DESIGN AND PROTOTYPE OF AN UNDER-BINDING PLATE TO REDUCE ACL INJURY

A Major Qualifying Project Report

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Abstract

The objective of this project is to design, produce, and test an under-binding ski plate which minimizes the risk of ACL injury due to the two main mechanisms of ACL injury in Alpine skiers; phantom foot and boot induced anterior drawer (BIAD). These two mechanisms of injury have yet to be addressed by a single ski binding design. Our final prototype is designed to absorb loads prior to the injury threshold.

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1   Introduction

1.1   Objective

The objective of this project is to design, produce a prototype, and test an under-binding ski plate which reduces the risk of ACL injury.

1.2   Rationale

A fifteen year study conducted from 1972 to 1987 showed that of all modes of severe injury only those related to the ACL had a statistically significant increase. This study recorded a 172% increase in reported ACL injuries; an increase from 3% to 16% of total reported injuries (Johnson, Ettlinger, & Shealy, 1989). A series of studies performed by the Norwegian Ski Lift Association over 10 seasons from 1996 to 2008 found an average of 26% of all reported injuries occurred at the knee. (Ekeland, A. and Rødven, A., 2001, 2003, 2006, 2010) (Ekeland, A. Rødven, A. and Sulheim, S., 2005)

These studies illustrate the need of greater knee protection in alpine skiing. This project focuses on the two main mechanisms of ACL injury suffered by alpine skiers; phantom foot and Boot Induced Anterior Drawer (BIAD), in order to facilitate injury reduction. A full description of these injury mechanisms can be found in Appendix A.

1.3   State of the Art

Research conducted found that few alpine ski bindings have been designed with the explicit purpose of reducing ACL injuries and those that have concentrate on reducing injuries caused by a specific mechanism of injury. The Pivogy™ and the Kneebinding™ are two examples of a binding designed to address the mechanisms of injury that comprise phantom foot

(Dodge, 2001; Howell, 2005). The Pivogy™, seen in Figure 1, uses a set of pivots located at the heel and toe to allow for the lateral release of the binding from either pivot. This allows eliminates the rotational shear loading that is in part responsible for a phantom foot injury.

Figure 1: Line Pivogy binding

The design of the Lange RRS ski boot enables it to prevent the BIAD mechanism of injury. The Lange RRS acts as a rigid boot during normal use. However, when a certain load toward the back of the boot is reached a device will disengage and allow the boot to flex much more significantly. This rearward flexing can save the ACL during a landing that would normally result in a BIAD injury.

A prototype designed by Wunderly and Hull is similar in design to the prototype proposed in this MQP, though with a difference in design intent (Wunderly and Hall, 1989). The Wunderly-Hull prototype allows for binding release before injurious loads can result in tibia

fracture. This is achieved mechanically by a double pivot and a cam-follower system of a prescribed curvature.

1.4   Approach

Current technology protects the skier from either BIAD or phantom foot. An axiomatic design process was used to develop a binding composed of decoupled features that act to absorb injurious loads in the lateral and vertical directions.

Axiomatic design promotes design simplicity by breaking down customer requirements into independent (decoupled) functional requirements that are met by equally decoupled design parameters. This design method ensures that every part in the prototype serves a distinct purpose, which eliminates complexity, non-value iterations, and time spent on design and machining.

The vertical absorption of loads was necessary to address the BIAD method of injury. To mechanically absorb these loads the top plate was allowed to rotate about a bi-directional joint located under the toe; moving vertically at the heel. This motion was constrained by a finger-follower system so that the top plate can only descend at the heel. This constraint allows the skier to maintain control while eliminating the biggest factor in a BIAD event.

A lateral load absorption system was also necessary for the prototype to successfully address phantom foot. The top plate was allowed to rotate laterally on the same bi-directional joint as the vertical system in order to achieve this. This motion was constrained was also constrained by the finger follower system.

2   Design Decomposition

FR Number	Functional Requirement	DP Number	Design Parameter
FR 0	Protect the knee from ACL injuries during skiing	DP 0	A mechanical system which displaces appropriately

The primary functional requirement of the prototype is to protect the knee from ACL Injuries sustained during skiing. This is designated as FR 0 according to axiomatic design nomenclature and is broken down into the four "child" functional requirements presented below. Each "child" functional requirement is fulfilled by a specific part of the prototype. The coordinate system used in this decomposition can be seen in Figure 2 below.
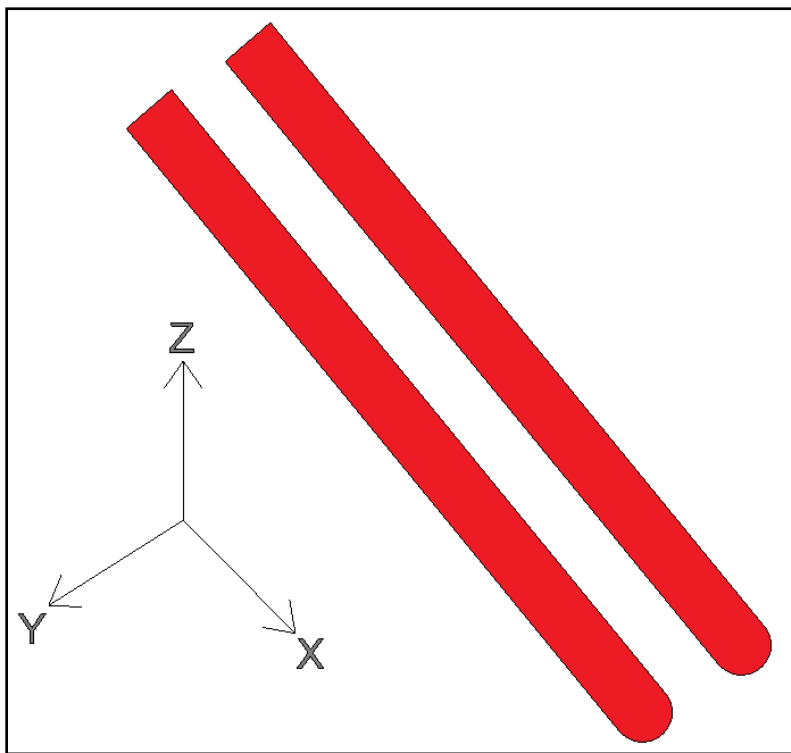
Figure 2: Coordinate System

2.1 FR 1: Provide an Interface Between Binding and Ski

FR Number	Functional Requirement	DP Number	Design Parameter
FR 1	Provide an interface between binding and ski	**DP 1**	A mechanical system which displaces appropriately
FR 1.1	Transfer loads from binding to top plate	**DP 1.1**	Screws attaching binding to top plate
FR 1.2	Transfer loads from top plate to base	**DP 1.2**	Bi-directional joint at the front of binding
FR 1.3	Transfer loads from base to ski	**DP 1.3**	Screws connecting prototype to ski

The prototype must act as an interface between a conventional ski binding and the ski itself. This requirement defines the prototype as a plate. FR 1 can be broken down into three "child" functional requirements. FR 1.1 is fulfilled mechanically by connecting a conventional binding to the top plate with three screws located at the toe and four at the heel. FR 1.2 is fulfilled through the bi-directional joint located under the toe, seen below in Figure 3.
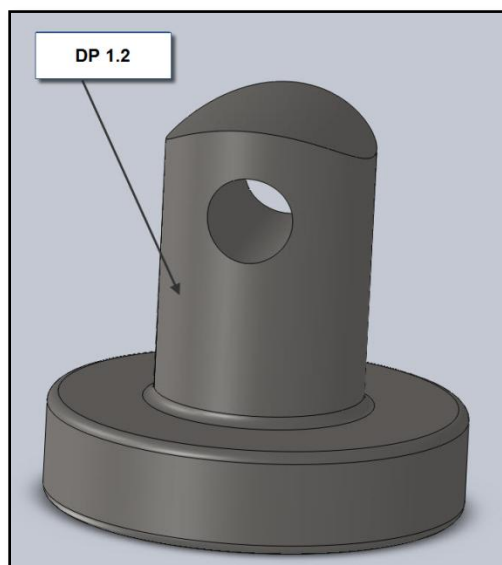
Figure 3: Bi-directional Joint

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FR 1.3 is fulfilled by the three different parts that are fastened to the ski itself through a set of twelve screws. The first of these parts is the bi-directional joint holder, seen in Figure 4 below. This part secures the bi-directional joint to the ski while allowing it to rotate about the z-axis.
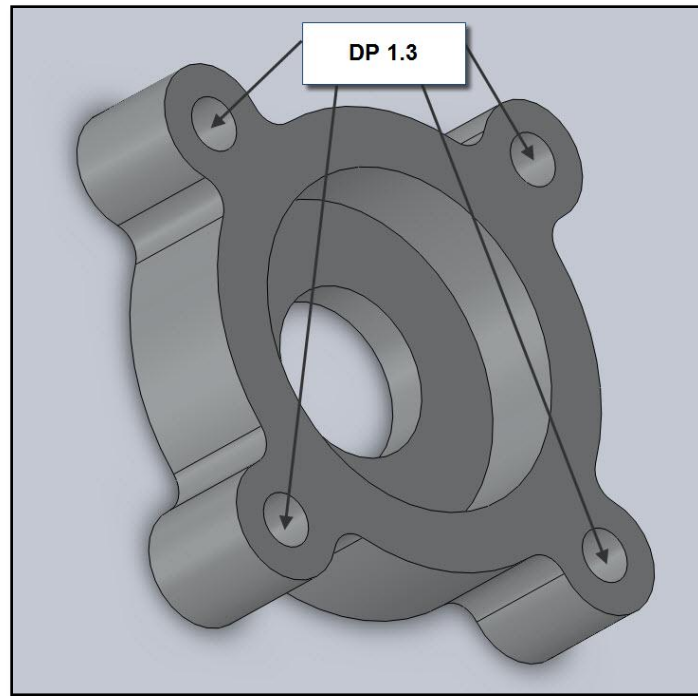
Figure 4: Bi-directional Joint Holder

The second part necessary for the transmission of loads to the ski is the leaf spring holder, seen below in Figure 5. This part was designed to allow the leaf spring to bend under 950 N while securely holding it in place. The four screws used to secure the leaf spring holder to the ski help satisfy FR 1.3 by transmitting loads to the ski.
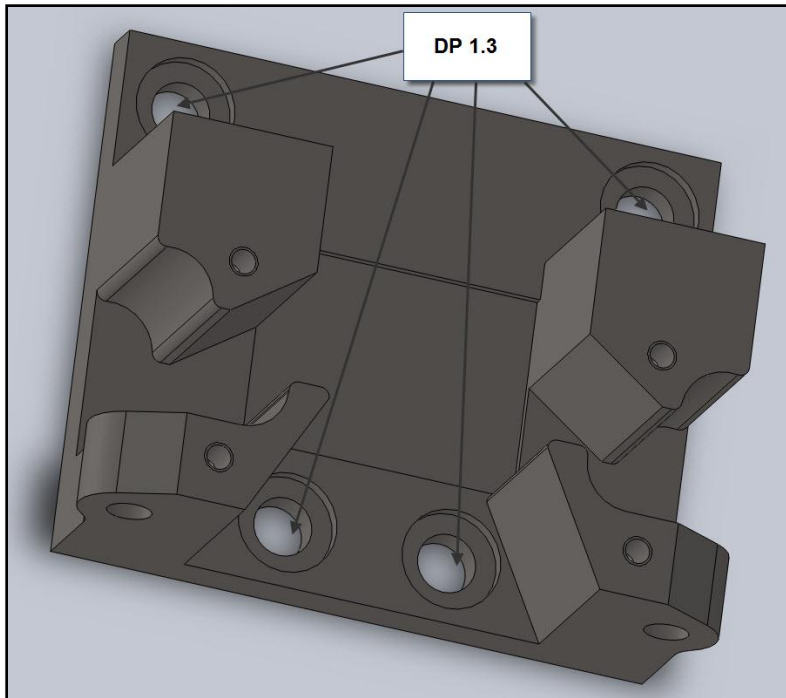
Figure 5: Leaf Spring Holder

The third and final part used to satisfy FR 1.3 is the guide rail holder, seen below in Figure 6. This part was necessary in holding the guide rails in the proper location, and satisfies FR 1.3 through the four screws which secure it to the ski.
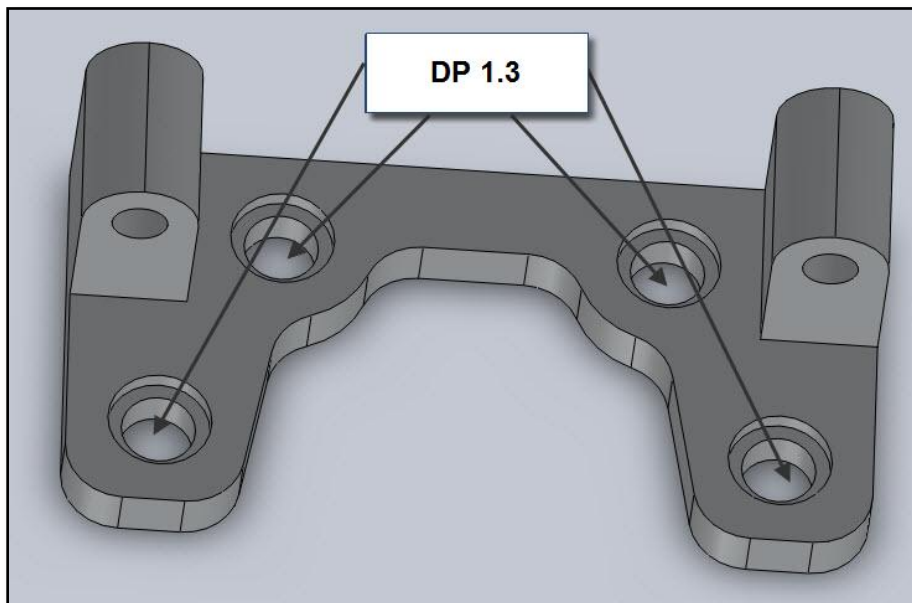
Figure 6: Guide Rail Holder

2.2 FR 2: Provide Horizontal Absorption of Loads Under High Load Conditions

FR Number	Functional Requirement	DP Number	Design Parameter
FR 2	Provide horizontal absorption of loads during high load conditions	**DP 2**	Horizontal absorption system
FR 2.1	Allow horizontal rotation about z-axis	**DP 2.1**	Bi-directional joint (z-axis of rotation)
FR 2.1.1	Limit impact of frictional forces	DP 2.1.1	Bearing plate
FR 2.1.2	Allow free rotation about z-axis	DP 2.1.2	Elimination of mechanical interference
FR 2.2	Control horizontal rotation of heel toward inside of ski	**DP 2.2**	Cup-Follower Spring System
FR 2.2.1	Prevent displacement until F=950 N	DP 2.2.1	Finger follower preload of 950 N
FR 2.2.2	Stop displacement at 12 degrees of rotation	DP 2.2.2	Horizontal dimensions of cup defined by a parabolic equation

The horizontal absorption of loads is necessary in the prevention of phantom foot. This functional requirement is designated as FR 2 and is composed of two child requirements. FR 2.1 was achieved mechanically through the bi-directional joint. The impact of frictional forces on the rotation of the bi-directional joint was minimized through the use of a Teflon bearing plate located between the bi-directional joint and the ski itself, as seen below in Figure 7.
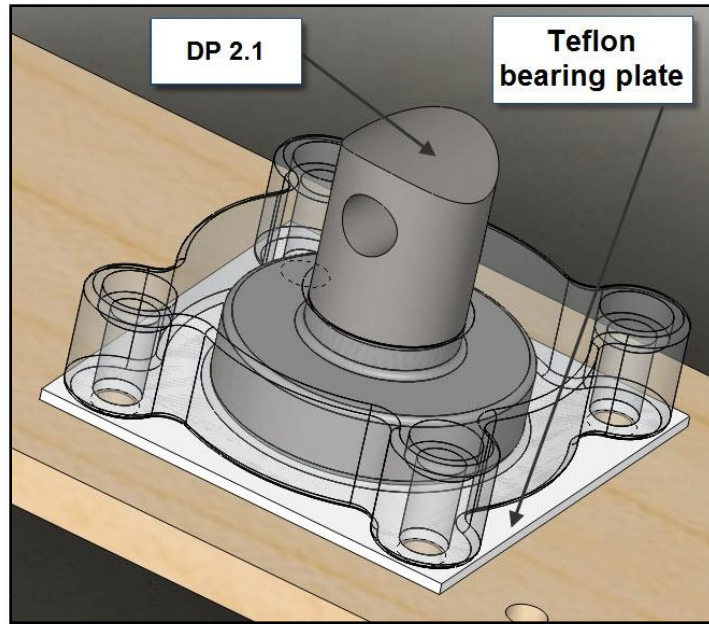
Figure 7: Teflon-ski interface

The child requirements that compose FR 2.2 were mechanically achieved by four parts: the cup, the leaf spring, the guide rail holder, and the finger follower.

Rotation about the toe was a critical design choice as bindings that allow rotation about the heel are blind to forces that occur at or near this location, which causes an increase in the loads transmitted to the ACL. This lateral rotation defines FR 2.2.

The horizontal dimensions of the cup, seen below in Figure 8, were designed so that the finger follower would begin to move along the curvature of the cup under the application of a 950 N load and reach the cup edge under the application of a maximum load of 1750 N.

Initial Finger Follower Location

Final Finger Follower Edge Locations (at 1750 N)

DP 2.2
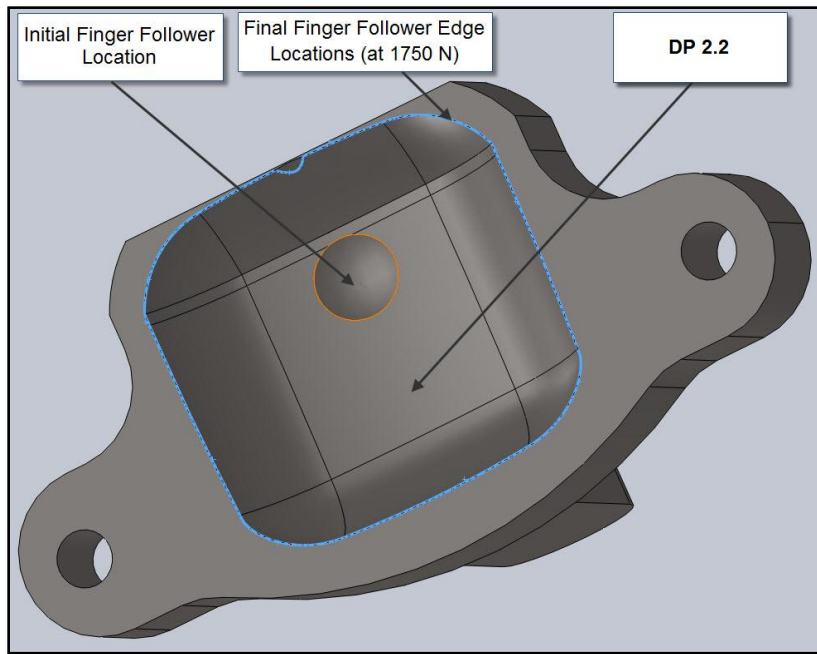
Figure 8: Cup

A 950 N preload applied to the finger follower by the leaf spring through the cup was necessary to ensure the finger follower would only begin to displace under a 950 N load, applied to the finger follower by the top plate. The finger follower was machined from Ti 6AL-4V to prevent failure and satisfies FR 2.2.1. A model of the finger follower and the finger follower holder, which connects the finger follower to the top plate, can be seen below in Figure 9.

DP 2.2.1: Finger Follower

Finger Follower Holder
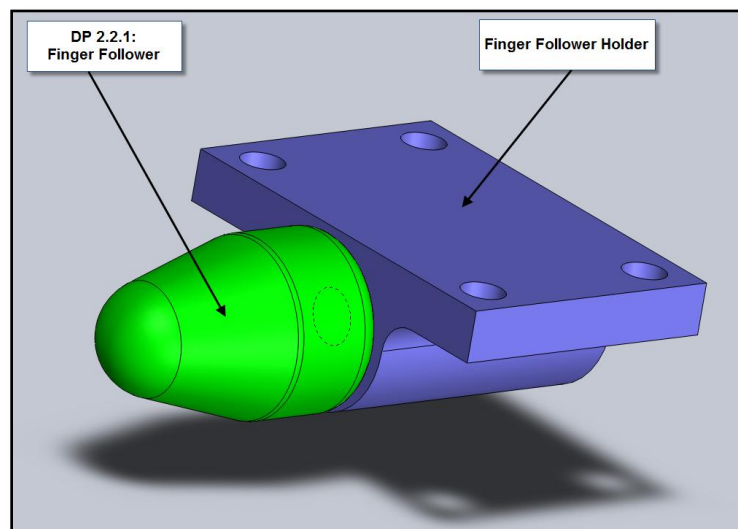
Figure 9: Finger follower and holder

A maximum rotation of twelve degrees was necessary to ensure ski control while protecting the ankle. This twelve degree rotation was controlled by the horizontal cup dimensions and the interaction between the guide rail holder and the finger follower.

The guide rail holder physically prevents any further horizontal rotation at 12 degrees under the maximum 1750 N load. Further rotation cannot occur due to the collision of the finger follower with the guide rail holder. This situation can be seen in Figure 10 below, where the intersecting surface is colored orange.
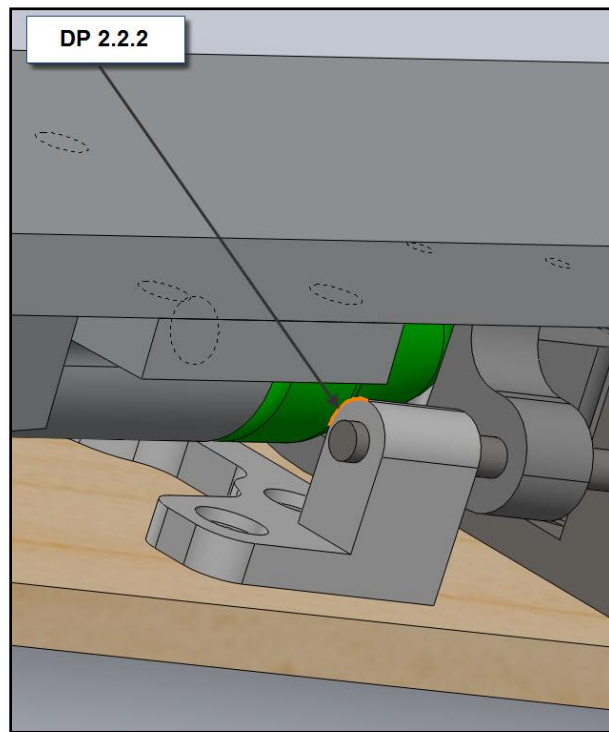
Figure 10: Collision of the Finger Follower and Guide Rail Holder

2.3   FR 3: Provide Vertical Absorption of Loads Under High Load Conditions

FR Number	Functional Requirement	DP Number	Design Parameter
FR 3	Provide vertical absorption of loads during high load conditions	**DP 3**	Vertical absorption system
FR 3.1	Allow vertical rotation about toe	**DP 3.1**	Bi-directional joint (y-axis of rotation)
FR 3.1.1	Limit impact of frictional forces	**DP 3.1.1**	Bearing plate
FR 3.1.2	Constrain rotation about the y-axis	**DP 3.1.2**	Top plate lip feature
FR 3.2	Control vertical rotation of heel downwards	**DP 3.2**	Cup-Follower spring system
FR 3.2.1	Prevent displacement until F=950 N	**DP 3.2.1**	Finger follower preload of 950 N
FR 3.2.2	Stop displacement at 0.6 inches	**DP 3.2.2**	Vertical dimensions of cup defined by a parabolic equation

The vertical absorption of loads is necessary for the prevention of a BIAD incident. This functional requirement was designated as FR 3, which was further decomposed into two child requirements. The first of which, FR 3.1, was mechanically achieved by the bi-directional joint. The top pate was fixed to the joint through a single bolt which allows vertical rotation about the toe. This can be seen below in Figure 11. A Teflon bearing plate was used to satisfy FR 3.1.1 in the same manner as FR 2.1.1 and can be seen above in Figure 7.
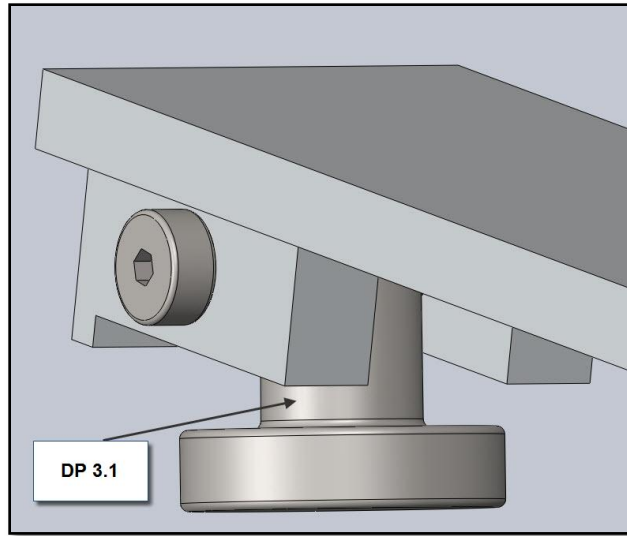
Figure 11: Top Plate Rotation

The vertical displacement of the top plate ends when the finger follower reaches the bottom lip of the cup and the top plate displaces the full 0.6 inches to rest on the ski. FR 3.1.2 is satisfied by the top plate's inability to move upwards, due to a lip located at the toe. This can be seen highlighted below in Figure 12.
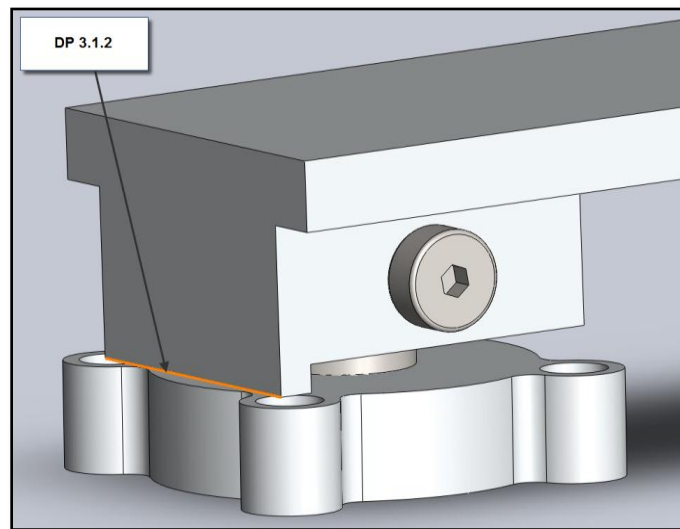
Figure 12: DP 3.1.2

FR 3.2 was mechanically achieved by the dimensions of the top plate and by the vertical curvature of the cup. FR 3.2.1, the first of the two child requirements of FR 3.2, was mechanically achieved by the finger follower in the same manner as FR 2.2.1. The finger follower can be seen in Figure 9 mentioned above.

FR 3.2.2 was achieved through the design of the vertical curvature of the cup, where the finger follower moves along the cup as a response to a 950 N load and reaches a maximum load of 1750 N at the edge of the cup. This can be seen below in Figure 13.
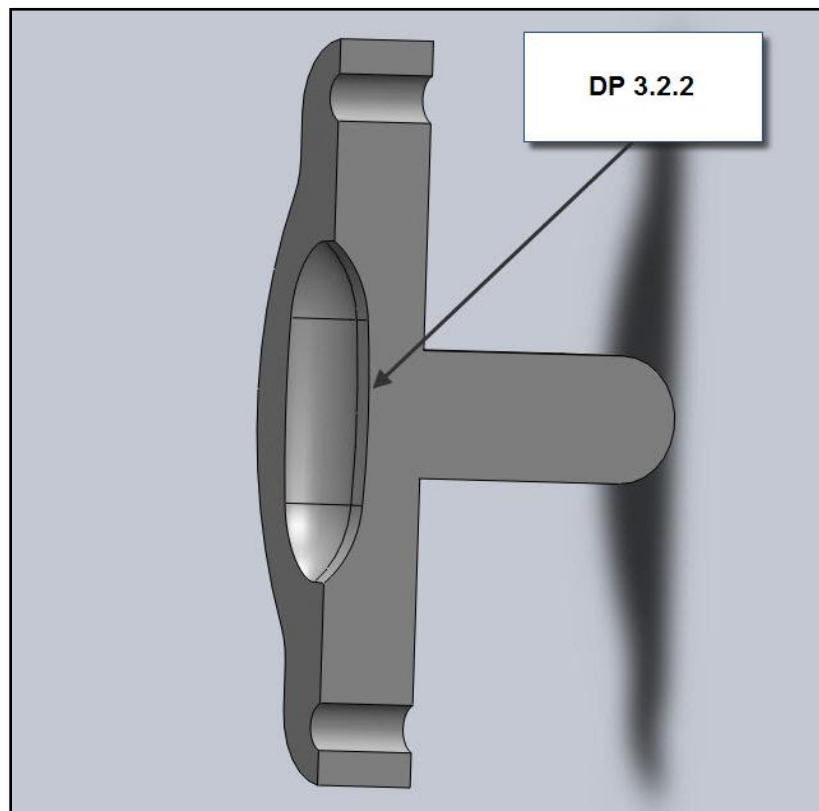
Figure 13: Vertical Cup Dimensions

2.4   FR 4: Limit Motion of Cup

FR Number	Functional Requirement	DP Number	Design Parameter
FR 4	Limit motion of cup	**DP 4**	Sliding rail system
FR 4.1	Allow motion of cup along x-axis	**DP 4.1**	Round rail through cup
FR 4.2	Prevent motion of cup along y-axis	**DP 4.2**	Side of rail system
FR 4.3	Prevent motion of cup along z-axis	**DP 4.3**	Top of rail system
FR 4.4	Prevent rotation of cup	**DP 4.4**	Double rail system
FR 4.5	Prevent translation of rail system	**DP 4.5**	Guide rail holder system

The motion of the cup itself was required to be constrained to movements solely along the x-axis in order for the leaf spring to respond appropriately to loads applied by the cup. This requirement, FR 4, was further decomposed into four children. These requirements were fulfilled mechanically through the use of two guide rails, which allow the cup to be displaced by the finger follower and return to its initial position after a high load situation. These rails are made of Ti 6AL-4V to prevent yield. The parts that satisfy FR 4 can be seen below in Figure 14.
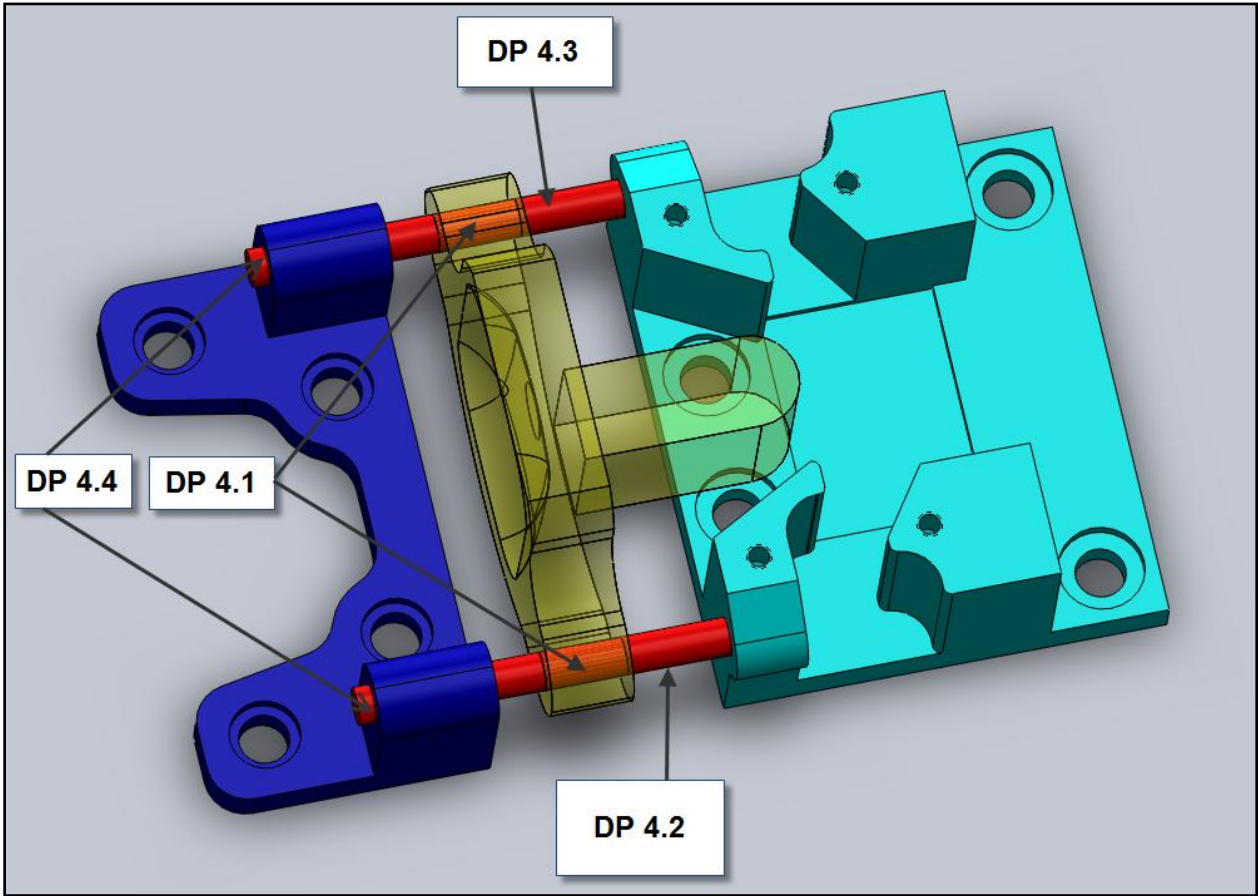
Figure 14: DP 4

2.5   FR 5: Absorb all Final Transmitted Loads

FR Number	Functional Requirement	DP Number	Design Parameter
FR 5	Absorb all final transmitted loads	DP 5	Leaf Spring
FR 5.1	Allow leaf spring bending	DP 5.1	Leaf spring holder curvature
FR 5.2	Prevent non-desired leaf spring translation	DP 5.2	Leaf spring holder points of contact

The leaf spring was manufactured using Ti 6AL-4V in order to absorb loads applied to the cup. This allowed the rotation of the top plate to be constrained until the application of a minimum load of 950 N, the point at which the leaf spring begins to displace. This titanium grade ensured that the leaf spring would not fail under higher load conditions. The leaf spring can be seen in Figure 15 below.
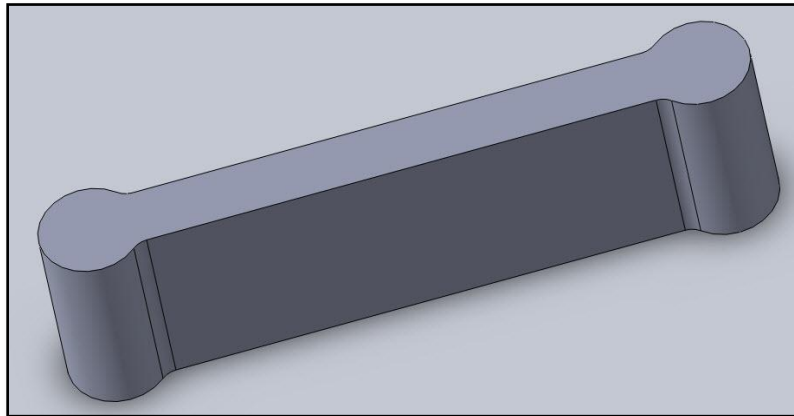
Figure 15: Leaf Spring

FR 5 was decomposed into two children requirements. FR 5.1 required the leaf spring to flex in order to allow the cup to displace an appropriate distance to allow the finger follower to traverse its curvature. This in turn allowed for the displacement of the top plate in response to applied loads. FR 5.1 was achieved by the design of the leaf spring and the leaf spring holder, which contains specific curvature that allows the two ends of the leaf spring to displace as it bends.

FR 5.2 was also achieved by the leaf spring and the leaf spring holder. Two points of contact between each end of the leaf spring and its holder prevent the leaf spring from moving undesirably. This allows the system to function as calculated. A top down view of the leaf spring and the leaf spring holder can be seen below in Figure 16.

Figure 16: DP 5

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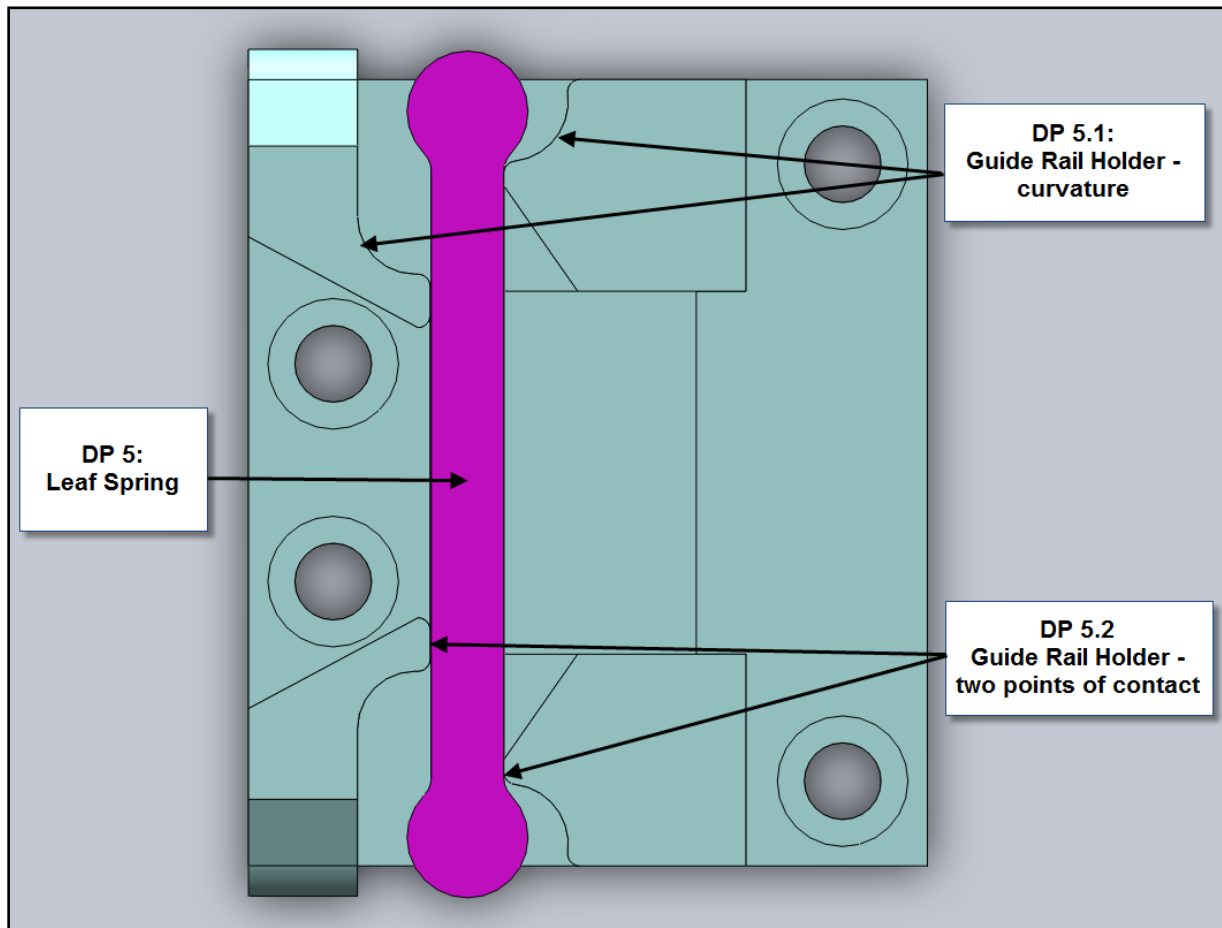
3 Physical Integration

The final step for the functional requirements and corresponding design parameters outlined in the previous section is to be physically integrated into one design that fulfills FR 0. Each individual part and the final assembly were designed using SolidWorks, a computer aided design (CAD) program. SolidWorks was also used to perform a finite element analysis (FEA) on each individual part of the prototype to determine failure under high load conditions.

3.1 Horizontal Load Absorption

The first main requirement of the prototype was to absorb horizontal loads to prevent phantom foot injuries from harming a skier's ACL. A mechanical system was designed to rotate about the z-axis while absorbing loads. This rotational displacement begins at an applied load of 950 N is ends at a twelve degree displacement. The maximum load that can be absorbed by this system is 1750 N. This calculated load absorption and displacement is sufficient to prevent phantom foot while allowing the skier to maintain control.

The load absorption system begins to work when a horizontal load is applied to the top plate. This load acts to rotate the top plate about the z-axis. Rotation is made possible by the top plate's connection to the bi-directional joint. This rotational system fulfills FR 2.1.

The horizontal load absorption system which satisfies FR 2.2 is described in the following paragraph and can be seen below in Figure 17.

Figure 17: DP 2.2

When a horizontal load is applied to the top plate it is translated to the finger follower. The finger follower, beginning at a horizontal load of 950 N, will begin to displace along the horizontal contours of the cup in the direction of the applied load. The finger follower applies an increased load to the cup, which in turn applies the load to the leaf spring, as it moves towards the edge of the cup. The leaf spring displaces as this load is applied, reaching a maximum displacement when the finger follower reaches the cup's edge. At this point the phantom foot situation has been averted due to the absorption of the injurious loads over an increased time span. The leaf spring returns to its initial condition, forcing the cup, finger follower, and finally the top plate to do the same. Figure 18 below shows a closer look at the absorption system.
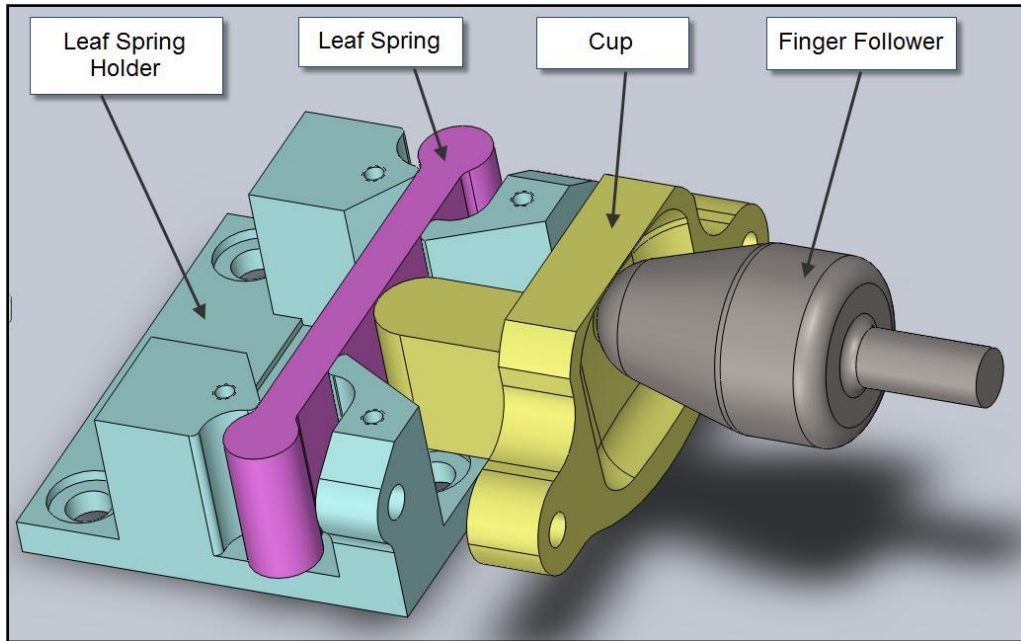
Figure 18: Absorption System

3.2   Vertical Load Absorption

The second main requirement, FR 3, of the prototype was to absorb vertical loads to prevent BIAD injuries from occurring. A mechanical system was designed to rotate about the y-axis while absorbing loads. This displacement begins at an applied load of 950 N is ends at a total displacement of 0.6 inches, at which point the top plate contacts the ski. This displacement is sufficient to prevent a BIAD injury while allowing the skier to maintain control.

The rotational system begins to work when a vertical load is applied to the top plate. This load acts to rotate the top plate about the y-axis. The downward rotation is made possible by the top plate's connection to the bi-directional joint and constrained against upward displacement by a lip located at the front of the top plate. This rotational system fulfills FR 3.1.

The vertical load absorption system which satisfies FR 3.2 is described in the following paragraph and can be seen below in Figure 19.
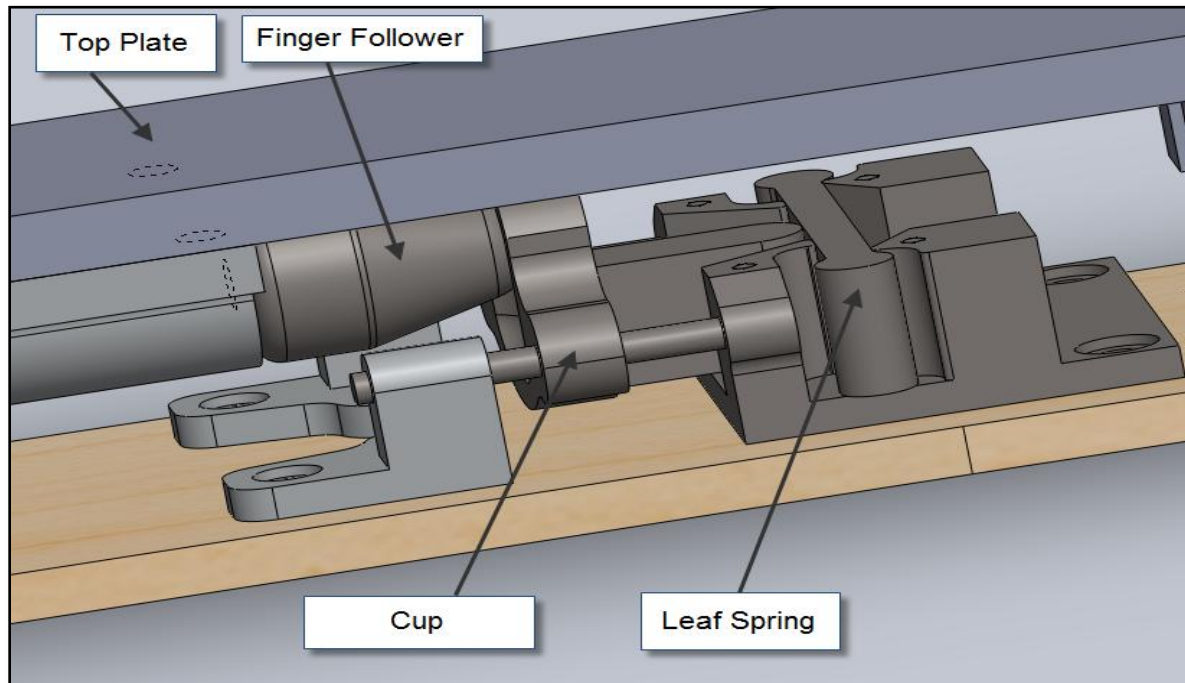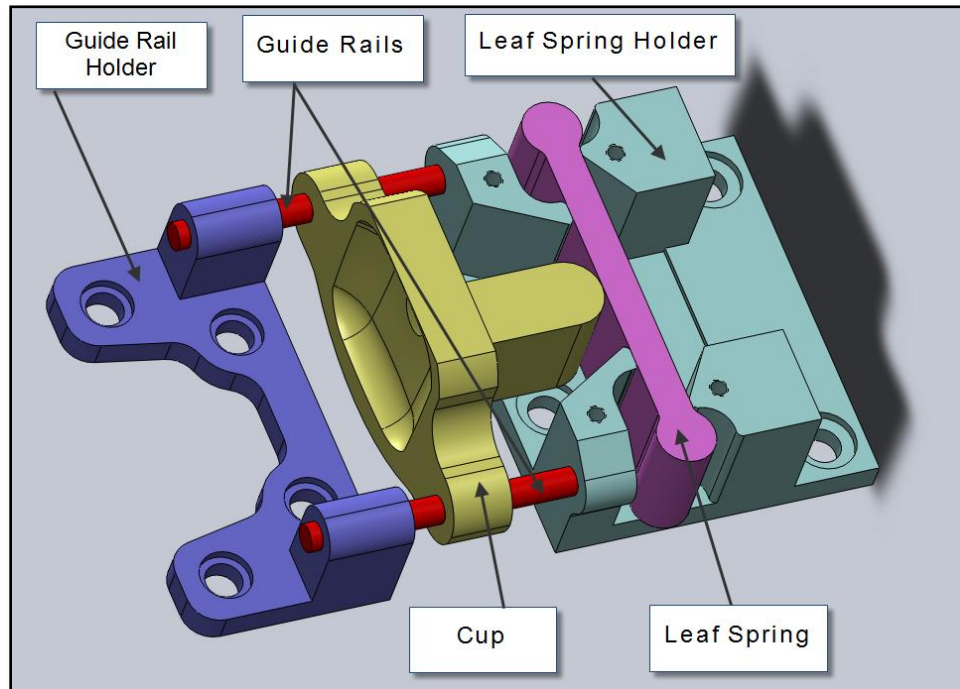

Figure 19: DP 3.2

When a vertical load is applied to the top plate it is translated to the finger follower. The finger follower, beginning at a vertical load of 950 N, will begin to displace along the vertical contours of the cup in the direction of the applied load. The finger follower applies an increased load to the cup, which in turn applies the load to the leaf spring, as it moves towards the edge of the cup. The leaf spring displaces as this load is applied, reaching a maximum displacement when the finger follower reaches the cup's edge. At this point the top plate displaces 0.6 inches downward to contact the ski, ending all further displacement. The leaf spring returns to its initial condition, forcing the cup, finger follower, and finally the top plate to do the same.

3.3　Finite Element Analysis

To see where material needed to be added or removed, a Finite Element Analysis (FEA) was conducted using SimulationXpress Analysis Wizard in the CAD program SolidWorks. FEA enables the designer to determine if a part can withstand the stresses applied from loading and unloading. An FEA was conducted for each part designed for the prototype. Below is a screen shot of the top plate of the under-binding plate with a control load of 950 N applied. In this screen shot, the deformation is shown, with a maximum of 1.408 mm.
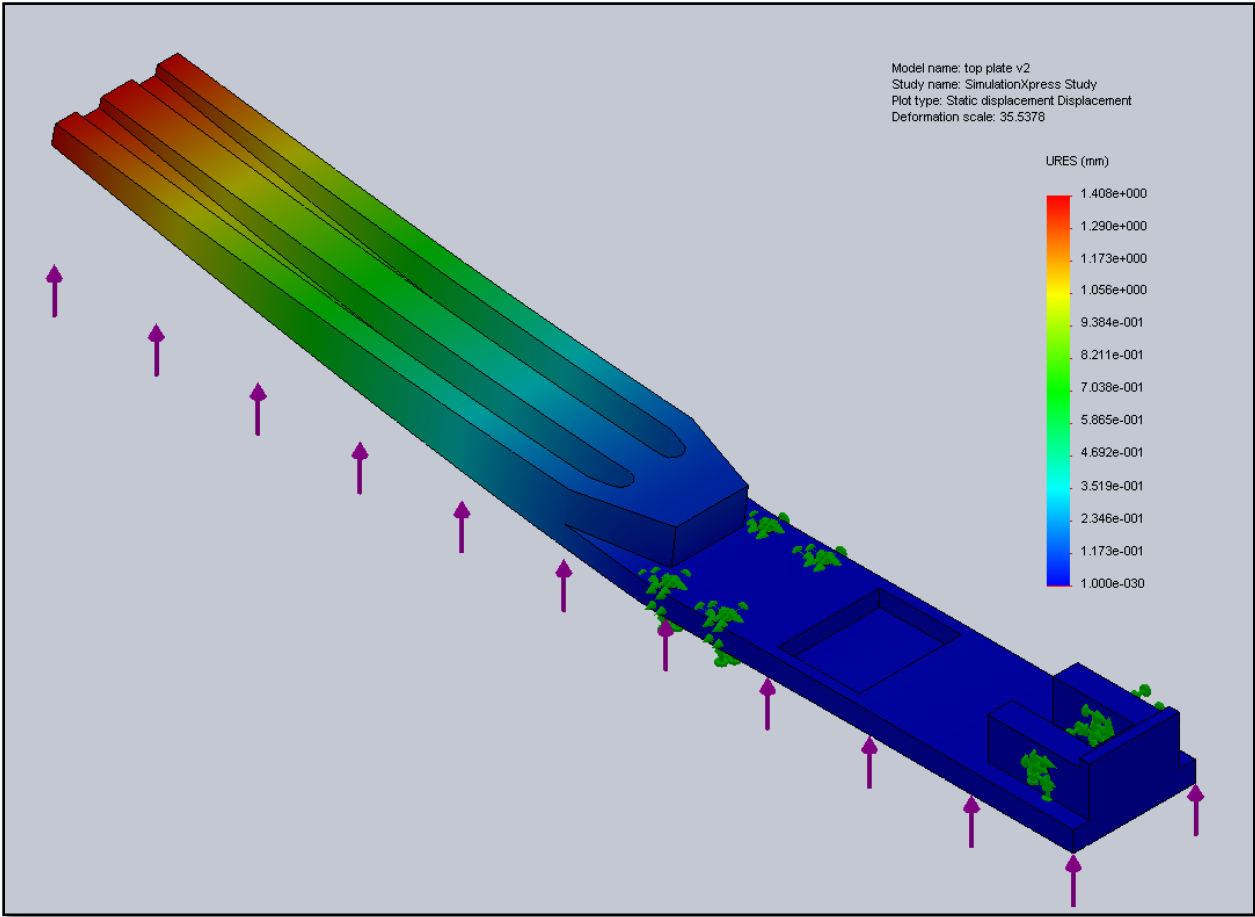
Figure 20: FEA of Top Plate at control load

Figure 21 shows the FEA of the joint holder with the max load of 1750 N applied. Each counter-bored surface was used as a fixture point for this part. Then the maximum load was applied upwards on the inside surface of the part. In this case, the Von-Mises stresses are shown, which do not approach the yield point of the aluminum alloy, which is 55.148 MPa. The maximum stress from this load is 22.64 MPa.
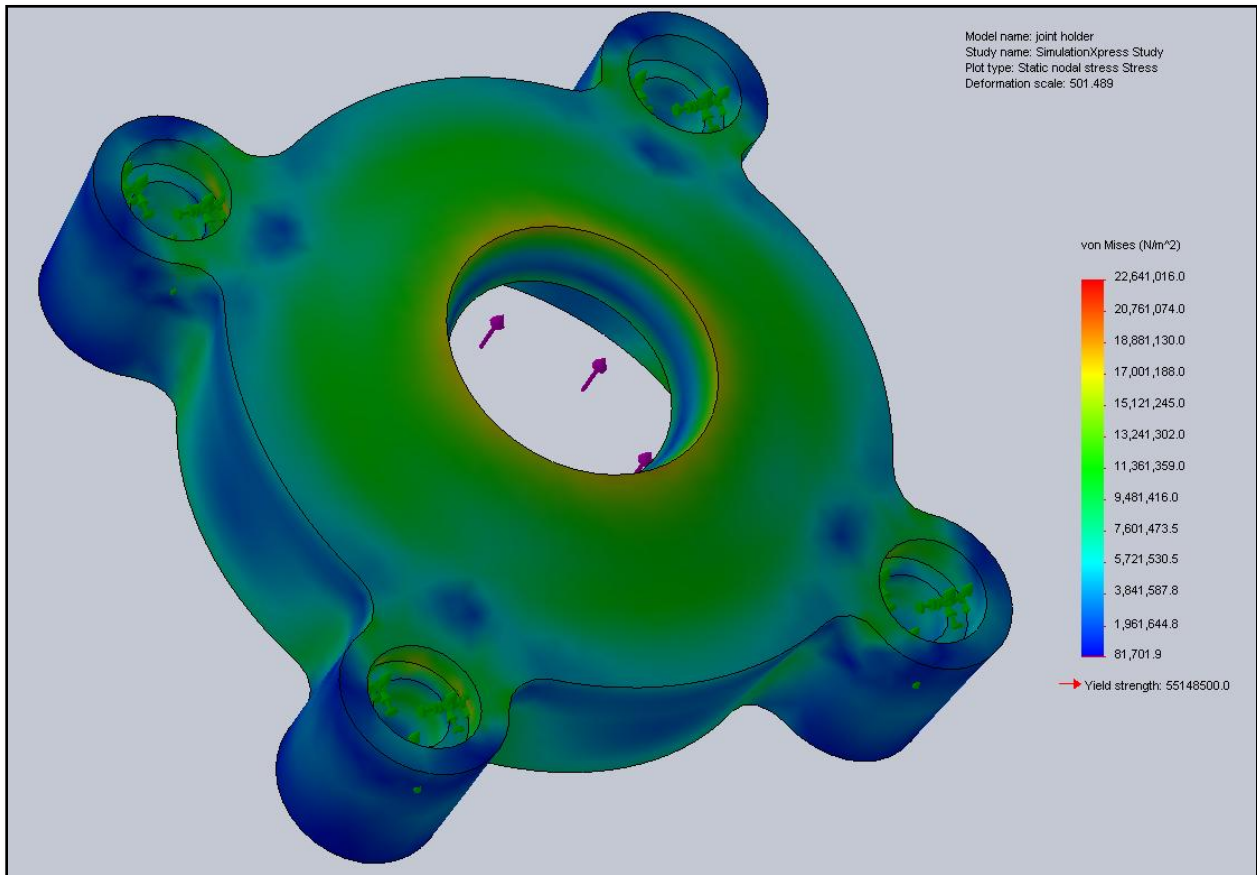
Figure 21: FEA of joint holder showing Von-Mises stresses at 1750N

An FEA was also conducted on the bi-directional joint to determine if it could handle the maximum load applied as the top plate displaces downward. The hole for connection to the top plate was used as the fixture point, while the load of 1750 N was applied downwards on the surface shown. This loading should be accurate to what is actually experienced as the system

displaces. With this loading, the maximum stress of the part is 21.76 MPa, which is well below

the yield point of the aluminum alloy used, which is once again 55.148 MPa.
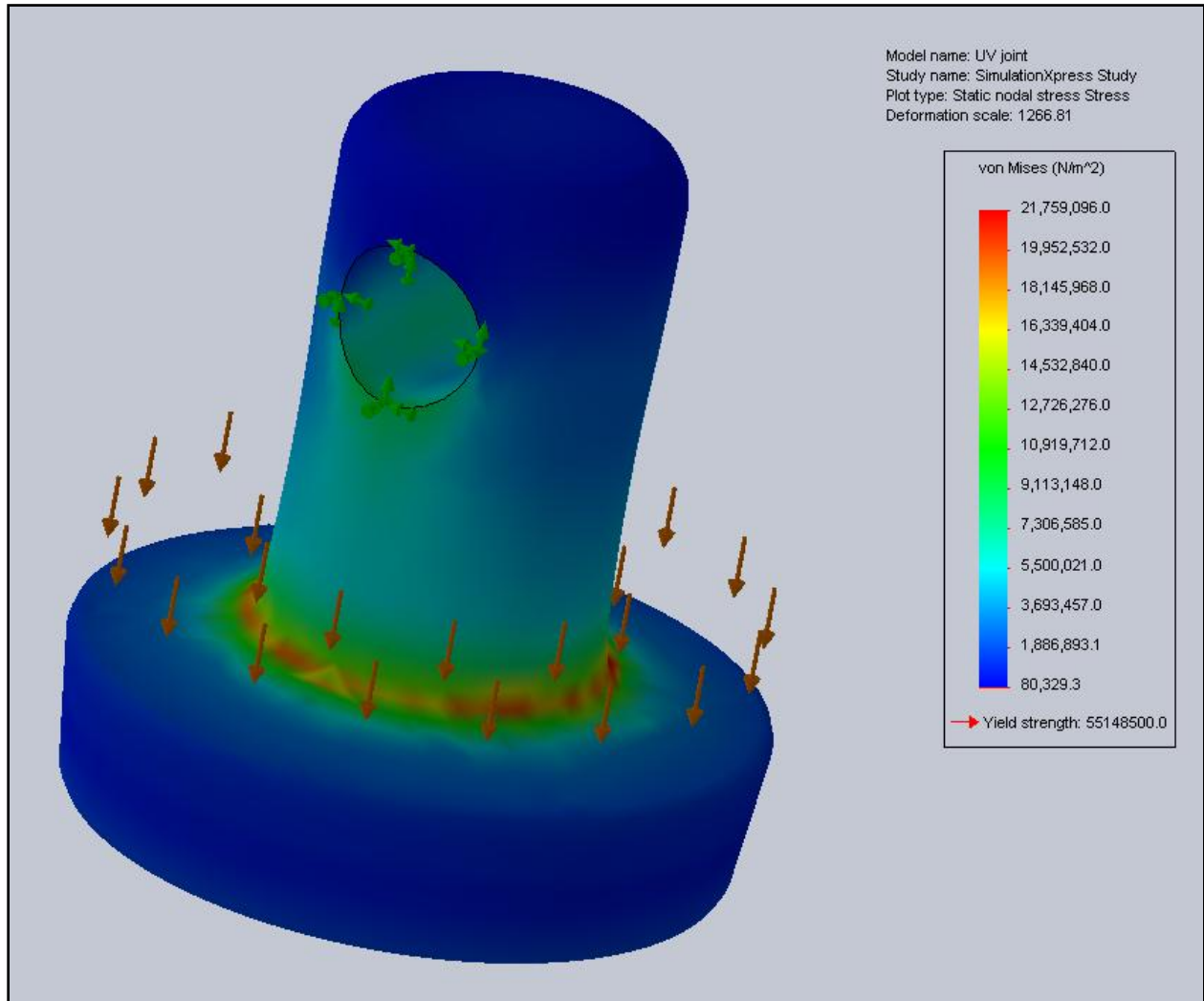
Figure 22: Bi-directional joint Von-Mises stresses

The leaf-spring holder was a part that had to deform minimally while still being light.

This was crucial due to the tight tolerances used for the manufacturing of the leaf-spring. In this

case, the counter-bored hole surfaces were used as the fixture points, while the maximum load of

1750 N was applied to the upright surfaces indicated by the purple arrows in Figure 23. After the

first FEA was conducted using 6061 Aluminum alloy, it was found the Von-Mises stresses

would be very close to the yield stress for this material. A second FEA was conducted using the titanium alloy Ti-6Al-4V. Using this material with a yield stress of 1.050 GPa provided a Factor Of Safety (FOS) of approximately 20, with the maximum Von-Mises stress of 52.481 MPa.
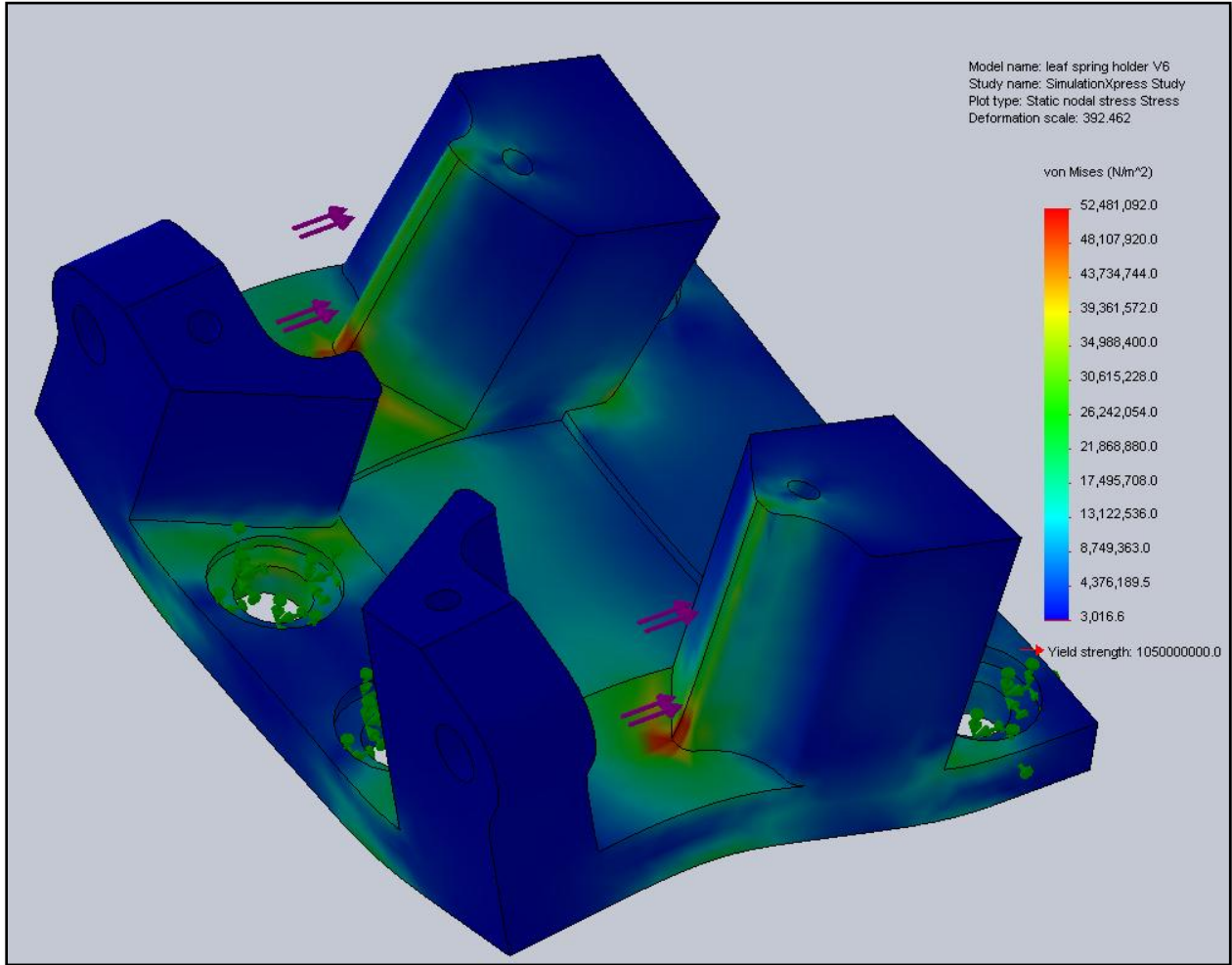
Figure 23: Leaf spring holder Von-Mises stresses

The last part that FEA was used for was the leaf-spring itself. This part is crucial because it has to deform enough to absorb the loads while not deforming past its yield strength. Rounds of the spring were used as fixture points for this FEA, with the applied load located in the center of the leaf spring, indicated by the purple arrows in Figure 24. Applying the maximum load of 1750 N to the center of the leaf spring produced maximum Von-Mises stress of 131.627 MPa.

This stress is well below the yield strength of the material used, which was 1.050 GPa, so this leaf-spring design is considered to be safe.
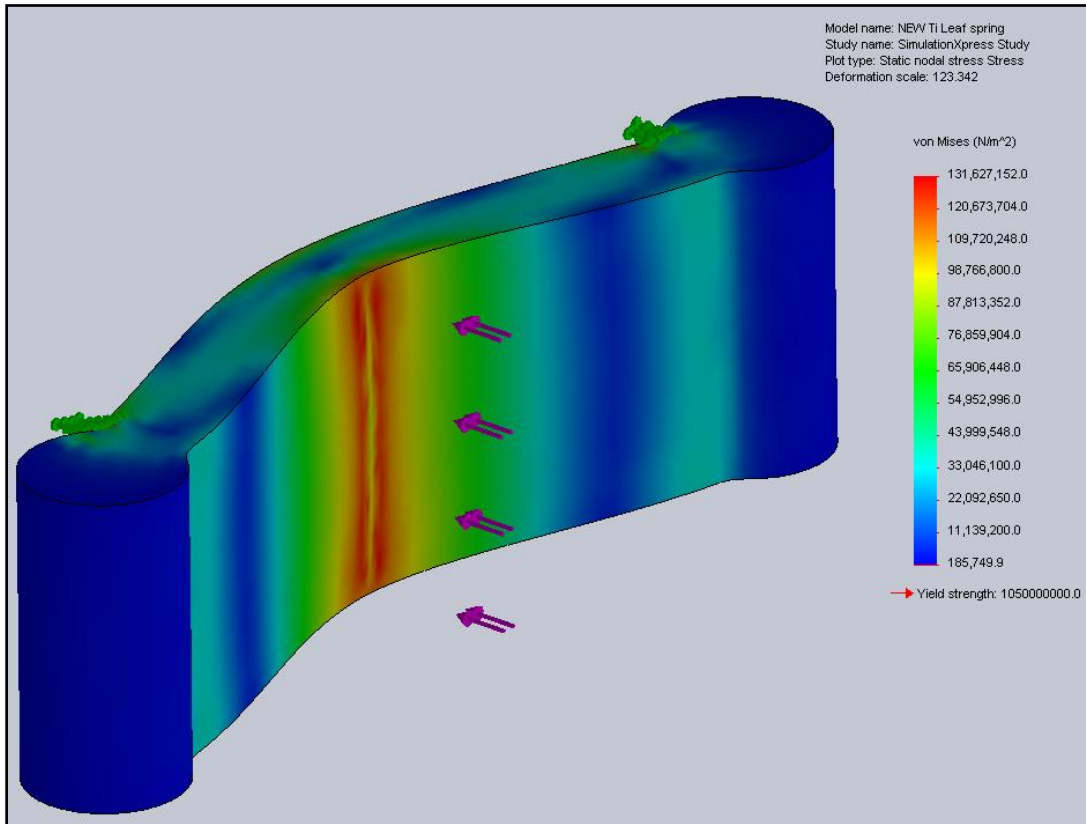
Figure 24: Leaf spring Von-Mises stresses at 1750N

3.4   Tolerances

Each moving part in the under-binding plate had to have a specific tolerance to ensure its proper movement and fit. An engineering tolerance tells the manufacturer how much variation is allowable in each part. For example, a part that is going to be CNC milled will have a relatively high tolerance if the feed rates and speeds are calculated correctly. Tolerances are necessary for a part to slide, or rotate freely. The parts that needed tolerancing in this design were the cup, the bi-directional joint, the joint holder, and the top plate. Different tolerancing methods were

needed for each part. Below is an example of a tolerancing chart from Knovel's Machinery's Handbook for standard running and sliding fits.

Nominal Size Range, Inches		Class RC 1			Class RC 2			Class RC 3			Class RC 4		
			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits	
		Clear-ance[a]	Hole H5	Shaft g4	Clearance[a]	Hole H6	Shaft g5	Clearance[a]	Hole H7	Shaft f6	Clearance[a]	Hole H8	Shaft f7
Over	To				Values shown below are in thousandths of an inch								
0 –	0.12	0.1 / 0.45	+0.2 / 0	−0.1 / −0.25	0.1 / 0.55	+0.25 / 0	−0.1 / −0.3	0.3 / 0.95	+0.4 / 0	−0.3 / −0.55	0.3 / 1.3	+0.6 / 0	−0.3 / −0.7
0.12 –	0.24	0.15 / 0.5	+0.2 / 0	−0.15 / −0.3	0.15 / 0.65	+0.3 / 0	−0.15 / −0.35	0.4 / 1.12	+0.5 / 0	−0.4 / −0.7	0.4 / 1.6	+0.7 / 0	−0.4 / −0.9
0.24 –	0.40	0.2 / 0.6	+0.25 / 0	−0.2 / −0.35	0.2 / 0.85	+0.4 / 0	−0.2 / −0.45	0.5 / 1.5	+0.6 / 0	−0.5 / −0.9	0.5 / 2.0	+0.9 / 0	−0.5 / −1.1
0.40 –	0.71	0.25 / 0.75	+0.3 / 0	−0.25 / −0.45	0.25 / 0.95	+0.4 / 0	−0.25 / −0.55	0.6 / 1.7	+0.7 / 0	−0.6 / −1.0	0.6 / 2.3	+1.0 / 0	−0.6 / −1.3
0.71 –	1.19	0.3 / 0.95	+0.4 / 0	−0.3 / −0.55	0.3 / 1.2	+0.5 / 0	−0.3 / −0.7	0.8 / 2.1	+0.8 / 0	−0.8 / −1.3	0.8 / 2.8	+1.2 / 0	−0.8 / −1.6
1.19 –	1.97	0.4 / 1.1	+0.4 / 0	−0.4 / −0.7	0.4 / 1.4	+0.6 / 0	−0.4 / −0.8	1.0 / 2.6	+1.0 / 0	−1.0 / −1.6	1.0 / 3.6	+1.6 / 0	−1.0 / −2.0
1.97 –	3.15	0.4 / 1.2	+0.5 / 0	−0.4 / −0.7	0.4 / 1.6	+0.7 / 0	−0.4 / −0.9	1.2 / 3.1	+1.2 / 0	−1.2 / −1.9	1.2 / 4.2	+1.8 / 0	−1.2 / −2.4
3.15 –	4.73	0.5 / 1.5	+0.6 / 0	−0.5 / −0.9	0.5 / 2.0	+0.9 / 0	−0.5 / −1.1	1.4 / 3.7	+1.4 / 0	−1.4 / −2.3	1.4 / 5.0	+2.2 / 0	−1.4 / −2.8
4.73 –	7.09	0.6 / 1.8	+0.7 / 0	−0.6 / −1.1	0.6 / 2.3	+1.0 / 0	−0.6 / −1.3	1.6 / 4.2	+1.6 / 0	−1.6 / −2.6	1.6 / 5.7	+2.5 / 0	−1.6 / −3.2
7.09 –	9.85	0.6 / 2.0	+0.8 / 0	−0.6 / −1.2	0.6 / 2.6	+1.2 / 0	−0.6 / −1.4	2.0 / 5.0	+1.8 / 0	−2.0 / −3.2	2.0 / 6.6	+2.8 / 0	−2.0 / −3.8
9.85 –	12.41	0.8 / 2.3	+0.9 / 0	−0.8 / −1.4	0.8 / 2.9	+1.2 / 0	−0.8 / −1.7	2.5 / 5.7	+2.0 / 0	−2.5 / −3.7	2.5 / 7.5	+3.0 / 0	−2.5 / −4.5
12.41 –	15.75	1.0 / 2.7	+1.0 / 0	−1.0 / −1.7	1.0 / 3.4	+1.4 / 0	−1.0 / −2.0	3.0 / 6.6	+2.2 / 0	−3.0 / −4.4	3.0 / 8.7	+3.5 / 0	−3.0 / −5.2
15.75 –	19.69	1.2 / 3.0	+1.0 / 0	−1.2 / −2.0	1.2 / 3.8	+1.6 / 0	−1.2 / −2.2	4.0 / 8.1	+2.5 / 0	−4.0 / −5.6	4.0 / 10.5	+4.0 / 0	−4.0 / −6.5

Table 3. American National Standard Running and Sliding Fits *ANSI B4.1-1967 (R1987)*

[a] Pairs of values shown represent minimum and maximum amounts of clearance resulting from application of standard tolerance limits.

Figure 25: Tolerance chart for standard running and sliding fits

The row highlighted in red shows the tolerances used for the holes in the cup, the holes for connection to the bi-directional joint in the top plate, and the bi-directional joint itself. This chart is appropriate for tolerancing these parts because the nominal size of the holes in the cup is 1/4 inches, while the holes in the top plate and bi-directional joint are 5/16 inches. Both of these nominal sizes correspond to the row highlighted in red. Each class at the top of the chart, RC1, RC2, RC3, and RC4 represent different classes of fits. Class RC3 was used for these parts because it is a *Precision Running Fit* (Oberg et.al). Once this fit was selected, the tolerance is then be added to the holes' diameter, for example, the cup's holes plus the RC3 tolerance is 0.25 inches plus 0.0006 inches, because the chart is shown in thousandths of an inch. Tolerancing is an essential task in designing parts.

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4   Prototype Production

After design of the under-binding plate was completed, it was produced using WPI's manufacturing laboratories in Washburn Shops. HAAS Automation provides WPI with CNC machines available for students' use. The Computer Aided Manufacturing (CAM) program Esprit was used to generate tool paths for each part of the prototype.

4.1   Manufacturing of Parts

When the solid model was completed each individual part had to be imported into Esprit. Once the part was loaded in Esprit the program would recognize the general shape of the part. Figure 26 shows the solid model of the joint holder as loaded into Esprit.
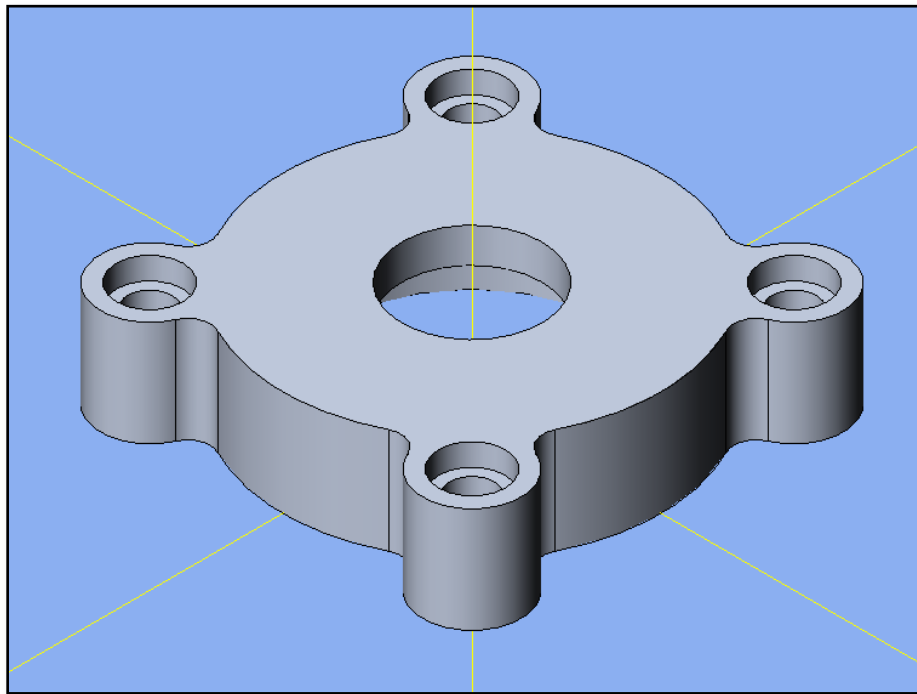
Figure 26: Joint holder in Esprit

At that point the user employed Esprit's interface and designated tool paths. The part had to be rotated and aligned within the Cartesian coordinates system so the machine could be zeroed and the stock would be milled correctly. With each tool path the user also had to select a tool,

choose a cutting strategy, select speeds and feeds for the machine, check clearances, and make sure the tool would not crash into the part or the fixture. Figure 27 shows the leaf spring holder with tool paths designated and the project manager open.
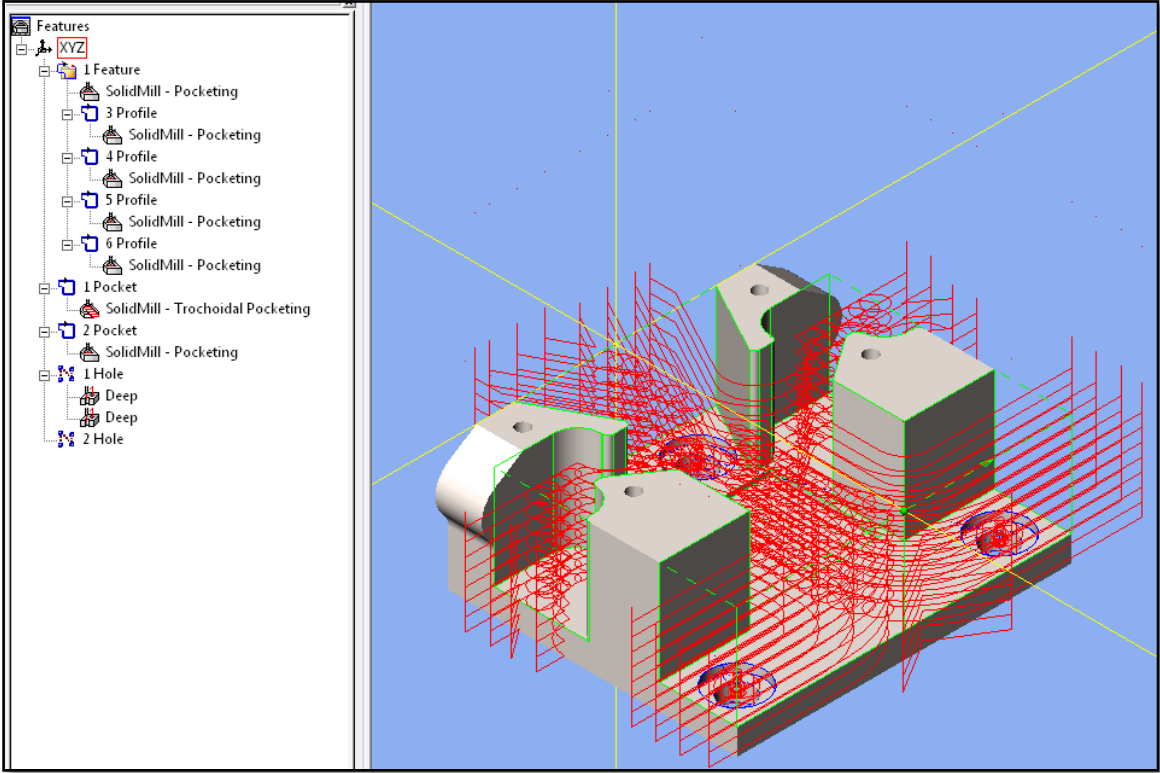
Figure 27: Leaf spring holder with tool paths in Esprit

Once the tool paths were created a digital stock was also created in Esprit and the entire operation was stimulated. The stimulation uses different colors to designate cut and uncut stock. It also shows crashes as red swaths in the material. A target can be created within a transparent stock to show where the finished part should be. Figure 28 shows a stimulation of the operations for the guide rail holder with transparent stock and visible target.
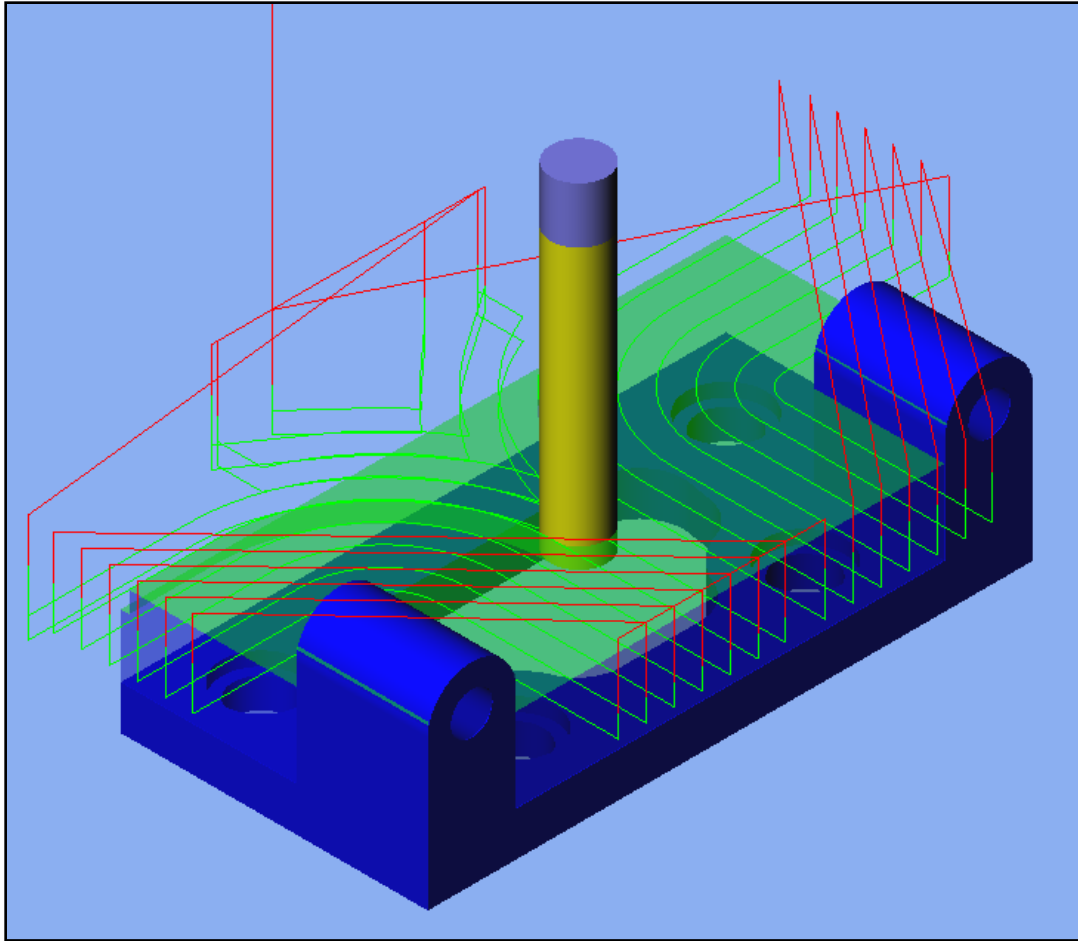
Figure 28: Guide rail holder simulation of tool path operations

After the operation was simulated in Esprit the program was ready to be used. Each HAAS CNC machine needs a different code language in order to correctly read the program. Esprit can write to each of these languages using different post processors designated for each class of machine. When the MiniMill was used, the appropriate MiniMill post processor was used to post the NC code for numerical control. The code could be transferred to the machine through a compatible disk or through DNC, direct numerical control.

Each part came from a larger piece of stock. First a band saw was used to cut the stock down to slightly larger dimensions than the digital stock from Esprit. For each part to be machined it then had to be fixtured in the machine. Parts with rectangular stock were held with a vice. Steel rectangles created with extremely high tolerances called parallels were used to hold

the stock off the bottom of the vice so holes could be drilled and so the tool would not crash into the vice while contouring or pocketing. When the stock was fixtured a probing tool was used to set the machine's zero for X, Y, and Z coordinates in the same place that the Esprit program had it. Facing operations were used to bring down the size of the cut stock to that of the digital stock. The final stock was zeroed a final time, the program was rechecked on the machine and then it was run. Figure 29 shows a piece of stock in the vice ready to be probed.
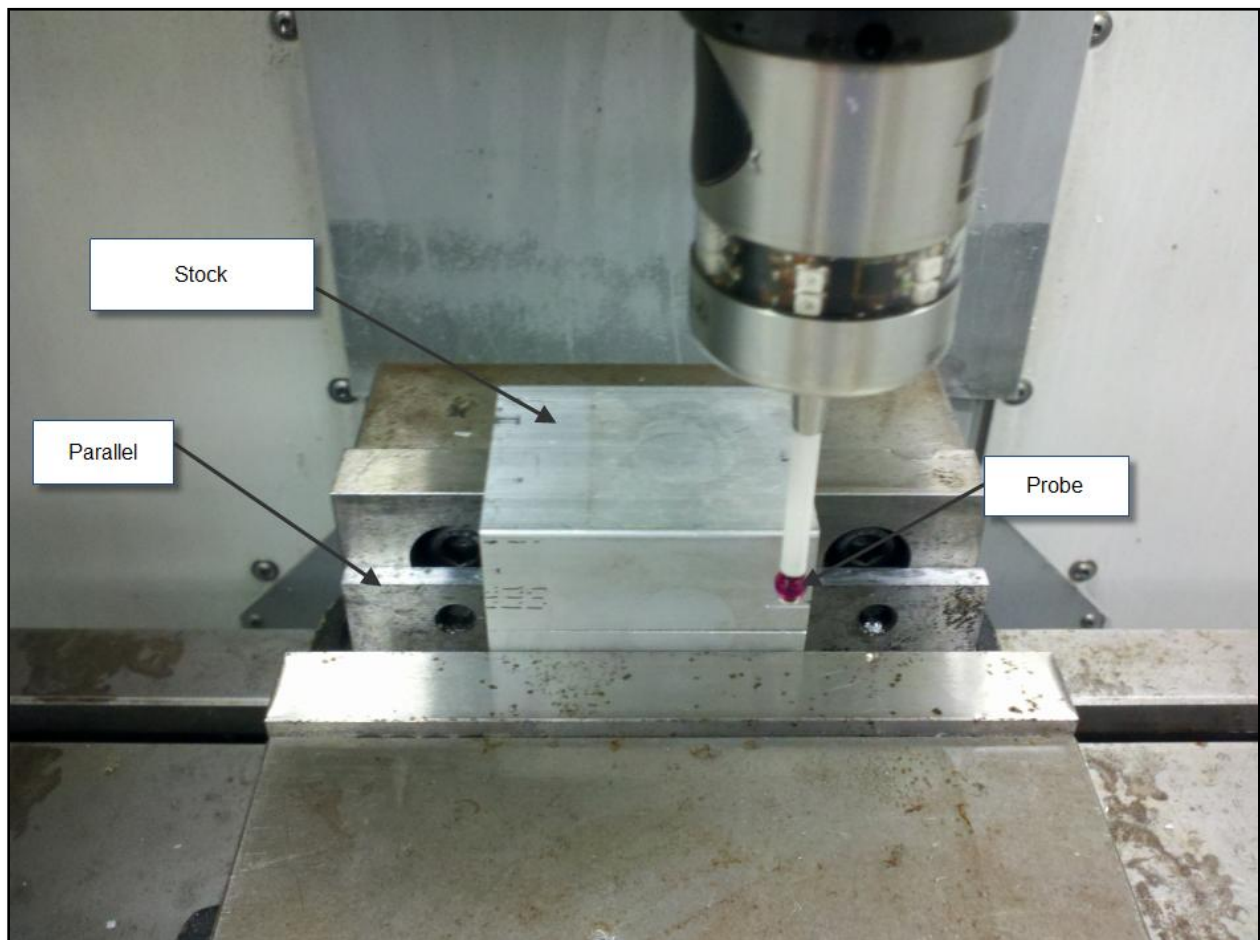

Figure 29: Stock in vice in CNC mill probing

4.2   Assembly Process

Once each part was manufactured, the prototype needed to be assembled for testing. The assembly began with the bottom plate being screwed into the ski using four 5/16-18 socket-head

cap screws. After this was completed, the joint holder was screwed down with the joint and Teflon bearing plate inside using four ¼-20 socket-head cap screws. Then the leaf spring holder was attached to the bottom plate using four ¼-20 socket-head cap screws. Then the guide-rail holder was attached to the bottom plate using the same ¼-20 screws as the joint holder and leaf spring holder. The guide rails were placed through the guide rail holder and placed through the holes in the cup. The guide rails were then screwed into the leaf spring holder. The leaf spring was then dropped into its location in the leaf spring holder. This sub-assembly of all the parts rigidly attached to the bottom plate and ski can be seen in Figure 30. After all these parts were mounted to the bottom plate, the top plate sub-assembly could be attached.
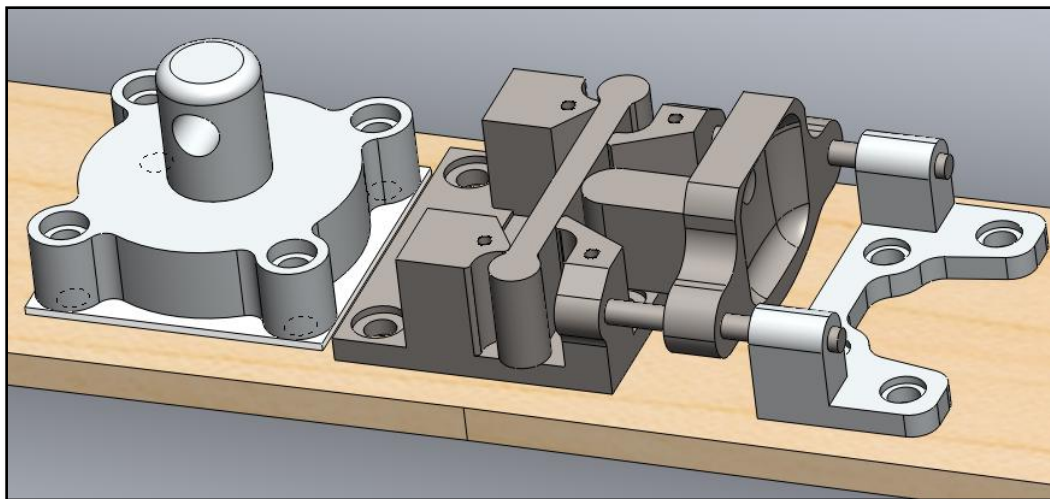
Figure 30: Sub-assembly of parts attached to ski

The top plate sub-assembly was made up of the top plate, finger-follower holder, and finger-follower. The finger-follower holder is attached to the top plate by four 5/16-18 socket-head cap screws. The finger-follower is threaded into the finger-follower holder by 5/16-18 tapping. This allows pre-load adjustment if the finger-follower is screwed in or out. The top plate sub-assembly is then placed on top of the ski sub-assembly. The top plate sub-assembly can be seen in Figure 31.

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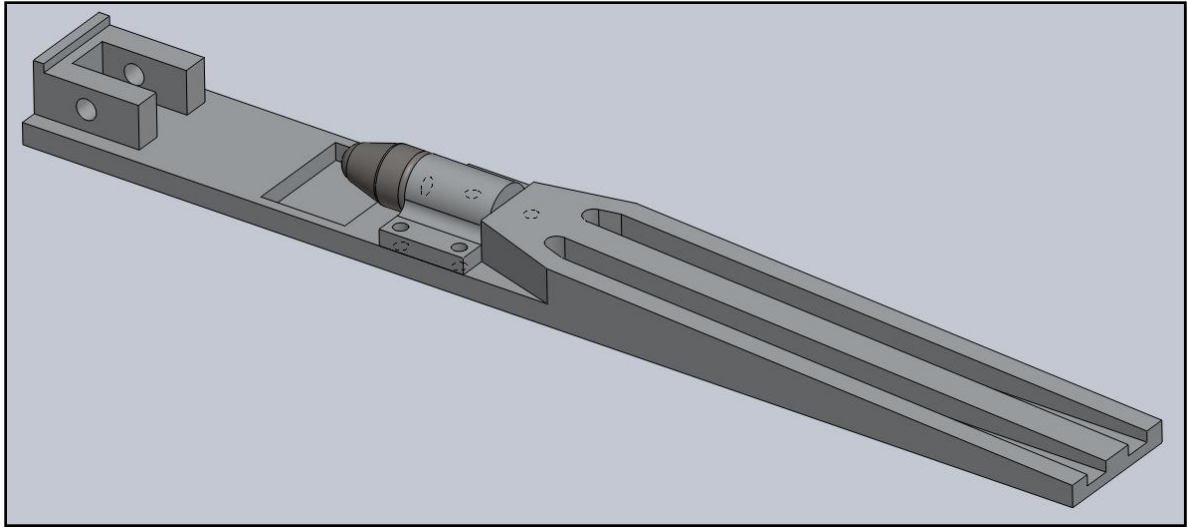
Figure 31: Top plate sub-assembly

The top plate assembly was then attached to the ski sub-assembly with a 5/16-18 shoulder

bolt. The bolt had to be hammered into place because of the force from the spring on the top

plate sub-assembly. The assembly was nearly complete at this point, and can be seen in Figure

32.

Figure 32: Under-binding plate assembled on ski

The only thing left to be assembled at this point was mounting the ski binding on the top

plate. Since the normal wood screws in binding mounting would not have worked in the top

plate, #10-24 screws were used at all seven binding mounting locations. The holes were drilled

for the binding manually, and then tapped for the #10-32 screws. After this mounting, the

assembly of the prototype was complete, as seen in Figure 33.

Figure 33: Under-binding plate assembled with binding mounted

5   Testing

After the prototype was assembled, it needed to be tested to determine whether it met its objectives. Once each part was manufactured, they were measured to see if they were within the tolerances specified during the design phase of the project.

Once the prototype was completely assembled, a group member donned a ski boot and stepped into the binding on the under-binding plate. The plate displaced until it contacted the ski. The group determined that the preload needed to be increased to be more effective. The preload was increased by unscrewing the finger follower from its holder. The group member then stepped into the binding again, and no displacement occurred. This ensured that the prototype would not displace under normal skiing conditions. After the preload was set correctly, additional testing with a torque wrench was performed.

No usable data was obtained from testing with the torque wrench. The moment exerted at the toe by the torque wrench caused the binding to release the boot before the prototype displaced. The same problem was encountered when the system was tested for lateral displacement. This happened because the torque wrench applies all its torque about the heel of the boot, causing the ski binding to release normally. The group did not have equipment to apply a load laterally at the heel.

Another problem encountered during testing was lifting of the front of the ski. As the top plate was loaded, it created a moment which lifted the tip of the ski off the ground. This could be troublesome to the skier, because the front of the ski acts as the controlling surface during a turn.

The last problem the group encountered during testing was friction. Because the finger follower slides on the cup, there is a large amount of friction present. As the top plate was displaced downwards, it tended to stay at its displaced position. The group could hear the sounds of the finger follower sliding on the cup surface as it was forced up or down.

6   Discussion

This prototype, as a proof of concept, functions correctly as it is able to displace both laterally and vertically as desired. There are several key aspects of the prototype that prevent it from acting as more than a proof of concept.

This first and most significant of these flaws was the high coefficient of friction between the cup and finger follower. This friction both prevents the return of the top plate to its original position after a vertical displacement and prevents lateral displacement entirely, as conventional bindings release the boot before horizontal displacement can occur. This high friction coefficient prevents the prototype from responding correctly to applied loads, which makes it doubtful that the prototype will prevent injury of any kind.

The second design flaw was the tendency of the front of the ski to bend upwards as a result of the vertical displacement of the top plate. The high load required to displace the top plate vertically, the location of the prototype in the middle of the ski, and the small length of the prototype all act to apply a large moment to the ski about the y-axis. This bends the ski tip upwards, removing the controlling edge of the ski from the slope. This would make the actual act of skiing on a slope exceedingly difficult.

This bending moment revealed another design flaw during testing. This moment proved too great for the screws used to secure the prototype to the ski, and shortly into testing resulted in the prototype being ripped from the ski. This flaw was addressed by the addition of an aluminum plate to bottom of the prototype. This bottom plate increased the length of the prototype-ski interface and reduced the moment of the plate about the y-axis. This prevented the prototype from tearing itself from the ski top at the cost of adding weight to the prototype.

The required load for vertical displacement and the application of this load at the heel resulted in the fourth design flaw; the bending of the top plate. Minimal testing resulted in a visible bend of the top plate. This flaw was addressed through the addition of two aluminum strips to the sides of the top plate. This solved the issue of bending, though added undesired weight to the prototype and negatively impacted the aesthetics of the design.

The final significant design flaws are the size and weight of the prototype. The height of the prototype is 3.31 inches. This does not conform to the International Ski Federation (FIS) binding standards, as the maximum allowable height between the bottom running surface of the ski and the sole of the ski boot is 55 mm (2.165 in.). This height, in additional to disqualifying the prototype as potential binding feature in alpine racing, would make skiing cumbersome. This is undesirable in both racing and normal alpine skiing. The weight of the prototype is primarily a result of the size of the aluminum top plate and adds to the cumbersome nature of skiing with the prototype installed.

6.1   Weight Analysis

The weight of the final prototype was calculated using SolidWorks' Mass Properties evaluator in the assembly. Weight of the under-binding plate is an important factor because it determines whether the system can be used in real-life skiing. The weight that was calculated using SolidWorks was 3.96 pounds. The evaluator can be seen below in Figure 34.
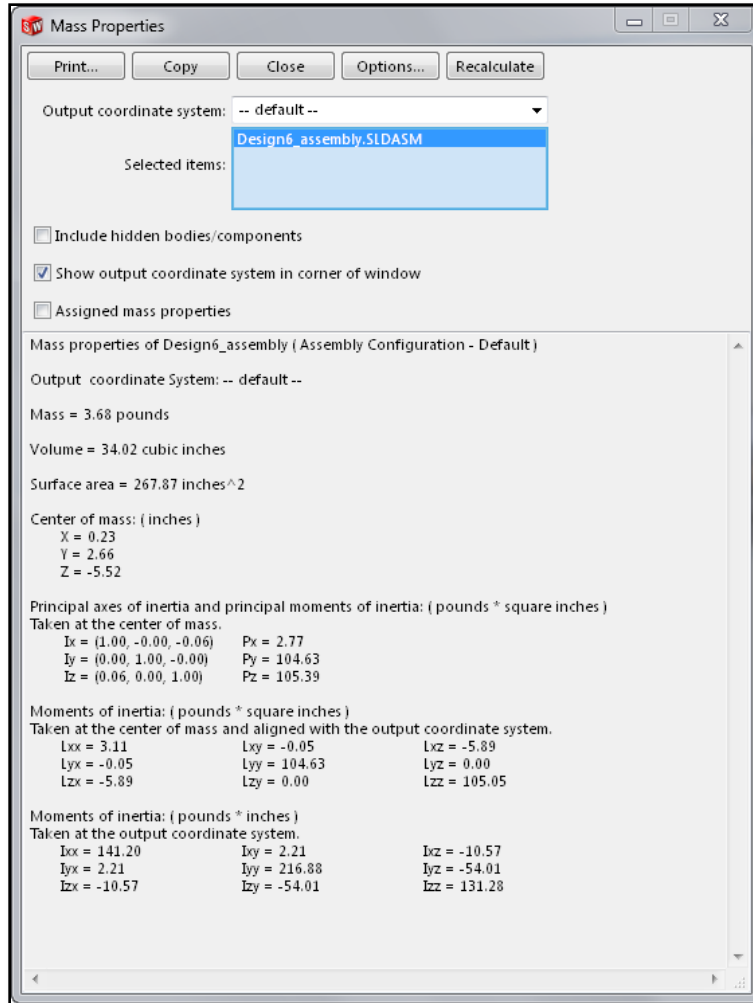
Figure 34: SolidWorks' mass properties evaluator

The weight of the prototype is excessive and must be reduced for the prototype function usefully during alpine skiing. The weight of the prototype could be reduced through the stringent application of finite element analysis on each individual part of the prototype.

The weight could further be reduced if the stationary parts of the prototype were machined as one individual part. This would increase the strength of the prototype and allow for further material removal. The decrease in height of the prototype, necessary for FIS riser compliance, would remove additional weight from the prototype.

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6.2   Potential Design Alterations

The most significant design alteration is the addition of Teflon tape to the cup's surface and the use of low friction coatings for the finger follower and cup. This would reduce the friction between the cup and finger follower and allow the prototype to function as desired. Without this alteration the prototype will do little to prevent either BIAD or phantom foot injuries.

Machining each stationary part from one piece of aluminum would help reduce the weight of the prototype and increase its strength. This single part would be longer at the base than the current prototype, which will reduce the moment applied by the prototype to the ski tip. This will also improve control of the ski.

The current height of the prototype must be reduced to conform to FIS riser standards. This reduction in height is possible without impacting the performance of the prototype. Each part must be refined through a series design iterations consisting of finite element analyses and redesign. This would allow all unnecessary material to be removed without impacting performance and would reduce both the height and weight of the prototype.

The greatest challenge in this design iteration process would be the redesign of the cup. The material selected for the finger follower would have to be stronger than Ti-6Al-4V so that both the finger follower and cup could be reduced in scale without experiencing failure under expected loads. Finally, a steel roller could be used if the coefficient of friction and function of the finger follower cannot be altered through a change in material and size. A roller would naturally result in a smaller coefficient of friction and if machined from steel could suffer a reduction in size without fear of failure.

7   Conclusions

ACL injury accounts for approximately $400 million dollars in medical bills annually (Christopher A. Brown, personal communication, September 2010). An under-binding plate system which displaces downwards and laterally at the heel could alleviate the two main modes of ACL injury, BIAD and phantom foot. Using axiomatic design, a prototype of an under-binding plate was designed and manufactured. Through the use of CAD software, a solid model was constructed to be used in CAM software. From the CAM software, CNC machines were used to manufacture each part of the prototype. The design went from a computer model to a physical prototype that was tested for functionality.

While this design is semi-successful, it would need to be improved further for real-world use. The prototype did show proof of concept that an under-binding plate system could be used to displace vertically and laterally to reduce ACL injury. If the system was refined further, pursuit of a patent could be advantageous.

APPENDIX

A. Injury Mechanisms

The phantom foot injury is usually equated with the following parameters:

1. Uphill arm back
2. Skier off balance to the rear
3. Hips below knees
4. Uphill ski un-weighted
5. Weight on inside edge of downhill ski tail
6. Upper body facing downhill ski

Figure 35: Phantom Foot injury mechanism

The phantom foot mechanism of injury causes large stresses to be applied to the ACL through tensile loading and rotational shear loading. This backward twisting fall causes the tail of the downhill ski to act as a lever, causing the top of the stiff ski boot to push the calf forward in relation to the knee. The forward strain from this lever action, combined with the twisting motion caused by the skier's body continuing downhill, create tremendous force on the ACL (Christopher A. Brown, personal communication, September 2010).

The other mechanism of injury that this under-binding plate reduces is Boot Induced

Anterior Drawer (BIAD). BIAD occurs most commonly when a skier is in the air and straightens

their legs. Because the legs are fully extended as they land, the tails of the skis hit the snow first,

creating large forces pushing forward on the boots. Just as in the phantom foot injury

mechanism, this forward pushing force on the back of the calf from the top of the tall, stiff boot

thrusts the knee forward, tearing the ACL (Christopher A. Brown, personal communication,

September 2010). An example of a BIAD event can be seen in Figure 36 below.
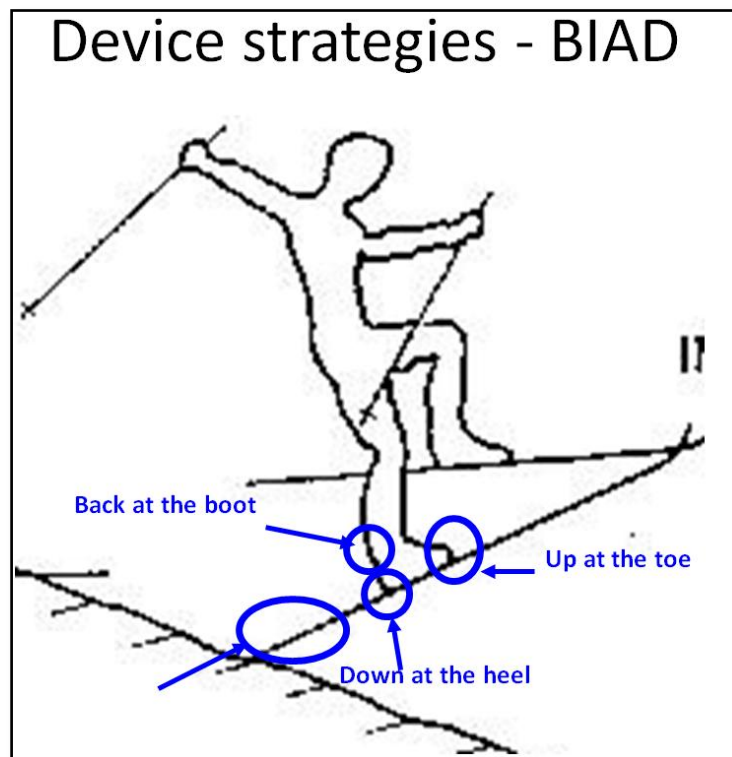

Figure 36: BIAD injury event

B. Constraints

Several constraints were necessary to ensure a properly functioning prototype in addition to the stated functional requirements. The first of these constraints was that the plate must perform as a hard binding during normal skiing conditions. This allows the user to have confidence that the DIN settings that are appropriate for modern bindings on the market are also appropriate for a binding utilizing the proposed plate prototype. This concept was further expanded with the next constraint; that the plate must be compatible with multiple makes of bindings on the current market. The plate was designed to be able to be drilled for multiple screw locations, to have a width not greater than the ski itself, and to not be smaller than standard binding attachment locations.

Another mechanical constraint is that the device should not absorb loads below the designated injury threshold. This ensures that the skier can maintain control while skiing and not increase the risk of injury to the skier. The maximum height from the sole of the boot to the ski was constrained to be to 2.165 inches to comply with FIS standards. Finally the device must resist environmental conditions in order to ensure proper function at all times.

Figure 37: Constraints in Acclaro

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C. Leaf Spring Calculations

To determine the dimensions required for the leaf spring, calculations were performed

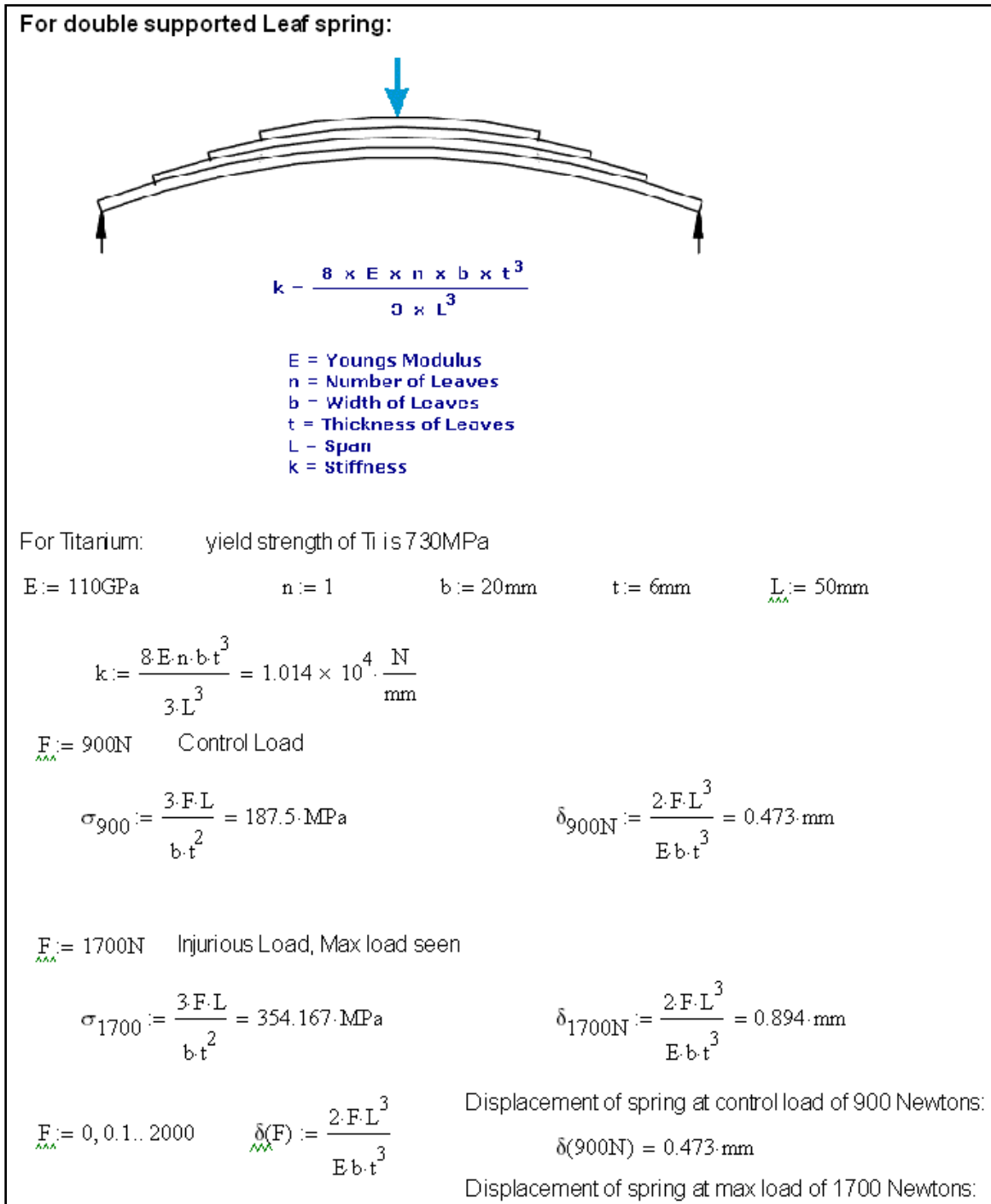using Mathcad. These calculations can be seen in Figure 38.

For double supported Leaf spring:

$$k = \frac{8 \times E \times n \times b \times t^3}{3 \times L^3}$$

E = Youngs Modulus
n = Number of Leaves
b = Width of Leaves
t = Thickness of Leaves
L = Span
k = Stiffness

For Titanium: yield strength of Ti is 730MPa

$E := 110GPa$ $n := 1$ $b := 20mm$ $t := 6mm$ $L := 50mm$

$$k := \frac{8 \cdot E \cdot n \cdot b \cdot t^3}{3 \cdot L^3} = 1.014 \times 10^4 \cdot \frac{N}{mm}$$

$F := 900N$ Control Load

$$\sigma_{900} := \frac{3 \cdot F \cdot L}{b \cdot t^2} = 187.5 \cdot MPa \qquad\qquad \delta_{900N} := \frac{2 \cdot F \cdot L^3}{E \cdot b \cdot t^3} = 0.473 \cdot mm$$

$F := 1700N$ Injurious Load, Max load seen

$$\sigma_{1700} := \frac{3 \cdot F \cdot L}{b \cdot t^2} = 354.167 \cdot MPa \qquad\qquad \delta_{1700N} := \frac{2 \cdot F \cdot L^3}{E \cdot b \cdot t^3} = 0.894 \cdot mm$$

$F := 0, 0.1 .. 2000$ $\delta(F) := \frac{2 \cdot F \cdot L^3}{E \cdot b \cdot t^3}$

Displacement of spring at control load of 900 Newtons:

$\delta(900N) = 0.473 \cdot mm$

Displacement of spring at max load of 1700 Newtons:

Figure 38: Leaf spring calculations

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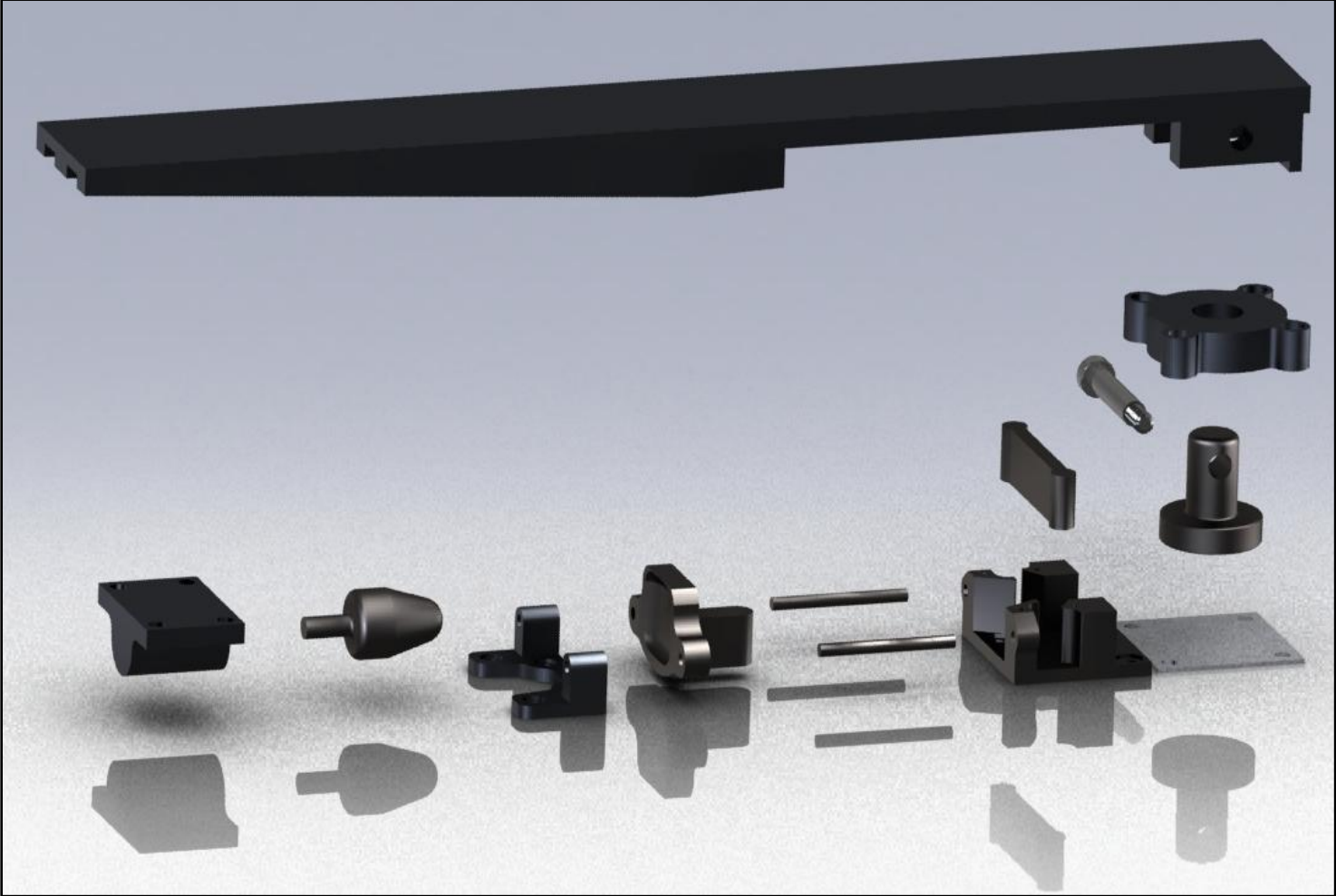
D. Exploded CAD rendering of prototype

Figure 39: Exploded CAD rendering of prototype

References

Brown, Christopher. (2010) Personal communication.

Brown, Christopher. ACL Injury Mechanisms presentation (2010).

Dodge, D. (2001) Ski Binding. US Patent application 20,020,101,063.

Ekeland, A. and Rødven, A., "Injuries in Alpine Skiing, Telemarking, and Snowboarding," Skiing Trauma and Safety: Thirteenth International Symposium, ASTM STP 1440, R.J. Johnson, M. Lamont, and J. E. Shealy Eds., American Society for Testing and Materials, West Conshohocken, PA, 2001, pp. 87-94.

Ekeland, A. and Rødven, A., "Injuries in Alpine Skiers, Telemarkers, and Snowboarders at Norwegian Ski Resorts," Skiing Trauma and Safety: Fourteenth International Symposium, ASTM STP 1440, R.J. Johnson, M. Lamont, and J. E. Shealy Eds., American Society for Testing and Materials, West Conshohocken, PA, 2003, pp. 97-104.

Ekeland, A. Rødven, A. and Sulheim, S., "Injury Rates and Injury Types in Alpine Skiing, Telemarking, and Snowboarding," Skiing Trauma and Safety: Fifteenth International Symposium, ASTM STP 1464, R.J. Johnson, J. E. Shealy, and M. G. Ahlbäumer Eds., American Society for Testing and Materials, West Conshohocken, PA, 2005, pp. 31-39.

Ekeland, Arne and Rødven, Andreas., "Injuries in Norwegian Ski Resorts 2002-2004," Skiing Trauma and Safety: Sixteenth International Symposium, ASTM STP 1474, R.J. Johnson, J.E. Shealy, and T. Yamagishi Eds., American Society for Testing and Materials, West Conshohocken, PA, 2006, pp. 1-7.

Ekeland, Arne, and Andreas Rødven. "Skiing and Boarding Injuries on Norwegian Slopes during Two Winter Seasons." Journal of ASTM International 7.4 (2010). Print.

Howell, R. (2005) Alpine Ski Binding Heel Unit. US Patent application 7,318,598.

Johnson, R.J., Ettlinger, C.F., and Shealy, J.E., "Skier Injury Trends," Skiing Trauma and Safety: Seventh International Symposium, ASTM STP 1022, R.J. Johnson, C.D. Mote, Jr., and Marc-Hervé Binet, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 25-31.

"Knee Injuries from Alpine Skiing - Ski Injury." 28 Apr. 2011. <http://www.ski-injury.com/specific-injuries/knee>.

Oberg, E.; Jones, F.D.; Horton, H.L.; Ryffell, H.H. (2000). Machinery's Handbook (26th Edition). Industrial Press.

Suh, N.P. (1990) The Principles of Design, Oxford University Press, New York.

Wunderly, G.S. and Hull, M. L., "A Mechanical Alpine Ski Binding with Programmable Release," Skiing Trauma and Safety: Seventh International Symposium, ASTM STP 1022, R.J. Johnson, C.D. Mote, Jr., and Marc-Hervé Binet, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 199-209. Oberg, E.; Jones, F.D.; Horton, H.L.; Ryffell, H.H. (2000). Machinery's Handbook (26th Edition).. Industrial Press.