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DESIGN OF AN ACL SAFE SKI ABSORPTION PLATE

A Major Qualifying Project Report

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by

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Abstract

The intent of this Major Qualifying Project is to design a device to reduce the risk of injury to the ACL while skiing. The method in which the device was designed utilized the axiomatic design principals to help facilitate the design processes while addressing customer needs and functional requirements. The device presented in this project is an absorption plate, connecting the binding to the ski and is intended to integrate with current ski equipment. ACL injuries are the commonly associated with a skier in a fall to the rear and a tall stiff boot pushing the calf forward. The objective of the absorption plate is to displace or rotate the heel about the ball of the foot, in turn displacing the boot cuff, in the event there are injurious loads applied to the back of the leg. This sequentially, reduces the applied loads to the ACL and thereby reducing the risk of injury.

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1. Introduction

The objective of this project it to design a device which reduces the risk of injury to the knee while skiing, specifically the anterior crucial ligament (ACL). The design of such a device holds significance because injury to the ACL is the most common traumatic injury occurring to alpine skiers (Johnson, et al., 2000). Common mechanisms which are causing injury to the ACL can be attributed to the equipment design. Serious knee sprains involving the ACL have shown the most significant increase over the course of a thirty four year study. An increase of injury rate by 194% was observed but with no significant change over the last decade (Johnson et al., 2000). Researchers from mountain resorts and countries have observed similar injury trends which suggest this is not an isolated phenomenon. In France, ACL injuries represent almost 13% of all ski injuries and have been steadily increasing since 1992 (Laporte et al., 2000). ACL and knee injuries are a common injury regardless of age, skill or gender in the sport of skiing, a problem which can be assumed to be present regardless of location (Greenwald and Toelcke, 1997; Cadman and Macnab, 1996). Therefore, a need is present throughout the ski industry for injury preventative equipment.

1.1 Mechanisms of Injury to the ACL

Researchers have observed the overall rate of injury has decreased but the rise in severe knee sprains indicates the factors which contribute to knee injury are still at work (Johnson et al., 1997). It can be conjectured that modern equipment has addressed factors which contribute to lower leg fractures and other injuries but failed to address the issues facing knee sprains and tears, as evident in observed injury rates. Research has identified two mechanisms for injury to the ACL with modern equipment, the phantom foot and the boot induced anterior drawer (BIAD). By understanding the underlying principals of each mechanism, the inherent flaws of modern equipment are identified, resulting in a design which addresses the problem. Both are a result of the tall, stiff boot pushing against the calf and the body generally falling or behind the knee, resulting in forces in the opposite direction. These forces stretch the tendon to beyond the limits of its mechanical properties, typically ensuing injury.

The Phantom Foot

The phantom foot is the more complicated injury mechanism. It involves the tail of the ski acting as a lever arm in the opposite direction of the foot. It is the most common ACL injury scenario, consisting of six components. The mechanism is the result of three types of situations: attempting to get up following a fall, attempting a recovery from an off balanced position, and attempting to sit down after losing control. The six elements are:

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

Through the video analysis, in every ACL rupture all six of the components were observed. Information on the “Phantom Foot” was taken from Vermont Safety Research’s “ACL Awareness Guide.” “When all six elements are present, injury to the ACL of the downhill leg is imminent” (Vermont Safety Research, 2002).

The Boot Induced Anterior Drawer

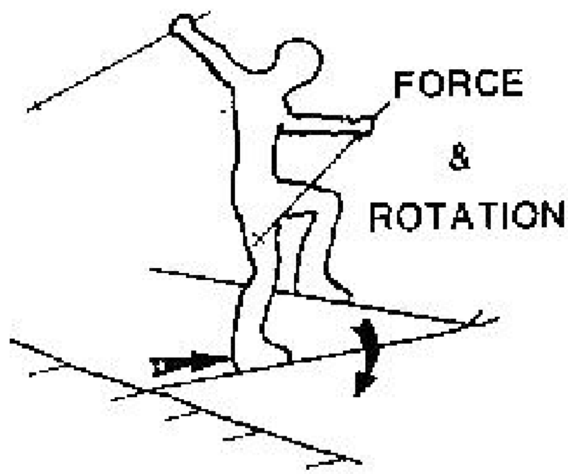


Figure 1

The boot induced ACL injury is considered the easiest injury to avoid altogether. It is an injury sustained by hard impact by off balanced skiers to the rear, as shown in Figure 1. When a skier lands from an aerial maneuver the tail of the ski lands first. As the center of pressure from the snow moves up the tail of the ski towards the skier, the pressure against the back of the leg from the boot increases. Natural instinct fully extends the legs and contracts the surrounding muscles to hold it in position which is coordinated simultaneously with the backward rotation of the arms. By the time the ski contacts the snow directly under the boot heal, everything that can be stretched has been stretched and everything which can be compressed has been compressed. With no more flexibility in the system to absorb the severe impact of the boot heal, the back of the boot is able to drive the tibia out from under the femur. This impact will partially tear or completely sever the ACL (Vermont Safety Research, 2002).

1.2 State of the Art

Knee Friendly Equipment

Ski equipment manufactures and researchers have tried to address the need for knee protective equipment, specifically to the ACL. Research has been able to identify the mechanisms behind injury and the trends associated with such injuries. Design has incorporated research's findings to address issues and also improve safety and efficiency inferred by the data. In addressing ACL injuries, spotlighting are two recent efforts on the corporate side which have had limited success. The rear release system, or RRS, produced by Lange for their boots and the Pivogy binding, produced by Line Skis. Research's involvement with new technology ideas and design has been instrumental in the reduction of ski injuries which have been integrated into corporate equipment. Some designs do not make it to the production line, such as Hull's electromechanical binding but are nonetheless important to finding solutions.

Lange RRS Boot

Figure 2

The Lange RRS boot addresses a major injury problem, ACL injury, and integrates it as a usable solution with common technology and equipment, see Figure 2. The rear spoiler of the boot is designed to give when an injurious force is present on the back of the leg. Essentially the RRS is a non-Grashof linkage which remains in a locked position supporting the calf until a force breaks the linkage and allows the rear spoiler to rotate backwards, preventing injury to the ACL (Norton, 2004). The magnitude of force which is required to break the linkage is set by adjusting a preloaded spring in the RRS, letting skiers of varying size and mass utilize the boot. After the RRS boot engages, all the skier needs to do is lean forward and the boot will reset the spoiler to its locked upright position.

Line Pivogy Binding

Figure 3

Line Skis developed a binding to help reduce the risk of injury to the ACL also by integrating it as a usable solution with common technology and equipment, see Figure 3. The main feature of the Pivogy binding is dual pivots, one about the toe and one about the heel of the boot. These pivot points allow the boot the rotate out ward or inward about the toe piece or heal piece of the binding, resulting in a dramatic reduction in torque to the knee (Line, 2007). This is a variant from the common ski binding, allowing only one pivot about the heel but. To prevent injury, the operational objective of the binding is total release by removing all forces to the lower leg.

Electromechanical Ski Binding

Hull, Swanstrom and Wade (1997) identified three limitations which are inherent to current binding designs, impeding bindings from a timely release and reducing their effectiveness to prevent injury at the knee. Injury to the knee most often is a result of twisting, relative between the boot and the upper body, and anterior bending. The limitations they identified were:

1. Bindings limit the load transmitted to the lower leg and knee, using lateral forces at the toe as indicators of torsion in the knee and lower leg. Attributed as a good indicator, it fails is when coupled with extraneous moments.
2. The level at which a binding releases in twist impacts the fixed release level. The binding limits the load to the knee but needs to cap the load below the strength of the knee, a fluctuating value and is dependent on the amount of muscle activity and knee angle.
3. Bindings are ineffective in anterior and posterior bending cases as they are dependent on upward forces at the heel as indicators of bending moments in the lower leg.

A prototype addressed the limitations by incorporating an electromechanical release mechanism which reliably released the boot from the ski. The binding is managed by electrical commands processed by a controller based on signals from strain gages and dynamometers.

Other Equipment

(a) (b)

Figure 4

The Marker Biometric binding, Figure 4 (a) (Marker, 2007), and Tyrolia Diagonal Toe binding, Figure 4 (b) (Tyrolia, 2007), are of similar design. Although they do not explicitly claim to reduce the risk of injury to the ACL, the binding is designed to reduce forces applied to the knee. In the event upward pressures are too large at the toe, both bindings have an upward release mechanism. The upward release is a product of forces and moments acting upon the toe piece, not necessarily those acting on the ACL. By completely ejecting the boot, the bindings consequentially will reduce the force of the boot driving the tibia forward relative to the femur.

Equipment Discussion

Each device reduces the risk of injury to the ACL but their approach is uniquely different. The Lange RRS boot provides a reduction of forces applied to the ACL directly at the point of pressure, the spoiler of the boot. The boot can be considered the most personal item in ski equipment, it is the initial link from your body to the ski. To optimize comfort and performance ski boots may require alteration work done for a proper fit. The Lange boot is designed to be compatible with current binding-ski systems without modification.

Line's Pivogy binding and Hull's electromechanical binding reduce the risk of injury to the ACL by total release of the boot. They are unique bindings which have different mechanisms for release from traditional bindings. Both bindings integrate with current boot designs but may not be compatible with all skis, as primary binding-ski connections are becoming common among new equipment. The Marker Biometric and Tyrolia Diagonal Toe bindings are both fully integrated into current equipment systems, as they are produced by major ski equipment manufactures. An advantage because almost all skier use equipment from major ski equipment companies and as suppliers, they have a driving force over what the public uses. These bindings may inadvertently reduce the risk of ACL injury by total ejection, they do not explicitly claim or advertise that fact. Additionally, completely releasing the skier from the binding may reduce the risk of knee injury but may also cause another injury similar to one caused by inadvertent release in traditional bindings.

1.5 Approach

Original Design

This project proposes a device which reduces the risk of injury to the ACL, primarily in the event of a boot induced injury. The device should only initiate a response when potentially dangerous loads to the ACL are present. Also, it should be used in conjunction with current boot-binding-ski (BBS) equipment without interfering with the safety functions or performance of the ski equipment. A reduced risk of all injury in the sport of skiing can be attributed to the evolution of BBS equipment. A device which incorporates current BBS equipment safety features and reduces the risk of injury to the ACL targets the problem without requiring all new equipment to be designed.

In order to design a device which reduces the risk of injury to the ACL, the mechanisms which are causing injury need to be understood. In both the phantom foot and boot induced instances the skier is off balanced to the rear and the ski tail is acting as a lever because the boot-binding system does not release the skier. The forces generated from each incident are large enough to tear the ACL but occur over a short amount of time, approximately 0.1 seconds (Bally et al., 1989). By distributing the force over time it may lead to a lower risk of injury to the ACL. A device to reduce risk of injury must be able to respond effectively to large instantaneous forces and recover with relative speed after the forces subside to prevent unintended consequences

Current boot-binding-ski systems do not allow for an injurious force to be absorbed by the equipment. In the event of an injury, there is a zero displacement of the boot relative to the ski see Figure 5. A devise which is able to displace the boot and absorb a portion of the forces generated at impact would prevent injury to the ACL. To demonstrate how a device could avoid reaching the injury threshold, the response behavior to forces applied to the ACL is modeled, see Figure 6. Note the shape of the curve, the top half is to absorb the forces which cause injury while the bottom half is to aid the device to return to zero displacement. Both figures are models based on a force applied and held at the same value for approximately 0.15 seconds. This is done for demonstration purposes and does not represent forces which are likely to be observed in normal skiing.

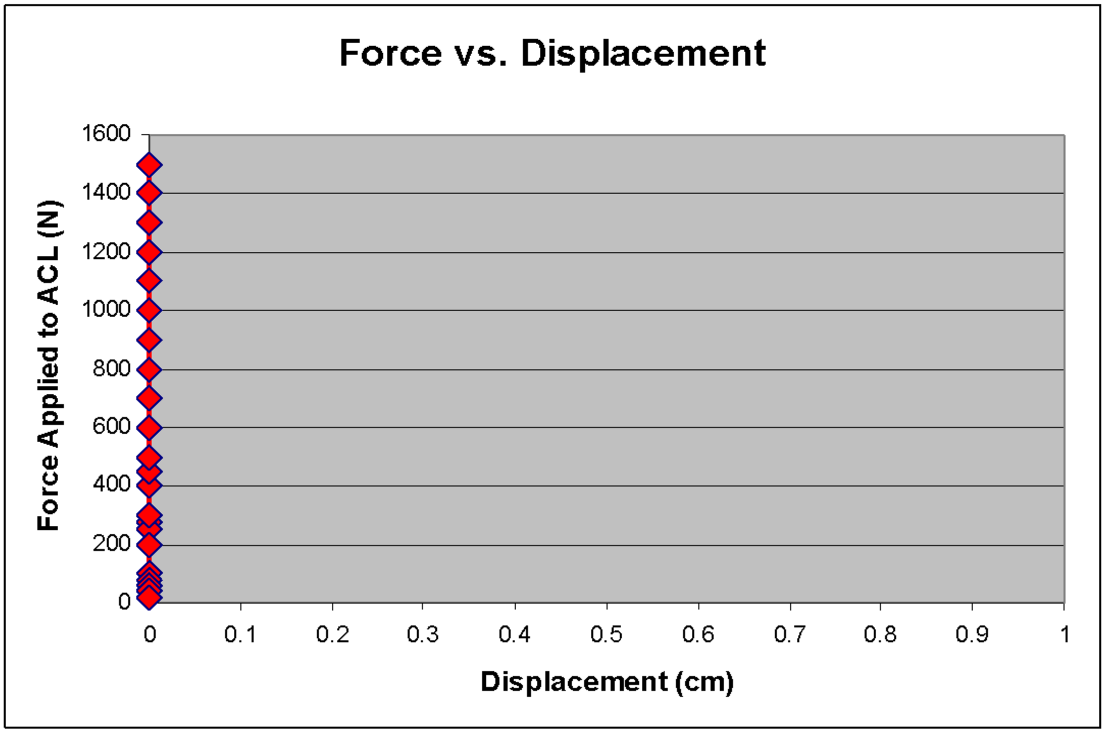


Figure 5

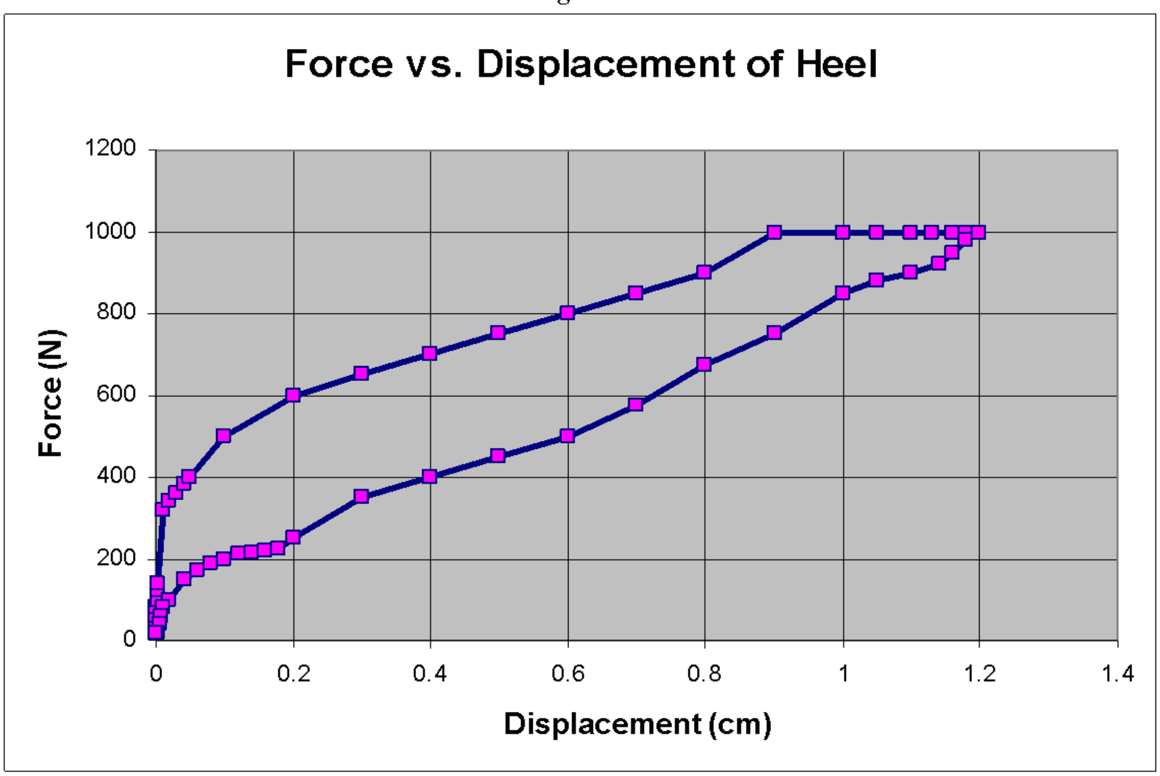


Figure 6

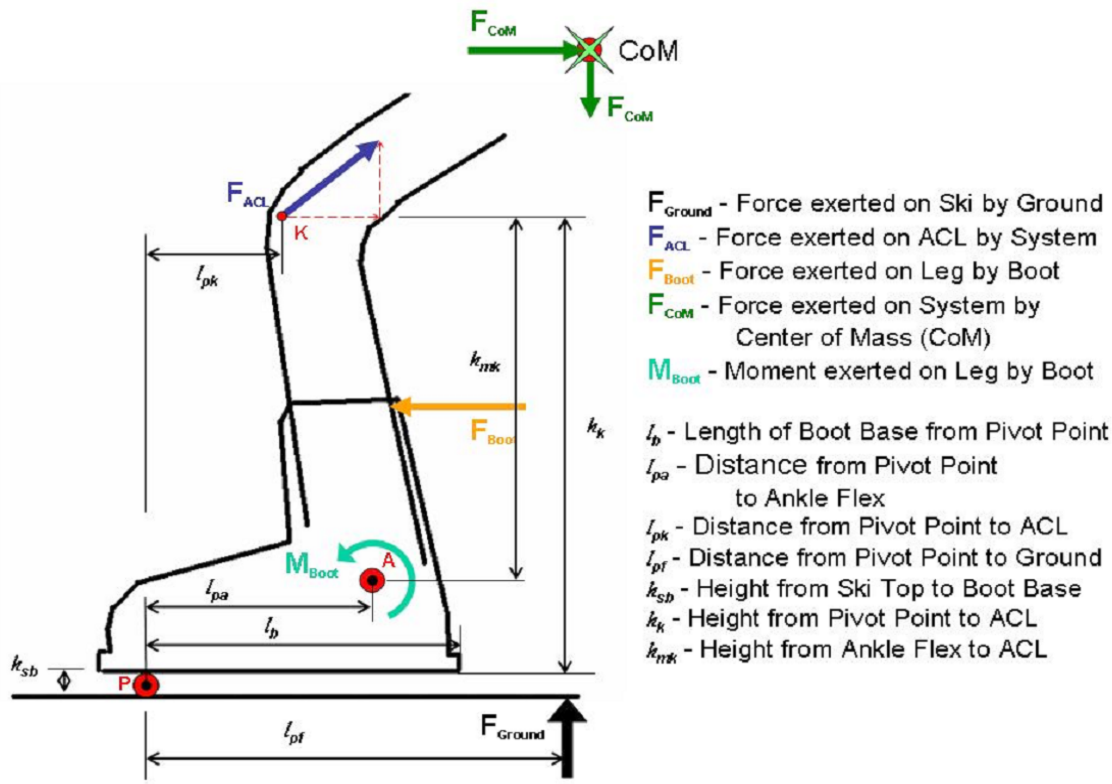
Considerations

Basic requirements must be satisfied to meet requirements driven by the consumer. The device must restrain the skier to the ski and transmit the moments generated by the skier to the snow. These moments need to be transmitted reliably and in a manor which doesn't interfere with normal skiing technique and maneuvers. The device needs to be rigid torsionally and be able to withstand impacts and severe loads. The device can not be bulky or significantly heavy, rather a lightweight compact design would be less obtrusive.

When the device engages it must only engage when injurious loads are present and assist in returning to its original position shortly thereafter. Additionally, if the device engages with injurious loads absent on the ACL, unintentional consequences may occur. These consequences may result in a loss of control, balance, an inadvertent release or unforeseen damage to the knee or other body parts. The device can not recognize the difference between a dangerous maneuver and a safe one preformed by a skier, it must respond to the torques which may cause injury. Forces on the knee are influenced by many factors, the origin of these factors need to taken under consideration.

Free Body Diagram

To fully understand the forces in the event of a boot induced ACL injury and how they are applied a free body diagram of the system was generated. Since the BBS equipment is not one piece, a free body diagram is necessary for each of the components including the human leg/body. Figure 7 was generated to help conceptualize the forces and loads.



F_CoM
CoM
F_CoM
F_ACL
K
l_pk
k_mk
F_Boot
k_k
M_Boot
A
l_pa
l_b
k_sb
P
l_pf
F_Ground
F_Ground - Force exerted on Ski by Ground
F_ACL - Force exerted on ACL by System
F_Boot - Force exerted on Leg by Boot
F_CoM - Force exerted on System by Center of Mass (CoM)
M_Boot - Moment exerted on Leg by Boot
l_b - Length of Boot Base from Pivot Point
l_pa - Distance from Pivot Point to Ankle Flex
l_pk - Distance from Pivot Point to ACL
l_pf - Distance from Pivot Point to Ground
k_sb - Height from Ski Top to Boot Base
k_k - Height from Pivot Point to ACL
k_mk - Height from Ankle Flex to ACL

Figure 7

2. Method

The analysis and design for this project was done using the Pro/Engineer Wildfire2 CAD software. The device was modeled and assembled in Pro/E's Standard application. The Mechanism application in Pro/E was used to assign forces and constraints as well as analyzing the performance of the part. The device is intended to go between the ski and binding, effectively acting as a riser plate connecting the binding to the ski when not engaged. When a damaging force to the ACL is present the device will displaces the heel closer to the ski. The device is designed to return to its initial position and the threshold of release is controlled an adjustable system.

2.1 Axiomatic Design

To address all the issues facing the design of such a device, axiomatic design was used to help focus the process and identify the best solution. Axiomatic design helps to prevent and identify coupling of functions inherent to a design. Additionally, by considering costumer needs, functional requirements and design parameters simplifies the design process. Table 1 is an axiomatic design decomposition table created for the design of the device. In order for the design to satisfy the axiomatic design method each design parameter must correspond to a functional requirement.

Functional Requirements		Design Parameters	
0 FR	Reduce Risk of ACL Ski injuries	0 DP	Device for reducing ACL ski injuries
1	Restrain Binding to Ski	1	Absorption Plate restraint system
1.1	Restrain binding to plate	1.1	Connection for restraining binding to plate
1.2	Restrain plate to ski	1.2	Connection for restraining plate to ski
1.3	Allow ski flex under the plate	1.3	Connection for allowing ski to flex under the plate
2	Transmit control moments from the binding to the ski	2	Structure for Skier generated moments for control
2.1	Transmit moments about the X-Axis at toe joint	2.1	Structure for transmitting moments about the X-Axis
2.2	Transmit moments about the Y-Axis at toe joint	2.2	Structure for transmitting moments about the Y-Axis
2.3	Transmit moments about the Z-Axis at toe joint	2.3	Structure for transmitting moments about the Z-Axis
2.4	Prevent forward rotation when at rest	2.4	Device for preventing forward rotation about Z-Axis
3	Filter out dangerous torques to skier ACL	3	System for filtering out dangerous loads to skier ACL
3.1	Limit degree of rotation of absorption plate	3.1	Design limiting the degree of rotation
3.2	Achieve desired Force-Displacement curve	3.2	Design achieving desired force-displacement curve
3.3	Restore Plate to initial orientation after filtering	3.3	System which restores initial orientation
3.4	Adjust Filtering for different skiers	3.4	Mechanism which allows filtering adjustments
4	Transmit Cam displacement	4	System for transmitting the Cam displacement
4.1	Allow Cam to rotate about the Z-Axis	4.1	Structure for allowing rotation about Z-Axis
4.2	Control Cam Rotation	4.2	System for conroling cam rotation
4.3	Constrain Slider Bar to Bottom Plate	4.3	Connection for securing Slider bar to Bottom Plate
4.4	Constrain Cam Arm to the Slider Bar	4.4	System for constraining Cam Arm to slider bar
4.5	Allow slider to move axially along the slider bar	4.5	Connection allowing slider to move axially on bar
4.6	Restore Cam to initial position	4.6	Profile to restrain cam to initial position
4.7	Dampen the slider displacement	4.7	Structure for dampening slider displacement
5	Prevent snow/ice from jamming the system	5	Design preventing snow/ice jams
6	Reduce risk of unintended injury	6	Design of smooth and rounded features
7	Minimize weight	7	Design for saving weight

Table 1

2.2 Constraints

There are several constraints which need to be identified as they are inherent to the function and success of the design. Constraints are significant factors which must be considered, such as its size, weight and cost. The taller a riser plate is, the larger the moments generated by the skier become. Downhill ski racers must adhere to strict rules as to the maximum stack height allowed, the distance between the ski boot sole to the bottom of the running surface of the ski. Both men and women are only allowed 55 mm, anything beyond that distance is a violation of FIS and USSA rules (FIS, 2006). Another constraint on the design is the weight of the device. The device is to be used in conjunction with current BBS equipment, the goal is to produce a device which will not significantly contribute to the overall weight of the system. Cost is the final constraint because the price of this device is important to the consumer. The average price for new boots, bindings and skis can be assumed to cost approximately $500 to $800; this device will become undesirable to a consumer if it costs significantly more.

2.3 Customer Needs

It is important to identify what the customer needs and wants in the design of such a device. In the ski industry, consumers look for a product that is reliable, versatile and safe.

Functionality

The performance of a devise is a product of its design, a devise which consistently performs properly is a necessity for ski equipment. Due to the variation of size, weight and gender of each skier there is a need for adjustability in a piece of equipment. The device needs to be adjustable such that a consumer can customize it for a proper fit but also be robust enough to not need constant maintenance. With use, parts should be expected to wear and further adjustment will be required. Flex, especially in the mid section, is crucial to a ski's performance greatly affecting the arc generated by the skier. Ski brakes retract up and under the boot when engaged as to not grind or drag on the snow, this a function the device should share as to not interfere with normal ski maneuvers in anyway.

Versatility

Since one of the fundamental concepts of the design is to be used in association with current BBS equipment the device needs to be designed in a way as to be transferable between brands of similar products. For the device to be practical and usable for the greatest population size, how it connects to the ski and how the binding connects to the device is considerable. For the device to be transferable from skis of different makes and models the connection needs to be accepted by a common method. The device also needs to be able to accept bindings of different makes and models and secure them appropriately. The device to needs to be adjustable for skiers not just of varying size and gender but needs to work for skiers of all skill level, in order to reduce the risk all of ACL injuries.

Control and Safety

Proper ski technique requires a considerable level of control of body movements on the part of the skier to remain safe and in command of their speed and trajectory. As a skier performs a maneuver, they should trust their equipment to not be faulty. Faulty or poorly designed equipment may result in loss of control or injury. In current BBS equipment, bindings are the only part which controls the release of a skier. They have been known to inadvertently release skiers while they perform maneuvers which they feel they have control over (Shealy et al., 1999). This device can not inadvertently engage or it risks causing unintended injury. An inadvertent engagement may cause the skier to loose balance and control, which may result in a fall or inadvertent release of the bindings. It is assumed that there is some threshold where the degree of toe raise, relative to the heel, is too large for a skier to remain in control.

2.4 Functional Requirements

The main functional requirement is FR0, to reduce the risk of ACL ski injuries. The requirement is accomplished through the design of an absorption plate. Functional requirements, or FRs, are formulated on consideration of the customer needs and research. FRs are compiled into a concise hierarchical list which describes the function of the device which satisfies the costumer needs and research (Brown, 2005). Axiomatic design requires functional requirements to be collectively exhaustive and mutually exclusive, CEME. Each FR can be decomposed into subsequent levels of functional requirements as long as each level can be deemed CEME.

FRs		Functional Requirements	Description
FR0		**Reduce the risk of ACL ski injuries**	An absorption plate which reduces the risk of injury to the ACL.
FR1		**Restrain Binding to Ski**	The absorption plate is to connect the top of the ski to the bottom of the binding and not interfere with the performance of the ski. The plate maintains a continuous connection between both top and bottom plates.
	FR1.1	**Restrain Binding to Absorption Plate**	The binding must be securely fastened to the top plate of the absorption plate as to not allow the binding to separate from the top plate. Additionally, the top plate needs to be able to secure different sizes, makes and models of bindings and allow proper placement.
	FR1.2	**Restrain Ski to Absorption Plate**	The ski must be securely fastened to the bottom plate of the absorption plate as to not allow the ski to separate from the bottom plate. Additionally, the bottom plate needs to be able to secure different sizes, makes and models of skis and allow proper placement.

	FR1.3	**Allow Ski to flex under the Absorption Plate**	The connections the device makes can not impede the shape of the arc the ski makes under the pressure of a turn. Skis are designed to utilize the entire arc generated by the ski flexing in a turn, anything less is inhibiting its performance.
FR2		**Transmit Control Moments from the Binding to the Ski**	The absorption plate transmits the control moments generated by the skier to the ski. These control moments are the forces which allow a skier to remain in control of their speed and trajectory. The device secures the top plate to the bottom plate and is sturdy enough to withstand forces acting at compound angles.
	FR2.1	**Transmit Moments about the X-Axis of the Absorption Plate Joint**	The moments generated about the X-Axis, tip to tail, directly transmit to the edges of the ski as they are inline with the axis. The forces will alternate in a positive and negative direction as the skier makes turns, transitioning edge pressure form one side to another.
	FR2.2	**Transmit Moments about the Y-Axis of the Absorption Plate Joint**	The moments generated about the Y-Axis, perpendicular to the top of the ski, are caused by maneuvers which have horizontal rotation about the skier. They are significant forces as they are the indicator forces which release the boot from the toe piece in a twisting release.
	FR2.3	**Transmit Moments about the Z-Axis of the Absorption Plate Joint**	The moments generated about the Z-Axis, side to side, directly transmit the amount of pressure the ski has on the snow beneath. The greater the forward rotational moments are the more pressure there is on the front half of the ski which is optimal for ski performance. When the tail of the ski is acting as a lever and potentially dangerous moments are present, the moments will be transmitted to the top plate about the Z-axis.
	FR2.4	**Prevent Negative Rotation about the Z-Axis when at rest**	The moments generated about the Z-Axis in the negative direction are directly related to the amount of pressure on the front of the ski. No negative rotation of the toe and heel is acceptable from the initial position as it may cause a loss of control.

FR 3		**Filter out Dangerous Loads to the ACL**	The absorption plate is designed to filter out dangerous loads to the ACL in order to prevent injury, as observed in the boot induced and phantom foot mechanisms. It is the most important feature of the device and needs to respond immediately when forces are present. The loads which contribute to injury are in the negative direction about the Z-axis. The plate is designed to compress, absorbing the forces on the ACL by rotating when a rearward load is forcing the skier to the back and their ski is forcing their boot forward. For the device to compress, the moments need to break the threshold set by the absorption plate. The plate allows displacement of the boot cuff thereby reducing the risk of injury to the ACL. The force is absorbed, injury is avoided and the skier remains in control.
	FR3.1	**Limit the Degree of Rotation of the Absorption Plate**	In both mechanisms of injury the skier is off balanced to the rear and the ski is acting as a lever. By compressing the plates together it reduces the forces exerted on the ACL. However, there is a limited amount of room the plates are allowed to rotate due to the constraints of the system. Additionally, limiting the degree of rotation gives the skier the best chance to recover from their maneuver while avoiding injury.
	FR3.2	**Achieve Desired Force-Displacement Curve**	In order to prevent injury yet allow the skier to remain in control and to perform maneuvers with confidence the absorption plate needs to be able to respond to appropriate forces. As the forces increase the displacement needs to be relatively small until it reaches the threshold set by the device to prevent injury. At that point the displacement increases as the force continues to increase but remains under the injury threshold.
	FR3.3	**Restore Absorption Plate to Initial Orientation after Filtering**	To give the skier the best chance to remain in control after the absorption plate engages the plate must also disengage almost immediately. After injury has been avoided the force on the system will decrease along with the displacement to aid the plate in returning to its initial position.

	FR3.4	**Adjust Filtering for Different Skiers**	The system is adjustable for a range of target groups in order to limit the maximum forces exerted on the ACL. Criterion for adjusting filtering levels is based on the skier's age, gender, height and weight as each group is susceptible to ACL injury.
FR4		**Transmit Cam Displacement**	The cam system is the main device which controls the displacement of the absorption plate. As the cam rotates its movements are translated into displacement of the top plate with respect to the bottom plate.
	FR4.1	**Allow Cam to rotate about the Z-Axis**	The cam is constrained as to only allow rotation about the Z-axis and no displacement within its housing. The Z-axis is perpendicular to the plane the top plate rotates when the absorption plate compresses.
	FR4.2	**Control Cam Rotation**	The rotation of the cam is controlled by the force the cam exerts on the follower to displace it. The speed at which the cam is allowed to rotate is controlled by the cam arm.
	FR4.3	**Constrain Slider Bar to Bottom Plate**	The slider bar connects the slider to the absorption plate, it is secured to the bottom plate.
	FR4.4	**Constrain Cam Arm to Slider Bar**	The cam arm is attached to the back of the cam and rotates at the same speed the cam rotates about its axis. The end of the cam arm is secured to the slider bar by way of the slider, controlling its displacement and restraining its movement to the same plane the top plate moves in.
	FR4.5	**Allow Slider to move axially along the Slider Bar**	The slider is allowed to move axially along the slider bar to respond to the displacement of the cam arm.

	FR4.6	**Restrain Cam to Initial Position**	The cam profile is designed to encourage the follower to remain in its initial position. Additionally, by elongating the vertical axis it encourages the follower to return to its initial position.
	FR4.7	**Dampen the Slider Displacement**	To control the speed at which the slider moves dampeners are used along the axis of the slider bar. The Dampeners are used to ensure the slider does not reach the end of its travel too quickly but still allowing the top plate to compress.
FR5		**Prevent Snow and Ice Jams**	It is important that the absorption plate does not jam up by ice or snow getting lodged between the top and bottom plate. If snow or ice were to get lodged the device would see a significant reduction in its performance and ability to keep the ACL safe.
FR6		**Reduce Risk of Unintended Injury**	This absorption plate is intended to reduce the risk of injury to the ACL. Additionally, there is a risk the user may become injured by other mechanisms while skiing. By rounding edges and sharp corners it may reduce the risk of injury if a skier was to collide with the equipment say from a fall resulting in a release or run away ski.
FR7		**Minimize Weight**	The absorption plate has been designed to keep its weight to a minimum while still maintaining the structural integrity of the plate. This product is be used in conjunction with current BBS equipment which already is of considerable weight. The total weight of all the equipment must be considered as heavier equipment makes the skier work harder.

Table 2

2.5 Design Parameters

The main design parameter is DP0, an absorption plate which reduces the risk of ACL ski injuries. Design parameters, or DPs, are formulated based on accomplishing the FRs and are part of the physical domain. DPs describe how the design looks, its physical attributes, and may include items such as a bill of materials and blueprints. Only one DP can correspond to each FR in complying with the independence axiom (Brown, 2005).

DPs		Design Parameters	Description
DP0		**A plate which reduces the risk of ACL ski injuries**	A plate which absorbs the forces on the ACL, reducing the risk of injury
DP1		**Absorption Plate Restraint System**	The absorption plate needs to be securely fastened to the skis and bindings in a method which can integrate modern equipment and use current mounting practices. Using an approach to connect the ski to the binding which is similar to that of a riser plate, the method of interface will ensure the absorption plate can be mounted easily and properly aligned. The top and bottom plates are connected by a rigid joint connection, which resists movement or rotation in all directions except the Z-axis. The joint is located just below the ball of the foot.
	DP1.1	**Connection for Restraining Binding to Plate**	The binding is connected to the top plate of the absorption plate in same manor bindings are attached to skis without or without a riser plate. Holes are to be drilled and short screws are to be sunk into the top plate. The one consideration for placing the binding is the location of the ball of the foot. The toe piece needs to be aligned such that the ball of the foot is directly over the joint.
	DP1.2	**Connection for Restraining Plate to Ski**	The ski is connected to the bottom plate of the absorption plate in same manor riser plates are attached to skis. Counter sunk holes are predrilled and short screws are to be sunk into the ski through the top plate.

	DP1.3	**Connection for Allowing Ski Flex beneath Absorption Plate**	In order to permit the ski to flex freely beneath the absorption plate, a flexible connection of sorts is used. The connection maintains a safe and constant connection by using predrilled elongated countersunk screw holes, set in the ends of the bottom plate in the direction of the length of the ski. As the ski flexes, the screw heads will be displaced along the elongated holes but will maintain a secure connection.
DP2		**Structure for Transmitting Skier Generated Control Moments**	To transmit the control moments generated by the skier, a rigid rotating joint which can withstand loads and impacts from compound angles and maintain a solid connection. The joint connection is as wide as the bottom plate, interlocking it to the top plate with a long pin.
	DP2.1	**Structure for Transmitting Moments about the X-Axis**	The primary structure which transmits the alternating control moments generated by the skier about the X-axis is the absorption plate joint. The width of the joint and its unbending properties perpendicular to the axis of rotation is what transmits the moments to the ski edges.
	DP2.2	**Structure for transmitting moments about the Y-Axis**	The Primary structure which transmits the moments generated by the skier about the Y-Axis is the absorption plate joint. The joint is a feature built into the top and bottom plate which resists rotation perpendicular to its axis of rotation. The joint resists rotation about the Y-axis due to its rigid design and allows the moments to be transmitted to the toe piece as indicator forces for a twist release.
	DP2.3	**Structure for Transmitting Moments about the Z-Axis**	The primary structure which transmits the moments generated by the skier about the Z-axis is the top plate of the absorption plate. The joint bends in this direction, maintaining the top plate's rotation in the same plane as the bottom plate, perpendicular to the Z-axis. The length of the top plate and the attached binding is what transmits the moments to the absorption plate about the Z-axis, and in turn to the ski, resulting as pressure on the snow.

	DP2.4	**Device to Prevent Negative rotation about the Z-Axis**	To prevent negative rotation of the top plate from its initial position, the moments generated by the skier about the Z-axis need a blocking device. A stopper is placed in the front of the absorption plate, between the two plates and below the toe piece to obstruct displacement. The stopper is a hard rubber compound which helps cushion the impact the top plate makes as it returns to its initial position.
DP3		**System for filtering out dangerous loads to the ACL**	To filters out dangerous loads to the ACL the absorption plate rotates about the joint which connects the top and bottom plates. The compression of the plates is controlled by a spring loaded cam-follower system, which only allows cam rotation once loads break the threshold set by the follower.
	DP3.1	**Design Limiting the Degree of Rotation**	The absorption plate is restricted in the amount of rotation it is allowed to move. From its initial position, the top plate has only 5.1 degrees of rotation before it reaches the bottom plate.
	DP3.2	**Design Achieving Desired Force-Displacement Curve**	In order achieve the desired force versus displacement curve a cam mechanism was designed. The fundamental property of a cam controlled by a spring loaded follower is it requires a moment applied to the cam to rotate thereby displacing the follower. As the cam rotates, its profile determines how much force is required to displace the follower.
	DP3.3	**System which restores initial orientation after filtering**	The cam-follower system aids the absorption plate in returning to its initial position. There is not enough displacement available in the device for the cam to rotate beyond its long axis. Therefore the once the top plate has reached the end of its travel, the follower is under greater pressure due to the rotation of the cam. The spring force is pushing against the cam assisting it in rotating back to its initial position, a lower pressure.
	DP3.4	**Mechanism which allows Filtering to be Adjusted**	The primary mechanism to adjust filtering is adjusting the spring force on the follower. The spring force is controlled by adjusting the preload screw, by increasing or decreasing the amount of displacement the spring is allowed

			to compress. Similar to the DIN settings on current alpine ski bindings.
DP4		**System for transmitting Cam Displacement**	The cam is part of the cam arm which acts as a link between the top and bottom plate. As the cam rotates, the cam arm rotates at the same rate. The displacement of the cam arm controls the rate at which the top plate compresses.
	DP4.1	**Structure allowing Cam to Rotate about the Z-Axis**	The cam and spring loaded follower along with their associated housing is secured to the tail end of the top plate plate. The cam is oriented to keep the axis of rotation perpendicular to the plane the absorption plate compresses in, parallel to the Z-axis.
	DP4.2	**System which Controls the Cam Rotation**	The rotational moment of the cam is controlled in combination with the amount of force exerted on it by the spring loaded follower and also the force the cam exerts on the follower when displaced. The rotational speed of the cam is controlled by the displacement of the end of the cam arm.
	DP4.3	**Connection securing the Slider Bar to the Bottom Plate**	The slider bars is secured along the center line at the tail end of the bottom plate, parallel to the plane of compression. It is attached by screws on the underside of the bottom plate.
	DP4.4	**System Constraining Cam Arm to Slider Bar**	The cam arm is attached to the slider bar through its connection with the slider. The slider is allowed to rotate freely about the axis perpendicular to the plane of compression, located at the end of the arm.
	DP4.5	**Connection allowing the Slider to move axially along the Slider Bar**	The slider maintains a constant connection and orientation along to the axis of the slider bar. As the slider moves along the slider bar the cam arm rotates about its connection to the slider, perpendicular to the plane the slider moves in.

	DP4.6	**Profile to Restrain Cam to Initial Position**	The cam profile is designed to restrain the cam to the initial position unless the forces break the threshold. At the initial position, the cam face against the follower is profiled as a flat surface. This is to prevent rotation of the cam prior to set limit of the loads acting upon the absorption plate.
	DP4.7	**Structure for Damping Slider Displacement**	Dampeners are added to the slider along the axis of the slider bar, limiting the speed at which the slider can move.
DP5		**Design Preventing Snow and Ice Jams**	The design has no major feature which prevents snow and ice jams from occurring or any debris or particle from interfering from the surrounding environment.
DP6		**Design of Smooth and Rounded Features**	The device has been designed with the intent to reduce the risk of unintended injury. Edges have been rounded to remove sharp corners as a precaution for the safety of the skier.
DP7		**Weight Saving Design**	The absorption plate has many features which have been designed to minimize weigh and remove excess material but also maintain its structural integrity. The underside of the top plate is channeled to maintain its rigidity but cut out excess weight. Material has been removed from the housing of both the spring loaded follower and cam to cut out weight.

Table 3

2.6 Design Matrix

To check for coupling between DPs and FRs this matrix was constructed. The matrix shows the relationship each FR has with each DP. The "X" marks denotes the DP has influence over the FR, a "O" denotes there is no influence. DPs with "X" marks other than the one it was intended to fulfill help reveal a coupled design.

	DP1	DP1.1	DP1.2	DP1.3	DP2	DP2.1	DP2.2	DP2.3	DP2.4	DP3	DP3.1	DP3.2	DP3.3	DP3.4	DP4	DP4.1	DP4.2	DP4.3	DP4.4	DP4.5	DP4.6	DP4.7	DP5	DP6	DP7
FR1	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	X
FR1.1	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	X
FR1.2	X	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0
FR1.3	X	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR2	0	0	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR2.1	0	0	0	0	X	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR2.2	0	0	0	0	X	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR2.3	0	0	0	0	X	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FR2.4	0	0	0	0	X	0	0	0	X	0	X	0	0	0	0	0	X	0	0	0	0	0	0	X	X
FR3	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	0	X	X	0	0	X	X	X
FR3.1	0	0	0	0	0	0	0	0	X	0	X	0	0	0	0	0	X	0	0	0	0	0	0	X	X
FR3.2	0	0	0	0	0	0	0	0	0	0	0	X	X	0	0	0	0	0	0	0	0	0	0	X	X
FR3.3	0	0	0	0	0	0	0	0	0	0	0	X	X	0	X	0	0	0	X	X	X	0	0	X	X
FR3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	0	X	0	X
FR4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	X	X	X	0	X	X	X
FR4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	X	X	0	X	0	0	0	X	X	X
FR4.2	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	X	0	0	0	X	X	X	X	X
FR4.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	X	0	0	0	X	X	0
FR4.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	X	X	0	0	0	X	X
FR4.5	0	0	0	0	0	0	0	0	0	0	0	0	X	0	X	0	0	0	0	X	0	X	X	0	0
FR4.6	0	0	0	0	0	0	0	0	0	0	0	X	X	0	0	0	0	0	0	0	X	0	X	0	0
FR4.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	X	0	0	0
FR5	0	0	0	0	X	0	0	0	0	0	0	0	0	X	X	X	X	X	0	X	X	0	X	0	0
FR6	X	X	X	0	0	0	0	0	X	X	X	X	X	0	X	X	X	X	X	0	0	0	0	X	X
FR7	X	X	0	0	0	0	0	0	X	X	X	X	X	X	X	X	X	0	X	0	0	0	0	X	X

Table 4

2.7 Material Selection

The materials have not been chosen as they have yet to be tested analytically, further analysis of the absorption plate is required. The material will undergo significant stress and strain and will need to maintain rigidity and shape. For prototyping purposes, most of the features could be made out of a polyoxymethylene plastic, a lightweight, low-friction, and wear-resistant plastic. For components which undergo higher stress or need particular friction properties, a different material should be used such as aluminum, stainless steel or brass. Through structural analysis, the material used should be selected to optimize the absorption plate's performance, weight, strength and reliability.

2.8 Force Modeling

There are many forces which are generated during proper ski technique which allow the skier to remain in control. These forces are a result of the skier's body position, the position of the skis and the velocity at which the skier is traveling. Large control forces are generated and transmitted as moments through the skier's boot, through the binding and then applied to the snow by the ski. Many of the highest force/moments are generated through events which appear to be unremarkable. By using current skiing technique and movements, control moments are generated by the equipment which is designed to execute these maneuvers safely. In fact, more advance skiers often do not generate large bending and twisting moments as they are utilizing proper ski technique (Scher and Mote, 1999).

BBS equipment fails when it is manipulated in such a way to cause injury, such as the tail acting as a lever, driving the top of the boot into the back of the leg as in a boot induced or phantom foot injury. A tall, stiff boot applies more force on the ACL during the first 0.1 second for applied moments of the same magnitude on softer spoilers (Bally et al. 1989). Webster and Brown (1996) modeled the force applied to the ACL over time in the event of a boot induced injury with respect to velocity and slope. Concluding the forces exerted on the ACL increase as a skiers' velocity and boot stiffness increase and as the slope of the landing decreases. The ACL is significantly loaded in tension within a short amount of time, around 60 milliseconds.

Data was taken from research was used to form valid assumptions used to develop the design parameters. The major points used were:

- Minimum time for binding release is 0.02 seconds (Scher and Mote, 1999)
- High Amplitude, short duration and low energy forces can be ignored (Scher and Mote, 1999)
- Dangerous forces are applied to the ACL approx 0.2 seconds after initial impact (Gerritsen et al., 1997)
- Maximum force human ACL can withstand 1700 N of force in young adult and 700 N in older adult (Noyes and Grood, 1976)
- Negative vertical forces mode observed at heel range from 0 N to -400 N (Scher and Mote, 1999)

3. Results

3.1 Final Design

Assumptions have been made in formulating design parameters in addressing the root requirement, to reduce the risk of ski related injury to the ACL. The design of the absorption plate incorporated data gathered from research and has the assumptions. The device consists of two plates, securing the binding to the top plate and the ski to the bottom plate by way of a single axis rotational joint. Forward rotation is prevented, only backwards rotation about the ball of the foot is allowed, lowering the heel and slightly raising the toe. The absorption plate allows a maximum 5.1 degree toe raise when the device engages, it is assumed at this degree a skier can remain in relative control and may be able to recover. To control the threshold of release and to assist the device to return to its initial position, the system utilizes an adjustable cam-spring system. Figure 8 is a picture of the assembled model in its initial position.

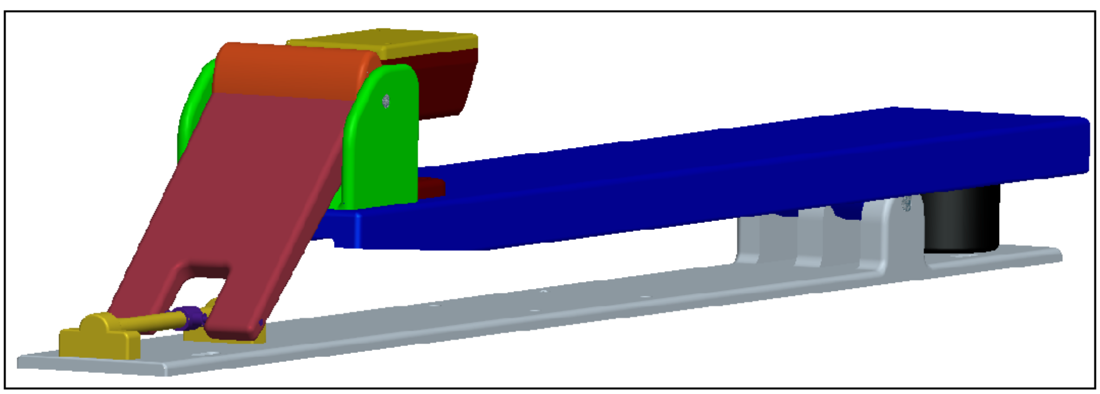


Figure 8

The resulting design was analyzed using Pro/Engineer's Mechanism application to determine if the functional requirements set by the objective were satisfied. The behavior of the system was observed for two different downward point forces, 400 N and 1000 N applied and held for approximately 0.1 seconds and applied instantaneously. Figure 9 and Figure 10 are comparisons of the forces applied to the system. The response of the design is dependent on the downward force of the heel. To reduce the risk of injury to the ACL, it is assumed there is a direct correlation between the downward force on the heel and loads applied to the ACL. The absorption plate is design to engage below the strength limit of the ACL as to avoid injury. Therefore, a minimum boundary must be established for a successful design. Through analyzing the research, an assumption was made for the minimum force boundary, 400 N, based on the observed mode of downward vertical forces at the heel (Mote et al., 1999) and is 300 N below the strength of an older adult's ACL (Noyes and Grood, 1976). For testing purposes, the upper force boundary was set to 1000 N. Partially because 1000 N is on the upper edge of observed downward vertical forces and because it is 2.5 times the magnitude of the lower limit, approximately the same relationship between the strength of the ACL of a young adult versus an older adult (Noyes and Grood, 1976). The whole goal of the device is to keep the forces applied to the knee, specifically the ACL, well below the threshold of injury.

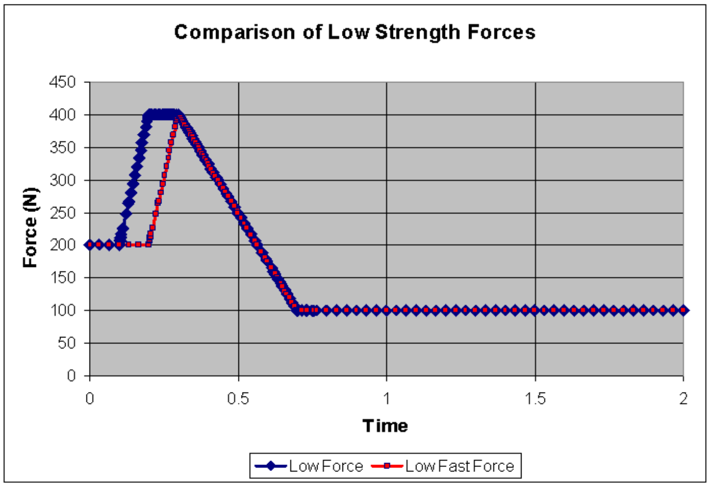


Figure 9

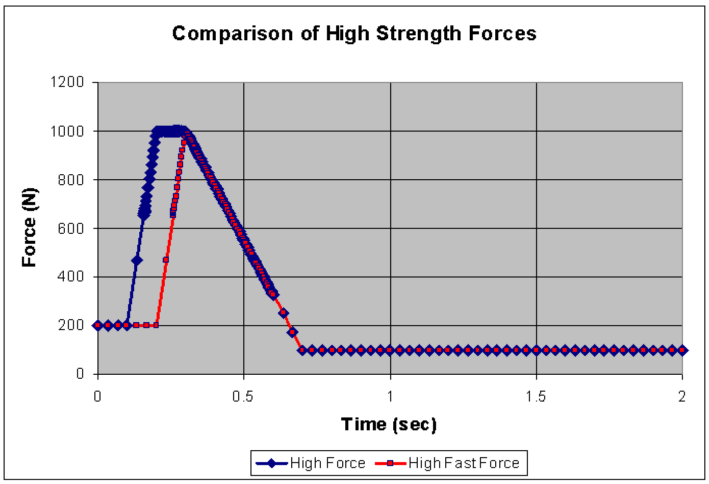


Figure 10

The absorption plate has been calculated to respond to specific forces in a particular behavior. The underlying principal of the device is to displace the heel and absorb the force by introducing work to the system. Figure 5 shows the relationship of force over a displacement on traditional bindings, the goal is to have the force displaced in a similar manor to Figure 6. The speed of the device is important as well, the displacement has to occur in a timely response to prevent injury and to return to its initial position to reduce the risk of inadvertent injuries. Figure 12 is a model created to show the response of a theoretical device when a force is applied, held then released. Its behavior is based on the design features which accomplish the functional requirements. A diagram of the absorption plate has been decomposed into a detailed drawing to illustrate how the design parameters fulfill and influence the functional requirements, see Figure 11.

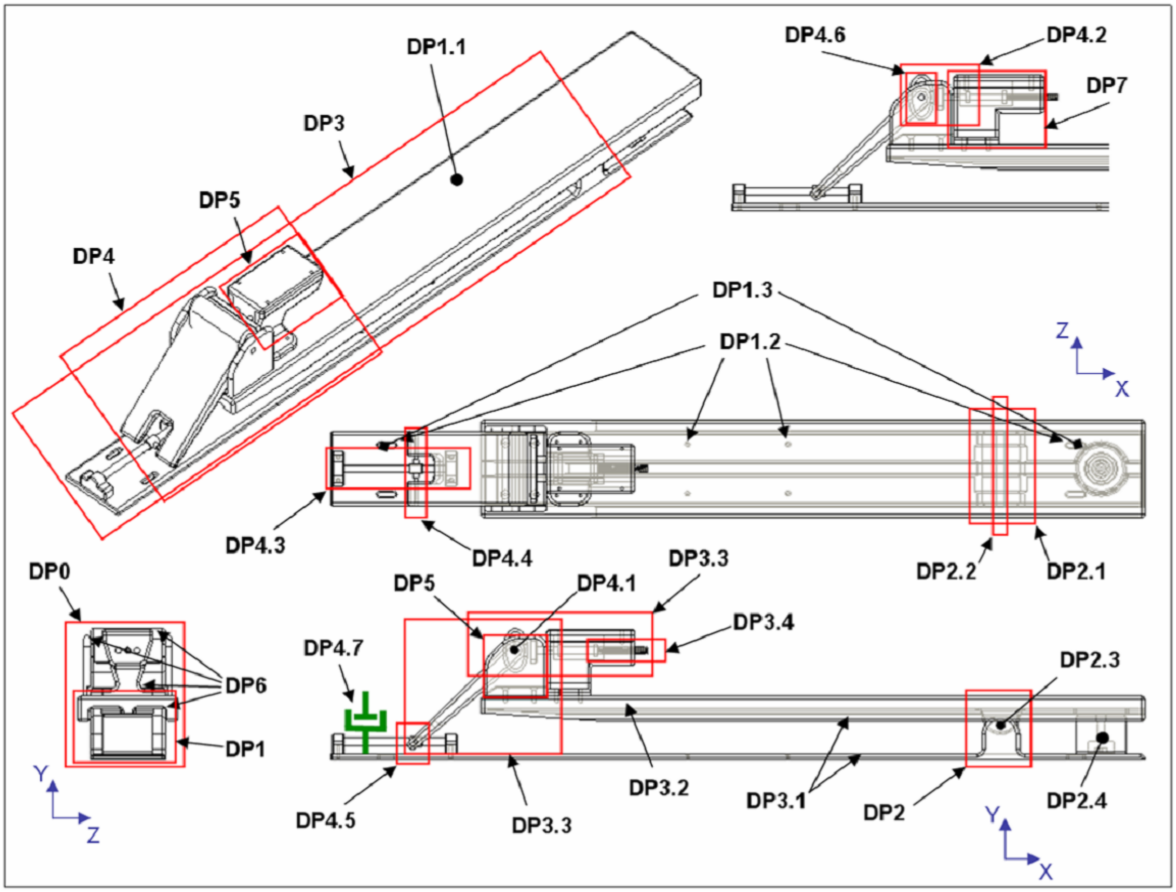


Figure 11

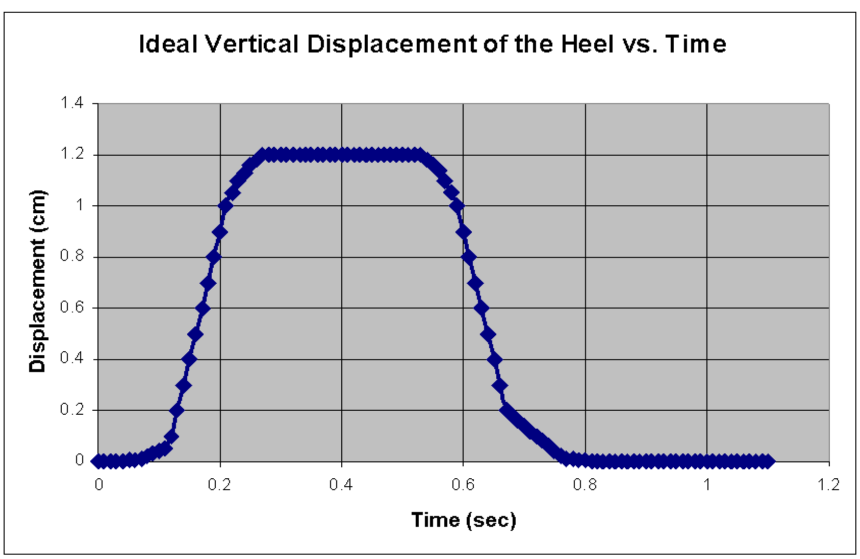


Figure 12

3.2 Performance of Final Design

The performance of the absorption plate has been analyzed to judge its effectiveness in accomplishing its functional requirements. The absorption plate was put through a series of analysis to test its performance for two forces, 400 N and 1000 N being held for 0.1 seconds and an instantaneous force. 0.1 seconds was used to demonstrate an applied exaggerated force, clearly showing the response of the system at the respective force and setting. The spring preload was set at 4 cm for 400 N, its initial compressed length. When the force increased the spring constant remained the same but the preload was increased, reducing the compressed length of the spring by 1cm. The behavior from these tests were collected and complied into a spreadsheet, from which information was assembled and compared. Figure 13 and Figure 14 are comparisons of the 400 N and 1000 N responses, respectively. They shows the similarity between the response of the absorption plate under different loads and how the heel does not displace as far under an instantaneous force compared to a force applied and held.

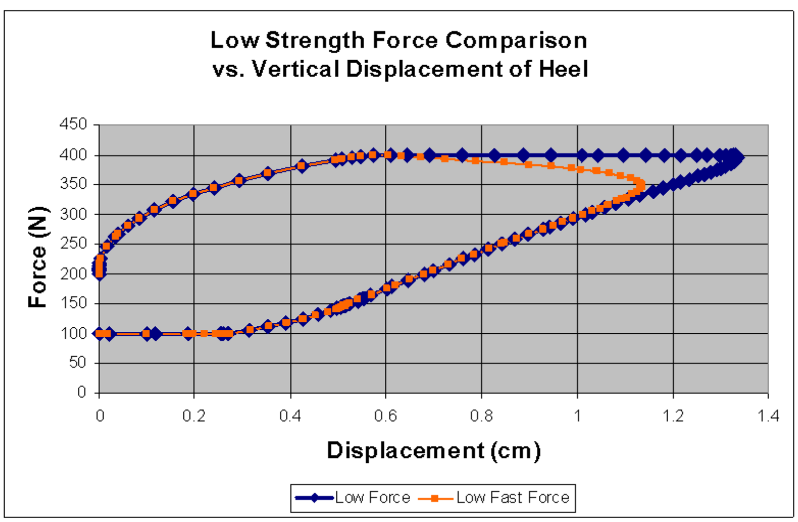


Figure 13

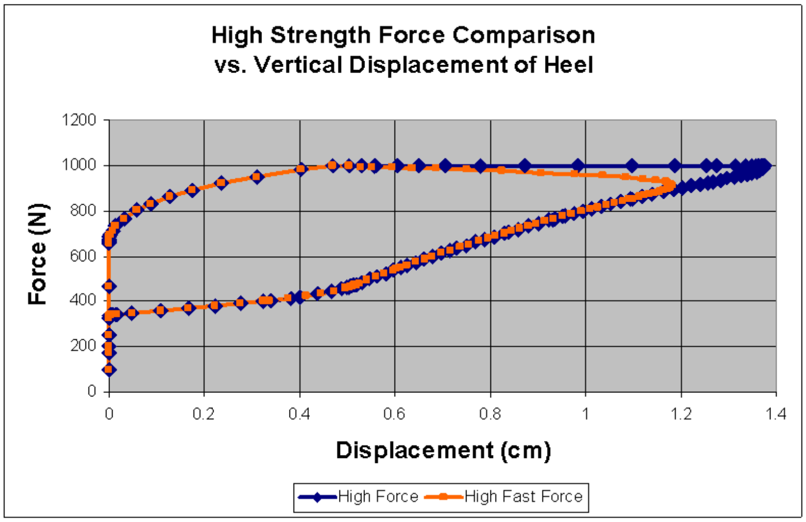


Figure 14

The spring constant and dampening coefficients were set experimentally to optimize the performance of the device by using the known force of 400 N. At a given force, the spring force controls how far the cam will rotate while the dampeners control the speed at which it turns. The spring was set at 2.75×10^8 N to allow the top plate to compress all but 0.84 cm of the available travel, this is to allow room for additional compression if more forces were applied. The dampeners were set to 350000 N/cm to reduce the acceleration of the cam's rotation and control its rotational speed. The behavior of the device was observed and compared against the two type of loading conditions, instantaneous and held forces. Figure 15 and Figure 16 are comparisons of the displacement of the heel over time of similar forces. Both forces have similar shapes of response but again reveal the instantaneous forces do not reach the same displacement of the applied and held force.

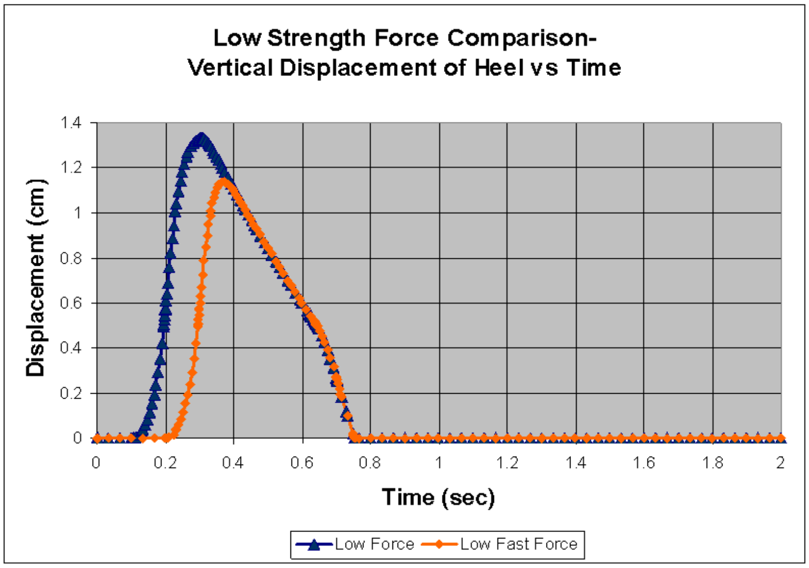


Figure 15

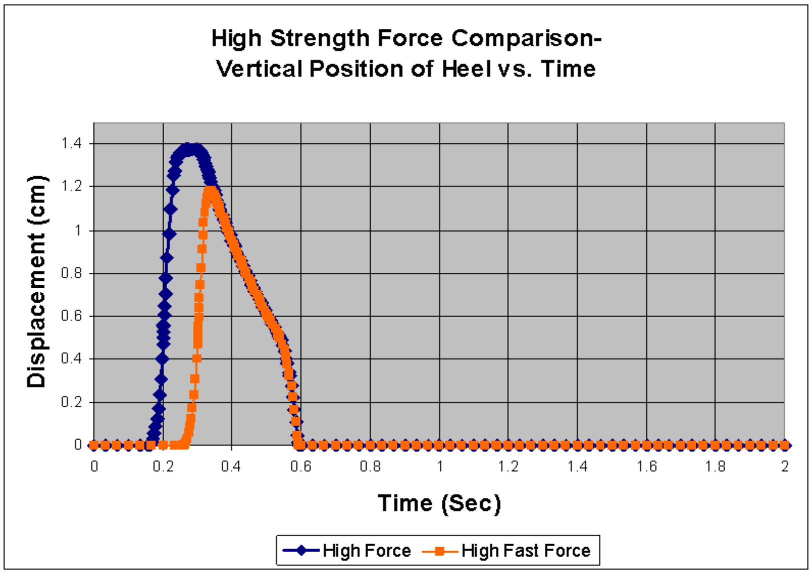


Figure 16

3.3 Performance Variables

The initial analysis did not produce a behavior which met the set criteria. The performance of the absorption plate changed when properties of the design were altered such as the cam profile. These changes didn't affect the overall shape and size of the device or how it interacted with the ski or binding but did have significant impact on the behavior of the absorption plate. Altering the spring constant, the preload length or dampeners had tremendous impact on the response of the plate but did not change the inherent profile of response. When dampeners are added and increased to the system, the speed at which the plate is displaced is reduced. This addition lowers the impulse of the system and lowers the risk of unintended injury by the user. The main adjustment for the device is the spring preload variable, this design allows the performance of the absorption plate to be set specifically for an intended user.

4. Discussion

4.1 How Design Parameters fulfill Functional Requirements

The nature in which injury occurs to the ACL is a result of a tensile force applied to a fixed material which exceeds its mechanical properties. The strength of a ligament is relatively constant, its strength deteriorates with age but can be assumed to be constant for each year of life. The strength of the knee, or rather the magnitude of forces and loads the knee is able to withstand without injury is not constant, controlled by independent variables. The amount of muscle activity surrounding the knee and the knee's flexion angle are primary influences of knee strength (Maxwell and Hull, 1989).

When current equipment is manipulated to apply a tensile load to the ACL coupled with a reduction of knee strength supporting the skier, a partial or complete tear of the tendon may occur. The absorption plate responds to the forces applied to the bottom of the boot heel, which in turn, relate to the forces on the back of the leg. For the boot to reduce the risk of injury, the heel of the boot is displaced downward by rotating about a pivot. Essentially the absorption plate is doing work on the system, applying a force over a distance to reduce the load on the knee. By reducing the magnitude of the force directly applied to the ACL and knee injury may be avoided. The operation of the absorption plate is dependent on three major functions, filtering and controlling the cam rotation as well as transmitting moments. Additionally, the weight of the absorption plate and user safe features is integral to the design.

Filtering and Cam Rotation

A spring loaded cam device was determined to have the best properties for reducing the risk of injury to the ACL. The absorption plate is able to respond to forces within a timeframe with the intent to prevent injury, less than 0.1 seconds. The cam and spring loaded follower mechanism control the rotation of the top plate and the moment it rotates. As the cam rotates, the follower is always in contact with the cam profile. The profile of the cam allows the plate to be displaced in a controlled motion. The spring loaded follower and dampeners control the speed at which the device responds and also apply force to aid the top plate to return to its initial position. Due to the profile of the cam, a moment threshold is created by the flat part of the profile against the flat faced follower. In order for the cam to rotate, the loads on the absorption plate must generate a moment large enough to break the threshold. The dampeners control the speed at which the plate compresses to avoid the top plate from slamming into the bottom plate. As the cam arm rotates, it displaces the top plate as it is the connection between the top plate and a slider link attached to the bottom plate.

Based on a performance analysis of the absorption plate it should be expect to work and respond to forces quite well. The inherent flaw of the design is the forces the absorption plate responds to. Injury to the ACL is the result of a moment, applied to the back of the leg by the ski boot spoiler. The absorption plate is designed to displace in the presence of such moments but also in the presence of downward forces applied at the heel, generating moments about the same pivot point. The difference between the two moments is the moment cause by just a downward force at the heel typically won’t cause injury as it is purely vertical, such has a hard square landing off a jump. The design can not choose to respond to a moment or not, even if it may not present any risk of injury. If forces are present and generate moments above the threshold, the absorption plate will engage. The ability or chance the device will respond to non-injurious forces has been increased by the design.

Transmitting control moments

The skier is allowed to transmit control moments when secured to the absorption plate due the pivot joint connection. The joint connection is located just below the ball of the foot, allowing rotation about the axis perpendicular to the plane the plate compresses. Forward rotational moments are supported by the stopper, located just below the toe piece. Backward rotational moments are subject to filtering. If a backward rotational moment is less than the moment threshold it will be transmitted through the binding to the tail of the ski. The joint is rigid axially, allowing moments controlling edge pressure and rotary motions to be transmitted.

Placing the pivot point of the plate below the ball of the foot and preventing forward rotation allows a skier to apply proper control moments to the tips and edges of the ski. A skier, in good body position, should be skiing with equal pressure on both feet with their center of mass perpendicularly above the balls of their feet. In most maneuvers, the downward heel pressure should not surpass the moment threshold of the device. There is an inherent flaw of the pivot placement and congruent top plate. If the skier was to shift their center of mass slightly backwards, the weight above the top plate would be unbalanced to the rear. This may result in the absorption plate unintentionally engaging or under loading conditions where it is more likely to engage.

Minimize Weight and Smooth Features

The parts which make up the absorption plate have been designed to keep weight to a minimum without jeopardizing the structural integrity of the absorption plate. A fundamental element of minimizing weight is features which cut out excess material. The use of channels on the underside of the top plate reduces weight but retains rigidity, as seen in Figure 17. The design of the cam and spring housing reduce weight by removing material in their walls and bases, viewed in Figure 18. Additionally, the rounding of edges and corners of each part reduces weight and the risk of user injury. There are less sharp edges and features are smoother to help avoid lacerations or other unintentional injuries in an impact event with a skier or user.

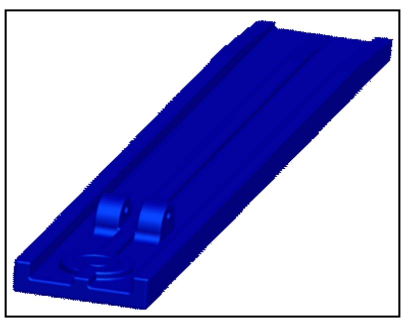


Figure 17

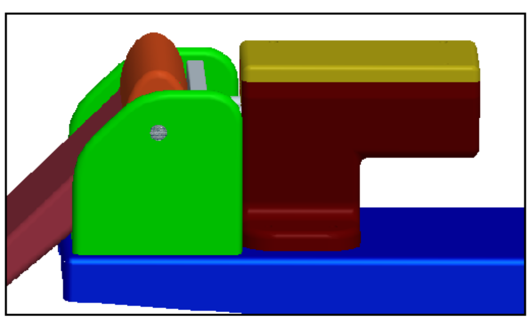


Figure 18

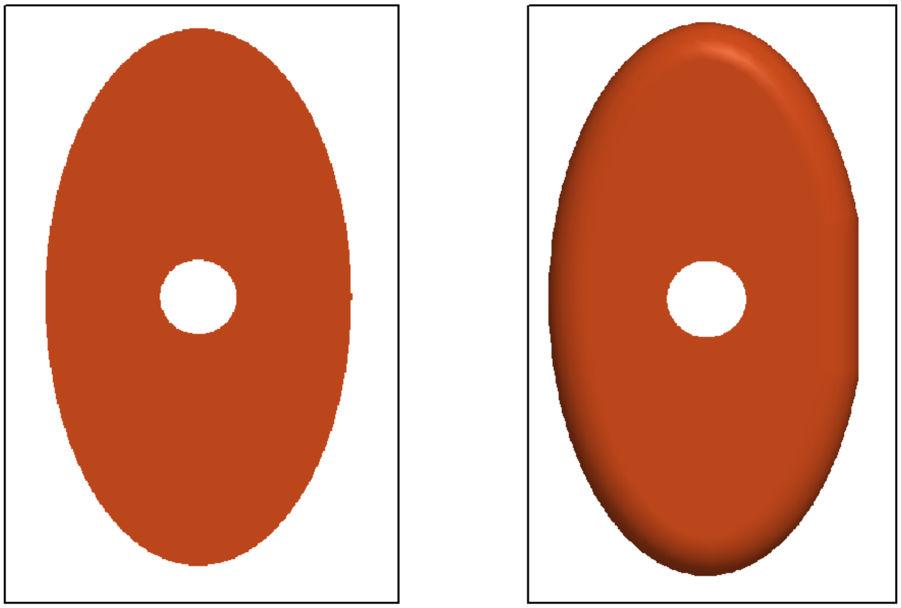
The design of DP5, to prevent snow and ice jams, was vastly overlooked in the design of the absorption plate. This can be attributed to a greater degree of focus placed on addressing higher level functional requirements. This device is intended for experimental testing and not for general use. In moving forward with the design of the absorption plate, FR5 should be more developed with a greater degree of significance pressed upon it. This is because the environmental conditions which the ski and absorption plate can be expected to operate in are highly variable. It can be assumed in many operating conditions, the current design of the absorption plate will be susceptible to snow and ice jams.

4.2 Design Iterations

Changes in Design

Throughout the design process several changes were made to reduce weight and bulk as well as to modify or alter performance. The performance or response of prior designs led to the need for features to be redesigned or scraped altogether. The current design is a result of several iteration of each component to best accomplish its required task. The mechanism releasing the top plate from its initial position, now controlled by a cam and follower system, has had the most design changes. The cam arm was designed in three stages, the initial cam profile, off setting the cam and changing the profile geometry. When the cam profile was changed from Figure 19 (a) profile to Figure 19 (b), the force displacement profile was altered to create a threshold for release. A more controlled compression is observed in due to the addition of dampeners and altered cam profile.

The final profile prevents the cam from rotating unless it breaks a rotational moment threshold and once it begins to rotate the orientation of the cam encourages it to return to its initial position by applying force in the opposite direction.



(a) (b)

Figure 19

Other ideas for a release mechanism were a spring loaded ball and cup joint and dual offset spring loaded cams. Both designs accomplished the same task of releasing the top plate and allowing it to pivot about the rotational joint in the presence of injurious loads. Additionally, both used a stationary tower attached to the bottom plate which secured the release devices at the height of the top plate's initial position. The spring loaded ball and cup joint was adjustable for a range of force magnitudes but was limited to only a release mechanism and did not apply any force to aid the top plate in returning to it initial position. The dual spring loaded cam design used the end of the top plate as the follower and two cams on a slider joint secured to the bottom plate tower. This design proved to be too complicated and was not effective, leaving it susceptible to ice and snow jams.

Once the top plate was released, the positioning and design of the cam did not efficiently assist the device to return to its initial position.

4.3 Need for Testing and Tables

The absorption plate is a device to be used in conjunction with current BBS equipment which has their own testing equipment and standards along with tables for proper adjustment. The absorption plate is another device which is to be tested and adjusted properly for its users to reduce the risk of injury to the ACL. Initially, tests need to be conducted to see if the device is working properly and to verify the force it takes to engage is consistent with settings on the device. The plate also needs pass the ASTM testing standards for current ski equipment developed by Committee 27 and published in ASTM Book of Standards Volume 15.07 (ASTM, 2006).

Tables for adjustment are needed for proper adjustment and need to incorporate a skier's gender and age, two factors which are linked to injury trends of the ACL. The chart's criteria should specify a skier's age, weight, height and gender as they are fundamental factors in the moments generated and threshold of injury. Other criterion which may want to be considered is the stiffness of the ski boot rear spoiler and whether or not the skier has had a knee ligament tear before, especially to the ACL. These tables must specify the spring force on the follower, based on the preloaded spring displacement. These tables will assist in the proper adjustment of the absorption plate, controlling the moment required to engage the plate when properly fitted with a binding on a ski.

4.4 Methods for Testing

If the absorption plate were to be manufactured and marketed, it must interface and abide by ASTM standards for securing, measuring and verifying the release values of alpine ski equipment. These standards have been developed by ASTM Committee F27, on Snow Skiing. The standards of interest are:

- F504 – 05: Standard Test Method for Measuring the Quasi-Static Release Moments of Alpine Ski Bindings
- F939 – 06: Standard Practice for Selection of Release Torque Values for Alpine Ski Bindings
- F1061 – 97: Specification for Ski Binding Test Devices
- F1062 – 97: Standard Test Method for Verification of Ski Binding Test Devices
- F1063 – 05: Standard Practice for Functional Inspections and Adjustments of Alpine Ski/ Binding/ Boot Systems

5. Conclusion

The most common traumatic injury in the sport of skiing is recognized as injury to the ACL. There is a need for equipment which reduces the risk of injury to the ACL, studies have identified each age groups from both genders are all at risk of injury. To address the need for a device which reduces the risk of injury to the ACL the absorption plate pictured below in Figure 20 was designed axiomatically. This design has incorporated data gathered from research and considered the limitations facing its effectiveness. Research data suggested a design which is durable and reliable for skiers to use and operate under varying conditions.

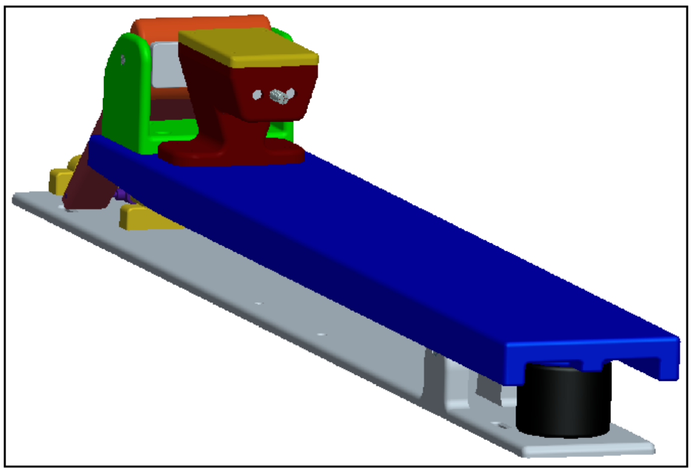


Figure 20

- The absorption plate addresses an inherent flaw in current boot-binding-ski equipment, the inability to reduce the pressure to the back of the leg in an event where the skier is generally rearward and their ski is acting as a lever. The loads apply a tensile force to the ACL which may lead to a partial or complete tear of the tendon.

- The absorption plate allows the boot to displace momentarily in the presence of injurious loads on the back of the leg, reducing the loads on the knee and ACL and thereby reducing the risk of injury.
- The movement of the plate is controlled by a spring loaded follower cam system. This system filters out injurious loads to the ACL and helps restore the plate to its original position.
- The absorption plate is designed to be structurally rigid and transmit control moments to the ski generated by skier movements.

6. Suggestions

6.1 Optimization of Design

Major questions are still unanswered about the design of the absorption plate and how it will perform. How the plate will perform if it is prototyped and the implications of the design are significant issues as well as its weight and reliability. A collection of questions have been complied to help facilitate improvements to the device.

Performance

- Will the absorption plate prevent the ski from fully flexing? Is the base of the absorption plate too long?
- Will the absorption plate engage inadvertently or be triggered by erroneous forces?
- Is the mechanism of release positively or negatively influenced by the design of the top plate?

Safety

- Have the rounded edges reduced the risk of unintended injury? Can further rounding and smoothing to device be done?
- Will the device be effective and work properly to help reduce the risk of injury?

Weight

- Is the absorption plate too heavy?
- Are the system devices too bulky and could they be simplified?

Reliability

- Will the device prevent snow and ice jamming?
- What is the durability of the plate? Will the parts hold up under operating conditions?
- What is an acceptable length of life for the absorption plate and its parts?
- How often does the device need to be inspected and maintained by a professional?
- Are the user friendly features effective and easy to understand? Are the settings similar to DIN settings on bindings?

6.2 Redesign Suggestion

While the device satisfies the objective and the design parameters fulfill the functional requirements, the device is complex. To reduce the complexity of the device would be beneficial to integrating the device in modern ski equipment and to the user. The device has an approximately 15 components, which satisfies a specific requirement. The essential element of the device, to reduce the risk of knee injury, may become jeopardized if the integrity of any component is lessened. Proper maintenance and alignment of the plates would be crucial to the absorption plate's operation. A device with reduced complexity and addresses similar, if not the same, functional requirements may be more adaptable to the environment while still reducing risk. The idea of keeping the design simple is desirable to manufactures and users alike. Adaptability is a result of a good design built for a wide range of environments, which ski equipment is put through. Simplicity in design stems from the conceptual phase and would need to be addressed in the initial phases of design.

Certain design parameters should be examined and alternative designs should be proposed to accomplish the requirements. The mechanism for release and filtering is an area which has a high degree of complexity in relation to other areas of the device. The release and filtering mechanisms are susceptible to exterior influences and environmental conditions. Potential solutions should investigate mechanisms which reduce the amount of influence the operational environment has in addition to reducing complexity. Preventing snow and ice jams and ensuring performance reliability are serious issues which curtail the effective operation of the absorption plate. These issues need to have a higher degree of consideration in the design process as they are prevailing concerns in the operational environment.

With the present design of the absorption plate, it can be assumed there will be a significant amount of complications with the connection of the ski and binding equipment. This is based on observed trends of primary binding connections which are integrated into the ski by manufactures. These primary connections may not allow the bottom plate to properly connect to the ski. To address this issue two suggestions are made; to produce brand specific bottom plates and to integrate the absorption plate into standard equipment. The nature of how the absorption plate is assembled and how it connects to the ski has a significant amount of flexibility. The bottom plate could be redesigned to and manufactured out of different material if necessary to increase the compatibility of the device with current manufacturer's primary connections. By building the absorption plate as an integrated device, either with the ski or binding, would eliminate the addition of a fourth piece of equipment and reduce the complexity of the system.

Another concern which should be examined is how to most effectively utilize the space an absorption plate has to operate. The space in which a riser plate is designed to operate in is limited to a relatively small area, approximately 5 to 10 cm wide, less than 4 cm tall and as long as it needs to be. The absorption plate is designed to operate under the same spatial constraints and subjected to significant loads. How the device responds to such loads and what mechanisms trigger the response is an area which should be examined with the intent it may lead to increased performance. The height of the plate, or stack height, plays considerable importance to the characteristics of the plate. In certain circumstances such as ski races, the stack height is restricted to 5 cm to comply with FIS rules. A higher plate generates larger moments about the ski edges which gives racers an increase in edge pressure and can result in better control but at a higher degree of force.

6.3 Prototype and Test

The device should be prototyped after it has been further analyzed and material has been selected. Additionally, a study needs to be done to determine whether or not the current design is even machinable, manufacturable and useable. Things to consider are creating, integrating or improving user friendly features to the device and removing or altering features to the device which can not be machined. Further analysis of the material selected for design features will reveal how the device can be modified or altered for weight optimization.

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8. Appendix

7.1 Background

The Sport of skiing has undergone many technological, political and policy changes since the 1920's, when skiing was first introduced in the United States. Trail design has changed from narrow, twisting horse cart paths to the now common wide open trails. Grooming was introduced and has been perfected to the point entire trails have a consistent snow pack. The equipment has also changed, boots were once soft low cut leather boots where now they are tall and stiff plastic shells. We now take for granted bindings as releasable with adjustability for each different skier, originally a skier was locked into a bear trap like binding. The ski itself has changed dramatically, once a tall, straight cut all wood ski are now high tech composite skis with metal edges and side cuts for performance. With all that change, interest in skiing has skyrocketed, now as one of the most popular winter sports (Johnson et al., 1997). Ski resorts have evolved into full service vacation destination with hundreds of thousands of skier visits each year. Skier codes and rules for the mountain have been developed along with markings and rating systems to help keep skiers safe and in control.

Johnson, Shealy and Ettlinger

Researchers began to investigate injury trends along with the mechanism behind common injuries. Through injury studies, experts were able to use scientific data in their own research and help further the safety of ski technology. Carl Ettlinger, Dr. Jasper Shealy and Dr. Robert Johnson established an injury survey at Sugarbush Mt. in Vermont in the 1972/1973 season. From their research they established Vermont Safety Research, which develop a video based program to help skiers develop techniques to avoid positions which they identified as mechanisms for ACL injury. When skiers are properly trained with the video it is the only product proven to reduce the risk of ACL injury, by 62% in an experimental training program (Johnson et al., 1997).

7.2 Body Mechanics

The Anterior Cruciate Ligament is one of four major ligaments in the knee. It connects the femur to the tibia in a manner which prevents the tibia from moving forward, relative to the femur. It also limits the side-to-side rotation of the lower leg and also keeps the knee from extending beyond its normal range of motion. The ACL is one of two cruciate ligaments, both the anterior and posterior provide front to back stability in the knee. Injury to the ACL has been observed mostly in sports and fitness activities. Tearing occurs when the ACL has been stretched and strained beyond its mechanical properties, typically from a sudden impact or force (Mayo Foundation, 2007). Ligaments do not repair themselves if they are torn, once they've separated they remain separated and surgery is necessary. The reconstruction surgery recovers stability and restores strength, range of motion and confidence in the knee (The Stone Clinic, 2007). For most, after surgery and rehabilitation people are able to return to normal levels of activity with reduced pain and improved knee function (Fu, 2000). The Mayo Clinic ascertains injuries to the ACL "are among the most common of all sports-related knee injuries."

They estimate "one in every 3,000 people sustain a ruptured or torn ACL" (Mayo Foundation, 2007).

The Knee's Characteristics and Strengths

The Knee consists of four major tendons, the ACL, MCL, PCL and LCL which share in the transmission of forces in joint movement. The anterior cruciate and posterior cruciate ligaments restrain the anterior and posterior tibia movements with respect to the femur. Additionally the ACL and PCL maintain the rotational stability of the knee. The medial collateral and lateral collateral ligaments stabilize the knee and bear a large portion of the total loads transmitted across the knee (Woo, 2003). The mechanical property of the ACL has been shown to decrease as a result of a maturation process, physical changes within the ligament over time. The strength of the ACL has been shown to significantly reduce with age between sixteen and fifty years old. The ACL of a young adult will fail at approximately 1700 N while an older adult will fail at approximately 700 N (Noyes and Grood, 1976).

7.3 Review of Research Reported in Literature

Evolution of Standards

Skiing has long been associated with injury; historically broken legs were commonly associated with the sport. In modern day, sprained knees and upper body extremities such as thumbs and wrists are the typical injuries. As the equipment evolved so did skier movements and techniques to fully utilize the performance of the ski. Safety began to become a concern, especially in the scientific community. In 1972 the ASTM F8 Committee on Sports Equipment formed Subcommittee F8.14 on Skiing Safety. In 1982, ASTM recognized the subcommittee as a separate technical committee and ASTM Committee F27 on Skiing Safety and Equipment was formed. Since 1972 the two committees have written eighteen standards and participated in the development of ISC standards (Bahniuk, 1996). ASTM F27 sponsors symposiums along with the International Society of Skiing Safety (ISSS) on Skiing Trauma and Safety. ASTM publishes a Special Technical Publications (STPs) which is the collections of peer-reviewed papers presented at the symposium (ASTM, 2007).

Who's at Risk

There have been several similar studies conducted by other researchers. Themes of research have developed as well, such as identifying who is at risk on the hill. Among the popular winter sports alpine skiing, telemark skiing and snowboarding, alpine skiing is the sport where participants are more prone to knee injury (Ekeland and Rodven, 2000). The mean days between injury (MDBI) of all injuries has increased from just over two hundred to just under five hundred. This is a decrease of 46% of the overall observed injury rate in alpine skiing (Johnson et al., 2000). Through other research, women have been identified as a group which has a higher risk of knee injury. ACL injuries represent 20% of all injuries in women compared to 9.2% in men, both over 24 years old (Laporte et al., 2000). At a ski area in Utah it was observed women are sustaining a high percentage of knee injuries and men, 53% to 31% respectively (Greenwald et al., 1997).

Age has also been identified to as a significant factor in injury, the majority of ACL injuries are occurring to skiers over the age of 24 (Laporte et al., 2000).

Common Injuries

As ACL injuries consistently increased, the rate of injury to others knee tendons remained constant. Injuries to the Medial Collateral Ligament (MCL) and Posterior Cruciate Ligament (PCL) are commonly connected to injury to the ACL but their rates of injury stable (Laporte et al., 2000). A large ski resort in Utah observed advance skiers are more likely to tear just their ACL as opposed to beginners which are more likely to tear a combination of the ACL with particularly the MCL but also the PCL and Lateral Collateral Ligament (LCL) (Greenwald et al., 1997). Injury to the MCL and ACL commonly occur in a fall where the knee experiences external axial rotation and a valgus moment, pressure away from the midline of the body. In this type fall, the MCL is the primary restraint to both moments, the ACL is a secondary, weaker restraint. If the MCL becomes torn, the ACL becomes the primary restraint and is likely to be torn (Hull, 1997).

Cause of Injury

The cause for injury has been identified to be typically caused by skier to skier accident, collision with a fixed object or snow and the result of a twisting or bending type motion. Through a two year study of ski patrol reports, Ettlinger and Shealy identified women are more likely to experience a twisting or bending injury than men. They also found men were much more likely to sustain an injury by being hit by their own equipment, the snow or a fixed object (Shealy and Ettlinger, 1996). Glaeser identified common causes for falling with the vast majority of falls due to lack of attention. Other causes for falling are a sudden change of snow conditions, hidden obstacles, inappropriate velocity, collision with an obstruction, poor visibility, and false release (Senner, 1999).

Gender and Age Considerations

There is no question that gender plays a factor in the health of the ACL. Research has found women have a higher risk of ACL injury in ski accidents (Laporte et al., 2000). Of knee injuries, the female to male ratio is almost two to one. Overall women have an injury rate of 3.44 per 1000 skier visits which is higher compared to men, with an injury rate of 2.21 per 1000 skier visits (Shealy and Ettlinger, 1996). Of all injures, studies have identify men as sustaining the majority of injury, between 53% (Greenwald and Toelcke, 1997) and 57% (Cadman and Macnab, 1996). Women and men are more prone to different injuries, men to head and shoulder injuries and women to knee injuries, which suggest the need for gender specific instruction and equipment (Cadman and Macnab, 1996).

Another consideration is the age of a skier, there are certain trends and traits which can be attributed to an age group. Younger people enjoy jumping, a maneuver which commonly leads to injury in ages 13 to 30. As women grow older they become more susceptible to injury, especially to the knees, shoulder and head. The age group 18 to 64 represents the vast majority of injuries, this can be attributed to the fact they also record the vast majority of ski visits. The injury rate for the 18 to 64 year olds, 0.50 injuries per

1000 skier visits, is the lowest of all groups by almost half. In certain injury groups such as head and facial injuries, young children, young adults and the elderly have injury rates which are double that of an adult (Cadman and Macnab, 1996).

Risk in Skiing

Risk taking is a cause of injury which is not commonly studied as it is a behavioral factor. Skiing can be a dangerous sport, how skiers enter into precarious situations and behave based on their experience and ability can provide a different insight to injury mechanisms. Research by Goulet, Regnier, Valois and Ouellet suggests "what characterizes the injured skier is not that they take more risks or that they are motivated by risky behaviors, but that they are less skilled" (Goulet et al., 2000). This connection can be seen in the research of Macnab, Cadman and Greenlaw (1999) which consisted of observation of injured and non-injured young skiers and snowboarders, ages five to seven. The injured skiers were found to have less knowledge of the Skiers Responsibility Code. In both non-injured and injured groups, almost half had no lessons and almost a third had their bindings adjusted by non-professionals. There was a lack of knowledge of safety and rules which suggests numerous injuries are avoidable (Macnab et al., 1999).

Forces at the Knee

There have been many studies which try to model the forces on the knee, more specifically the ACL. These models have been either analytical, computer and physical models which try to simulate the loads and forces associated with skiing. Webster and Brown found the forces on the ACL in a BIAD incident were largest as the slope pitch decreases and the skier's speed increases along with a stiff ski, boot and binding with high damping (Webster and Brown, 1996). Other computer models such as Gerritsen's simulation looked at the difference between a normal landing movements and dangerous landing movements also in a BIAD situation. The model observed two alternating forces, initially on the PCL upon ground impact followed by the ACL. The next force is a much larger force on the PCL followed by another larger force on the ACL a result from recovery from a fallen back position. The first force on the ACL occurs at 0.053 seconds while the second force occurs at 0.182 seconds. In the normal landing movements the ACL first experiences a peak force of approximately 275 N followed by a second peak force of approximately 975 N. The Dangerous landing movements observe a higher initial force on the ACL of approximately 345 N while the second force is observed to be approximately 390 N (Gerritsen et al., 1997).

Maxwell and Hull's study reported the measurements of knee strength variables which influence the loading and overall strength of the knee during skiing, such as muscle activity, hip and knee angle as well as forces along the tibia shaft. They observed the knee strength variables fluctuate greatly during skiing. The knee forces they observed were approximately 600 N and moments of 100 Nm in parallel skiing (Maxwell and Hull, 1989). Johnson and Hull showed the variables fluctuated as much as 60% for axial moments about the knee (Maxwell and Hull, 1989).

Retention Settings

Scher and Mote looked at how the recommended ASTM retention settings and the actually need retention forces compared. They found ten out of twelve subjects did not use more than 68% of the retention forces allowed by ASTM, a 336 to 711 N difference in allowable to needed. All of the runs were video taped, many of the highest force/moments were generated through events which appeared unremarkable. For one of their subjects, the upward vertical heel force never exceeded 1000 N and typically ranged from 0-500 N. They also observed subjects which skied at above average speed and aggression often did not generate large bending and twisting moments. This can be attributed to the use of proper ski technique which generated the necessary moments and forces through weight bearing (Scher and Mote, 1999). Hull demonstrated through his research that knee injuries do occur even when bindings are properly adjusted (Hull et al., 1997).