The Redesign of a Ski-Binding System to Reduce the Incidence and/or Grade of Knee Injuries

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Department of Mechanical Engineering
December 14, 2001

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Contents

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Abstract

Skiing remains an extremely popular activity with international enthusiasm. Over the past two decades, a number of modifications have been made to skiing equipment to enhance performance and reduce lower leg injuries. Unfortunately, this same period has seen a dramatic increase in the incidence of ski-related knee injuries, especially to the anterior cruciate ligament. While there are a number of reasons this trend may be present, satisfactory options to reverse it do not seem present. The following paper offers a look at the various methods one may pursue to help prevent ski-related knee injuries, and then presents a new design approach that may help skiers avoid or reduce the grade of knee trauma.

Introduction

Sustaining an injury is a very plausible and harsh reality for any skier. Of particular concern to present-day alpine skiers is the prospect of trauma to the knee. While injuries *below* the knee have decreased by about 85%-90% since 1980, the incidence of injuries occurring *at* the knee have increased from 3% (of all ski injuries) in 1972 to nearly 20% in 1994 [Ettlinger, Johnson, & Shealy, 1995]. The most disturbing statistic is the increase in trauma to the knee's anterior cruciate ligament (ACL), arguably the most debilitating and unpleasant knee injury. In 1979, ACL disruptions constituted 6% of all skiing injuries [Johnson, Pope, and Weisman, 1979], but by 1996 these injuries jumped to 20%. This translates to a conservative estimate of at least 20,000 ACL disruptions per year in the United States, alone [Beynnon and Fleming, 1998]. This epidemic has been independently studied, confirmed, and presented by a number of sources, and all report very consistent numbers.

Such a high rate of injury undoubtedly warrants attention. Professor M. L. Hull (of the Department of Mechanical Engineering and Biomedical Engineering Program at the University of California, Davis) conducted a study correlating knee injuries to various ski-binding issues. In it, he concluded that binding-release settings and the actual mechanism of release from the binding are instrumental in preventing injury [Hull, 1997].

It stands to reason, then, that efforts should be made to design a ski-binding system that will reduce knee injuries. In fact, many binding companies are doing just that. Unfortunately, these attempts seem to be inadequate, as evidenced by the steady rate of knee injuries still being sustained (the percentage of knee injuries is still rising very gradually). The modifications made to ski equipment starting two decades ago, while reducing lower-leg injuries and improving performance, have likely led to the increase in ski-related knee injuries seen today [Ettlinger et al., 1995].

Since it does not appear that satisfactory steps are being taken to design a system that will lead to a reduction in the number of ski-related knee injuries, we have decided to approach this challenge on our own. More specifically, we are designing a ski-binding system that will allow some degree of rotation (instead of an "all-or-none" release), thereby transferring torque that would normally be placed on the knee to the binding system. In this system, energy is temporarily transferred and stored in a compression spring when the skier is in a compromising position. If the skier recovers, the spring will return to its neutral position, transferring the energy to the skier once he or she is capable of accommodating it. Otherwise, the skier will release from the binding system.

Before discussing the project any further, it is necessary to provide some basic information about skis and their components, and general information about the knees.

Ski Basics

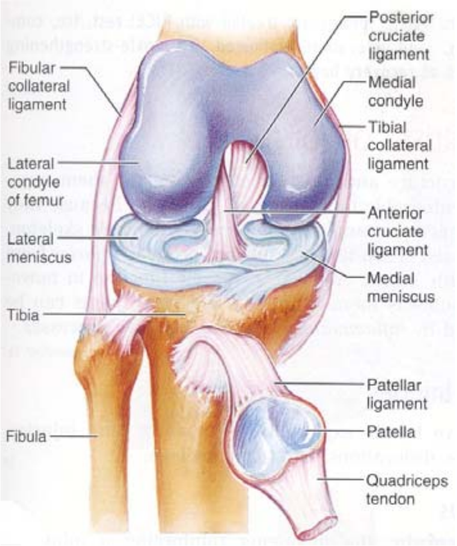
The term “ski” refers to a slightly more involved system consisting of the actual ski itself, a boot, and a binding. The ski is the device the component that slides along the snow. The binding is actually a binding system, which typically consists of a toe- and heelpiece, each with an associated baseplate. Each heelpiece also has a brake to stop the ski when it is released. The skier wears the boot, which is the only component in direct contact with his or her body. The boot will release from the binding in different circumstances, depending on the design. The main item to bear in mind about current release mechanisms is how they release—all or none, with no in-between. These typical components can be seen in Figure 1 below.

[Salomon, 2001]

Figure 1: Salomon skis, boots, and ski bindings. On left, from top to bottom: sectioned front of ski, sectioned rear of ski, ski binding, and entire ski. On right: Salomon boots.

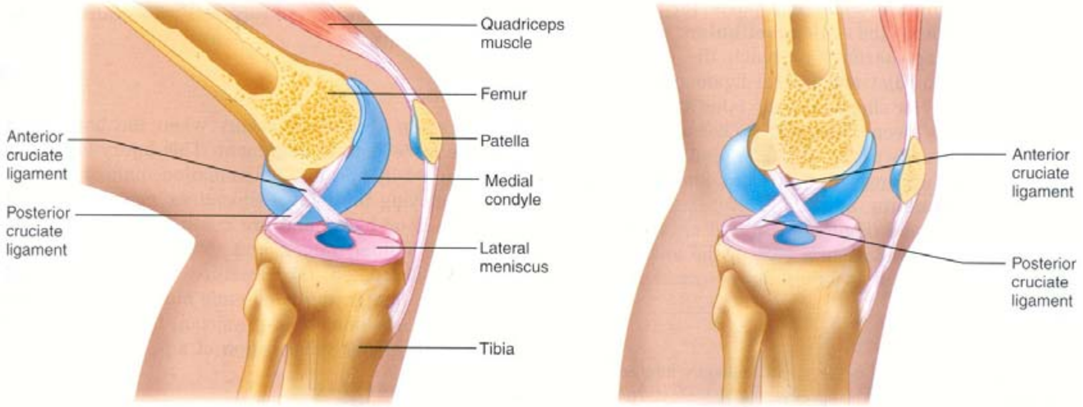
Knee Basics

As with the skis, a working knowledge of the major aspects of the knee is important to understanding the design scenario. To begin, the anatomical components of primary concern to the project should be reviewed. While there are a number of components to the knee (it is the largest and most complex joint in the body), the four major ligaments that contribute the most to knee stability are the medial and lateral collateral ligaments (MCL and LCL, respectively), and the anterior and posterior cruciate ligaments (ACL and PCL, respectively). The MCL runs from the femur to the tibia on the medial side of the knee, whereas the LCL runs from the femur to the fibula on the lateral side of the knee. The cruciate ligaments cross in the center of the joint. At one end, the ACL attaches at the anterior and slightly medial portion of the tibia, and at the other, it attaches to the posterior and slightly lateral portion of the femur. In contrast, the PCL runs from the posterior and slightly lateral tibial plateau to the anterior and slightly medial portion of the femur [Marieb & Mallatt, 2001]. The components of the knee are illustrated in Figures 2 and 3 below, and pictured in Figure 4.



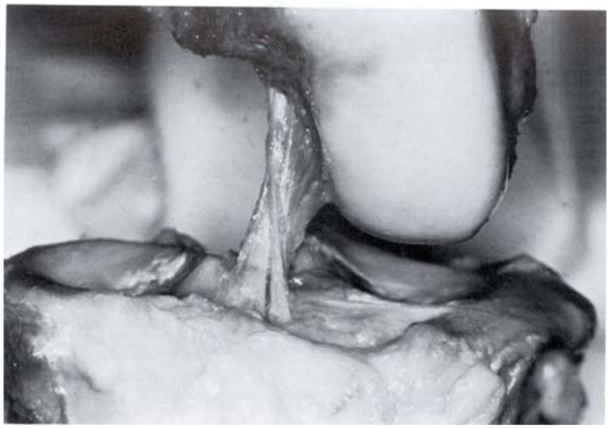
[Marieb et al., 2001]

Figure 2: front view of the human knee with the patellar quadriceps tendon detached



[Marieb et al., 2001]

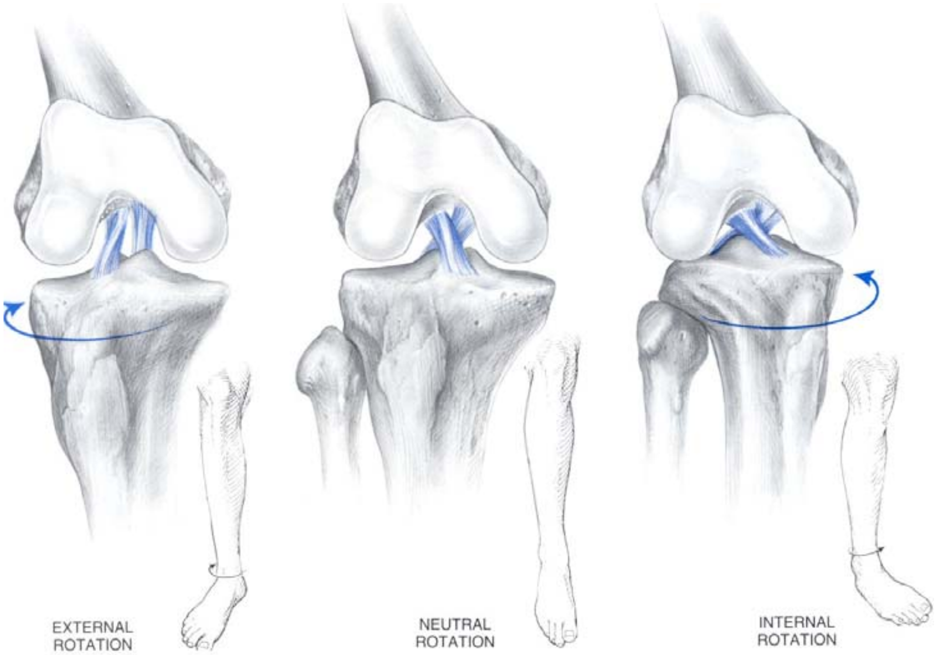
Figure 3: medial views of the human knee with femur medial condyle removed. The Left side is the knee in flexion while the right side is the knee in extension.



[Burks, 1990]

Figure 4: human knee, ACL intact, with all other ligaments and tissue removed. Note the nonlinear nature of the ligament.

The previously mentioned ligaments play a crucial role in the function of the knee. Along with the muscles surrounding the joint, the MCL, LCL, ACL, and PCL ensure the stability of the knee. While the muscles are the primary stabilizers of this area, when they fail, the ligaments are the last line of defense to prevent any laxity in the joint. The collateral ligaments prevent hyperextension, and medial and lateral movements in the knee. The ACL prevents the tibia from sliding *forward* relative to the femur, whereas the PCL prevents the *rearward* sliding of the tibia relative to the femur [Marieb et al., 2001]. The ACL also serves as a minor secondary stabilizer of external tibial rotation and a major secondary stabilizer of internal tibial rotation [Shoemaker & Daniel, 1990]. This function may be seen by examining Figure 5. If any or all of these ligaments fail, the knee will likely be rendered unstable, and a number of complications may follow [Bryant & Cooke, 1994]. This may include further injury by falling or incorrect biomechanics within the joint, as well as pain. Surgery is often needed to repair the damaged ligament, followed by intense physical therapy sessions, neither of which is enjoyable.



[Feagin, 1994]

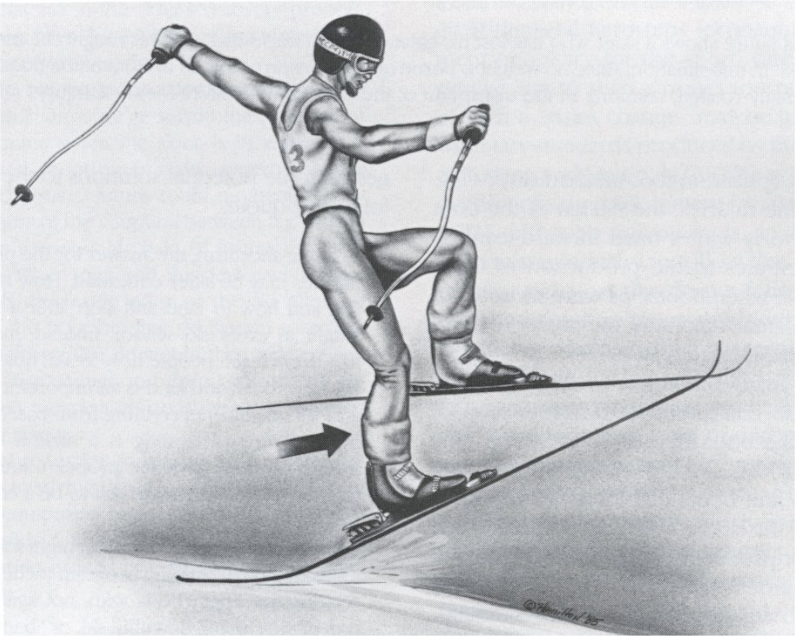
Figure 5: the cruciate ligaments, the ACL anterior and PCL posterior, in 3 different axial rotation position

Obviously, all reasonable measures should be taken to prevent injuries. Knee injuries, in particular, are substantially debilitating, especially trauma to the ACL. These ligaments heal very poorly with no intervention, and must be repaired via surgery in most cases [Marieb et al., 2001]. For this reason, the proposed design intends to reduce both the incidence and the grade of knee injuries.

In order to assert how the redesigned ski-binding system should reduce injuries, it is important to understand the major variations in which one may sustain trauma to his or her knees. There are three primary categories of knee-injury mechanisms: tensile, shear, and torque-induced injuries.

Tensile trauma to the knee ligaments very rarely, if ever, occurs. However, this is often how material properties are determined. As the name implies, this mechanism of injury takes place when two ends of a given ligament are pulled apart until it fails.

A more common mechanism of injury to the knee revolves around anterior shear forces. The most common injury results from a force being applied to the back of the lower leg. In skiing, this mechanism usually occurs as a result of poor landing technique after a jump. If a skier goes off a jump, and lands hitting the tail of the ski first, the ski acts as a lever. The ski tail creates a moment as more of the ski comes in contact with the ground. This moment is transferred to the back of the ski boot, which is rigid and does not allow any rearward laxity, resulting in an anterior force applied to the tibia. This pushes the tibia forward relative to the femur, which may cause ACL failure. This series of events is called the “Boot-Induced” ACL failure [Ettlinger et al., 1995]. This scenario is illustrated in Figure 6 on the next page.



[Ettlinger, 1985]

Figure 6: rendition of “Boot-Induced” ACL injury mechanism. Notice forward force upon the rear of the tibia.

A similar and complicated method involves the unbalanced contractions of leg muscles. When the quadriceps muscles contract forcefully, the tibia may be pulled forward relative to the femur, causing additional force through the ACL [Bach & Hull, 1999].

The most common method by which the knee, and especially the ACL, sustains trauma in downhill skiing is via a torque-induced mechanism. The most well-defined, torque-induced injury in skiing is the “Phantom Foot” mechanism. Although somewhat complicated, the following explanation, along with Figure 7 below, will aid in its understanding. The Phantom Foot basically “refers to losing your balance backward while your skis are still turning,” [Lerman, 2000]. In essence, the tail of the ski acts as a lever causing internal axial rotation about the tibia. This situation typically arises as follows: a skier is skiing downhill and somehow the individual loses his or her balance falling backward (this may only be for a very short moment). Once this occurs, a majority of the skier’s weight is on the tail of the downhill ski (that is, the ski closest to the base of the ski run). Due to the loss in balance, the skier is unable to turn properly, and momentum keeps his or her body headed down the hill. Unfortunately, the downhill ski is still turning, and continues turning. The turning ski rotates the boot internally, which causes internal rotation of the foot. This in turn rotates the lower leg internally relative to the upper leg. This leads to the ACL becoming stretched, then sprained, and if the breaking point is reached, it tears [Ettlinger et al., 1995].

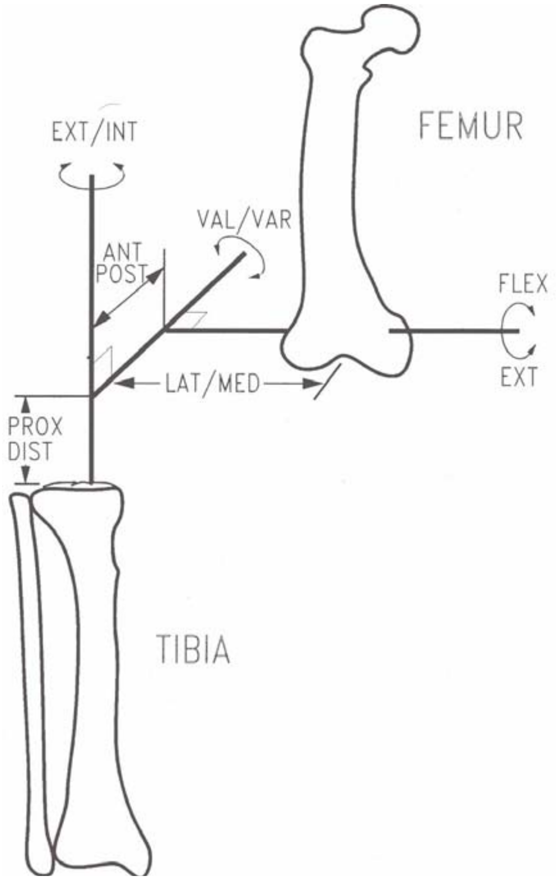
[Elmqvist and Johnson, 1994]

Figure 7: A skier is illustrated who has lost his balance, with rear, inside edge of ski digging into the snow, causing internal rotation of the tibia

Another category of forces and moments are also important to examine when considering knee injuries. These are called valgus and varus moments or forces. A valgus moment causes a separation of the medial section of the knee while a varus moment causes a separation of the lateral section of the knee. A valgus moment is illustrated in Figure 8 (on the next page), where it is being created clinically. Another example of how a valgus moment may be generated is by creating a lateral force on the medial side of the ankle. This will cause the knee to separate as illustrated in the diagram. Varus and valgus moments may also be created dynamically through cutting maneuvers performed by skiers. In essence, these are moments about an axis that runs from the anterior to the posterior relative to an individual’s knee. These moments and their axis, as well as other axes relevant to knee injuries, are diagrammed in Figure 9 [Markolf, Burchfield, Shapiro, Shepard, Finerman, & Slauterbeck, 1995].

[Daniel, 1990]

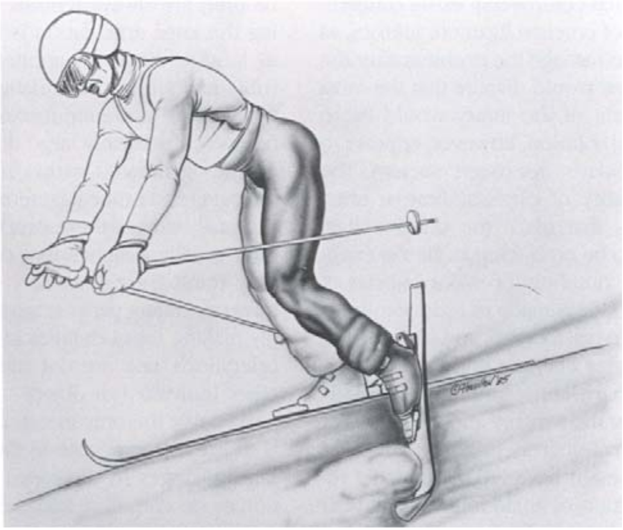
Figure 8: a valgus moment is being created clinically, causing a separation as illustrated in the inset circle



[Berns, Hull, & Patterson, 1993]

Figure 9: A three-dimensional coordinate system illustrates the three sets of forces and three sets of moments that may be exerted upon the knee joint. Of particular importance to skiing are anterior forces, external and internal rotation, and valgus and varus moments. Note that the valgus/varus axis is free to move in space but is perpendicular to the other two.

A similar injury modality to the Phantom Foot is the Forward Falling mechanism. These injuries usually involve an external tibial rotation at or near knee extension (when the ACL is most vulnerable) as well as a valgus moment. This is why the MCL is often affected by forward falls before the ACL undergoes a noticeable load. A forward fall is illustrated in Figure 10. If the MCL fails, the ACL will take over much of the MCL's load. This is why during forward fall injuries the pair often fail together, or only the MCL fails [Hull, 1997].



[Elmqvist and Johnson, 1994]

Figure 10: a skier is illustrated at the beginning of a forward fall. Note how the force generated at the front inside edge of the ski will cause external tibial rotation and combined with a forward velocity an extension of the knee.

The knee will fail differently under different loads. Table 1 displays the results of a cadaver study that loaded the knees with different loads or combinations of loads until failure. It should be noted that most of the cadavers were elderly and results cannot be directly generalized to younger individuals.

Table 1: failure modes and observed damage of various knee ligament specimens. Int = internal rotation, Ext = external rotation; Val = valgus moment, Var = varus moment; Ant = anterior force, Med = Medial force.

Leg	Specimen Age	Angle of Flexion	Load Type(s)	Ratio	Max Loads	Failure Point
1	69	45°	Int	-	40 Nm	Proximal ACL
2	69	10°	Val + Ext	4:1	22 Nm, 5 Nm	Deep superior MCL
3	81	10°	Ant	-	560 N	Distal anterior ACL avulsion
4	81	10°	Ant + Med	1.2:1	460 N, 360 N	Distal ACL avulsion
5	82	30°	Ext	-	39 Nm	Deep superior MCL
6	82	30°	Val + Ext	1.7:1	48 Nm, 26 Nm	Anterior superior MCL
7	33	0°	Int	-	43 Nm	Posterior capsule
8	33	30°	Ant + Int	8.7:1	560 N, 68 Nm	Longitudinal MCL
9	89	30°	Ant	-	550 N	Distal anterior ACL avulsion
10	89	30°	Ant + Int	8.7:1	350 N, 38 Nm	No failure
11	82	30°	Val	-	41 Nm	Longitudinal superior MCL
12	95	30°	Int	-	28 Nm	Deep MCL
13	88	30°	Var + Int	1:1	40 Nm, 45 Nm	Posterior MCL

[Reproduced from Berns et al., 1993]

Design Constraints

While there are a number of design constraints to be considered for this project, the tradeoff between safety and performance are of primary importance. Simply stated, although safety should be the foremost concern when dealing with any equipment or any situation, very few athletes (at any level), especially skiers, are willing to sacrifice sports performance. Therefore, the safety benefits arising from the device must far outweigh any loss in performance. More detailed explanations of these, and other constraints pertaining to the project, are provided in the product design specifications (PDS) in Appendix A.

Alternatives

There are three major, conceptually different approaches to reducing knee injuries while skiing. These are better training, "software" adjustments, and "hardware" adjustments. The training and software approaches are not the focus of this project's efforts, but should be acknowledged.

Training simply refers to the physical condition of one's body. Muscles are the primary support and stabilization agents in one's body. Therefore, as the muscles are worked into stronger and better condition, the likelihood for sustaining an injury decreases. This fact remains true for the knees, and especially important for its stability are the quadriceps and hamstrings muscles [Marieb et al., 2001]. Any skier should try to maintain a high level of fitness.

Aside from training, skiers can take it upon themselves to be better prepared for the sport. This can be accomplished via the software method, which refers to education and testing. The biggest proponent for skier education is the Vermont Safety Research organization. Based on data from a 26-year ongoing study of mechanisms of ski injuries and injury scenarios, this organization has developed a program to educate skiers on methods to identify potentially harmful situations and how to avoid injury [Vermont Safety Research, 1999].

Besides education, the other aspect of the software method is testing. One of the better-known organizations emphasizing the testing of one's knees is the Steadman Hawkins Sports Medicine Foundation. They propose formal testing to determine the degree of stability of a skier's knee. If the knee is deemed "deficient," a number of options are available, such as undergoing physical therapy or being fitted with a custom knee brace [Thys, 1997].

While the training and software methods are excellent complements to any skiing regimen, they may not be sufficient. Training is very important, but even very fit individuals eventually fatigue or encounter unexpected situations. Even Olympic skiers, who should be in top physical condition, injure themselves. The software method is also helpful, but has limits on how much it will improve injury rates. Even if a skier is well educated about different situations he or she may encounter, and even if the individual can identify most adverse situations, he or she still may not be able to respond fast enough to prevent injury [Barrack & Skinner, 1990]. As far as testing is concerned, while the actual testing falls under the software method, the effecter mechanisms fall into either the training approach (physical therapy) or hardware approach (knee brace).

The third conceptually different approach to preventing skiing injuries is the hardware approach, which refers to the ski equipment itself. This is the primary area of focus for the design project. Before discussing the current solution being pursued, a few hardware alternatives are presented. Generally speaking, the hardware solutions currently being offered do not seem to be sufficient.

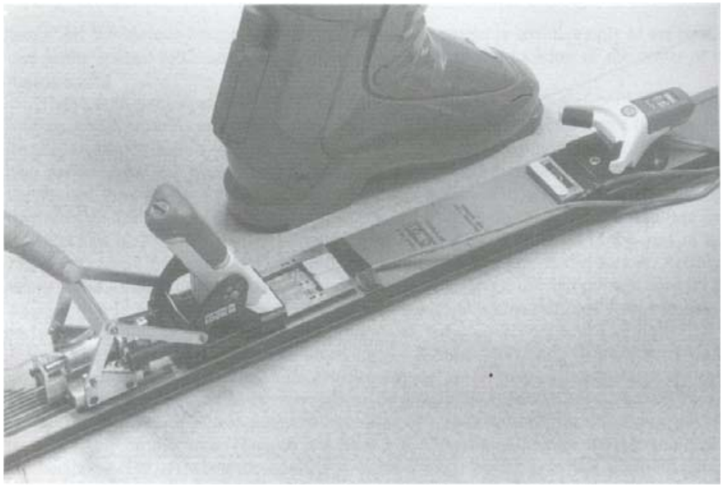
The first of these is the concept of a multi-release binding. Basically, instead of just releasing laterally at the to and heel, these systems allow the boot to release in different directions, such as up. One such model is offered by Look and is shown in Figure 11 on the next page. While companies making these types of bindings claim that ski-related knee injuries will be reduced, there is, as of yet, no evidence to back their claims.

[Look, 2001]

Figure 11: Look Pivot ski-binding system, allowing release at the toe in multiple directions

Lange, one of the major ski boot companies, is taking a more promising hardware approach. It has introduced the V-9, a boot with a flexible back. With this design, the boot rotates backward about 15^o in the event that the skier leans back. The tension on this mechanism is variable. While this design seems to have potential for relieving Boot-Induced ACL injuries, it is doubtful that it will adequately address Phantom Foot injuries [Lerman, 2000].

The final hardware alternative that will be presented is an electromechanical ski binding. An electromechanical system would function by electronically determining the forces acting upon the bindings and friction plate, causing a reduction in binding retention levels when certain threshold forces were observed. It appears that a binding that incorporates some method of determining knee strength is warranted in order to simultaneously satisfy release and retention requirements. The most recent new binding development in this category is offered by Hull et al., who have developed an electromechanical ski release model with mechanical backup, shown in Figure 12. They made their modification to a conventional binding. A toepiece sensor indicates the twisting moment while an antifriction device and heelpiece sensor indicate the anterior bending moment being transmitted to the leg. To gain electronic control of the binding release, a solenoid-actuated mechanism was added that translated the heelpiece rearward along the ski to decouple the boot from the binding. Otherwise, the binding allows normal mechanical function and release, even when the electrical system fails [Hull, Swanstrom, & Wade, 1997].



[Hull et al., 1997]

Figure 12: electromechanical binding prototype with dynamometers

Although such a solution seems functionally feasible, we believe the ski market is not ready for such a radical change as electromechanical interfaces to be introduced. Not only does this put too much technology at the feet of recreational skiers, but the weather effects of winter conditions would take a toll on the intricacies of the electronics, causing frustrating maintenance and repair needs. Additionally, such a system may be too bulky, sacrificing performance. We believe that a simpler and purely mechanical design may be able to more elegantly address the problem of ski-related knee injuries.

Current Direction

As evidenced by the earlier discussion of the knees, injuries to the joint, and especially to the ACL, are an ever-present concern for skiers. Although a number of steps are being taken to combat this problem, satisfactory results do not seem to be forthcoming. And while training and software methods are a good supplement to any skiing regimen, the above review of hardware alternatives makes a clear case that equipment-based solutions for the injury epidemic must be addressed.

Since the primary mechanism for knee injuries while skiing is the Phantom Foot, it seems logical that the focus of prevention should be centered on easing the torque passing through the joint. In a ski system, the major device that accommodates torque is the release mechanism, which is part of the binding. It seems natural, then, that the binding is the area of scrutiny for the project.

The main problem with current ski-binding systems is the “all-or-none” nature of the release. That is, in a release situation, the user either completely releases from his or her binding, or is completely retained. There is no middle ground. It is hypothesized that if the ski binding is given some degree of rotation when the skier is experiencing a situation in which his or her knee is twisting, some of the strain on the knee will be alleviated by transferring some of the torque from the knee to the ski binding.

When addressing release issues, the first item that can be easily modified is the tension setting. However, the Deutsches Institut fur Normung (DIN) settings are an internationally accepted standard, and any change to this constant would not be wise.

Instead, modifications were chosen to be made at the toepiece. Although the heelpiece could have been modified instead, it is far more involved and less accessible that the toepiece. While changes are being made in the general area of the toepiece, to the extent possible, it is desirable to make minimal modifications to the existing equipment. For this reason, a new component is being added between the existing baseplate of the toepiece and the ski—the *mesoplate*. It is through this new plate that the desired radial motion will be afforded to the ski-binding system, and in turn, the skier.

Once it was decided that radial motion would be necessary to transfer torque from the knee, and that it would somehow incorporate the new mesoplate, the exact mechanism to accomplish this goal had to be designed. The system needed to have a neutral position in which it would stay locked unless the skier was off-balance. In the neutral position, the boot would release from the binding just like a boot in a standard ski-binding system. In the event that the user was falling forward or backward (i.e., he or she is off-balance), the system would unlock and the radial movement could take place. This system only engages in the event of forward or rearward falling because that is the compromising action that most often leads to the Phantom Foot injury. In order to allow for rotation back and forth, a fulcrum would be needed, which has been incorporated as part of the mesoplate.

Initially, an *I-track* system was pursued. However, this design presented too many complications, the biggest stemming from an issue of relative motion. Then the idea of a friction plate between the baseplate and mesoplate was considered. Again, there were a number of complications with using a friction plate, but it was a step in the right direction. The friction plate evolved into a pin that would be located under the baseplate, and would slide and lock in a slot on the mesoplate.

Since the baseplate would be sitting on the mesoplate, the top of which is a fulcrum, some item would be needed to prevent an ongoing and annoying teetering of the baseplate. This could be accomplished by the use of springs to hold the baseplate in the neutral position until a sufficient force was placed on it to warrant rotation about the fulcrum.

Finally, compression springs were added to the side of the mesoplate to adjust the ease with which the baseplate could move radially.

The above discussion relayed the thinking process that led to the current design. Now the components of the device, and how it actually works, will be presented. To help visualize the product, please review Figures 13 and 14 on the next page.

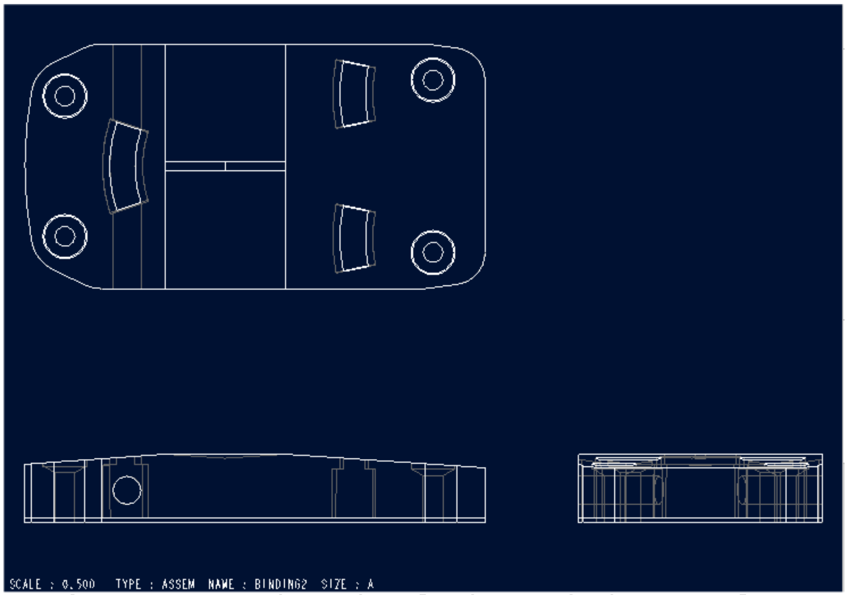


Figure 13: 2-Dimensional views of the mesoplate

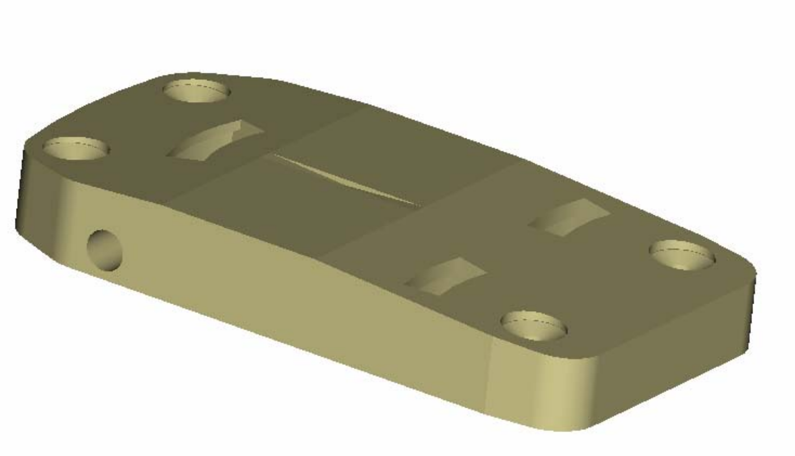


Figure 14: 3-D view of the mesoplate. Notice the lock-slot on the top face, the three radial slots, and the angles faces forming the fulcrum.

The first items to discuss are the components of the proposed ski-binding system. Aside from the typical components of the ski (the ski, boot, and binding), the proposed device has an additional plate, the mesoplate, to be added between the baseplate of the toepiece and the ski. Since this mesoplate will be adding height to the system, a complimentary riser will be added between the baseplate of the heelpiece and the ski. The baseplate of the toepiece will have a small triangular pin attached to its bottom side, seen in Figure 15. A top-down view of the combination is offered in Figure 16. This pin will fit in a lock slot on the top face of the mesoplate. The mesoplate is angled down from the center on both sides. This creates a fulcrum, allowing for forward and backward rotation. On these angled faces will be radial slots. It is these slots that will allow the rotational movement of the device when it is not locked. Finally, compression springs on the side of the mesoplate in the front slots will restrict radial motion.

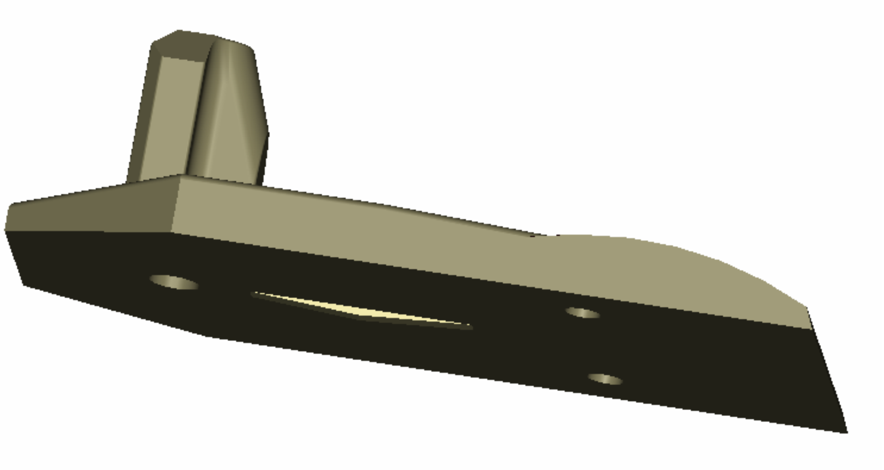


Figure 15: the base plate with the triangular locking pin on its bottom face

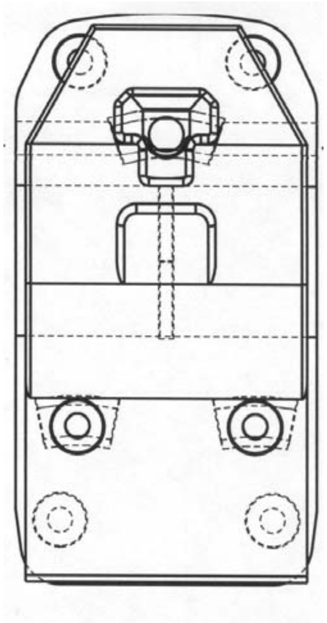


Figure 16: overhead view of the mesoplate with the baseplate sitting on top of it

All these components have very important implications for the function of the ski-binding system. When the system is in a neutral position, i.e., the skier is not off balance, the baseplate sits horizontally on the fulcrum of the mesoplate (with reference being the ski itself) as seen in Figure 17 on the next page. The horizontal orientation is maintained by springs, whose function will be discussed shortly. The pin underneath the baseplate sits in the lock slot on the mesoplate, keeping the system locked in the neutral position. While in the neutral mode, the release mechanism works like it would in any standard binding system. The reason no modifications are being made to reduce injuries in the neutral position is because most skiing injuries do not occur when the skier is neutral.

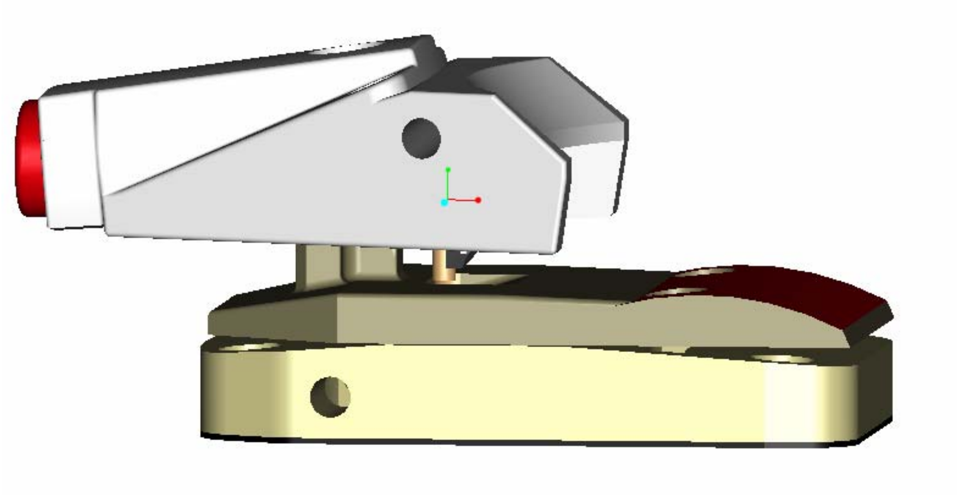


Figure 17: the base plate resting on the mesoplate in the neutral position. The lock-pin is in the lock-slot, and the baseplate is horizontal.

It is when the skier begins to lose his or her balance, either forward or backward, that the modifications to the ski-binding system will take effect. Since the mechanism is essentially the same whether falling forward or backward, only the backward off-balance situation will be explained, since it is consistent with the Phantom Foot mechanism of injury.

If the skier starts falling backward, the baseplate will rotate forward about the fulcrum. This corresponds to counterclockwise rotation about the fulcrum in Figure 18 below. As the baseplate rises off the fulcrum, the pin also rises and disengages from the lock slot.

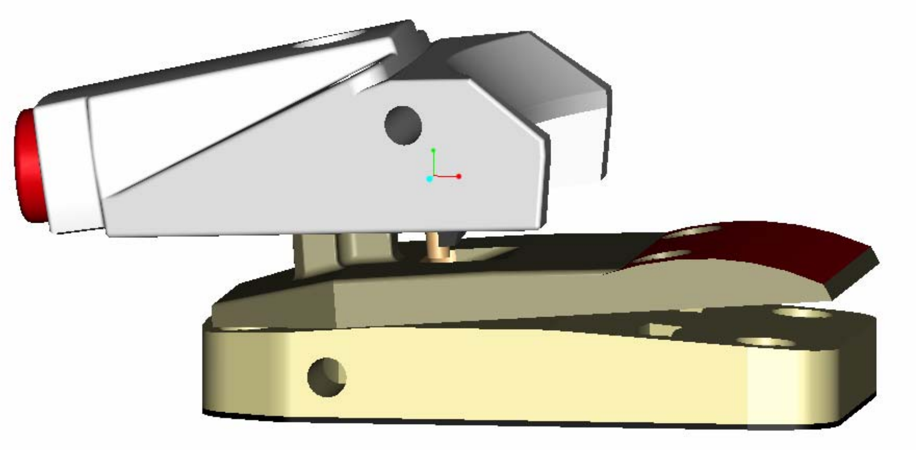


Figure 18: the baseplate rotates forward on the mesoplate when a skier falls backward. The lock-pin is disengaged from the lock-slot in this position.

At this point, if the ski begins to turn and the skier is not quite in sync with the ski, he or she is afforded some degree of radial movement. This comes courtesy of the radial slots located on the inclines of the mesoplate. Radial movement will take place only if the torque being created is enough to overcome the resisting force from the compression springs. The function of the compression springs will be discussed below.

In the event that radial movement does take place, there are two options. First, the pins in the slots may come to the slot ends and release. This release will be very similar to the release that takes place in a standard binding, but it will happen more easily. This is a result of the looser boot-binding interface. The second option for the baseplate moving along the radial slots is to be forced back into the neutral position by the compression springs. This will only happen if a recovery is made. The compression springs are located on the side of the mesoplate, and their springs extend into the radial slots. These springs are very similar to the main spring used to adjust the tension setting on the front of the binding. These springs are illustrated in Figure 19. An example of how they oppose radial movement is displayed in Figure 20.

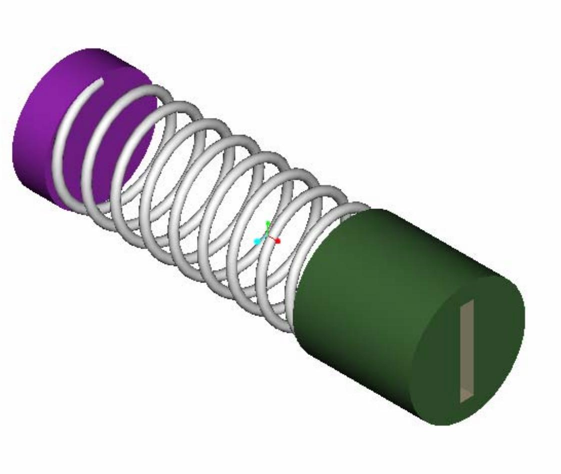


Figure 19: compression spring

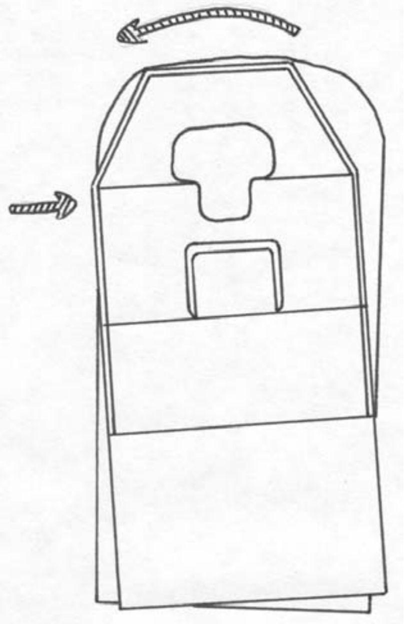


Figure 20: as the baseplate rotates to the left, the compression spring opposes the motion (lower arrow)

Another important aspect of the design to explain is the mechanism by which the baseplate stays attached to the mesoplate, and how the baseplate is allowed to move. Figure 21 shows the three radial slots on the mesoplate, one in front and two in the rear. A dual headed pin assembly runs from each of these slots to the baseplate. As Figure 22 shows, there are a number of components to this assembly. Starting at the ski and moving up through the slots, there is a friction plate, the bottom head of the pin, a spring, a metal washer, another softer washer (Teflon), the top end of the mesoplate, space between the mesoplate and the baseplate, the baseplate, and then the top head of the pin. An exploded view of the springs and baseplate are shown in Figure 23. The pin is a rigid, fixed distance and will comprise of a screw. Its primary functions are to keep the two plates attached, and to provide a shaft for the springs to align along.

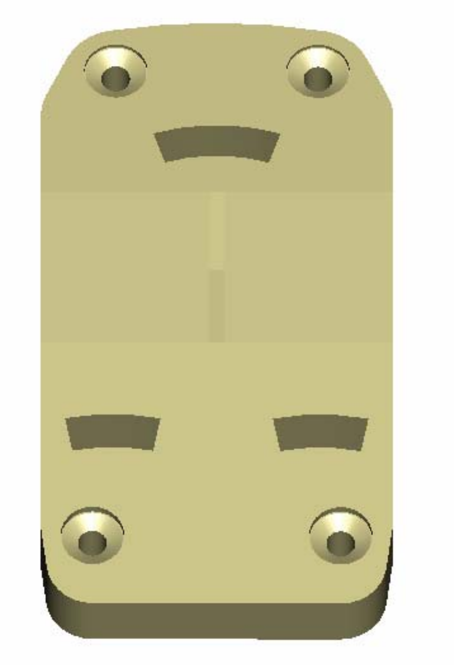


Figure 21: top face of mesoplate, showing the radial slots

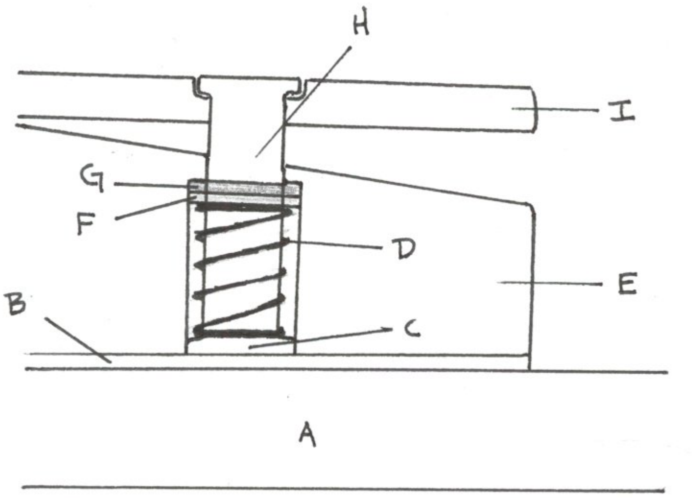


Figure 22: pin assembly with various components as follows: (A) ski, (B) friction plate, (C) lower head of pin, (D) spring, (E) mesoplate, (F) metal washer, (G) softer washer, likely Teflon, (H) remainder of pin, and (I) baseplate

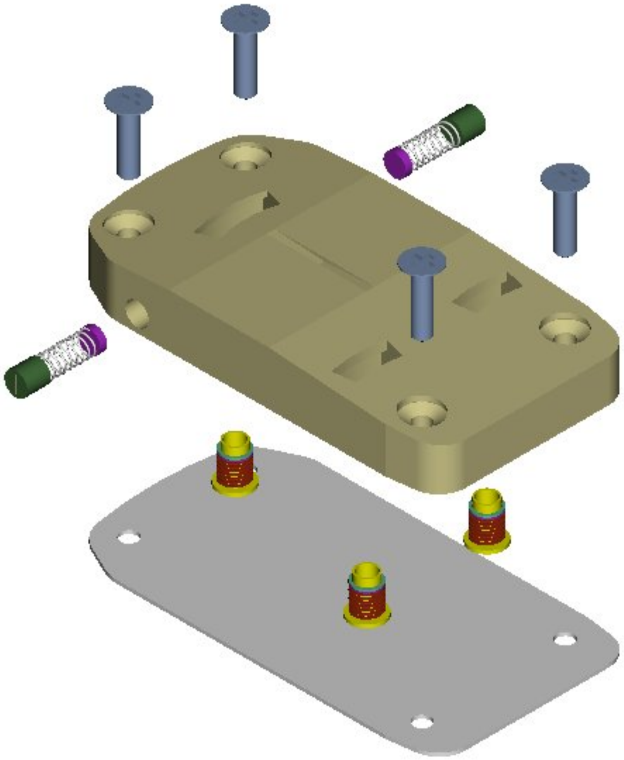


Figure 23: exploded view of friction plate, mesoplate, compression springs (on side of mesoplate), and spring assembly described above

When falling forward or backward, the mechanism of function for this assembly is essentially the same, so only a backward fall will be discussed. The scenario is diagrammed in Figure 24 below. As an individual loses his or her balance backward, the toe of the boot pushes up on the toepiece. This leads to an equal and opposite force on the pin running through the toepiece and baseplate. These forces create a couple in front of the fulcrum, resulting in forward rotation about the fulcrum (counterclockwise in the figure). As the front of the base plate pushes down, the rear is lifted up. This action pulls the rear pins up, which causes the spring to be compressed between the lower head of the pin and the top of the mesoplate. This compression of the spring is what opposes the forward rotation. If the skier were falling forward, a similar sequence of events would take place, with the front and back slots being reversed.

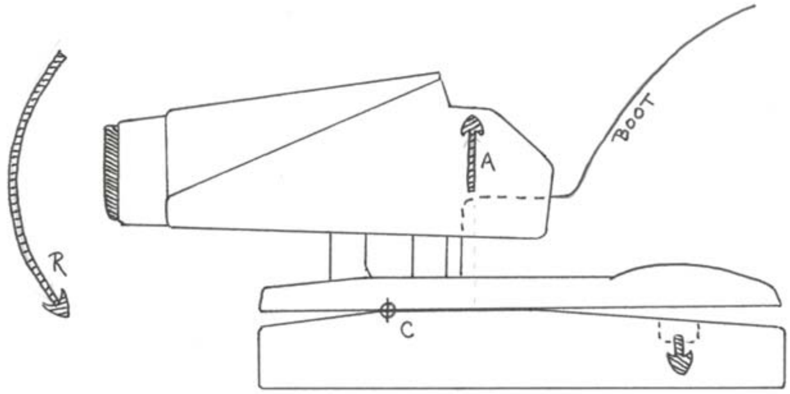


Figure 24: diagram illustrating the rearward-falling situation and why the baseplate rotates forward

The final item to present regarding the mesoplate is its attachment to the ski. It sits on a friction plate, which provides a surface for the pin assembly to rotate on. The mesoplate and friction plate are screwed together into the ski at four points. A waterproof material, such as vinyl, cases off all moving parts between the baseplate and mesoplate.

Future Direction

At the present time, a number of key design issues have been decided upon, as discussed above. However, much work must still be completed. To begin, a number of details about the device must be decided. These include the exact measurements and exact materials to be used. Additionally, there needs to be a more detailed analysis of the forces that will be acting both on the ski-binding system and on the knee. Earlier efforts in the semester to quantify forces on the knee were somewhat misguided. Too much time was being spent on trying to analyze the forces that would lead to failure on the individual components within the joint. Instead, more effort should be spent quantifying when the knee fails in different situations, regardless of what is happening in the joint cavity. Once these forces are quantified, we can work backward to compute what settings would be advisable on the binding system. This setting will be based on a number of variables, including the dimensions of the user, expertise level, and the failure forces on the knee.

Once these items have been addressed, a functional prototype must be built. Only then can the device actually be tested. In theory, this ski binding system should reduce knee injuries. Its effectiveness will truly be seen after it starts being used in greater quantities. The trends for injuries in those skiers will be very closely monitored. The testing to take place in the nearer future will revolve around the forces applied and resulting performance of the device in a lab setting, as well as test to ascertain the feel of the design. The latter of these must be accomplished by actually using the product. As stated earlier, the performance must remain at an acceptably high level. Additionally, the safety of the device must be tested before marketing.

Some items that will be pursued that are not directly related to the design are as follows: first, a patent will be applied for. A business model will be built around the ski-binding system, and hopefully a successful company will follow. A number of concerns will have to be addressed in this arena, including target market and methods of manufacturing. Additionally, the device's adaptability to current binding systems will have to be assured.

Conclusion

Skiing is a very popular sport throughout the world. Along with the joys of flying down mountains comes the reality of ski related injuries, especially those to the knee. There are a number of mechanisms by which the knee can sustain trauma during the sport, the most prominent being the Phantom Foot. Many approaches claim to combat these injuries, but these methods do not seem to be effective.

The proposed ski-binding system will likely address this need. Much work still needs to be done in order to present a useful product, but the principle design seems to offer much promise for skiers. At some time in the near future, this device will hopefully present itself as an effective option to combat ski-related knee injuries, which should lead to more enjoyable time on the slopes.

APPENDIX A: The Product Design Specifications (PDS)

The Redesign of a Ski-Binding System to Reduce the Incidence and/or Grade of Knee Injuries

Team Members

Nikhil Bagadia, Jason Berta, James Burke, and David Manthei

December 14, 2001

Function: Over the past two decades, a number of advances in downhill ski equipment technology have led to a significant decrease in the incidence of ski-related ankle, foot, and other lower leg injuries. Unfortunately, a number of these same advances have led to an increase in the incidence of knee injuries, most of which involve the anterior cruciate ligament.

The current design project seeks to modify one of the components of the ski binding, the ski plate, in a manner that should lead to a reduction in ski-related knee injuries. This may be accomplished by designing a ski-binding system that allows some degree of rotation, thereby temporarily transferring torque that would normally be placed on the knee to the ski binding. This energy will be transferred back to the body if the user regains some stability; otherwise he or she may engage the bindings release mechanism and come free before sustaining injury.

Design requirements:

1. Physical and Operational Characteristics

1. *Safety*: as this is a product to be used for sporting activity, safety is a key concern. Skiing is often a high-speed sport. Use of equipment that has safety standards to meet these conditions is necessary. For this project, the binding mechanism must release smoothly when expected. It should do so before an injury is incurred. It should not release prematurely or when unexpected, during normal activity. Its components must be securely fastened and not come loose.

2. *Performance requirements*: the ski binding performance should serve a twofold purpose: First, the binding will allow rotational movement of the ski boot when sufficient force is generated by an off-balance skier to move a locking pin out of the

locking slot. This rotational "give" subsequently reduces the torque experienced by the skier's knee, thereby reducing potential for knee injury, especially the rupturing of the anterior cruciate ligament. Secondly, because of the rotational movement of the binding, a twisting force will act upon the ski boot, thus easing the binding release of the boot during a high-impulse event. Again, this reduces the chance for knee injury.

> a. *Accuracy and Reliability*: the slots that allow rotational movement must be precision ground to minimize the friction forces. The reliability of the design will become equally important as the success of the binding depends on the ability to function properly. Equipment may be used from once or twice a year to over 120 days a year. The design must be repeatable throughout both function and manufacturability.
>
> b. *Weight*: the design's weight is critical to the performance of the overall ski. Performance is of utmost importance and the heavier the design becomes the more performance is sacrificed. The design, to account for performance, must minimize the weight. Current bindings range from 870g to 1570g, and the midrange binding, which most people ski on, is 1480g. We intend our final design to be near this midrange of about 1400g.
>
> c. *Size*: the size of the ski will be the same, as our product adapts to current skis and bindings. Therefore, our ski plate mechanism must be no wider than the width of the ski, and not much longer (or shorter) than the bindings. Our current mesoplate design is 115mm in length X 61mm in width X 16mm in height. For currently marketed risers, the nominal height is 10-12mm, but some extend to 22mm.

3. *Ergonomics:* the mesoplate will conform to Salomon ski bindings. It will be able to be mounted on downhill skies and be able to accept downhill ski boots that work with the Salomon bindings under normal conditions. It should be adjustable or available to conform to all skiers' sizes and skiing abilities.

4. *Materials*: primarily metal and plastic. These materials will be able to function properly given the varying ski weather conditions, quite possibly the same materials already used for ski equipment. They will be rust-resistant with a low deterioration rate. The plastic and metal parts will also be easily mass-manufactured for mass production and interchangeable part replacement purposes.

> a. *Mesoplate plastic*: Delring. Delring has high strength and good wear resistance. It is what the current toe piece and base plate are made out of.
>
> b. *Locking pin*: 440 stainless steel with heat treatment. Corrosion resistant with excellent strength and good impact properties.
>
> c. *Springs*: Hardened spring steel, 17-7 PH stainless steel. From Smalley Spring Corporation.

d. *Sliding washers*: Teflon. For low coefficient of friction properties.

e. *Other sheet metal*: Plated carbon steel. For corrosion resistance and cheap material cost.

f. *Casing*: Vinyl.

5. *Operating Environment*: The operating environment in which the binding will be subjected includes numerous variables. The temperature range that the binding will be exposed to varies from well below zero (-30^{o}F) to spring skiing (65^{o}F). The design needs to be resistant to corrosion and wear. The binding will also be subjected to dirt and dust, although not to an extreme extent, except in neglect. The design needs to be robust and durable to allow for numerous abuses throughout its life.

6. *Life in Service*: ten years, given seasonal maintenance, which includes size and tension adjustments and mechanical checks.

7. *Aesthetics, Appearance, and Finish*: this product has to fit in with the look of the existing skis and bindings. It should look nice, perhaps being available with different finishes to match current systems. It should also be entirely enclosed to keep people, and contaminants, out of the mechanical components.

8. *Shelf Life*: most people probably store skis in the garage or basement. We must make sure the components will not rust or warp and encourage proper maintenance.

2. Production Characteristics

1. *Target Product Cost*: competitive with current products, although a slight increase in price is expected for a more involved, safer piece of equipment. Current bindings range from $100 to $400 dollars. Our product should be competitive with the middle to upper price range.

2. *Quantity*: the design must be able to be mass-produced. Initially small quantities will be expected to be used as the product is field-tested. However, instead of having to purchase the entire binding, the specific plates can be bought and fitted to the skier's original binding. If the design is accepted as a means to reduce injury, the quantity produced will increase.

3. Miscellaneous

1. *Standards and Specifications*: the design must comply with existing attachment locations, such as screws, and ski and binding dimensions. Currently, the Deutsches Institut fur Normung (DIN) standards are used as a scale for release levels. They are based upon the skier’s weight, height, age, ability, and boot size.

2. *Customer*: The primary customer is the ski manufacturing industry. It is most likely that the design will need to be incorporated by an existing company into its bundled wares to gain wide use. Awareness among consumers of the product and its injury reduction while maintaining performance will cause a desire for the product that the ski manufacturing industry will then want to fill.

3. *Competition*: Major ski binding companies include Salomon, Marker, Rossignal, Tyrolia, and Look. Other groups, like that of M. Hull are currently designing new solutions as well.

4. *User-related concerns*: Because this is unlike any existing binding, the skier will have to adapt to its performance characteristics. With proper maintenance, the skier should not have to worry about the performance features operating correctly. However, this does not mean that a person can ski recklessly while using this binding. Although it helps reduce injury, one must always ski with one’s head.

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