A New Electromechanical Ski Binding With Release Sensitivity to Torsion and Bending Moments Transmitted by the Leg

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This paper describes the design of a new electromechanical ski binding whereby release in both twist and forward bending is controlled electronically and the release level in twist is modulated electronically based on the neural stimulation of muscles in the quadriceps group. To provide signals for controlling release in the two modes, the binding incorporates two dynamometers. Each dynamometer measures loads that have been shown to correlate strongly ($r^2>0.90$) to torsional and bending moments at the lower leg injury sites. Although the binding consists of both a toepiece and heelpiece, the toepiece does not permit release of the boot from the ski in the twist mode but rather serves as one of the dynamometers. Consequently the heelpiece was designed to provide the release function in both modes. Release is realized by a low-force solenoid that actuates a multilink trigger mechanism. To prove feasibility, a prototype was constructed and evaluated.

Alpine skiing is a winter sport that produces many injuries each year. A study by Johnson, Ettlinger, and Shealy (1989) compiled data on skiing injuries over a 15-year period which indicated that the overall injury rate is on the decline. However, injuries to the lower extremity still occur. Two prominent injury mechanisms are twisting and anterior/posterior bending loads. One twisting type of injury that is common is medial collateral ligament (MCL) damage with or without anterior cruciate ligament (ACL) damage (Howe & Johnson, 1985; Johnson, Pope, Weisman, White, & Ettlinger, 1979). Another twisting type of injury is the spiral fracture of the tibia. Bending related injuries include bending fractures of the tibia across the boot top and isolated ACL damage as a result of hyperextension (Shino, Horibe, Nagano, & Ono, 1987).

To appreciate why the injuries continue to occur, it is necessary to understand the functions of conventional heel-toe type bindings in use today. The conventional ski binding comes in two main parts, a toepiece and a heelpiece. In a forward-falling situation, the leg is subjected to an anterior/posterior bending moment that results from contributions of the bending component of the boot sole moment as well as the normal (perpendicular to boot sole) and tangential

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(parallel to long axis of boot sole) components of the boot sole force[1] acting over their respective moment arms (Maxwell & Hull, 1989). However, the load causing release of the heelpiece is an upward force (normal to the ski) at the boot heel.

This force has been shown to correlate only weakly (avg. $r^2 \sim 0.6$) to the bending moments actually developed at the injury sites (Quinn & Mote, 1991). Thus, a binding wherein release is sensitive to a load that correlates more strongly to injury-site bending moments could be expected to better protect skiers against injuries resulting from excessive bending than would conventional bindings that rely on the upward heel force to actuate release.

The conventional toepiece also has drawbacks, one of which is the fixed release level. As discussed by Eseltine and Hull (1991), the strength of the knee joint (i.e., load to cause an injurious level of ligament strain) appears profoundly influenced by the degree of contraction in muscles crossing the joint. Generally, muscle contraction causes a loss in flexibility with a concomitant potential increase in strength. If the release level is set to protect the knee at its lowest strength, then the binding's retention function cannot be met because the muscles are typically contracted during skiing (Maxwell & Hull, 1989), thus making the knee strong and allowing relatively high loads to be safely transmitted by the joint.

If the release level is set to protect the knee at its greatest strength during skiing, however, then knee injury is imminent if the skier falls and the muscles are relaxed, thus lowering the knee strength. Accordingly, the fixed release level in the toepiece is a drawback because the binding cannot be adjusted to simultaneously protect the skier from injury and provide adequate retention. This may help explain why ligamentous knee injuries due to the twisting mechanism are so prominent in skiing with the use of conventional ski bindings.

Thus there is the need for an injury preventive ski binding system that better protects against both twisting and anterior/posterior bending related injuries. The intent of the project described in this paper was to illustrate a new design of an electromechanical ski binding that overcomes the previously mentioned shortcomings of conventional bindings. The following paragraphs describe the binding design in detail, present testing results of the prototype, and evaluate how well the binding meets specified design criteria.

Design Description

The design criteria for the new binding system were as follows:

1. Offer release sensitivity to binding loads that correlate strongly with twisting and anterior/posterior bending moments actually developed at the injury sites of the leg;
2. Modulate the release level in twist to reflect the changing strength of the knee joint as influenced by muscle contraction;
3. Maintain the norm of the skiing industry in regard to size, shape, and weight;

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[1]The boot sole force and moment are the resultants acting at a point located by the base of the boot sole directly beneath the ankle joint at the center of the ski.

4. Maintain release mechanism adjustability to meet different skiers' specifications and level of expertise;
5. Maintain longitudinal and both rotational (twisting and anterior/posterior bending) elasticities within the norm of the industry;
6. Operate reliably in the Alpine environment (snow, ice, water, dirt, shock);
7. Minimize boot elevation above the ski (<3.0 cm);
8. Provide adjustability for varying boot lengths;
9. Provide ease of reentry and manual release;
10. Provide a braking system;
11. Minimize electrical power consumption.

To effectively meet the above criteria, the ski binding system shown in Figure 1 was designed to measure loads that correlate strongly to the twisting moment about the tibia shaft and the anterior/posterior bending moment at the boot top, comparing these loads with the knee strength indicated by a muscle electromyogram (EMG) and the ultimate tensile strength of the tibia, respectively. To measure a load indicative of the twisting moment about the tibia shaft, a Tyrolia 360D toepiece was modified, implementing resistive strain gages as the load sensing elements. A load indicative of the anterior/posterior bending moment in the leg was measured in the antifriction device (AFD) also utilizing resistive strain gages. Upon measurement of these loads, special electronic circuitry conditioned and analyzed these signals. The strengths of the knee and tibia ultimately determined the release levels. If the loading exceeded the strength of either the knee or tibia, then the circuitry actuated a trigger release mechanism in the heelpiece to release the boot from the ski.

Toepiece

The primary function of the toepiece is to measure the lateral boot force, a load that correlates strongly (avg. $r^2 \sim 0.87$) to the twisting moment about the tibia shaft axis (Quinn & Mote, 1991). To accomplish this, the Tyrolia 360D toepiece was modified. To appreciate the design of the modified binding, one must understand the original. Referring to Figure 2, which shows a schematic of the Tyrolia 360D toepiece, when the lower extremity of the skier undergoes twist, force from the skier's boot acts laterally on the binding boot wing, creating leverage on the T-bar. The T-bar is then pulled toward the boot compressing the spring. The boot force required for release is preset by tightening an adjustment bolt (not shown) which preloads the spring. Depending upon the amount of preload applied to the spring, the boot will begin to displace laterally when the lateral force at the boot wing is such that the compression force of the spring is exceeded. Release occurs when the boot rotates to the point where it is no longer constrained by the boot wing.

The new design utilizes the axial force transmitted through the T-bar to measure the lateral force applied to the boot wing. Because the T-bar axial force is a nonlinear function of the twisting moment about the tibia axis if the boot toe displaces, the binding was modified to inhibit this displacement by simply replacing the spring with a spacer. The axial T-bar force is measured by resistive strain gages mounted on the T-bar. Two 90° rosettes mounted on opposite sides of the bar enabled a fully temperature compensated Wheatstone bridge circuit.
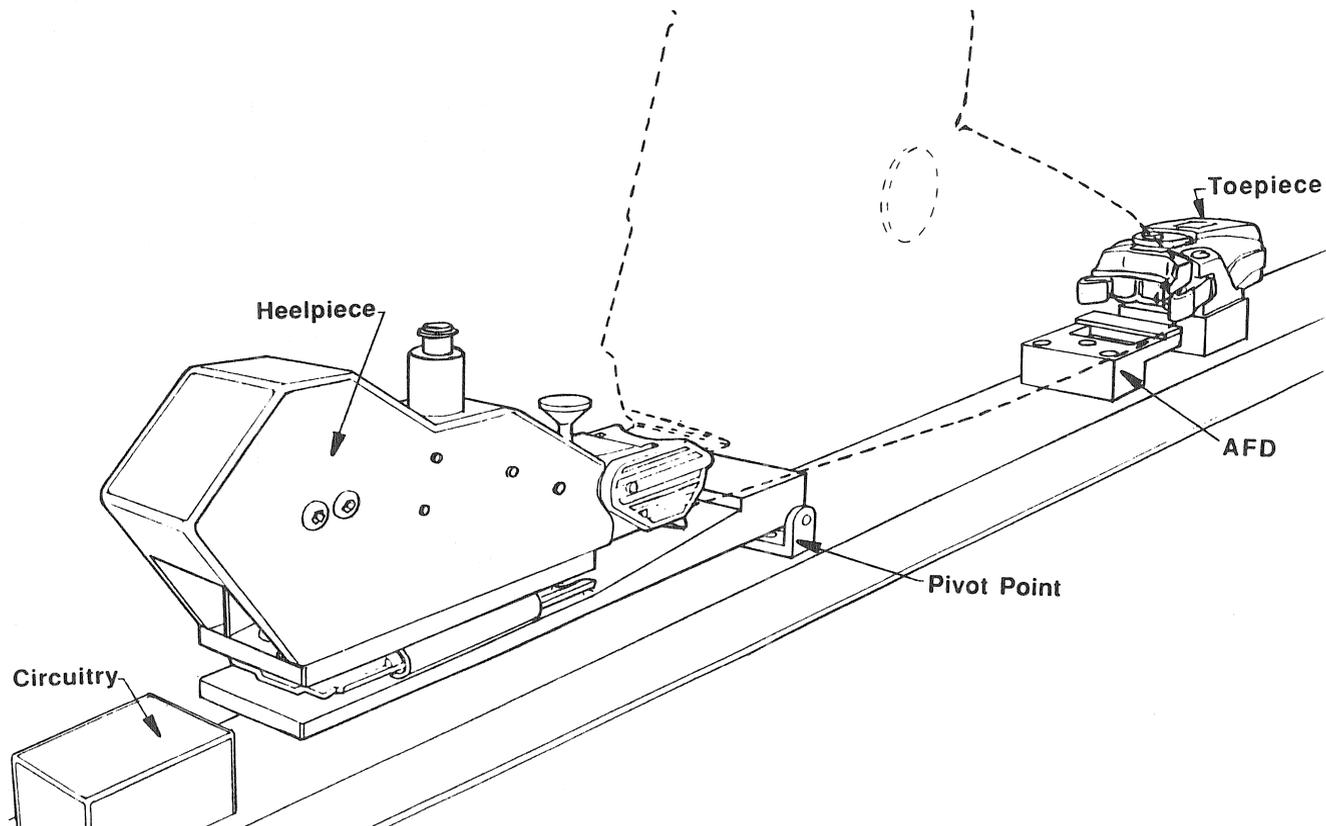
Figure 1 — Ski binding system, comprising 4 subassemblies: two dynamometers which measure boot load components that correlate strongly to moments at lower leg injury sites (a modified Tyrolia 360D toepiece and the antifriction device), the heelpiece that provides elasticity and releases the boot from the ski upon an electrical command signal from the release control circuitry, the final subassembly.

AFD

The AFD function is to provide a signal related to the boot sole anterior bending moment, a load that apparently correlates strongly (avg. $r^2 \sim 0.94$) to the boot top anterior bending moment (Quinn & Mote, 1991). To provide the desired signal, rotation of the boot under anterior/posterior bending is constrained to be about a transverse pivot directly beneath the ankle joint (see Figure 1). Thus the normal force beneath the boot toe, which creates the dynamometer signal, is related only to the boot sole bending moment and not the normal component of the boot sole force.

As illustrated in Figure 3, the design utilizes two cantilever beams to measure the normal force beneath the boot toe. Strain gages are mounted on the top and bottom surfaces of each beam and connected into a fully temperature compensated Wheatstone bridge circuit. This produces a force measurement independent of the application point. This becomes important when the center of pressure is not along the center axis that commonly occurs when the ski is
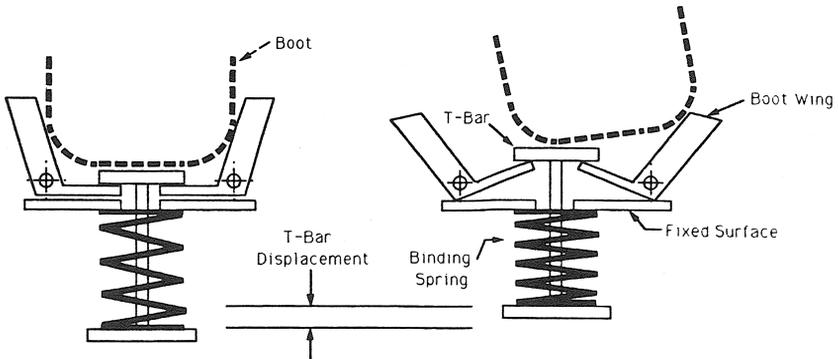

Figure 2 — Schematic of Tyrolia 360D toepiece. A dynamometer measuring the boot/boot wing reaction force was realized by modifying this design. The spring was replaced with a spacer and strain gages were mounted on the T-bar shaft.
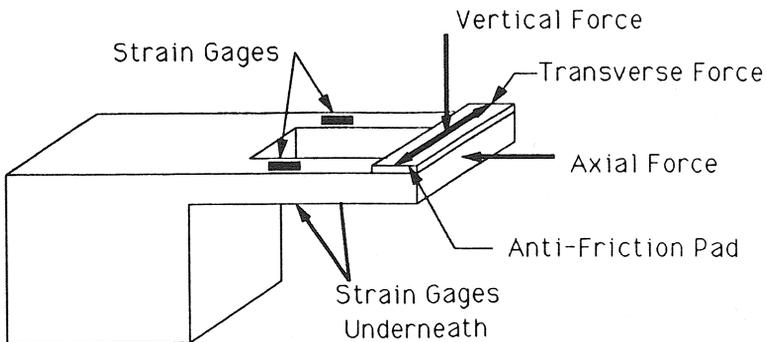

Figure 3 — Antifriction device (AFD), a dynamometer that measures the normal force developed between the boot sole and AFD surface. The dynamometer consists of strain gages mounted on parallel cantilever beams.

edged in turning maneuvers (Wunderly, Hull, & Maxwell, 1988). Also, the force measurement is electrically decoupled through the Wheatstone bridge from axial loads that may develop due to ski flexion. Further, the measurement is inherently insensitive to transverse forces, both because strain gages are located on the neutral axes of bending in the transverse plane and because the beams are stiff in this direction.

Heelpiece

The functions of the heelpiece are to provide both elasticity to the binding system and release of the boot from the ski. Because the heelpiece is able to move relative to the ski with three degrees of freedom, the heelpiece provides not only longitudinal elasticity but also two rotational elasticities. Similar to some conventional heelpieces, longitudinal elasticity is achieved by mounting the base-plate of the binding to a track so that the baseplate can slide longitudinally with this motion resisted by springs. The rotational elasticities are achieved through a cam and follower in conjunction with a modified spherical bearing. The modified spherical bearing limits the rotation of the heelpiece housing to two rather than three degrees of freedom.

As shown in Figure 4, the heelpiece housing is connected to the baseplate at the rear of the binding through a ball joint. The spherical mating surface is machined into a cylinder that rotates with the heelpiece housing. Extending laterally from the cylinder on both sides are pins that engage slots milled longitudinally in the baseplate bracket. These slots inhibit rotation of the heelpiece housing about the longitudinal axis of the ski. Note that because the axis of the pins are coincident with the transverse rotational axis of the ball joint, rotation of the binding housing about the transverse axis is not constrained.

A two-dimensional cam surface and spring-loaded follower provide resistance to the two rotational movements (see Figure 4). The spring-loaded follower has a spherical head and is connected to the baseplate through a support bracket. The cam has a conical surface and rotates with the heelpiece housing. The conical shape of the cam allows the heelpiece housing to rotate in the desired directions. Resistance to this rotation is provided by the follower spring force. As forces develop on the heelcup, the spring is compressed, which allows the binding to rotate in the direction of the loading. The resistance of the spring is preset by tightening an adjustment bolt on the follower to accommodate skier weight and ability. To prevent the boot from a premature mechanical release, the spring is designed to reach solid height before the boot can release.

The release function of the binding is achieved by controlling the resistance to rotational movement provided by the spring-loaded follower on the two-dimensional cam surface. The cam surface is machined into a cam arm that is pinned to the binding housing through Pin C (see Figure 5). As loads are applied to the heelpiece cup, these develop reaction forces between the cam and follower which create moments about Pin C. In the latched position, a trigger release assembly restrains the cam arm from rotating about Pin C so that the boot cannot release from the ski. When the assembly is actuated, however, the restraint is removed.

The principal problem in the design of the trigger release assembly was to enable a low force (<40 N) solenoid to reliably release the binding under large
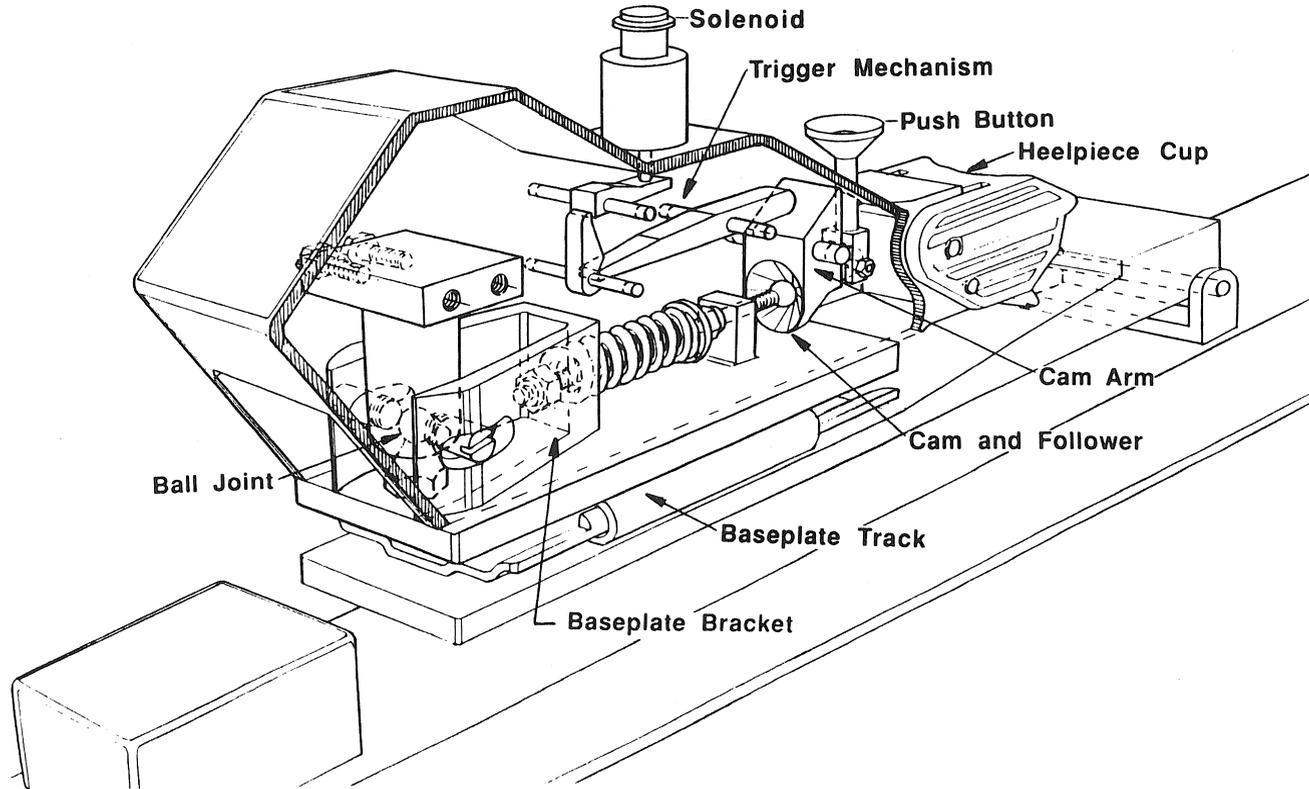
Figure 4 — Heelpiece with side wall removed. The heelpiece was designed to provide the three types of elasticity found in commercial bindings and to enable electromechanical release. Longitudinal elasticity is achieved by mounting the baseplate to a spring-loaded track while rotational elasticities for both twist and forward bending release modes are enabled through a spring-loaded follower riding on a two-dimensional cam surface. A solenoid in conjunction with a multilever trigger mechanism offers electromechanical release.
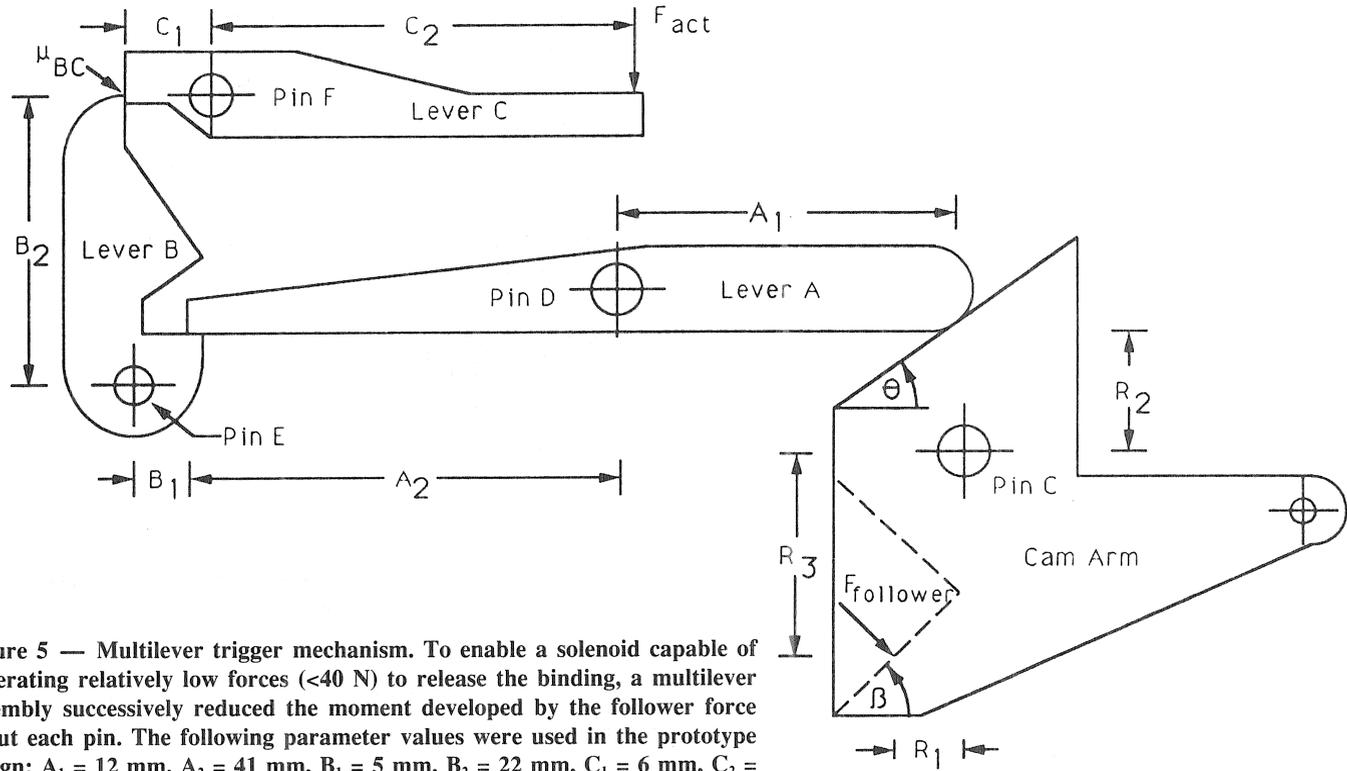
Figure 5 — Multilever trigger mechanism. To enable a solenoid capable of generating relatively low forces (<40 N) to release the binding, a multilever assembly successively reduced the moment developed by the follower force about each pin. The following parameter values were used in the prototype design: A_1 = 12 mm, A_2 = 41 mm, B_1 = 5 mm, B_2 = 22 mm, C_1 = 6 mm, C_2 = 32 mm, R_1 = 10 mm, R_2 = 13 mm, R_3 = 25 mm, μ_{BC} = 0.7, β = 45°, θ = 55°.

and variable loads necessary to restrain the cam arm from rotating. To solve this problem, a multilever mechanism similar to that in a previous design (Caldwell, Landry, & Hull, 1991) was used. The trigger mechanism consists of three levers, each providing a mechanical advantage that results in a small actuating force to release the binding.

An integral component of the trigger mechanism is the cam arm. The top surface that drives the trigger mechanism is angled such that the reaction force on Lever A is directed just above Pin D. This provides two key elements to the mechanism. First, by directing the force above the lever pivot, a moment is created on Lever A that tends to disengage the release mechanism. That is, if Lever A is allowed to rotate in the direction the cam arm is pushing it, then the follower will leave the cam surface and the binding will release. Second, by directing the normal force just over Pin D, the moment is kept small compared to the force exerted by the follower, thus requiring less force to hold Lever A in place.

The series of levers successively reduces the force while keeping the binding latched. Lever A exerts a reduced normal force on Lever B which, due to its geometry, exerts further reduced normal force on Lever C. The normal force exerted on Lever C is directed straight through its pivot (Pin F) and so creates no moment. As a result, Lever C will not rotate unless an external force is applied. As long as it does not rotate, the release mechanism is engaged and the binding is latched.

In order to release the binding, Lever C must be rotated to release Lever B, which will rotate and release Lever A. Lever A then will be pushed away by the cam arm, which will swing clear of the follower to allow the boot to release in the direction of the loading. To initiate the process, an unlatching push solenoid is placed above Lever C to apply a large enough force to overcome both the frictional force between Levers B and C and the frictional moment at the pivot of Lever C.

To ensure that the solenoid could provide sufficient force to actuate the binding, a mathematical expression was found for the actuation force, F_{act}, in terms of the design variables illustrated in Figure 5. Neglecting moments about the mechanism pivots due to either friction or reset springs, the expression becomes,

$$F_{act} = \mu_{BC}\cot\theta\left(\frac{A_1B_1C_1}{A_2B_2C_2}\right)\left(\frac{R_1 + R_3\tan\beta}{R_2}\right)\left(\frac{L_1 + L_2}{L_1}\right)F_{heel} \tag{1}$$

where L_1 is the distance from the follower to the spherical bearing, L_2 is the distance from the heelcup to the follower, and F_{heel} is the upward force at the heelcup. Using a frictional coefficient of 0.7, L_1 and L_2 values of 114 mm and 76 mm, respectively, and other dimensions indicated in Figure 5, an actuation force of 27 N was predicted to release the binding under an upward force of 1,000 N (280 Nm bending moment). The frictional coefficient of 0.7 is appropriate for unlubricated surfaces, hence giving an upper bound on the predicted actuation force.

To reset the heelpiece, a push button is attached to the cam arm (see Figure 4). Torsional springs attached to the levers oppose the release moments. When the button is pushed down by the skier, the follower spring is compressed and

the cam arm is rotated until all the lever arms rotate into place. The push button is then released and the binding is latched.

Circuitry

The function of the circuitry is to implement a release control algorithm where the release level in forward bending is constant but the release level in twist is modulated by the electrical activity of one of the uniarticular quadriceps muscles. To implement such an algorithm, the circuitry consists of a number of functional blocks, one of which is the block that develops the modulating signal derived from the muscle electromyogram (EMG). As illustrated in Figure 6, the circuitry in this functional block consists of a number of stages, the first of which is the preamplifier. Signals from two surface electrodes mounted over either the vastus lateralis or medialis are amplified differentially by a 1NA101G high accuracy, high input impedance operational amplifier located at the site of electrode placement. The signal from a third electrode establishes a reference voltage. Following preamplification, the raw EMG signal is band-pass filtered, full-wave rectified, and finally low-pass filtered with a cutoff frequency of about 3 Hz to develop a filtered, rectified EMG signal that indicates the level of neural stimulation of the muscle. The circuitry illustrated in Figure 6 is modeled after that of Lieu and Mote (1980).

Next the filtered, rectified EMG is sent to the release level modulator functional block (see Figure 7). This block uses the processed EMG signal to modulate the release level in twist. This function is accomplished by first adding to the EMG signal a bias voltage that establishes the minimum release level. The maximum release level is established by a Zener diode clamp. The processed EMG plus bias are then compared to the amplified signal from the strain gage dynamometer in the toepiece. When the dynamometer output exceeds the processed EMG plus bias, the change in comparator state triggers binding release by discharging a capacitor through the solenoid. Note that the bias voltage is necessary to ensure a minimum release level greater than 0 Nm, since without this voltage and without muscle activity, any dynamometer output would cause the comparator to change state. Also, the Zener clamp is necessary to bound the maximum release level so that it does not exceed the strength of the weakest link in the lower leg. It is important to note that, since the EMG signal varies over a continuum, so too will the release level.

In contrast to release in twist, the release level in forward bending is not modulated by the processed EMG signal but rather is constant. Thus the amplified output of the AFD dynamometer is simply compared to a reference voltage level. The change in state of either comparator (i.e., twist or forward bending) causes the capacitor to discharge through the solenoid.

A special power supply provides sufficient power at requisite voltages to charge the capacitor and drive the circuitry (see Figure 8). Powered by three batteries (size AAA), the supply develops ±10V for the strain gage excitation and operational amplifiers and +30V to charge the capacitor, which discharges through the solenoid.

Testing

To confirm the operation of the design, a prototype binding was built and tested. One test was the measurement of the force required to actuate the trigger assembly.
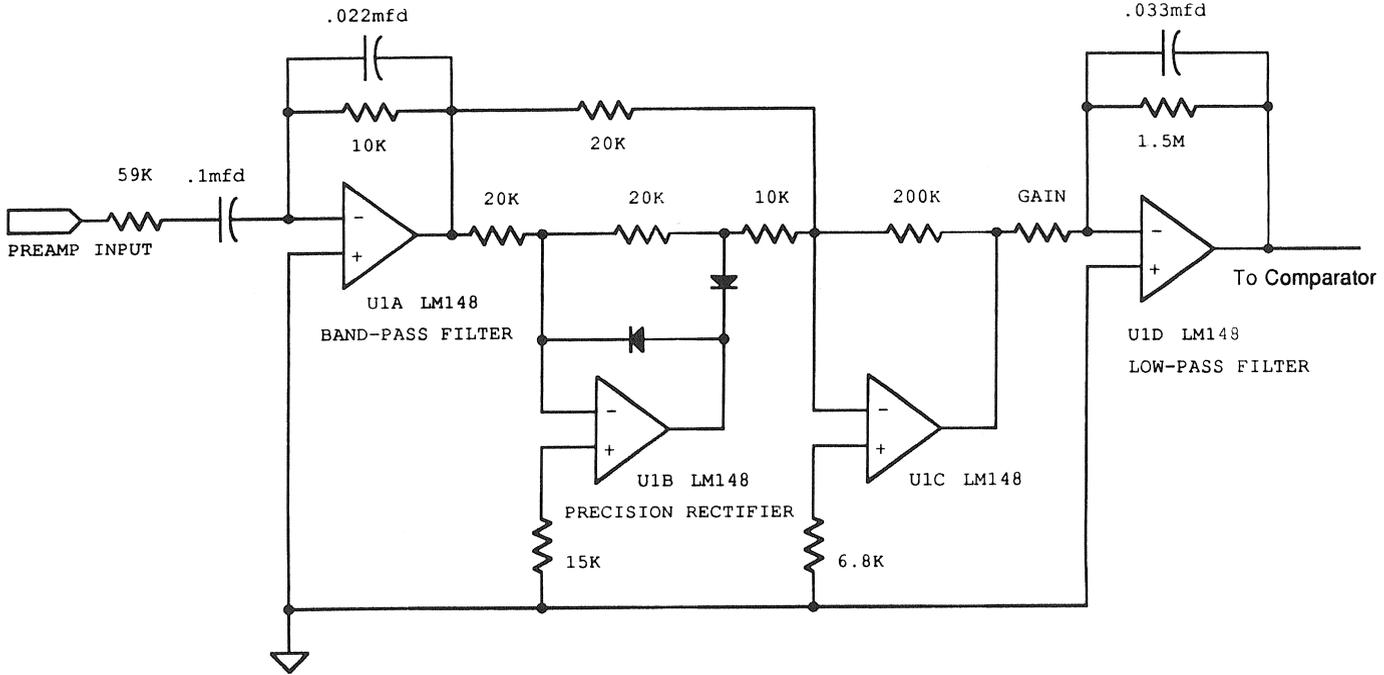
Figure 6 — Electromyogram (EMG) conditioning circuit, which generates a filtered, rectified EMG signal for one of the vastii muscles. This signal is used to modulate the release level of the binding in twist.
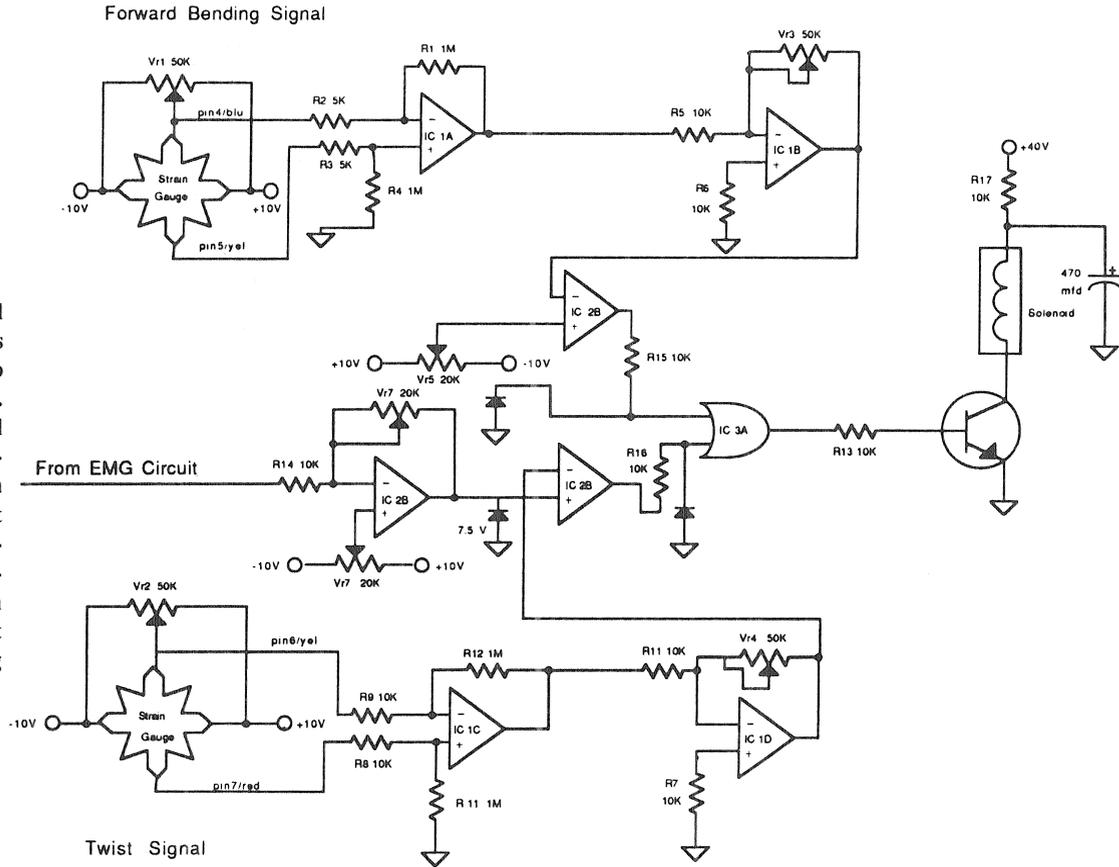
Figure 7 — Release control circuit, which enables signals from either dynamometer to cause the binding to release. For the forward bending signal developed by the AFD dynamometer, release occurs when this signal exceeds a fixed preset level. When the twist signal emanates from the toepiece dynamometer, release occurs when this signal exceeds a level that varies continuously depending on the EMG circuit output.

BATTERY

1.2K

1mfd

+4.5V

FULL WAVE BRIDGE

−

+

470mfd

+30V

100 K

1.2K

100 K

FULL WAVE BRIDGE

+

−

150 K
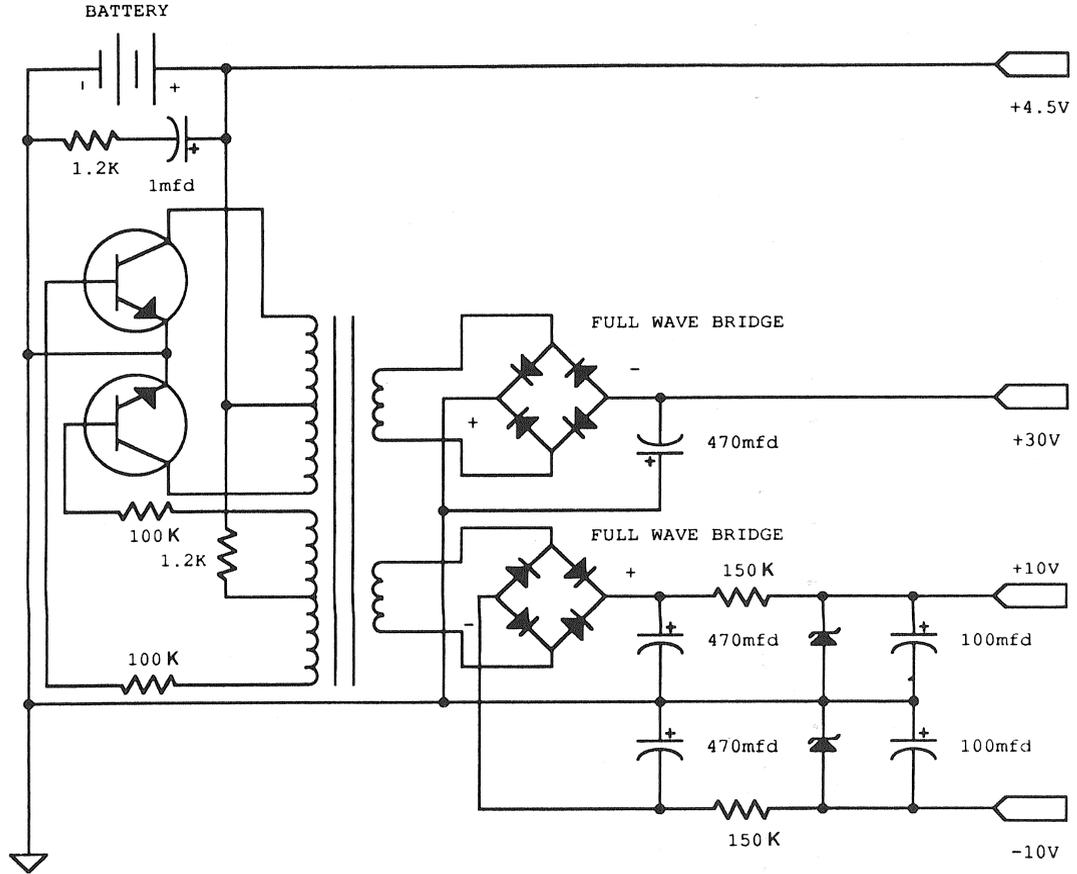
+10V

470mfd

100mfd

470mfd

100mfd

150 K

−10V

Figure 8 — Power supply, which converts 4.5V provided by three batteries to voltages necessary for the release control circuitry.

To establish a maximum actuation force under typical operating conditions, the trigger mechanism was first lubricated. Following lubrication, a boot was locked into the binding and a forward bending moment of 280 Nm was applied with a Vermont Ski Calibrator. Multiple readings were taken with the aid of a spring scale, and the average was 4.9 N with a coefficient of variation of 0.06 N. Substituting a coefficient of friction of 0.15—which would be appropriate for lubricated metal surfaces—into Equation 1 yields an actuation force of 5.8 N, which corresponds approximately with that measured.

To check the independence of AFD transducer output on the lateral location of the point of load application, two load levels were applied at three points. Two were the midpoints of each beam and the third was the midpoint of the entire transducer. Average values at each load level were essentially the same for all three points, confirming the ability of the transducer to indicate load independent of application point.

The final test involved checking the overall function of the prototype. This test required that the transducers, release control electronics, and binding mechanism all be integrated. In this test the prototype functioned as intended in that signals from either of the transducers caused the binding to release, and the release level in twist was continuously modulated by the degree of contraction in the vastus lateralis muscle.

Discussion

Through the use of standards such as ASTM Standard F939 (1985), which recommend release levels, conventional two-piece mechanical bindings now satisfy the retention requirement, but the prevalence of both twisting and bending related injuries indicates that they do not satisfy the release requirement. Therefore the intent of the design presented here was to better satisfy the release requirement in both modes while not compromising the retention requirement. Recognizing the industry's reluctance to abandon the traditional two-piece design, it was decided to maintain this but depart from conventional mechanical designs fundamentally in those respects necessary to achieve desired improvements.

One respect is the load that controls the release of the binding in forward bending. Rather than the upward heel force that controls release of conventional bindings, it was decided that the boot sole bending moment should control release of the new design. This decision stemmed from the work of Quinn and Mote (1991), who reported that a linear combination of the toe and heel boot forces normal to the ski correlated strongly (avg. $r^2 \sim 0.94$) to the anterior/posterior bending moment at the boot top. Because the coefficients of the forces were opposite in sign but of comparable magnitude, this combination apparently indicated the boot sole bending moment. It should be emphasized, however, that the correlation to the boot sole bending moment was not reported, thus the corresponding average r^2 value remains unknown. To firmly assess the potential effectiveness of the design concept in protecting skiers against boot top injuries due to bending loads, this information is necessary.

Although lacking the r^2 value inhibits any quantitative assessment, a qualitative assessment is possible. Basing the release decision on the bending moment at the boot sole would generally be conservative. This is because the boot top bending moment results not only from the boot sole bending moment but also

from the moments created at the boot top by the normal and tangential components of the boot sole force acting over their respective moment arms. Because each boot nearly always supports a portion of the skier's weight (Wunderly et al., 1988), and because the tangential force stems from ski/snow friction, the sense of these components is such that the boot top forward bending moment is lower than the boot sole forward bending moment. Although some degree of conservatism is certainly desirable to achieve a safety factor greater than one, too much conservatism could lead to problems with premature release. Thus it would be useful to carefully evaluate the potential of this problem.

It is also of interest to assess how effectively a binding wherein release is based on the boot sole bending moment would combat forward bending related injuries at the knee. Recall that excessive forward bending appears to be a common mechanism of isolated tears to the anterior cruciate ligament (Shino et al., 1987). As reported by Quinn and Mote (1991), the average correlation for the linear combination of toe and heel boot forces normal to the ski was only $r^2 \sim 0.62$. Furthermore, the coefficients of the forces were neither opposite in sign nor of the same magnitude. Thus the linear combination did not indicate the boot sole bending moment, so the correlation to this moment would be expected to be even weaker than $r^2 \sim 0.62$. Consequently it does not appear that a heel release based solely on the boot sole bending moment would effectively satisfy release and retention requirements as far as bending injuries at the knee are concerned. The contributions to the anterior knee moment by the other two boot sole load components must be considered as well.

A second respect in which the design differs fundamentally from conventional bindings is that the release level in twist is modulated based on muscle contraction. Owing to the changing strength of the knee as influenced by muscle contraction, modulation was necessary to simultaneously satisfy release and retention functions. To indicate the contraction state of the muscles crossing the joint, the filtered, rectified EMG signal recorded from surface electrodes over one of the vastii muscles was used. The potential limitations of using the EMG signal to indicate muscle contraction, and of modulating the release level based on the contraction developed by only one of many muscles crossing the joint, have been elaborated upon by Eseltine and Hull (1991) and will not be repeated here.

Departing from conventional bindings in a third respect, namely electronic release, greatly facilitated the modulation of the release level. Inasmuch as the strength of the knee would be expected to vary continuously depending on the force developed by the muscles crossing the joint, it was desirable to vary the release level continuously as well. To achieve continuous variation, the modulation scheme implemented here simply added the EMG signal to a bias signal and then compared the composite to the twist dynamometer output.

One unresolved issue concerning the release level modulation is the functional relationship of muscle force to knee strength. Assuming for the moment that the EMG signal directly indicates muscle force, the modulation scheme implemented above then assumes a linear relation between force and strength. The actual relation between force and strength is unknown, however. Clearly the determination of this relationship is important for implementing a modulation scheme that enables the binding to optimally satisfy release and retention requirements.

A second unresolved issue concerning the release level modulation is establishing the minimum and maximum release levels as determined by the bias voltage and Zener diode clamp, respectively. To ensure protection from both spiral fractures of the tibia and tears at the medial collateral ligament, ideally the release level limits should correspond to the lower of the strengths for the two injury types. In the case of the minimum release level, the knee in the absence of muscle contraction generally has the lower strength (Piziali, Nagel, Koogle, & Whalen, 1982). In the case of the maximum release level, however, it is possible that the strength of the knee in the presence of full muscle contraction exceeds the tibia fracture strength for some individuals. This may be inferred from the large stiffness increases of the knee in axial rotation with the muscles contracted (Hull & Johnson, 1989; Louie & Mote, 1987).

Although it would be desirable to establish release levels based on knee and tibia strengths, practicality may demand an alternative approach similar to that for setting release levels in conventional bindings. This approach calls for setting levels to meet retention requirements during controlled skiing maneuvers. To assess whether the two approaches are in conflict for this design concept, it would be useful to obtain a data base of loads and muscle activity during actual skiing and then simulate the modulation process. Through this simulation, the maximum and minimum release levels for retention might be determined as well as an appropriate modulation function.

A final respect in which the design differs fundamentally from conventional bindings is in using the heelpiece to release the boot from the binding in both release modes, twist and forward bending. This heelpiece function is similar to that described by Lieu and Mote (1980). Such a use of the heelpiece is a natural consequence of the electronic control of binding release; it is unnecessary to enable release of the toepiece and heelpiece separately because the electronics can easily control either release through a single mechanism. Because the toepiece cannot decouple the boot from the ski in forward bending whereas the heelpiece can decouple in twist, the heelpiece was the only possible mechanism that could decouple in both modes.

In comparing the present design to a previous one by Eseltine and Hull (1991) which also modulated the release level in twist, the present design offers two key advantages. One advantage is concerned with the release level variation. Modulation in the previous design was accomplished electromechanically such that only two release levels were possible. As previously mentioned, however, continuous variation in release level is desirable and was realized in the present design through electronic modulation.

A second advantage concerns power requirements. Because of the electromechanical modulation, the toepiece of Eseltine and Hull (1991) necessarily incorporated a means for converting electrical energy to mechanical energy. Although this conversion was made with a latching solenoid to conserve battery power, the continual actuation of the solenoid in response to changing muscle activity was expected to potentially limit the time during which the binding could be used. Through the use of low-power integrated circuit devices in electronic modulation, power requirements were reduced dramatically.

In assessing the practicality of the design in the skiing environment, one important criterion was that electrical power consumption be minimized. Because the circuit power requirements for electronic modulation were small, the largest

consumer of power was the strain gage bridges. To limit power consumption, 350 Ohm gages were selected, but still the current draw through the two bridges was about 100 mA with the ±10V excitation. This could easily be reduced to 10 mA by using high resistance (1,000 Ohm) strain gages and a 5V excitation. Alternatively, the transducer current consumption could be eliminated altogether by incorporating piezoelectric crystals for the load sensing.

Two other criteria were that the size and weight of the binding be within the industry norm. The toepiece is identical to the Tyrolia 360D binding with only slight modifications so that this easily fits the norm of the skiing industry. When comparing the heelpiece to conventional bindings, the addition of the release mechanism and solenoid as well as the rotating plate to which the heelpiece mounts added undesirable size and weight. The weight of the new heelpiece assembly increased to about double the approximate 1-kg weight of the conventional assembly.

To decrease both the size and weight, two improvements appear worthwhile. One improvement is the material selection of all parts. Although a material analysis was done on the heelpiece housing, further refinement in the material selection particularly through the use of plastics could lead to weight reductions. The other improvement is the size of the trigger mechanism. Equation 1 indicates that the actuation force is directly related to the length ratios of Levers A, B, and C. Decreasing the total lengths of these levers but maintaining the length ratios would reduce the size of this assembly. Thus, through careful design and material selection, the size and weight criteria could be satisfied.

Another important criterion centered on the elasticity of the binding. Conventional bindings offer elastic movement in the longitudinal and the two rotational directions corresponding to the release modes. The rotational elasticity in twist is provided by the toepiece while the heelpiece offers the remaining two elasticities. In the present design, the elasticity in the Tyrolia 360D toepiece was inhibited in order to ensure a linear relation between the dynamometer output (i.e., T-bar axial force) and the lateral component of the boot/boot wing reaction force. Thus the heelpiece provided all three elasticities.

Other criteria concerned adjustability, both to provide different release levels depending on skier variables (mass, expertise, etc.) and to accommodate different boot sole lengths. Through the circuitry, the binding may be easily programmed by accessible potentiometers to adjust the minimum and maximum release levels. To accommodate different boot sole lengths, the binding was mounted on a Tyrolia 360D mounting track.

Another design criterion was to minimize the boot elevation above the ski. The boot elevation is approximately 3.5 cm. Although the height exceeds that of conventional heel-toe bindings by 2.5 cm, a study with expert skiers using boots elevated to a height comparable to the one here reported that this height difference was undetectable during skiing (Maxwell & Hull, 1989). Consequently, the need to achieve a low boot elevation is questioned.

To ensure operational reliability in the Alpine skiing environment, the criterion was that snow, dirt, and shock must not affect binding function. With the cam and follower, trigger assembly, and solenoid protected by the heelpiece housing, the binding should be just as immune to snow and dirt as any conventional binding. With the force required to actuate the trigger assembly being small, however, there is some concern as to whether the shock transmitted to the

binding through the dynamics of ski-snow interaction would be sufficient to inadvertently actuate the trigger release mechanism. To address this problem, torsional springs were placed on each lever arm to counteract the moments applied on the levers to help stabilize the trigger mechanism. Also the trigger levers could all be designed such that the center of gravity coincides with the pivot axis. To properly evaluate the ability of the mechanism to resist shock, testing the prototype under this type of loading is ultimately desirable.

The final criterion was that the binding provide operational conveniences such as the braking system, ease of manual release, and step-in entry. Since the binding was mounted on the Tyrolia 360D track, the braking system was preserved. Ease of manual release was achieved by a push button mounted on the circuitry box. When the button is depressed, the solenoid is activated, releasing the trigger assembly which allows the binding to open. Reentry was made possible by a spring and push button located at the rear of the heelpiece. When the binding is open, the spring pulls the heelpiece open in an upright position. Once the skier steps into the binding, the push button is depressed, compressing the follower spring. This allows the cam arm to rotate counterclockwise, enabling the trigger assembly to fall into place. The push button is then released and the binding is latched.

Although not listed in the design criteria, another factor relevant to the practicality of the binding concerns transmitting the EMG signal to the control electronics. In the prototype binding this was accomplished through the use of a cable. From a skier's point of view, this is unacceptable and must be replaced by some other means. One alternative method would be to transmit the filtered, rectified EMG signal to the binding through the use of radio telemetry. Although this would require additional circuitry and power source, both could be miniaturized (Loeb & Gans, 1986).

Conclusion

Because injuries to the lower leg and knee persist in Alpine skiing, the goal of this project was to design a binding that would better protect against ski injuries than the conventional bindings available today. To achieve this goal, the new binding retained the conventional two-piece mechanism but differed fundamentally from conventional designs in a number of respects. In particular, release in both twist and forward bending modes was made sensitive to load components measured at the ski boot which correlate strongly to moment loads actually developed at the injury sites. Further, the release level in twist was modulated to reflect the influence of muscle force on the strength of the knee joint. The modulation was performed electronically, thus requiring an electromechanical binding mechanism. A special heelpiece enabled release in either mode through a trigger mechanism actuated by a low force solenoid.

Construction and testing of a prototype confirmed the workability of the design. In its present form, however, the prototype is not suitable for skiing, primarily because of excessive weight. It is believed that the weight can be reduced substantially both by reducing the size and by more carefully choosing the materials. Consequently, the development of a skiable prototype appears to be a worthwhile next step.

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