Axiomatic Design and the Evolution of Conventional Alpine Ski Bindings

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Abstract

This work uses axiomatic design to critically examine several key developments of ski binding designs during the period when injury rates in skiing were declining dramatically. It is shown that evolutionary design tends to retain components from previous designs that are not necessarily the best approach and can result in coupling, a violation of the independence axiom. This coupling is associated with problems in retention that lead to inadvertent release and potentially dangerous loss of control. The control and protection functions are decoupled by the level of force. The forces for control are less than those that cause injury, providing a window in which the binding response can change from load transmission for control to filtering of potentially injurious loads.

1. Introduction

The objective of this work is to critically examine conventional, mechanically actuated alpine ski bindings from the perspective of axiomatic design. In the process of this examination, this work identifies design considerations and approaches that could impact standards for the design of human-machine interfaces, where there is a risk of injury because high levels of mechanical energy are involved. The key issue is to be able to transmit control loads across the interface from the user to the tool, without transmitting injurious forces from the tool to the user.

Alpine ski bindings, which were originally developed to attach the boot to the ski solidly enough to provide the control required to allow for turning while skiing down hills, provide examples of essential design challenges for many kinds of human-machine interfaces. The bindings must transmit control loads from the skier, via the ski-boot, to the ski, which is acting as a tool to control the skier's motion. The binding must also transmit some feedback loads from the ski to the boot. However, the binding should not transmit loads to the boot that could cause injury to the skier. In a generic sense, the basic approach to this design, or portions of it, are the same for many other kinds of human-machine interfaces where there are high levels of mechanical energy, such as for seats and restraint devices in many kinds of vehicles and for some kinds of power tools.

Axiomatic design has been applied to a wide range of engineering designs (Suh 1990, Suh 2001). It is based on the proposition that all good designs comply with two axioms: maximum independence and minimum information. The application of these axioms drives design descriptions to have a certain structure and the design process to follow a certain sequence as well. Axiomatic design has not been reported to have been applied to ski bindings.

Ski binding design has evolved significantly since the 1940s. There has been a 50% reduction in lower extremity injuries over this period, (Johnson et al. 2000). The dramatic rate of decline, which can be largely attributed to the evolution in ski binding design, ended in about 1985 (Johnson et al. 2000). This paper will concentrate on design changes through the mid-70s; these designs had the most profound influence on injury rates, and many of them are still in use today.

Currently, there are millions of people who partake in alpine skiing in the United States. Modern alpine skiing, particularly competitive alpine ski racing, includes some exceptionally challenging situations regarding control. In the competitive downhill event, competitors travel at speeds over 100km/hr down a course that demands that they make turns while adapting to terrain changes and changes in the mechanical properties of the snow. Over these courses, skiers are generally able to control their descent such that they can stay within a meter or less of their selected line. Recreational skiing is less intense and slower paced. However, there are frequently situations when a recreational skier's trajectory, unchanged, would take the skier into a tree, another skier, or ski area equipment at speeds of 30km/hr or more, which are sufficient to result in death (Brown et al. 1996). Yet death occurs in less than one in a million skier visits (Shealy and Thomas 1996). The exceptional control that skiers are able to exert is due in part to how their boots are attached to the skis.

The approach in this paper is to summarize the essential elements of axiomatic design, to review major modifications that have occurred in the evolution of the design of ski bindings, and to critically examine these trends in the context of axiomatic design.

2. The Elements of Axiomatic Design

Axiomatic design can be decomposed into three essential elements (Brown 2005). Each of these three can be further decomposed into two components. The axioms, maximizing independence and minimizing information, are the most important part of axiomatic design, and they are the criteria by which to assess whether a design is good (Suh 1990, 2001). The application of the axioms requires a structure to the design, which supplies the second element. This structure also assures that the design is functionally based and logically decomposed. The third element, process, is strictly for implementation, creating the structural decompositions and integrating them into the final form.

Table 1 Elements of Axiomatic Design

Elements		***Components***	
1	Axioms	1.1	Maximum independence
		1.2	Minimum information
2	Structures	2.1	Lateral domains
		2.1	Vertical hierarchies
3	Processes	3.1	Zigzagging decomposition
		3.1	Physical integration

The axioms are the main elements that distinguish axiomatic design from the other design methods. They are the common criteria against which all designs can be evaluated.

Compliance with axiom one, also known as the independence axiom, assures that the design will be adjustable and controllable without iteration, and that unintended consequences will be avoided. Compliance with axiom two, also known as the information axiom, assures that the design will be robust, maximizing the probability that the functions will be fulfilled. There are a number of useful corollaries and theorems, based on the axioms (Suh 1990), that will not be considered individually here.

The structure encompasses lateral domains that include customer needs (CNs) functional requirements (FRs), design parameters (DPs), and constraints (Cs). The FRs describe what a design needs to accomplish and should be stated in the imperative. The DPs describe what a design looks like and are selected to fulfill the FRs. The lateral domains are decomposed vertically into hierarchies that describe the design at increasing levels of detail. FRs should be selected so that they are mutually exclusive and so that they collectively exhaust the customer needs, or their parent FRs, in the hierarchical decomposition.

To fulfill axiom one, maximizing independence, there should be one DP that fulfills each FR. Ideally, a DP should not influence any FRs other than the one it was selected to fulfill. The relation between the FRs and DPs can be represented in a design matrix, where the matrix elements describe the relation between the FRs and DPs. The design matrix provides a means for visualizing the independence or lack thereof, which provides a check for axiom one. A diagonal matrix is ideal. In this case, all the off-diagonal terms are zero, indicating that the DPs only influence the FR they are selected to influence. Any order of adjustment of the DPs is appropriate in a diagonal matrix. A triangular matrix is workable as well, although there is only one order of adjustment of the DPs that must be followed to satisfy the FRs without iteration.

In this paper, where existing designs are analyzed, the assignment of FRs to the existing DPs is somewhat speculative, although there are patent descriptions that can be used to better understand the intent.

In the context of axiomatic design, there are two issues that must be solved: 1. decoupling protection and control, i.e., transmitting control loads without transmitting injurious loads; and 2. increasing the probability of success, i.e., reducing the risk of a loss of control or an injury due to the binding.

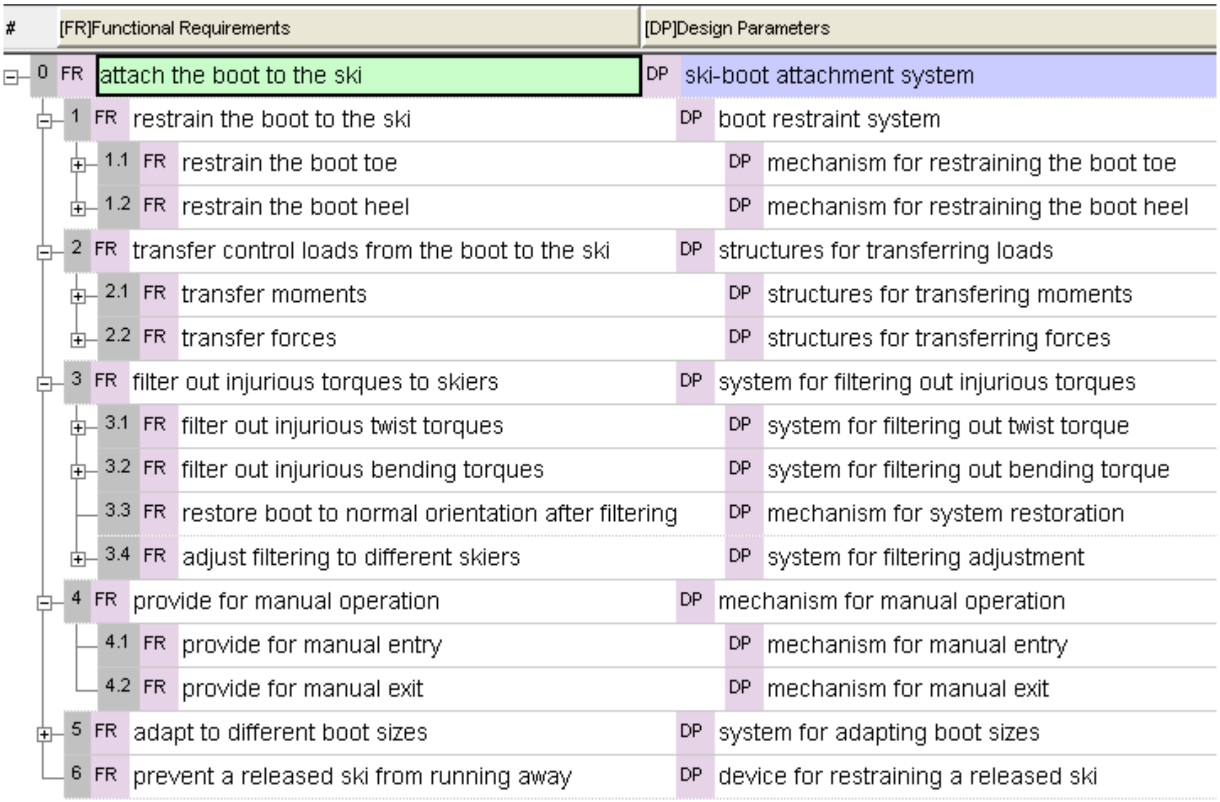
3. The Origin of Alpine Skiing and a Decomposition of Binding FRs and Generic DPs

Skis were used to improve mobility over the snow in Scandinavia as long as 4500 years ago (Lund 1996). The original highest level FR for the binding was: hold the skier's forefoot on the ski. This might be decomposed into two child FRs: FR1, transfer forward motion of the foot to the ski; and FR2, transfer vertical motion from the foot the ski. These FRs were satisfied by a leather toe strap anchored to the ski that went over the foot somewhere between the toes and instep. A constraint, which it is doubtful that anyone even thought of violating, was that the skier's heel had to be free to move vertically to facilitate walking and running on the skis. The kind of skiing that this was adapted for came to be known as Nordic skiing, to differentiate it from the kind of skiing that began to be developed in the Alps around 1900.

Alpine skiing emphasizes gliding down hills and turning as opposed to walking or running on skis. And as people started to spend more time gliding down hills and turning, they were going faster, had to avoid trees, cliffs, and other skiers; consequently, they needed more control. Alpine bindings require FRs for control for turning and stopping and for retaining the skis. New FRs that can be considered would require the transfer of control loads from the boot to the ski. Then the key question in implementing these new FRs, without transmitting injurious loads to the skier, is a problem of decoupling, i.e., applying axiom one. A proposed list of FRs and generic DPs are listed in Table 2. The generic DPs describe generally what is needed to satisfy the corresponding FR. Specific examples of DPs will be supplied from the patent literature.

The binding design problem is slightly more complex than just coming up with a design that can sort control loads and injurious loads and respond appropriately. There are other loads on the binding that are not control loads applied by the skier, and they are not injurious loads. Some of these loads are good for sensory feed back to the skier, some are sub-injurious loads. Furthermore, if the binding reacts to a potentially injurious load by allowing displacement between the boot and the ski, then the binding itself influences the load that it is sensing, and effectively transforms a potentially injurious load into a sub-injurious load. Conventional bindings eventually respond to a potentially injurious load by releasing the boot from the ski. If the release happens during a fall, then the release does not contribute to loss of control, since control was already lost. Sometimes a ski releases while the skier is still in control and no potentially injurious loads are present. This is called an inadvertent release. Inadvertent releases result in loss of control, which has been cited as contributing factor in a majority of skiing accidents (Shealy 1985, Brown et al. 1996). In the context of axiomatic design, an inadvertent release is a failure to fulfill the attach and the control FRs (FR1 and FR2, Table 2), and could result from the inability to decouple them from the filter FRs (FR3, Table 2). Inadvertent release is certainly a violation of axiom 2, as it is an indication of a reduced probability of success, which in turn indicates a nonrobust design. Inadvertent release could result from a violation of axiom 1, since the control and filter functions are not fully independent.

Table 2. Decomposition of the Highest Levels of FRs and DPs on an Alpine Ski Binding Using Acclaro www.axiomaticdesign.com.



#		[FR]Functional Requirements		[DP]Design Parameters
0	FR	attach the boot to the ski	DP	ski-boot attachment system
1	FR	restrain the boot to the ski	DP	boot restraint system
1.1	FR	restrain the boot toe	DP	mechanism for restraining the boot toe
1.2	FR	restrain the boot heel	DP	mechanism for restraining the boot heel
2	FR	transfer control loads from the boot to the ski	DP	structures for transferring loads
2.1	FR	transfer moments	DP	structures for transfering moments
2.2	FR	transfer forces	DP	structures for transferring forces
3	FR	filter out injurious torques to skiers	DP	system for filtering out injurious torques
3.1	FR	filter out injurious twist torques	DP	system for filtering out twist torque
3.2	FR	filter out injurious bending torques	DP	system for filtering out bending torque
3.3	FR	restore boot to normal orientation after filtering	DP	mechanism for system restoration
3.4	FR	adjust filtering to different skiers	DP	system for filtering adjustment
4	FR	provide for manual operation	DP	mechanism for manual operation
4.1	FR	provide for manual entry	DP	mechanism for manual entry
4.2	FR	provide for manual exit	DP	mechanism for manual exit
5	FR	adapt to different boot sizes	DP	system for adapting boot sizes
6	FR	prevent a released ski from running away	DP	device for restraining a released ski

Constraints do not appear in Table 2. One constraint is that the binding should not interfere with the ski-snow interaction (C1). Another is that the binding, in its operation, should not increase the risk of injury to the user or other skiers (C2).

The decomposition shown in Table 2 is constructed for a discussion of some developments of alpine ski bindings and is not optimized from the perspective of axiomatic design. The purpose of this decomposition is to attempt to have a complete list of design components that will encompass most, if not all, of the systems, mechanisms and devices on a modern alpine ski binding. The FRs should be mutually exclusive, and they are not in this decomposition. The restraint branch, FR1, overlaps with FR2.2, at the least, if not with all of FR2. The children of FR2 are redundant, in that forces are required for transferring moments. In an actual design exercise, FR1 and FR2.2 could be eliminated. FR1 would drive the design to a system with a heel piece and a toe piece, which is how the bindings evolved, and may not be optimal.

The injurious load filtering branch, FR3, is simplified, based, in part, on the bindings that dominate the market. Other kinds of loads besides twist and bending could be injurious. In addition to adding a roll moment, forces in three directions could also be considered. Furthermore, there are combined loading situations that could be injurious, where none of the individual component loads are. Recent attempts have been made to design bindings that protect the knee from combined loading situations (Dodge 2001).

It should be noted that “release” is the term commonly used in the ski industry rather than “filtering”; however, the term release is thought to be too limiting or leading in the context of a generic design decomposition, as presented here. Filtering is more general. Release, meaning complete separation of the boot from the binding, is one form of filtering. In addition, there are other potentially injurious loads that are not considered. Combined loading situations are not considered. Also filtering of vibrations is not considered separately.

In load transmission for control, the relative displacement of the boot and ski should be small for efficient load transmission. It is the load-displacement relation that is the most important relation in defining the efficiency of transmission. The other factors are the mass of the binding and the rate sensitivity of the coupling. These latter two will not be considered here. Therefore, in the control branch, FR2, functional tolerances on the FRs and success of a DP in satisfying the FR, could be defined in terms of the stiffness of the coupling through the range of forces required for control in skiing maneuvers. While work has been done for some time on measuring forces on the bindings during skiing (e.g., Lieu et al. 1982), it is not the purpose of the current paper to specify the force levels but rather to analyze how to incorporate them in the design. At this point, it is noted that the FRs in the control branch are defined by the mechanical stiffness of the system, ki, applied to some definable upper limit in load, Tcon, and that a tolerance on the stiffness could be determined, ±Δk. The mechanics of the structure that transmits the control load define the stiffness at some level. Therefore, it is the geometry and section modulus of appropriate members in the structure transmitting the control loads that would be used to define the DPs in this branch quantitatively. Success is based on achieving the desired stiffness of the structure, and, more basically, on reliably transmitting the loads up to Tmax.

The filtering branch, FR3, in contrast to the control branch, requires relative displacement between the boot and ski, and implies a relatively compliant structure to allow this displacement. The filter transmission characteristics are simple. Pass all loads below a certain limit necessary for control, Tcon, and don’t pass any above another limit that would cause injury, Tinj. Obviously, to fulfill this, Tcon must be less that Tinj. There is a tolerance on how well the limit Tinj is respected. Measurements of loads while skiing have established that that Tcon appears to be less than Tinj (Scher and Mote 1999). Measurements of injury thresholds are more elusive. Tinj is a function of several factors, including muscle activity, which can act to protect the leg from injury. There is some question as to what the muscles should be expected to do to influence Tinj. If Tcon and Tinj are underestimated, then there is a risk of loss of control that could lead to serious injury. The filtering should take place above Tcon and below Tinj. It is the difference between these two that provides an opportunity for simple mechanical mechanisms to accomplish the essential decoupling of the control and filtering functions.

With substantial ski industry involvement, ASTM (F 1063-04) has defined several tolerances on the measured performance of the ski-boot-binding system for filtering. The lowest is ±15% of the reference value. The reference value is selected to be in the range between Tcon and Tinj. The functional implication, or assumption, associated with the tolerances is that the difference between Tcon and Tinj is sufficiently larger than the tolerance. Errors in selecting the reference value for system adjustment would negligible, if the difference between Tcon and Tinj is large enough. Success could be defined based on how well the system performance, the actual control and filtering limits in practice, can stay within the tolerances specified in the standard.

4. An Early Toe Piece with Filtering

Versions of the binding shown in Fig. 1 were manufactured from about 1946 to 1972 (Masia 2002), in advance of any standards. In this early embodiment, the heel is not restrained, in the vertical direction, by the cable (2). The filtering of twist torques (FR3.1) is achieved through a mechanism involving a kind of leaf spring (5) that impinges on the mechanism for restraining the boot toe (FR1.1), which is integrated with the structure for transferring control loads (FR2). A lever for manual operation (FR4) is not shown, but would normally be a lever that would tighten or loosen the cable (2). While the binding violates the C1 constraint not to interfere with ski-snow interactions, since it has components that extend past the width of the ski, and could contact the snow during carving, that technique was not yet developed to the point where it would be a problem when this binding was popular. Adjustment (FR3.4) is accomplished raising or lowering the forward end of the attachment for the leaf spring (5). The motion required to filter the loads is accomplished by rotating the plate, (6) which holds the restraint and load transfer structures, about one of the pivot screws (7 or 8), while compressing the spring (5). The spring (5) exerts a preload on the plate (6) to limit the relative motion of the boot and ski until a supposed control load limit, Tcon, has been reached. The inventor was reported to have broken his leg while skiing on a prototype of this design, although it was attributed to a previous fracture not having healed properly. The earlier fracture, which was on a nonfiltering binding, motivated the design (Masia 2002).

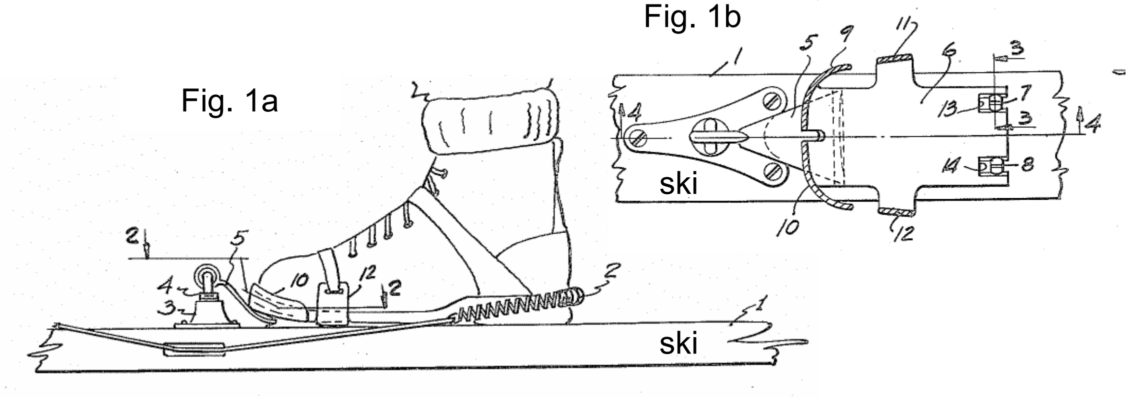


Fig. 1a

Fig. 1b

Fig. 1. Early patent for a ski binding with a “high degree of safety” (Hvam 1941).

5. Two Conceptions of Releasable Toe Piece

The binding in Fig. 2 employs a cam-follower arrangement, loaded with a coil spring, in the toe piece. As shown in Fig. 2b, this arrangement allows for significant displacement of the boot relative to the ski before the boot releases. This displacement provides good anti-shock capabilities and contributes to compliance with the information axiom, by avoiding inadvertent release in many situations.

Fig. 2a

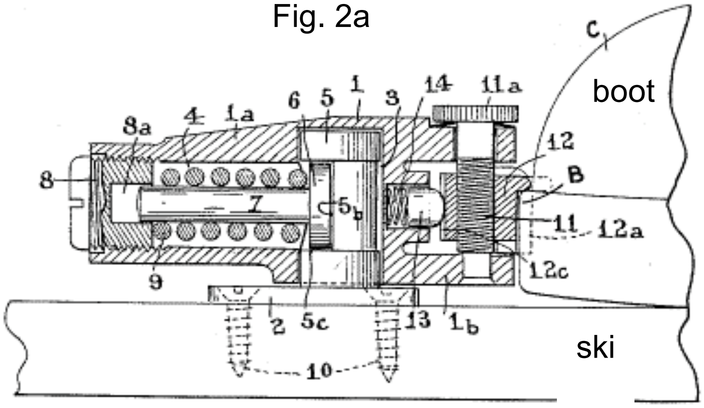


Fig. 2b

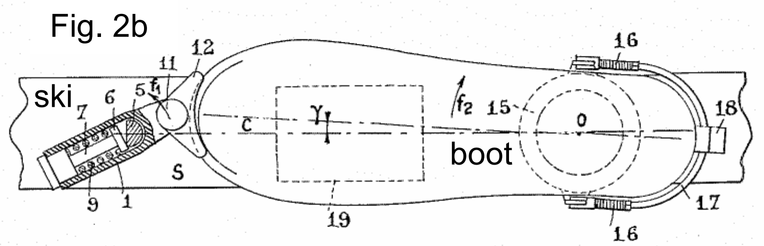
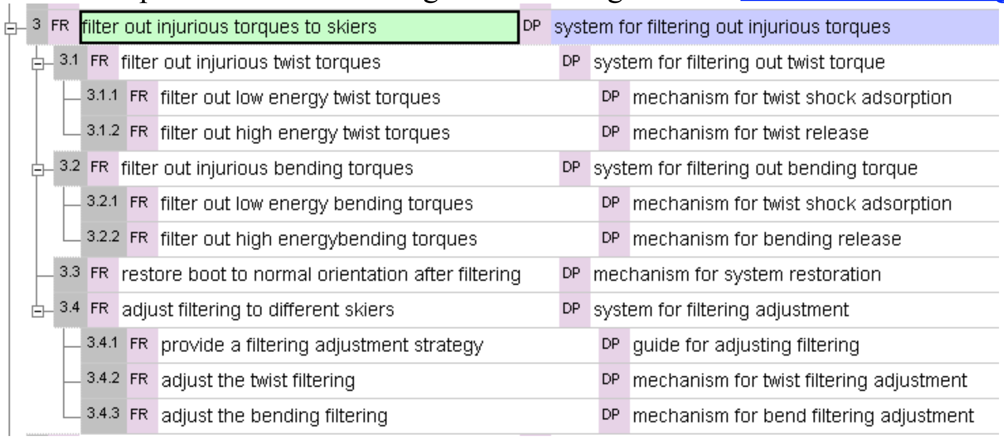


Fig. 2. Toe piece used in the late 50s and 60s (Beyl 1962).

The key to this binding component performance is cam-follower shapes (5&6 Fig. 2), with large flat spots, combined with a preload from the spring (7 Fig. 2). This arrangement provides for a certain magnitude of lateral forces at the toe in the control phase FR2, before the load-reducing displacement begins. Two aspects of the geometry of this cam-follower arrangement for a DP effectively decouple control FR2, control with filter FR3. Tcon is a function of the preload on the spring and the width of the flat spot on the cam and the distance to the boot toe interface (B Fig 2a).

Table 3. Expansion of the Filtering Branch Using Acclaro www.axiomaticdesign.com.



		FR		DP
3	FR	filter out injurious torques to skiers	DP	system for filtering out injurious torques
3.1	FR	filter out injurious twist torques	DP	system for filtering out twist torque
3.1.1	FR	filter out low energy twist torques	DP	mechanism for twist shock adsorption
3.1.2	FR	filter out high energy twist torques	DP	mechanism for twist release
3.2	FR	filter out injurious bending torques	DP	system for filtering out bending torque
3.2.1	FR	filter out low energy bending torques	DP	mechanism for twist shock adsorption
3.2.2	FR	filter out high energybending torques	DP	mechanism for bending release
3.3	FR	restore boot to normal orientation after filtering	DP	mechanism for system restoration
3.4	FR	adjust filtering to different skiers	DP	system for filtering adjustment
3.4.1	FR	provide a filtering adjustment strategy	DP	guide for adjusting filtering
3.4.2	FR	adjust the twist filtering	DP	mechanism for twist filtering adjustment
3.4.3	FR	adjust the bending filtering	DP	mechanism for bend filtering adjustment

The filtering function is satisfied by the lateral displacement of the boot toe up to the position where it disengages from the interface (B Fig. 2a). This is controlled by some of the same DPs or geometric features as the control FR; however, they are in a different configuration, which is accomplished by the spring-loaded pivot (14 Fig 2a, 11 Fig 2b) that maintains the interface during filtering displacements, and this provides some decoupling.

There is essentially a two-stage filtering system, as shown in the expansion of FR3 filtering (Table 3): a first stage that could be called anti-shock, for low-energy, potentially injurious torques, and a second stage that is called release, for high-energy, potentially injurious torques. The limits of the anti-shock phase are controlled by the same geometrical feature DPs as the release and the control phases, again in different configurations. There is some potential for independent adjustment of these FRs by changing the geometry of the contact interfaces between the components in their different configurations. Another way of considering the anti-shock capacity is the work, W, required for releasing the binding, or taking it to the point where it can no longer recover itself, as a function of the torque, T, and displacement, θ:

$$W = \int T d\theta \quad [1].$$

This is the work that the binding can adsorb from the external environment before separation of the boot from the ski (Fig. 3).

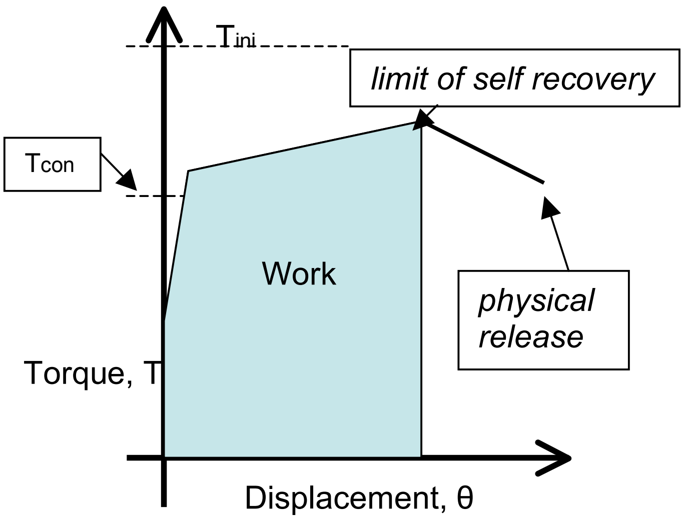


Fig 3. Idealized Torque-Displacement curve for a ski binding

The restoration function FR3.3 for Beyl's toe (Fig 2), for restoring the boot-ski orientation following loading, is also satisfied by essentially the same components, although the springs are acting in extension rather than compression, so there is potential to adjust these functions separately by adding an extra element, if desired. In the context of a new design, if such an independent adjustment function is not desired, then it should not appear in the FR decomposition.

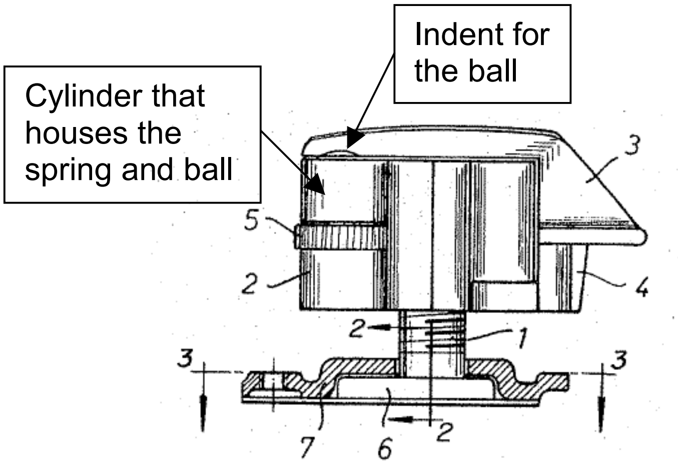


Fig. 4. Toe iron for safety ski bindings (Marker 1967). During release, the upper and boot side of the binding portions (3 and 4) rotate away from the lower forward portion as the ball moves out of the indent.

At the time Beyl's toe piece was made by Look-Nevada in France, its main competitors relied on a mechanism that included a spring-loaded ball bearing, which would get sheared out of an indent in order to release the boot toe laterally at the toe. The most popular embodiment of this ball-bearing mechanism was made by Marker in Germany and is shown in Fig 4. These ball-bearing mechanisms tended to have little anti-shock capacity, they were prone to inadvertent release, and they had to be manually reset after a release. The ball-bearing-mechanism bindings had a much higher degree of coupling between FR2 and FR3 for control and filtering than Beyl's did, leading to their many shortcomings.

Another disadvantage of Marker's design was that the adjustment spring was short. This is the same spring that attempted to satisfy the control and filtering FRs, coupling them so that filtering was largely absent. Shorter and stiffer springs leave a smaller window for adjusting forces, and therefore, reduce the probability of successfully adjusting the force within the desired tolerance. The theory is that, all other things being equal, it is better to have a softer spring highly stretched or compressed to supply a certain force than a stiffer one less compressed, because small differences in the displacement causing the compression or tension will result in a smaller change in force, thus creating less risk of exceeding a tolerance. Therefore, mechanisms with springs that are shorter and stiffer often are not as robust as they could be, and can be judged as inferior by the information axiom (Suh 2001, ch.2).

Neither Beyl's nor Marker's toe pieces needed an adjustment for boot width FR5, since they didn't interface with the boot sides. This was an important advantage in the years before boot geometry standards. Only a height adjustment was required, and this was achieved using a screw (11 and 11a Fig. 2 and 1 Fig 4). Both designs accomplished this without introducing coupling with other functions.

All three of the toe pieces discussed require a forward force to keep the ski boot retained, and this is supplied by the heel piece. This situation introduces a fundamental coupling between the toe and the heel piece. The manifestation is in seen in the influence on ski flex and in the potential for inadvertent release.

6. Nonreleasable Heel

Fig. 5 is an example of a heel piece that can provide the required forward force to satisfy the FR1.1, restraining the toe by means of a spring (3 Fig. 5) that is tensioned with a lever (5 Fig. 5) for manual operation (FR4). It also has threaded links (7 and 8 Fig. 6) for length adjustment FR 5.2, and the pivotal mounting (10 Fig 5) allows for different heel heights. This is a good example of physical integration of several DPs while maintaining functional independence. The rotation of the heel as supplied by the rotating coupling between 1 and 2 (Fig 5) defines a center of rotation for the boot in releasing in twist from the toe, so there is a clear relation between the force for displacing the toe and the torque required to release the boot from the toe. This is important, since it is the torque that is responsible for putting the tibia at risk of a spiral fracture. Beyl's heel piece was, in many respects, an important improvement over the cable arrangement in Fig 1. It could also be used with the kind of toe piece shown in Fig 1. Beyl's heel piece as shown in Fig 6, however, makes no attempt to filter out injurious bending torques to satisfy FR3.2, leaving the leg at risk from a bending type fracture and the Achilles tendon at risk of rupture.

Fig. 5a

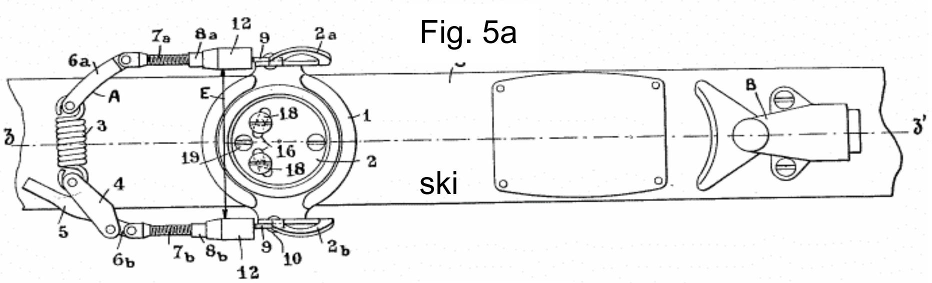


Fig. 5b

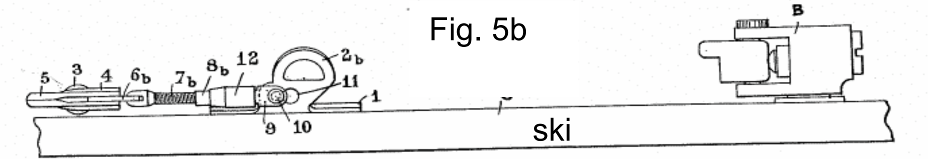


Fig. 5 Heel piece used in the late 50s and 60s (Beyl 1965).

The kind of heel piece shown in Fig. 5 violates the constraints in that it can contact the snow during extreme edging, and it interferes with the flex of the ski. The boot acts to stiffen the ski when the ski tries to flex, because the heel and toe are mounted directly to the ski, so the boot acts like a beam in parallel with the ski, stiffening the center of the ski.

7. Releasable heel

Many different versions of releasable heels were patented and saw use starting in the 50s. Nonreleasable heels were commonly used into the 70s by top competitors who were especially concerned about the risks of inadvertent release. Nonreleasable toes, by contrast, disappeared about a decade earlier. Boots switched from leather to injection molded plastics about in the late 60s to early 70s, and standards started to be introduced for boot geometry and ski binding function.

The releasable heel shown in Fig. 6 embodies many of the same features found in popular models of heel pieces beyond the 90s. The essential elements for release and retention are the cam surfaces (indicated by 9, 10, and 11), the follower (46), the spring (3), and the release adjustment (5). In order to release the boot from the heel, the cam surfaces, which are integral with the heel, hold down component (1), push the follower back, compressing the spring.

The length-adjustment mechanism and the forward-pressure spring, which are important components of this heel piece and all similar heel pieces, are not shown in Fig 6. The length-adjustment mechanism can be a track that the heel can move along, and it can be fixed in an appropriate position for the boot sole. The track assembly for length adjustment can be mounted on the ski. The forward-pressure spring then acts between the track and the heel piece. The entire heel piece can, and should, move rearward a certain amount when the boot is inserted, thereby supplying a compressive force longitudinally on the boot sole to keep it engaged with the toe and heel.

Since the upper shelves on the extensions of the boot sole on the heel and toe are only about 7mm long, there is some potential for inadvertent release due to the movement of the heel against the forward-pressure spring. This can happen in at least two ways. One way is explained below. In the other way, when the ski flexes, the straight-line distance between the toe and the heel is shorter, so the boot sole, which occupies this straight-line position, drives the heel back against the forward pressure spring. Eventually the ski unflexes, and if the forward pressure spring under the heel piece does not recover the heel piece position quickly enough, then the boot can escape from the binding significantly below the control limit (Brown and Ettlinger 1985). This kind of inadvertent release is a direct consequence of violating axiom one, coupling the toe and heel retention functions.

During vertical motion of the boot to satisfy FR3.2, filtering out injurious bending loads, the follower needs to slide back in the housing (48 Fig. 6). Since the cam exerts a vertical force on the follower, the friction between the top of the follower and the interior of the housing can influence the binding performance. If the friction is large enough, then the action of the boot sole extension on component 1 can drive the heel back against the forward-pressure spring. This can lead to stick-slip behavior, as enough force builds up in the forward pressure spring by driving the binding rearward to overcome the static friction between follower and the housing. If the heel is driven rearward far enough before the forward-pressure spring recovers, then the boot heel can escape from the heel piece before the control limit is reached. This is another kind of inadvertent release resulting from a violation of axiom one by coupling the toe and heel pieces.

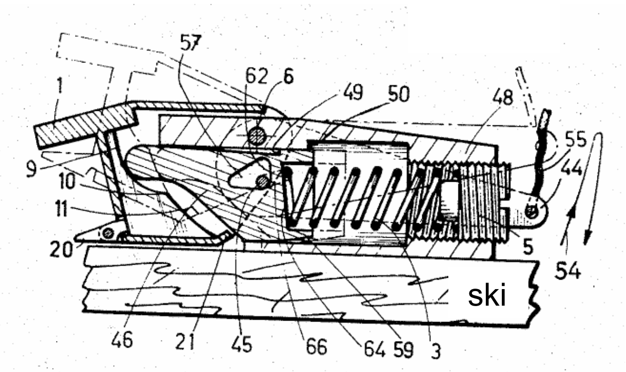


Fig 6. Releasable heel (Salomon 1973). The boot is held down by component 1, and centered by elements not shown. Component 20 is used to close the 1 onto the boot. The indicated motion of 44 is to manually open the binding for exiting.

8. Axiomatic Design Based Strategies

The approach to achieving a good design according to the Principles of Axiomatic Design (Suh 1990), is to select the correct upper-level FRs, then correspond DPs, then zigzag down to more specific FRs and DPs, creating the design hierarchy. A design can be no better than the original FRs. A bad design cannot usually be patched up; it is usually best to begin again with the upper-level FRs. The FRs should be selected in a solution-neutral environment. At each level, undesirable coupling should be minimized, ideally so that each FR has its own DP to satisfy it, and each DP only influences the FR it has been selected to satisfy. This assures the compliance with axiom one, the independence axiom. After axiom one is assured then the information content is minimized to assure compliance with axiom two.

The bindings above are examples of evolutionary designs. While evolutionary designs might eventually converge on satisfactory designs from an axiomatic perspective, the design of ski bindings appear to be struggling with a heel-toe configuration in such a way that it is leading to coupling and the resulting inadvertent release problems. Some aspects of the coupling are integrational, in that coupling comes from the way the heel and toe are integrated. The toe and heel pieces have tended to evolve separately, even though they are inherently coupled by the need to retain the boot. Furthermore, traditionally, the toe and heel piece were each mounted separately on the ski, even though this coupled the ski performance to the binding and vice-versa.

Currently mounting plates are frequently used between the binding and the ski. It is also common now for manufacturers to match bindings with skis, which include special mounting devices. The primary motivation in both cases is to reduce or control the influence of the binding on the ski. The plates can also add damping to the ski-boot-binding system. They often have internal friction or use viscous material as a component.

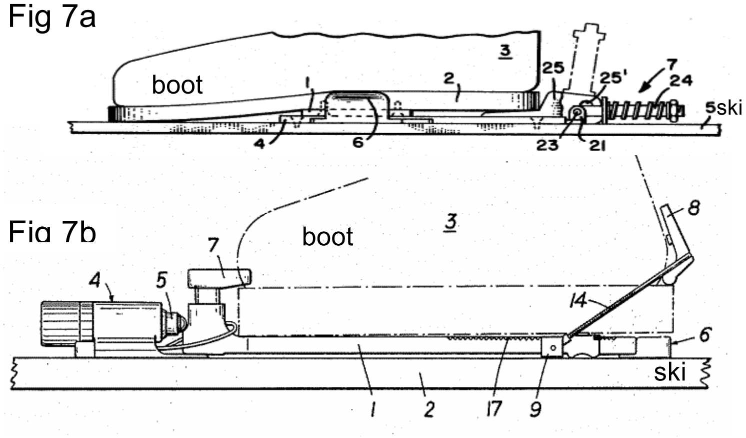


Fig. 7. Plate bindings. (7a Spademan 1971; 7b Gertsch and Gertsch 1975)

Plate bindings could be interpreted as a kind or redesign of the binding in a solution-neutral environment, ignoring the traditional heel-and-toe piece approach. Many variations on plate bindings were patented in the 70s (e.g., Spademan 1971, Gertsch and Gertsch 1975). Plate bindings decoupled the retention and filtering or release functions by having a plate attached to the boot, and then having the filtering and release take place between the plate and other binding components. Spademan's plate was screwed on to the boot, and was held on the sides by the rest of the binding. Gertsch's plate was removable and stayed with the rest of the binding, except when there was a release. Spademan's spring for adjusting release levels was in the rear (7 Fig 7a), and Gertsch's was in the front in this embodiment (inside 4 Fig 7a). The plate bindings had some popularity in the 70s. They lacked independently adjustable release levels for the different directions. The ratios of loads required for release in the different directions were dictated by the shape of cam interfaces (6 Fig 7a; 5 Fig 7b). This was probably not the shortcoming that kept them from becoming a continuing success on the market, since most people have the twist and forward bending releases set at the recommended ratio (ASTM 2004).

Inadvertent release continues to be a problem for ski bindings. Inadvertent release can result in a sudden loss of control and have tragic consequences. Occasionally, inadvertent releases result in injuries that include paralysis or death. Inadvertent releases could be reduced by increasing the work to release. Extending the displacement before the limit of self-return is reached could reduce the risk of inadvertent release (Fig. 3). This is difficult to do with the designs that are shown above (Fig 2, 4, 5 and 6), as both the heel- and toe-retention mechanisms employ pivoting members that rotate on arcs that take the interface away from the boot as it rotates. That is, the binding and boot interfaces rotate on arcs that tend to separate them during the filtering phase. The consequence is that the retention and filtering are inherently coupled. The twist release on some plate-type designs are exceptions, in that they locate the center of rotation for twist release under the boot (Wulf 1975, Salomon 1980, Dodge 2001); however, the amount of travel before release is not adjustable. Only the latter has been introduced as a product (Line Pivogy), and it is not being marketed for the rotation under the foot-rotation feature. In any event, it is not clear from the literature how much travel there should be before release. Short skis, e.g., about 1 meter in length, might not even need a release in twist, just filtering.

The main contribution of the ski binding to human-machine interface design is the decoupling of the load transmission control and protection functions by the level of the load. There are applications of the principles learned from ski-binding design for other human-machine interfaces. For example, power hand tools require the transmission of control loads, but have enough kinetic energy, or power, to cause injury. The adjustable drag, or torque limiting device on the chucks of some power drills is usually set not to strip screws, but it also functions to limit the torque that is transmitted to the user. The principles could be applied to mechanisms for cushioning shock for the passengers when a vehicle collides with something. In this case, the release at the end of travel is not an option, so there is some further consideration required about what to do at the end of travel. However, it is clear that, in order to maximize protection capacity, shock-adsorbing travel should begin just below the injury threshold and continue to the limit allowed by the vehicle design. If, like the bindings, at least part of the travel in vehicle-impact designs had some restoration capability, then the mechanism could be used to address multiple impact collisions.

9. Concluding remarks

Axiomatic Design provides an insightful context for systematically examining binding development. The years when the design developments were particularly interesting are those during which injury rates declined dramatically, through the mid 80s.

The principal problem is to differentiate control and injurious loads according to the magnitude of the load. This is solved by using the magnitude of the load, since the loads required for control are below those that have the potential to cause injury.

Evolutionary design tends to retain functional requirements and design parameters that may not provide optimal solutions to the design problems. To avoid the shortcomings of evolutionary design, the FRs and DPs could be rederived in a solution-neutral environment, without the encumbrance of previous solutions.

The reliance on using some of the same DPs for retaining and releasing the toe and heel, results in coupling, which violates axiom one, and contributes to inadvertent release, which continues to be a problem.

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