1.2.2	Fully recoverable	Loaded axle spring (mouse trap spring)		
1.1.1.1.3	fit current boots	Dimensions should match boot tip/heel		
1.1.1.2	Allow voluntary ingress	pressure plate attached to clamp		
1.1.2	attach binding to ski	screws to be compatible with modern skis		
1.2	transmit Roll	roll LAF device at toe and heel		
1.2.1	Transmit moment about x-axis at toe	Roll LAF device at sides of toe		
1.2.2	Transmit moment about x-axis at heel	Roll LAF device at sides of heel		
1.3	transmit Pitch	vertical LAF device		
1.3.1	Transmit moment about y-axis at toe	Vertical LAF device at back of heel		
1.3.2	Transmit moment about y-axis at heel	Vertical LAF device at tip of toe		
1.4	transmit Yaw	lateral LAF device at toe and heel		
1.4.1	Transmit moment about z-axis at toe	Lateral LAF device at back of heel		
1.4.2	Transmit moment about z-axis at heel	Lateral LAF device at tip of toe		
1.5	transmit translational forces	rigid body		
1.5.1	about x-axis	rigid body that prevents spring from bending left to right		
1.5.2	about y-axis	rigid body that prevents spring from bending forward and back		
1.5.3	about z-axis	rigid body that prevents expansion of spring in the positive z-direction beyond the starting position		



2	maintain forces up to x% above control loads	Layered system that provides recoverable displacement of boot in the direction of applied force (when
2.1	maintain force of vertical loads	Vertical displacement device at toe and heel (compressive spring)
2.1.1	maintain "rigid relation" until x% above control load z-axis	Pre load spring for x% above control load
2.1.2	maintain x% above control load under conditions that would normally exceed control load	Compressable spring
2.1.2.1	allow for maximimum displacement	Spring with lowest full compression length
2.1.2.2	convert force greater than x% above control to x% above control	Housing that allows for spring to move when loads above x% are achieved
2.1.3	Allow for complete recovery	Housing that restricts spring to motion along a single axis
2.1.3.1	returns to initial position	Clearence of moving parts to make full recovery
2.1.3.2	retains properties through life cycle	Appropriate material selection for conditions
2.2	maintain force of torsional loads about the tibia	Lateral displacement device at toe and heel (compressive spring)
2.2.1	maintain "rigid relation" until x% above control load *insert axis*	Pre load spring for x% above control load
2.2.2	maintain x% above control load under conditions that would normally exceed control load	Compressable spring
2.2.2.1	allow for maximimum displacement	Spring with lowest full compression length
2.2.2.2	convert force greater than x% above control to x% above control	Housing that allows for spring to move when loads above x% are achieved
2.2.2.3	fully recoverable	Housing that restricts spring to motion along a single axis
2.3	maintain force of bending about y axis (forward and backward bending)	system of two vertical displacement devices working inversely at toe and heel (compressive spring)
2.3.1	Allow for toe and heel to respond independently	Hinge at connection between boot plate and vertical response tower

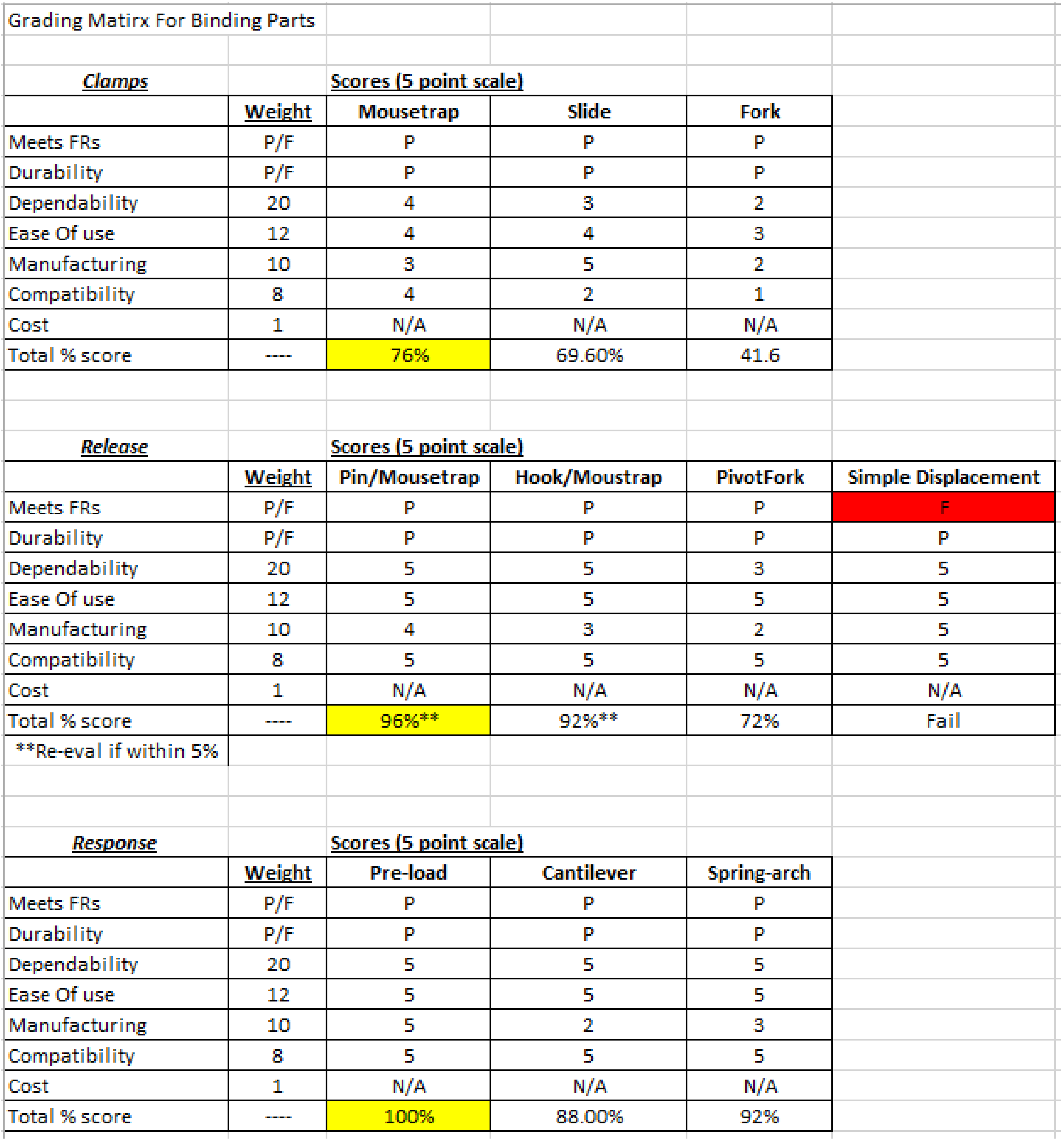


3	release only at defined circumstances	release mechanism
3.1	prevent IR	system of mechanisms that maintains full contact between boot and binding while in use
3.1.1	prevent IR due to chatter	system of mechanisms responding to ski flex
3.1.1.1	prevent IR due to change in distance between the toe and heel of the binding in the	Rail and slider at heel to allow forward and afward displacement
3.1.1.2	prevent IR due to tilting of clamping mechanisms	Displacement must occur within the binding, not at boot binding interface
3.1.2	prevent IR due to poor boot/binding interface	rigid heel and toe clamp
3.1.2.1	obvious signal when not fully secure	is full open and doesn't work see FR 3.3.2.1
3.1.2.2	stetch/bend in the Z direction to ensure tight grip on edge of boots	Fit clamp to boot tip/heel, high density rubber within clamp
3.2	allow manual release of connection between boot and ski	lever/fulcrum to activate release
3.3	fully release connnection when max displacement is achieved	release mechanism
3.3.1	simultaneously release heel and toe of boot (prevents boot from being caught whe	simultaneous release mechanism
3.3.1.1	trigger a release through displacement	rigid body/bowden cable system
3.3.1.2	communicate release to both heel and toe release mechanisms	two bowden cables connected to release lever at toe and heel
3.3.2	quickly release connection between boot and ski	spring-loaded release mechanism (ratchet)
3.3.2.1	open fully to achieve state of least energy	spring loaded so that preferred state is open
3.3.2.2	triggered by injurous force with minimum delay	rigid body, pin, hook, etc.
3.4	prevent contamination from environment	snow resistant devices
3.4.1	prevent enviroment from entering between gear and plates	enclosure
3.4.2	prevent snow build up between boot and ski	Hydro-phobic surface



4	accommodate a wide range of skiers	various adjustable mechanisms
4.1	must fit a range of boot sizes	adjustable boot heel-toe length mechanism along with a mechanism that allows for adjusting width of
4.2	accommodate skiers within a range of body weight	adjustable recoverable displacement mechanisms
4.3	accommodate skiers of varying risk levels	adjustable release mechanism

Appendix C: Decision Matrix



Grading Matirx For Binding Parts

Clamps		Scores (5 point scale)		
	Weight	**Mousetrap**	**Slide**	**Fork**
Meets FRs	P/F	P	P	P
Durability	P/F	P	P	P
Dependability	20	4	3	2
Ease Of use	12	4	4	3
Manufacturing	10	3	5	2
Compatibility	8	4	2	1
Cost	1	N/A	N/A	N/A
Total % score	----	76%	69.60%	41.6

Release		Scores (5 point scale)			
	Weight	**Pin/Mousetrap**	**Hook/Moustrap**	**PivotFork**	**Simple Displacement**
Meets FRs	P/F	P	P	P	F
Durability	P/F	P	P	P	P
Dependability	20	5	5	3	5
Ease Of use	12	5	5	5	5
Manufacturing	10	4	3	2	5
Compatibility	8	5	5	5	5
Cost	1	N/A	N/A	N/A	N/A
Total % score	----	96%**	92%**	72%	Fail

**Re-eval if within 5%

Response		Scores (5 point scale)		
	Weight	**Pre-load**	**Cantilever**	**Spring-arch**
Meets FRs	P/F	P	P	P
Durability	P/F	P	P	P
Dependability	20	5	5	5
Ease Of use	12	5	5	5
Manufacturing	10	5	2	3
Compatibility	8	5	5	5
Cost	1	N/A	N/A	N/A
Total % score	----	100%	88.00%	92%

Appendix D: Hydraulic Assumptions and Calculations

General Assumptions

- Because the spring selected for this design was rated to be 31.3 lbs, the assumption was made that the cracking pressure of the relief valve would be set to 70 PSI (the force over the area of the .75in diameter primary piston).
- Based on the dimensions of the cylinder, the capacity of the cylinder, or volume required for full displacement, was calculated. This was found to be $9.56*10^{-4}$ gallons.
- An assumption was made for how quickly the binding would need to release. This was stated to be 0.1s.
- Based on this, we know that the required flow rate must be able to achieve the maximum of $9.56*10^{-4}$ gallons within 0.1s. This equates to a flow rate of 0.57 GPM.

Hydraulic

- The flow rate above was then tested against the equation $F = (\Delta P r^4)/8(\mu L)$
- Assuming ΔP= 70 PSI, r = 0.375in., μ= 10 N*s/m^2, and L=1in.
- In order to determine how viscosity is affected by temperature, the Sutherland Equation is used.
    - $u = (b * T^{3/2})/(T + S)$
    - where b and s are constants and T is temperature. For air b=1.456*10^-6 kg/(m*s*K$^{3/2}$) and S=110.4K