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Skiing Trauma and Safety: Thirteenth Volume

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Design of a Learning Binding for Alpine Skiing

REFERENCE: Gulick, D. W. and Mote Jr., C. D., "Design of a Learning Binding for Alpine Skiing," *Skiing Trauma and Safety: Thirteenth Volume, ASTM STP 1397*, R. J. Johnson, P. Zucco, and J. E. Shealy, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 30–49.

ABSTRACT: Advances in binding design for alpine skiing have been unable to eliminate injuries to the lower leg and knee. Studies to identify appropriate release settings have concluded that the maximum forces during skiing are not predictable using any measurable anthropometric parameters, and furthermore, that they are variable during skiing due to changes in snow conditions, skiing style, and other unmeasurable variables. This paper considers the feasibility of an alpine skiing binding with variable release settings that adapt to changes in the force magnitudes during skiing. Release settings are determined according to difference equations involving previous and current force measurements. To facilitate comparison with contemporary commercial bindings, the learning binding design includes three release modes: external twist and internal twist governed by the lateral force component at the toe and forward lean governed by the vertical force component at the heel. Binding forces measured during more than 36 min of skiing experiments are used to determine values for the design parameters within the adaptive algorithm. Then the performance of the learning binding is judged by comparing the release settings to the settings recommended by ASTM Standard F 939-93.

The release settings of the learning binding algorithms are on average more than 22% less than the ASTM recommended settings for each skier, with a maximum reduction of 50% for one subject. No inadvertent releases are predicted throughout the skiing data. The reduced release settings adapt to temporal changes in forces and yield earlier releases in several falling scenarios experienced in the data. These results suggest that a learning binding can significantly improve the safety of alpine skiing.

Nomenclature

- $F_{hz}(t)$ Filtered vertical force component at the heel binding (N)
- $F_{ly}(t)$ Filtered lateral force component at the toe binding (N)
- $F_{hz}(k)$ Maximum value of $F_{hz}(t)$ over k^{th} time interval (N)
- $F_{ly}(k)$ Maximum value of $F_{ly}(t)$ over k^{th} time interval (N)
- $F_{hz}(k)$ Minimum value of $F_{hz}(t)$ over k^{th} time interval (N)
- F_{ASTMhz} ASTM recommended release setting for forward leaning release (N)
- F_{ASTMly} ASTM recommended release setting for external and internal twisting releases (N)
- k Discrete index
- t Time (s)
- w Subject weight (N)

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ΔF_{ext}	Offset for external twisting release (N)
ΔF_{int}	Offset for internal twisting release (N)
ΔF_{up}	Offset for forward leaning release (N)
ε	Speed ratio
$p(t)$	Release setting function
$p_{ext}(t)$	Release setting function for external twisting release
$p_{int}(t)$	Release setting function for internal twisting release
$p_{up}(t)$	Release setting function for forward leaning release
$\sigma'(t)$	Skier state function
$\sigma_{ext}(t)$	Skier state function for external twisting release
$\sigma_{int}(t)$	Skier state function for internal twisting release
$\sigma_{up}(t)$	Skier state function for forward leaning release

Injuries to the lower leg and knee persist in alpine skiing despite the advent and improvement of releasable ski bindings. In a 22-year study culminating in 1994, Johnson, Ettlinger, and Shealy [1] found that although the injury rate for all skiers decreased by 44%, the number of serious Grade III knee sprains (complete disruption of at least one ligament, usually involving the anterior cruciate ligament) *increased* by 228%. Other studies [2–5] confirm that knee injuries and lower leg injuries continue to constitute a considerable fraction of all alpine skiing injuries. Reducing the risks of injury during downhill skiing remains a critical research issue.

One effort to improve ski binding design is focused on the mechanics of injury to the lower leg and knee. Studies identify specific injury scenarios in alpine skiing, predict *in vivo* loads at common injury sites, and quantify human bone and tissue strengths [6–8] in order to predict the regime where ski binding release settings would reduce the likelihood of injury. This line of research faces significant challenges because there are currently no adequate predictors of *in vivo* tissue strength, forces on specific tissues during a skiing injury have never been measured, and the loads on individual tissues during skiing depend on muscle activity, body posture, and joint flexion.

Another means of identifying appropriate binding settings is to concentrate on the forces and moments that are produced during normal skiing, which includes any maneuvers completed while skiing that do not present undue risk of injury. This is known as the retention problem. The function of retention is satisfied as long as the binding release threshold is above the maximum skiing forces and moments. Several studies have addressed the minimum release threshold that satisfies this property, also referred to as the *minimum retention* setting. Shealy and Ettlinger [9] investigated minimum retention using an empirical approach where release settings were adjusted as skiers completed a series of maneuvers, and Brown and Ettlinger [10] demonstrated loading scenarios that could induce inadvertent releases in standard release bindings. The conclusions of both studies were dependent on the contemporary binding design and did not quantify the dynamic loads during normal skiing. More recently, two studies have measured the forces and moments at the toe and heel bindings using two 6-degree-of-freedom dynamometers. For eight of the ten subjects in the experiments conducted by Scher and Mote [11], the maximum forces at the toe and heel bindings did not exceed 68% of the forces allowed by the ASTM recommended settings [Standard Practice for Selection of Release Torque Values for Alpine Ski Bindings F 939-93] in any release mode. However, one skier exceeded 81% of the settings in both external and internal lateral forces at the toe. The researchers conclude that weight, height, and age are not significant indicators of minimum retention requirements. Crawford and Mote [12] similarly showed

that these parameters do not correlate well with the minimum retention envelope, and also noted that the maximum forces generated during skiing varied from run to run and year to year for a subject.

Without a good predictor of minimum retention requirements for alpine ski bindings, an alternative is warranted. The research presented in this paper considers a *learning binding*, a binding concept with time-varying release settings that adapt to the forces experienced during a skiing run. The binding settings approach the maximum forces generated during skiing according to a first-order difference equation. By adapting directly to measured forces during normal skiing, the binding algorithm does not depend on any presumptions about the correlation between minimum retention and weight, height, skiing ability, snow conditions, terrain, or other parameters. Furthermore, the binding settings adjust according to the minimum retention requirements of an individual skier as well as temporal changes in the maximum forces.

The objective of the current study is to determine the feasibility of a learning binding for alpine skiing. Of primary interest is the reduction of the release settings from the currently accepted industry standards without inducing any inadvertent releases. Reduced settings are desired to facilitate releases in a wider variety of situations, thereby reducing the likelihood of a failure to release in a dangerous situation, and also to promote rapid binding release. In the case of a dangerous situation where there is likelihood of injury, such as in some falls, the binding must release. However, not all falls require release; for instance, the ski may be unloaded completely during a fall and thus release is not necessary or even desirable. This study limits the consideration of learning bindings to those which use only standard modes of release: the lateral force component at the toe determines the internal or external twisting release, and the upward force component at the heel controls the forward lean release. This restriction allows comparison of the learning binding's performance to that of a traditional binding utilizing the current release setting standards.

Although a learning binding requires real time measurement of force components and calculation of binding settings, performance of the learning binding algorithm is best judged by using previously measured forces produced while skiing on traditional commercial alpine bindings. The performance of the learning binding's algorithm can then be compared to that of the traditional binding used in the experiments that recorded the forces. Field experiments were conducted during 1997 and 1998 to collect force and moment data during downhill skiing, and then the learning binding algorithm was tested using this data upon returning to the laboratory.

This paper presents (1) a summary of the experimental methods and equipment, (2) a theory of learning binding algorithms, (3) a specific algorithm to be compared with commercial binding performance, (4) a comparison between the release settings proposed by the algorithm and those recommended by ASTM Standard F 939-93, and lastly (5) the virtual performance of the learning binding during runs that include falls and releases.

Materials and Methods

Instrumentation

Measuring forces and moments acting on the toe and heel bindings are accomplished with two force sensors mounted on the left ski as shown in Fig. 1. The mounting ensures that the entire loading between each binding and the ski is transferred through a force sensor, which measures three force components as well as three moment components at the binding. Thus the loading conditions of the toe and heel bindings on the instrumented left ski are completely known. Designed according to Quinn and Mote [13], the force transducers have

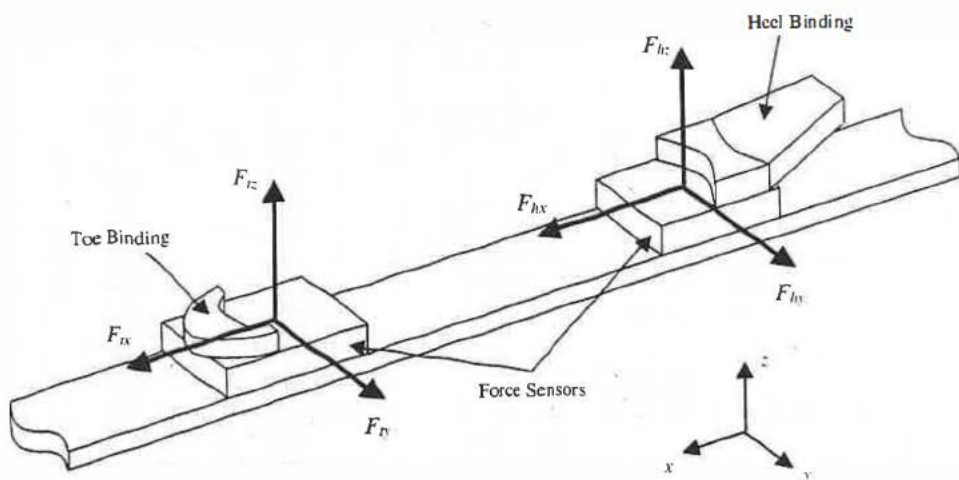


FIG. 1—Instrumented ski and force components.

full-scale ranges of 1.7, 2.1, and 5.1 kN for forces in the x -, y -, and z -directions (see Fig. 1), respectively; similarly, the full scale ranges are 132, 124, and 102 Nm for moments in these directions. Over these ranges the force transducers are highly linear, with a linear correlation coefficient greater than 0.999 in each direction. Calibration of the force sensors was completed prior to experimentation using a static load test.

Loads on the bindings create small voltage imbalances measured using Wheatstone bridges in the force sensors. Analog circuitry then amplifies and filters these voltages in preparation for sampling at 256 Hz by an analog-to-digital converter. Twelve-bit digital resolution within the analog-to-digital converter gives force resolutions of 1, 1, and 4 N, and moment resolutions of 0.1, 0.5, and 0.4 Nm in the x -, y -, and z -directions, respectively. Finally, the sampled signals are stored in a portable laptop or a PC/104 computer. All of the electrical circuitry and data storage equipment are packaged in a backpack, weighing less than 5.4 kg (11.8 lbs), worn by the skier.

Procedures

Force and moment data were collected over several days of testing during 1997 and 1998. The test subjects, whose skill levels ranged from beginner to expert to professional racer, skied on terrain that was appropriate for their skiing abilities. Each of the subjects signed an informed consent form prior to participating in the ski tests. The research in this paper uses data from 35 runs by eleven test subjects (see Table 1) of which eight runs contain falls. The runs that do *not* contain falls are denoted as *normal runs*; similarly, the runs that do contain falls are denoted as *special runs*. Each of the 27 normal runs is longer than 30 s in duration, and the total time of all the normal runs together exceeds 34 min. Over the course of these tests, the snow conditions included spring (corn) snow, packed powder, powder, and ice. Several of the runs involve distinct transitions of skiing style or terrain. As an example, two runs (CH5 and SB3) begin with skiing on powder snow on steep terrain, and then transition to skiing on packed, powder on moderate terrain.

Video footage recorded during each of the special runs shows the manner in which the subject falls and whether the instrumented binding opens, thus releasing the ski. A qualitative

TABLE 1—*Subject information.*

Subject	Weight (N)	Height (cm)	Skill Level	ASTM Recommended Settings		Normal Skiing Time (s)	Falls
				External and Internal Twist (N)	Forward Lean (N)		
AH	697	180	Advanced	185.3	736.4	272.4	—
CH	556	163	Expert	205.7	816.4	310.3	—
HS	706	176	Expert	228.7	929.0	54.4	3
JF	579	170	Advanced	179.2	707.5	421.3	—
MD	516	150	Intermediate	158.6	618.5	63.3	—
PG	890	178	Expert	249.0	1019.0	145.5	—
PS	614	168	Beginner	170.2	669.2	—	3
SB	658	167	Expert	232.7	937.9	237.4	—
SH	689	165	Expert	226.2	909.0	152.5	—
SS	467	163	Intermediate	147.1	571.7	423.8	—
YY	1012	188	Intermediate	186.1	958.2	—	2
Average	671	170	—	197.2	806.6	—	—

decision of whether the ski *should* have released was determined by reviewing video of the fall, analyzing the force and moment history data from the run, and interviewing the test subject (see Table 2). In two runs, PS1 and HS8, no release occurred during the falls despite the fact that the lateral force data exceeded the ASTM lateral twist release setting for a period exceeding 15 ms; hence, in these runs, the desired result is for a lateral twisting release. During run HS9, an external twisting release preceded the subject's forward fall. Because the external lateral force at the toe remained below the ASTM release setting and the subject believed that the release was inadvertent, the desired result is that no release occurs.

Learning Algorithm Theory

Prior to discussing the details of an algorithm for learning bindings, a theory is developed. The binding must accomplish two roles: first, during normal skiing, the binding must hold

TABLE 2—*Summary of special runs.*

Run ^a	Description of Fall	Actual Result ^b	Desired Result ^c
PS1	Backward fall to the right	NR ^d	Internal
PS2	Backward fall to the right	NR	NR
PS3	Right ski releases, subject falls, then instrumented ski releases	Internal	Internal
YY3	Backward fall to the left with no release	NR	NR
YY5	Instrumented ski rotates externally and backward, then releases	External	External
HS1	Backward fall to the right while stopping	NR	NR
HS8	Subject falls and releases uninstrumented ski	NR	External
HS9	Forward fall, instrumented ski releases in twisting at toe; subject claims ski should not have released	External	NR

^a Run identification label.

^b Observed response of conventional binding during ski experiment; where applicable, release direction is indicated.

^c Qualitative decision of whether the ski should have released.

^d NR = No release.

the boot firmly to the ski (retention); second, in a potentially injurious situation, the binding must release the boot from the ski, reducing the possibility of injury. Thus, the binding has two discrete and complementary states, either retention or release. The learning binding algorithm must determine when the transition from retention to release occurs. This is done by comparing two functions, one that indicates the current loading of the ski and another that is the current binding setting. The former, referred to as the *skier state* and denoted by $\sigma(t)$, can include the unfiltered measurement of a force, such as the lateral toe force, the same measurement filtered, or a combination of forces. The latter, called the *release setting* and denoted by $p(t)$, is calculated using an algorithm that can incorporate prior measurements, initial conditions, or other specifications. The final component of the learning binding theory is a rule for comparison of the skier state and the release setting. For instance, this rule might state that the binding would release when the skier state variable $\sigma(t)$ is larger than the release setting $p(t)$. Bindings that have multiple modes of release may have several skier state variables, release settings, and corresponding comparison rules.

As a simple example of the above theory, consider the upward release at the heel for a traditional binding. The skier state variable $\sigma(t)$ is the vertical force at the heel binding, and the release setting $p(t)$ is specified by the ASTM Standard F 939-93. Thus, the release setting function is a constant value for a traditional binding. The comparison rule is that if the heel vertical force exceeds the release setting ($\sigma(t) > p(t)$) then the binding opens to release the boot from the ski. Another example is shown in Fig. 2. In this design, both skier state and the release setting are functions of time. Release occurs when the skier state variable's value exceeds the release setting.

This theory of learning bindings can handle many different design ideas. Various choices of skier state variables, release settings, and comparison rules can be included in the design. The following section outlines one specific design concept.

Design of Learning Algorithm

The first choice to be made in the design of the learning binding algorithm is which release modes to include. The design in this paper includes three release modes, specifically an external twisting release controlled by the lateral force on the toe binding, an internal

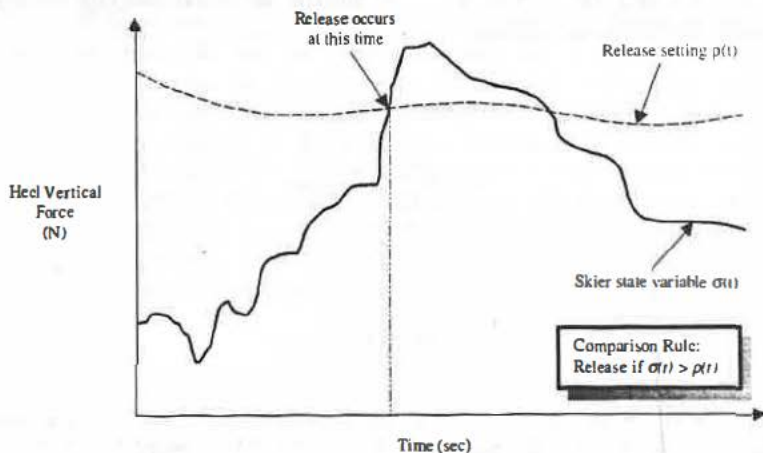


FIG. 2—Example of learning binding algorithm.

twisting release controlled by the medial force on the toe binding, and a forward leaning release controlled by the upward force at the heel binding. These are the release modes of a conventional, state-of-the-art binding, thus enabling a comparison of the release settings on the learning binding to those specified by the ASTM binding standard F 939-93.

A direct result of the choice of release modes is that there are three skier state variables, $\sigma_{ext}(t)$, $\sigma_{int}(t)$, and $\sigma_{up}(t)$ and three corresponding release setting variables, $\rho_{ext}(t)$, $\rho_{int}(t)$, and $\rho_{up}(t)$ associated with the external twisting, internal twisting, and forward leaning modes, respectively. The state variables are simply

$$\sigma_{ext}(t) = F_n(t), \quad (1a,b,c)$$

$$\sigma_{int}(t) = F_{\alpha}(t),$$

and

$$\sigma_{up}(t) = F_{hz}(t),$$

where $F_n(t)$ is the filtered lateral force component at the toe binding and $F_{hz}(t)$ is the filtered vertical force component at the heel binding. Filtering is necessary to reduce the effects of noise and to eliminate outliers within the data. Another critical reason for filtering is to reduce the effect of (low energy) impulsive forces that have a high magnitude for only a short duration of time, say lasting 10 ms or less. All of these aspirations require a low-pass filter, which unfortunately increases the time delay before release. In fact, the lower the cutoff frequency of the filter, the greater the delay. As a compromise, the data is filtered using a 40 Hz second-order Butterworth filter. This filter reduces the effects of both noise and short duration force impulses, and yet incurs only approximately a 4 ms delay.

The design incorporates a first-order difference equation to recalculate the release settings every 2.0 s. Shorter time steps result in a higher than desired variability of the release settings, since a ski may be unweighted or only partially weighted during a portion of a skiing maneuver. Using discrete notation, the release settings from $2k$ sec to $2(k+1)$ s are denoted by $\rho_{ext}(k)$, $\rho_{int}(k)$, and $\rho_{up}(k)$ $\{k = 0, 1, 2, \dots\}$. Initially the release settings are equal to the recommended ASTM release settings:

$$\rho_{ext}(0) = F_{ASTMn}, \quad (2,a,b,c)$$

$$\rho_{int}(0) = -F_{ASTM\alpha},$$

and

$$\rho_{up}(0) = F_{ASTMhz},$$

where F_{ASTMn} is the lateral release force at the toe and F_{ASTMhz} is the vertical release force at the heel recommended for the particular skier in ASTM Standard F 939-93. Thereafter, the settings are determined by the following difference equations:

$$\rho_{ext}(k) = \varepsilon(\bar{F}_y(k-1) + \Delta F_{ext}) + (1 - \varepsilon)\rho_{ext}(k-1), \quad (3a,b,c)$$

$$\rho_{int}(k) = \varepsilon(\bar{F}_y(k-1) + \Delta F_{int}) + (1 - \varepsilon)\rho_{int}(k-1),$$

and

$$\rho_{up}(k) = \varepsilon(\bar{F}_{hz}(k-1) + \Delta F_{up}) + (1 - \varepsilon)\rho_{up}(k-1),$$

for $k = 1, 2, 3, \dots$. The variables $\bar{F}_y(k-1)$, $\bar{F}_y(k-1)$, and $\bar{F}_{hz}(k-1)$ are extrema of the filtered binding forces over the previous 2 s increment and are calculated by

$$\bar{F}_y(k-1) = \max\{F_y(t) | 2(k-1) \leq t < 2k\}, \quad (4a,b,c)$$

$$\bar{F}_y(k-1) = \min\{F_y(t) | 2(k-1) \leq t < 2k\},$$

and

$$\bar{F}_{hz}(k-1) = \max\{F_{hz}(t) | 2(k-1) \leq t < 2k\}.$$

Controlling the rate with which the release settings respond to a change in binding forces, the constant design parameter ε in Eqs 3a,b,c is assigned a value between 0 and 1. The remaining design parameters, ΔF_{ext} , ΔF_{int} and ΔF_{up} , are called *offsets* and influence the magnitude of the response.

The settings calculated in Eqs 3a,b,c are weighted averages between (1) the previous settings and (2) the maximum forces during the previous time period plus the offset. The parameter ε weights the relative importance of these two terms. If ε is close to zero then the release settings adapt slowly; if ε is close to one then the release settings adapt quickly, closely following the trend of the most recent forces on the bindings. Although an ε value close to 1 is desirable in order to respond quickly to changes in skiing forces, the release setting in this case is excessively reduced when the ski is lightly weighted during a ski maneuver, resulting in release settings that are below those required for normal skiing. The design parameter ε is set equal to an intermediate value of 0.4 in all further calculations. With this value, the release settings approach 92% of their steady state values within 10 s.

The purpose of the offsets ΔF_{ext} , ΔF_{int} , and ΔF_{up} is evident by considering the steady state response if the maximum filtered toe lateral force were to be a constant value ($\bar{F}_y(k) = \bar{F}_y = \text{constant}$). In this case the release setting for external twist would approach $\bar{F}_y + \Delta F_{ext}$ over time. An offset with a larger magnitude directly correlates to larger release settings; therefore, to meet the objective of reduced release settings, it is desirable to choose the smallest offset where no inadvertent releases occur, which is called the *minimum offset*. This paper considers two different design ideas concerning the offsets. One concept is to assign the offsets the same values for each skier. Another concept is for the offsets to be functions of an anthropometric variable, such as weight or height. Assuming a linear relationship, the problem is then reduced to determining desirable values of a and b in the equations

$$\Delta F_{ext}(\phi) = a_{ext}\phi + b_{ext}, \quad (5a,b,c)$$

$$\Delta F_{int}(\phi) = a_{int}\phi + b_{int},$$

and

$$\Delta F_{up}(\phi) = a_{up}\phi + b_{up},$$

where ϕ is the given anthropometric parameter. The slope a in each equation is equal to the slope of the least-squares linear relationship between test subject weight and minimum offset. Then, the intercept b is assigned a value so that the offset's magnitude calculated in the equation is larger than the minimum offset for each subject.

The release settings calculated using Eqs 3a,b,c can exceed the ASTM recommended settings, which would potentially place the skier in an untested regime of skiing settings. To avoid this situation, the largest magnitudes that the release settings are allowed to obtain are the ASTM recommended settings.

Finally, the skier state variables are compared to the release settings. Release occurs when at least one of the following conditions is satisfied:

$$\sigma_{ext}(t) > \rho_{ext}(t), \quad (6a,b,c)$$

$$\sigma_{int}(t) > \rho_{int}(t),$$

or

$$\sigma_{up}(t) > \rho_{up}(t).$$

Results

Results of this study consist of (1) a comparison between the maximum forces generated during normal skiing and the forces necessary to release the binding according to ASTM Standard F 939-93, (2) the minimum offsets in the learning binding algorithm necessary for normal skiing without inadvertent releases, (3) release settings for two design concepts, and (4) response of these designs during falling runs.

The maximum external and internal lateral forces at the toe and the maximum vertical force at the heel are calculated for each of nine subjects during 27 normal runs, spanning 2080 s (34.7 min) of skiing tests. Prior to calculating the maxima, the force data are filtered with a 40 Hz second-order Butterworth filter. The ratio between the lateral force required to release according to ASTM Standard F 939-93 and the maximum external lateral force at the toe for an individual is on average 1.88, as noted in Table 3. Similarly, the average ratios comparing the ASTM release settings and the maximum forces are 2.02 in the internal twist direction and 2.17 in the forward lean direction. As a measure of the variation between individual skiers, the standard deviations of these ratios are 0.65, 0.65, and 1.04 in the external twist, internal twist, and forward leaning directions, respectively.

The minimum values of the design parameters, ΔF_{ext} , ΔF_{int} , and ΔF_{up} , for which no inadvertent releases occur are calculated for the 27 normal runs. In these computations, the offsets are varied at 10 N increments in the internal and external twist directions and 30 N increments in the forward lean direction. An example of the release setting history for a skiing run by subject JF is shown in Figs. 3a, 3b, and 3c for various offset values. The minimum offsets for which no inadvertent releases occur range from 30 N (Subject JF) to 100 N (Subjects AH and SH) in external twist, -30 N (MD) to -100 N (AH) in internal twist, and 120 N (MD) to 480 N (PG and SH) in forward lean. Overall, there is a stronger relationship between the minimum offsets and subject weights than with either subject heights or ASTM settings. The correlation coefficients for a linear relationship between the

TABLE 3—Release settings according to ASTM Standard F 939-93 and calculated using two offset formulas,
External Twist
 ($r = 0.4$)

Subject	Maximum External Toe Force (N)	ASTM Setting		Design 1: $\Delta F_{ext} = 100$ N		Design 2: $\Delta F_{ext} = 0.103$ Weight + 29.2	
		Release Setting (N)	Ratio of ASTM Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force
AH	155.4	185.3	1.19	154.2	0.99	154.9	1.00
CH	70.6	205.7	2.92	134.5	1.91	122.0	1.73
HS	143.6	228.7	1.59	175.4	1.22	177.0	1.23
JF	60.6	179.2	2.96	127.0	2.10	116.1	1.92
MD	115.5	158.6	1.37	144.7	1.25	131.0	1.13
PG	138.9	249	1.79	178.0	1.28	196.4	1.41
SB	110.6	232.7	2.10	148.6	1.34	145.7	1.32
SH	150.4	226.2	1.50	149.6	0.99	149.6	0.99
SS	100.4	147.1	1.47	126.2	1.26	104.4	1.04
Average	116.2	201.4	1.88	148.7	1.37	144.1	1.31
Std. Dev.			0.6532		0.38		0.33

Internal Twist
 ($r = 0.4$)

Subject	Maximum Internal Toe Force (N)	ASTM Standard F 939-93		Design 1: $\Delta F_{int} = -100$ N		Design 2: $\Delta F_{int} = -0.139$ Weight - 3.0	
		Release Setting (N)	Ratio of ASTM Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force
AH	-148.9	-185.3	1.24	-144.4	0.97	-144.4	0.97
CH	-96.4	-205.7	2.13	-147.7	1.53	-129.8	1.35
HS	-115.4	-228.7	1.98	-168.3	1.46	-169.5	1.47
JF	-108.3	-179.2	1.65	-121.1	1.12	-105.3	0.97

TABLE 3—Continued.
Internal Twist
(*r* = 0.4)

Subject	ASTM Standard F 939-93			Design 1: ΔF_{int} = -100 N			Design 2: ΔF_{ext} = -0.139 Weight - 3.0		
	Maximum Toe Force (N)	Release Setting (N)	Ratio of ASTM Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force
MD	-46.7	-158.6	3.39	-120.5	2.58	-97.3	2.08	-97.3	2.08
PG	-157.8	-249	1.58	-180.1	1.14	-204.1	1.29	-204.1	1.29
SB	-111.7	-232.7	2.08	-153.8	1.38	-148.9	1.33	-148.9	1.33
SH	-143.9	-226.2	1.57	-162.4	1.13	-161.4	1.12	-161.4	1.12
SS	-57.4	-147.1	2.56	-115.2	2.01	-84.4	1.47	-84.4	1.47
Average	-109.6	-201.4	2.02	-146.0	1.48	-138.3	1.34	-138.3	1.34
Std. Dev.			0.65		0.52		0.34		0.34

Forward Lean
(*r* = 0.4)

Subject	ASTM Standard F 939-93			Design 1: ΔF_{up} = 480 N			Design 2: ΔF_{up} = 0.786 Weight - 61.42		
	Maximum Heel Force (N)	Release Setting (N)	Ratio of ASTM Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force	Mean Release Setting (N)	Ratio of Mean Setting to Max. Force
AH	521.0	736.4	1.41	619.9	1.19	625.3	1.20	625.3	1.20
CH	342.0	816.4	2.39	627.7	1.84	532.3	1.56	532.3	1.56
HS	413.1	929.0	2.25	673.5	1.63	685.6	1.66	685.6	1.66
JF	200.5	707.5	3.53	505.7	2.52	422.3	2.11	422.3	2.11
MD	153.3	618.5	4.03	474.5	3.09	349.3	2.28	349.3	2.28
PG	990.8	1019.0	1.03	846.0	0.85	955.0	0.96	955.0	0.96
SB	602.0	937.9	1.56	615.0	1.02	593.0	0.99	593.0	0.99
SH	814.9	909.0	1.12	831.2	1.02	831.2	1.02	831.2	1.02
SS	257.8	571.7	2.22	452.1	1.75	284.1	1.10	284.1	1.10
Average	477.3	805.0	2.17	627.3	1.66	586.5	1.43	586.5	1.43
Std. Dev.			1.05		0.75		0.50		0.50

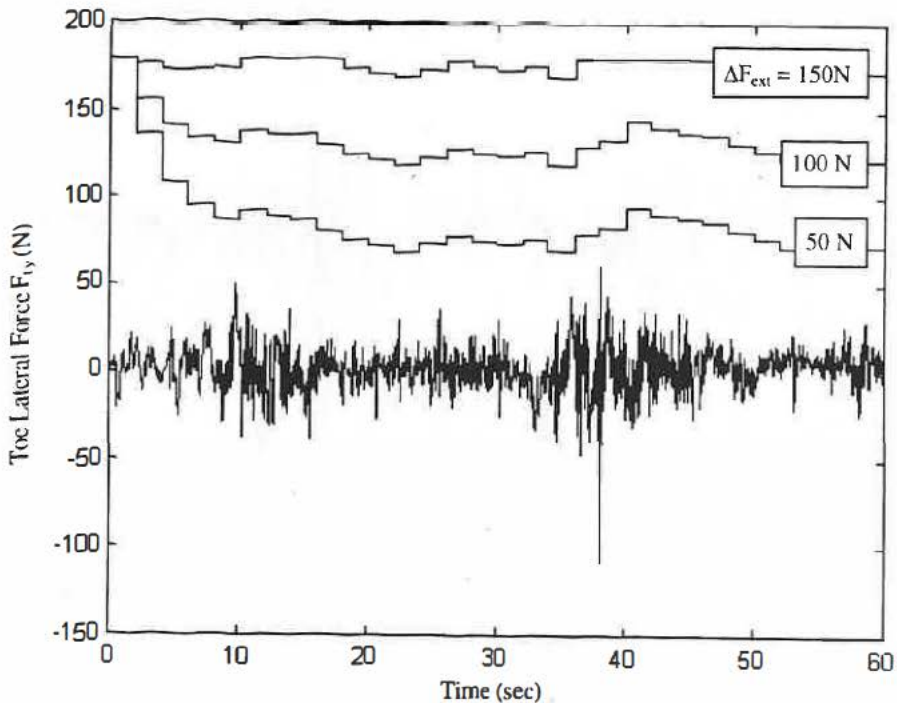


FIG. 3a—Learning binding response history for run by subject JF with three different offsets ΔF_{ext} in external twist mode.

minimum offsets and the subject weights are $r = 0.56$ for the external twist offset, $r = -0.68$ for the internal twist offset, and $r = 0.73$ for the forward lean offset (see Fig. 4).

For the first design, the offset in each direction is assigned the largest magnitude of the minimum offset across all of the subjects: 100 N in external twist, -100 N in internal twist, and 480 N in forward lean, as indicated by the horizontal lines in Fig. 4. With this specification of offsets, the ratios comparing the mean release settings for the learning binding to the maximum forces generated during normal skiing are 1.37 for external twist, 1.48 for internal twist, and 1.66 for forward lean (see Table 3), all of which are lower than the previously calculated ratios of ASTM settings to maximum forces. For calculation of these ratios, the mean release setting for an individual is the time average of the release setting over all of the normal runs for that subject. The standard deviations of these ratios are 0.45, 0.52, and 0.75, respectively. Moreover, the ratio is less than 1.00 in four cases, corresponding to a situation where the mean release setting is less than the maximum force, and attains a minimum value of 0.85 for subject PG in the forward lean direction.

In the second design, the offset is a function of the subject's weight, as shown in Fig. 4 by the dashed lines. Equations 5a,b,c become

$$\Delta F_{ext}(w) = 0.103w + 29.2, \quad (7a,b,c)$$

$$\Delta F_{int}(w) = -0.139w - 3.0,$$

and

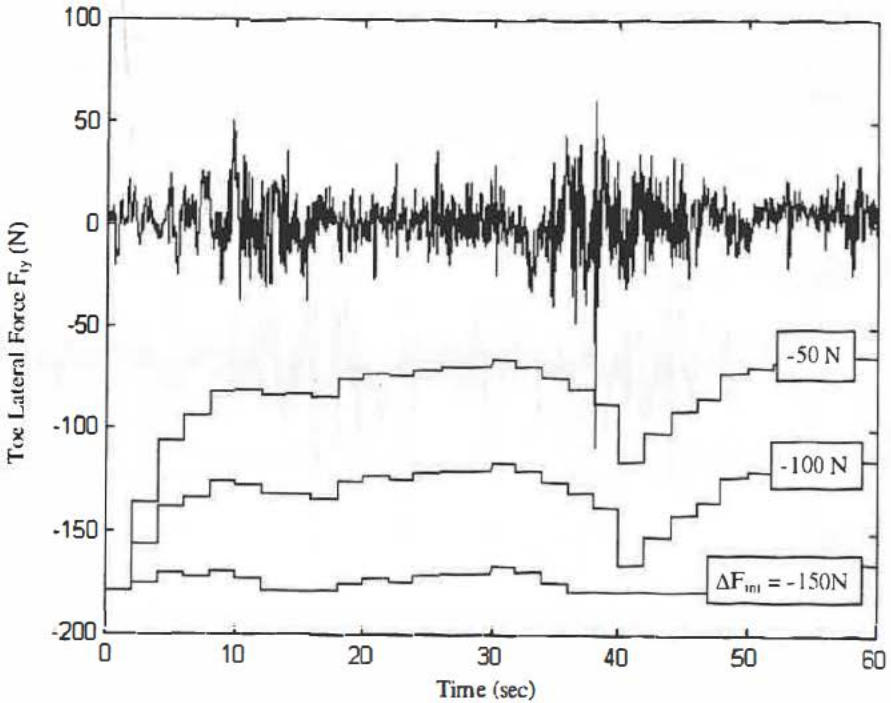


FIG. 3b—Learning binding response history for run by subject JF with three different offsets ΔF_{int} in internal twist mode.

$$\Delta F_{up}(w) = 0.786w - 61.4,$$

where w is the subject weight in Newtons. With this design, the ratios of the mean release settings to the maximum forces during normal skiing are reduced to 1.31 in external twist, 1.34 in internal twist, and 1.43 in forward lean modes with corresponding standard deviations of 0.33, 0.34, and 0.50, respectively. A value of 1.00 or lower is attained in six cases. Whereas the minimum value of the ratio for the first design is 0.85, this design's minimum ratio is only 0.96, obtained for subject PG in forward lean; however, the first design's maximum ratio of 3.09 is larger than this design's maximum ratio of 2.28, obtained for subject MD in forward lean.

Release settings are calculated for the eight special runs, all of which include falls, to ascertain when the learning binding designs release; these results are summarized in Table 4. Where release occurs, the release direction and time, referenced from the beginning of the skiing run, are both given. In seven of the eight runs with falls, releases according to the learning binding designs agree with the desired responses. The learning binding designs recommend release at the same time as the binding with ASTM settings in runs PS3 and YY5. In two other runs, PS1 and HS8, the learning binding designs release 23 and 78 ms earlier than a binding with ASTM settings. In the last run, HS9, the lateral force at the toe never exceeds the ASTM lateral twist setting, yet both learning binding designs predict release in the external twist direction.

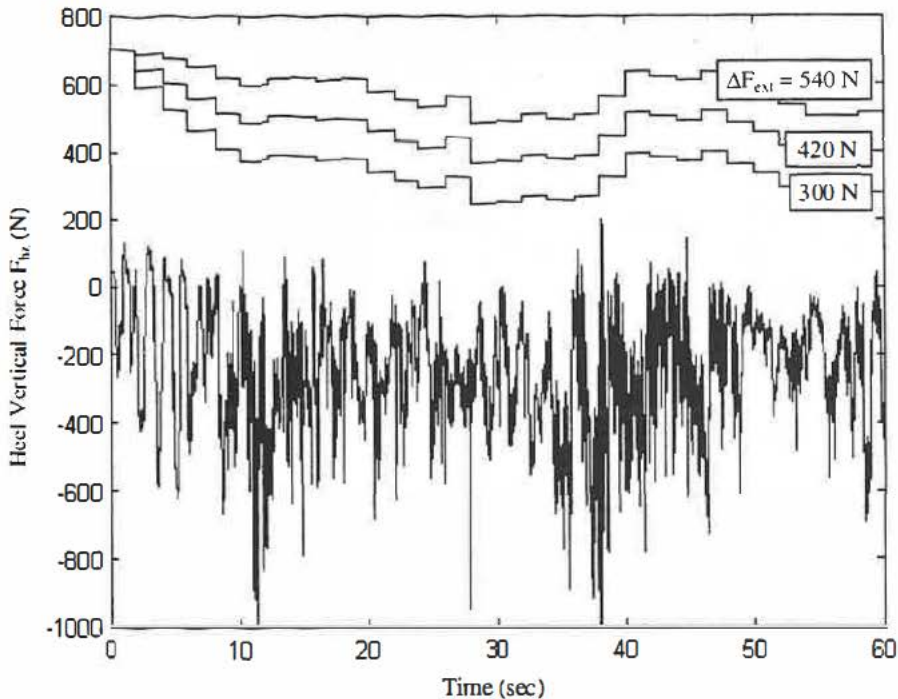


FIG. 3c—Learning binding response history for run by subject JF with three different offsets ΔF_{op} in forward lean mode.

Discussion

As reported in other studies [11], the ASTM recommended settings allow forces at the bindings that are significantly larger than the maximum forces occurring during normal skiing. For the nine subjects completing at least one run without a fall, the forces allowed by the ASTM settings were on average 88, 102, and 117% more than the maximum measured forces in the external twist, internal twist, and forward lean modes, respectively. However, the disparity between the ASTM settings and the minimum retention requirements does not hold globally—one skier (subject AH) produced forces that are within 80% of the recommended release threshold in both the external and internal twist modes and within 71% in the forward lean mode. Another skier (subject PG) generated a maximum vertical force at the heel binding equal to 97% of the force allowed by the ASTM standard. It is this variation of maximum forces from skier to skier that makes the identification of the minimum retention envelope difficult and a simple reduction of the ASTM recommended settings across the board for all skiers impossible.

The release settings specified by the learning binding algorithms are up to 50% less than the ASTM recommended settings. For Design 1, the design with offsets specified independently of weight, the release settings are reduced on average by 26% (52.7 N) in the external twist mode, 27% (55.4 N) in the internal twist mode, and 22% (177.7 N) in the forward lean mode; correspondingly, the release settings are lowered by 28% (57.3 N), 31% (63.0 N), and 27% (218.6 N) for Design 2, the design with offsets that are a function of weight.

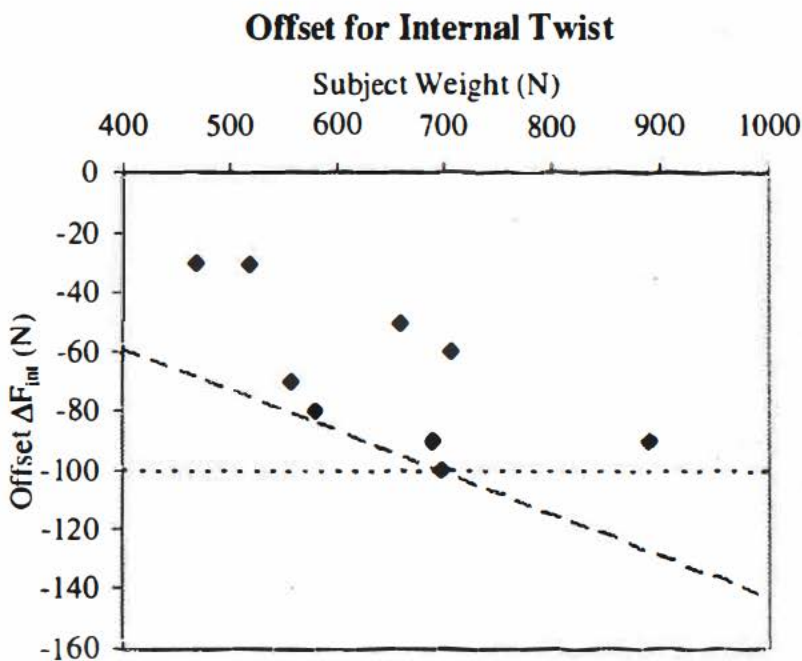
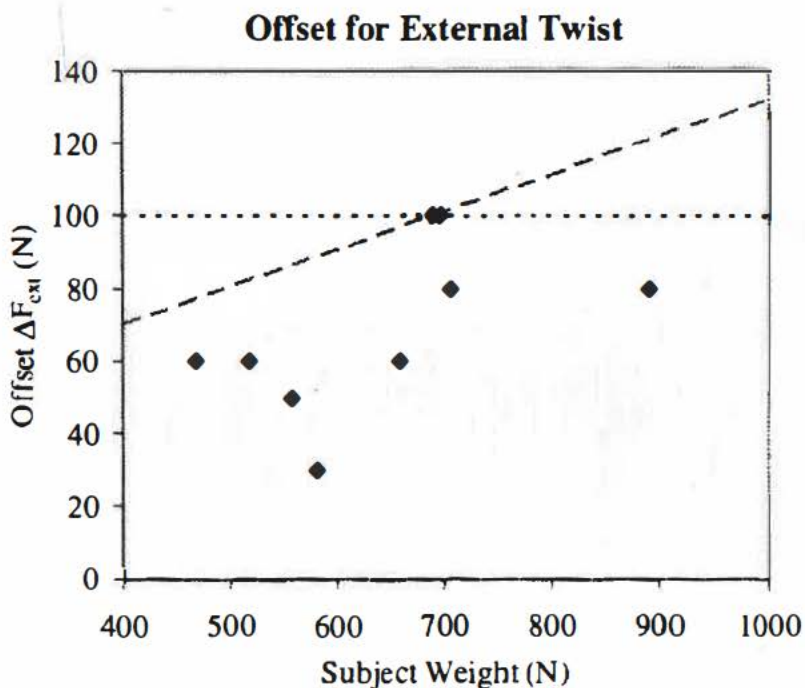


FIG. 4—Minimum offsets, and offsets for Design 1 and Design 2. Dots correspond to test subject data.

Offset for Forward Lean

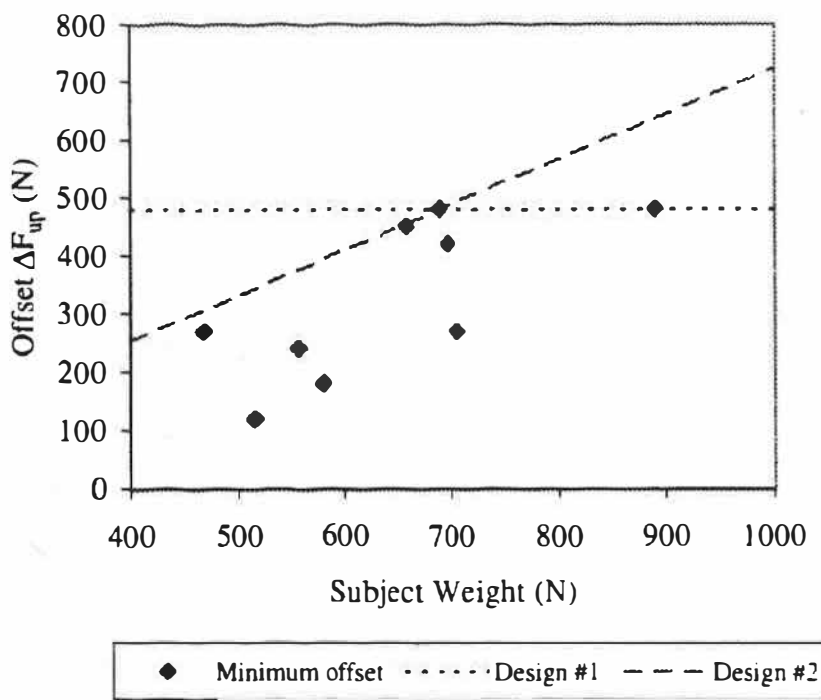


FIG. 4—Continued

TABLE 4—Release directions and times for special runs.

Run ^a	ASTM Standard F 939-93		Design 1		Design 2	
	Result ^b	Release Time (s)	Result ^b	Release Time (s)	Result ^b	Release Time (s)
PS1	Internal	4.98	Internal	4.96	Internal	4.96
PS2	NR	—	NR ^c	—	NR	—
PS3	Internal	6.15	Internal	6.15	Internal	6.15
YY3	NR	—	NR	—	NR	—
YY5	External	4.96	External	4.96	External	4.96
HS1	NR	—	NR	—	NR	—
HS8	External	14.61	External	14.53	External	14.53
HS9	NR	—	External	11.71	External	11.71

^a Run identification label.^b Predicted response of binding during fall; where applicable, release direction is indicated.^c NR = No release.

Those skiers who weigh the least benefit the most from the latter design. For example, according to Design 1, the mean release setting in the forward lean mode for the lightest skier (subject SS) is 75% (194.3 N) above the maximum heel vertical force; however, with Design 2, the mean release setting in this direction is only 10% (26.3 N) greater than the maximum force.

In several cases, the release settings obtain values during normal runs that are less than the maximum force by the same skiing subject. Consider the forward lean release settings for subject PG specified by Design 1. The mean upward release setting is only 85% of the maximum vertical force at the heel during normal skiing, and the *minimum* release setting is even smaller at 59% of the maximum vertical force. This occurs because of a change of skiing style during the subject's runs. During two runs, subject PG executes wide carving turns (characteristics of giant slalom turns). Over the time period of 93 s, the upward vertical heel force never exceeds 600 N, and the mean release force is 798 N. In the 51 s third run, subject PG makes tight slalom-like turns, creating a series of upward vertical heel force peaks that exceed 600 N six times with a maximum of 991 N. Accordingly, the algorithm calculates a higher release setting having a mean value of 942 N for this run, indicating that the learning binding adapts to changes in skiing style that cause a dramatic change in the required retention settings.

In addition to a simple reduction in the release settings, the learning binding designs can also respond more quickly to excessive loads than a standard binding that is calibrated to release at the ASTM recommended settings. For instance, the learning binding designs release 78 ms earlier than the standard binding in run HS8 (see Fig. 5). This earlier release is directly due to a lower release setting in the case of the learning binding. Similarly, release in one other run, PS1, occurs 23 ms earlier for the learning binding than the conventional binding. An earlier release is not guaranteed in all cases, however. The internal twist release in PS3 occurs at the same time for the learning binding and the conventional binding because the learning binding's release setting is equal to the ASTM recommended value at the time

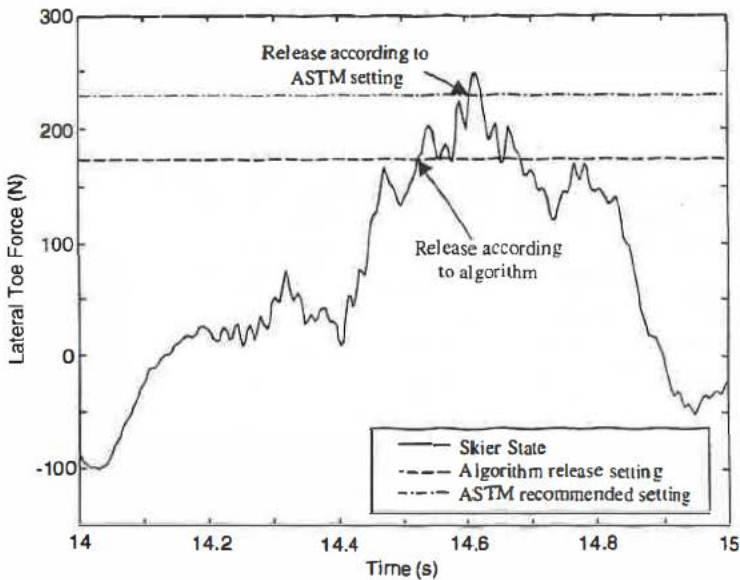


FIG. 5—Release in external twist mode (Run: HS8).

of release. Another reason that the two bindings may specify the same release time is an extremely quick rise time of the skier state variable, such as in run YY5. In this example, the lateral toe force increases from -70.6 to 416.7 N in only 8 ms, exceeding both the learning binding's release setting and the ASTM recommended setting at the same time.

A learning binding would likely be an electromechanical design, with sensors measuring the forces on the bindings, electrical circuitry calculating and comparing the skier state and release settings, and a release mechanism actuated electromechanically. A survey of past binding designs indicates that the design of a binding that uses measurements of the lateral force at the toe and the vertical force at the heel is attainable [15–17]. Earlier electromechanical binding designs have addressed either specific injury scenarios, such as a backward leaning fall that often results in an injury to the anterior-cruciate ligament (ACL), or changes in the strength of the leg due to muscle activity [15]. Bindings have measured force components at the toe and heel binding units using strain gages and have measured muscle activity with electromyogram (EMG) surface electrodes. Both Lautier [16] and Lieu and Mote [17] have designed bindings that specifically measure the lateral force at the toe and the vertical force at the heel. The primary issue that must be addressed for the realization of the learning binding presented in this paper is the inclusion of a microprocessor that would calculate the release settings. Identifying a power supply that is capable of powering the microprocessor for an extended duration and is an acceptable size is likely the crux of the design.

Conclusions

1. The release settings established by ASTM Standard F 939-93 for alpine ski bindings substantially exceed the maximum forces generated by a great majority of skiers during normal downhill skiing. Nonetheless, several skiers generated forces in close proximity to the recommended release settings.
2. Two learning binding algorithms presented in this paper use measurements of the lateral force at the toe and the vertical force at the heel as inputs to predict the release settings in the external twist, internal twist, and forward lean release modes. Resulting release settings are on average at least 22% less than the corresponding ASTM recommended settings in each of the three directions. The maximum reduction for any skier was a 50% decrease in the forward lean mode. These reduced settings result in no inadvertent releases predicted for any test subjects during the 36 min of normal skiing conducted in this study.
3. The variable release settings calculated by the learning binding algorithms adapt from run to run for each skier to accommodate changes in skiing style, snow conditions, and other parameters.
4. The performances of the learning bindings are inconclusive in falling scenarios. Although the algorithms' decisions of whether to release agree with the desired outcome in seven of the eight falls, the sample size is too small to be conclusive. In comparison to bindings utilizing the ASTM recommended settings, the learning bindings facilitate earlier release (up to 78 ms) in two of the four falls where release is desired, and equal the release time in the other two.

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References

- [1] Johnson, R. J., Ettlinger, C. F., and Shealy, J. E., "Skier Injury Trends—1972 to 1994," *Skiing Trauma and Safety: Eleventh Volume, ASTM STP 1298*, R. J. Johnson, C. D. Mote, Jr., and A. Ekeland, Eds., American Society for Testing and Materials, 1997, pp. 37–48.
- [2] Ekeland, A., et al., "Previous Skiing Injuries in Alpine Olympic Racers," *Skiing Trauma and Safety: Eleventh Volume: ASTM STP 1289*, R. J. Johnson, C. D. Mote, Jr., and A. Ekeland, Eds., American Society for Testing and Materials, 1997, pp. 7–13.
- [3] Greenwald, R. M., et al., "Significant Gender Differences in Alpine Skiing Injuries: A Five-Year Study," *Skiing Trauma and Safety: Tenth Volume, ASTM STP 1266*, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. S. Schaff, Eds., American Society for Testing and Materials, 1996, pp. 36–44.
- [4] Shealy, J. E. and Ettlinger, C. F., "Gender-Related Injury Patterns in Skiing," *Skiing Trauma and Safety: Tenth Volume, ASTM STP 1266*, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. S. Schaff, Eds., American Society for Testing and Materials, 1996, pp. 45–57.
- [5] Molinari, M., Bertoldi, L., and Zucco, P., "Epidemiology of Skiing Injuries in a Large Italian Ski Resort During 1988–1992," *Skiing Trauma and Safety: Tenth Volume, ASTM STP 1266*, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. S. Schaff, Eds., American Society for Testing and Materials, 1996, pp. 87–97.
- [6] Fischer, J. F., et al., "Injury Mechanism of the Anterior Cruciate Ligament in Alpine Skiing: Case Studies," *Skiing Trauma and Safety: Tenth Volume, ASTM STP 1266*, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. S. Schaff, Eds., American Society for Testing and Materials, 1996, pp. 270–279.
- [7] Barone, M. D. O., et al., "Muscle Activity During the Backward Fall—Protection for the ACL?" *Skiing Trauma and Safety: Tenth Volume, ASTM STP 1266*, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. S. Schaff, Eds., American Society for Testing and Materials, 1996, pp. 244–253.
- [8] Bach, J. M. and Hull, M. L., "A New Load Application System for In Vitro Study of Ligamentous Injuries to the Human Knee Joint," *Skiing Trauma and Safety: Tenth Volume, ASTM STP 1266*, C. D. Mote, Jr., R. J. Johnson, W. Hauser, and P. S. Schaff, Eds., American Society for Testing and Materials, 1996, pp. 232–243.
- [9] Shealy, J. E. and Ettlinger, C. F., "An Investigation of Ski Binding Settings Based Upon Minimum Retention Requirements," *Ski Trauma and Skiing Safety IV*, W. Hauser, J. Karlsson, and M. Magi, Eds., TÜV-Edition, 1982, pp. 113–121.
- [10] Brown, C. A. and Ettlinger, C. F., "A Method for Improvement of Retention Characteristics in Alpine Ski Bindings," *Skiing Trauma and Safety: Fifth International Symposium, ASTM STP 860*, R. J. Johnson and C. D. Mote, Jr., Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 224–237.
- [11] Scher, I. S. and Mote C. D., Jr. "Comparison of Needed and Recommended Retention Settings for Snow Skiing," accepted for publication in *Skiing Trauma and Safety: Twelfth International Symposium*, American Society for Testing and Materials.
- [12] Crawford, R. P. and Mote, C. D. Jr., "Ski Binding Minimum Retention Requirements," *Skiing Trauma and Safety: Eleventh Volume, ASTM STP 1289*, R. J. Johnson, C. D. Mote, Jr., and A. Ekeland, Eds., American Society for Testing and Materials, 1997, pp. 93–108.
- [13] Quinn, T. P. and Mote, C. D., Jr., "Optimal design uncoupled six degree of freedom dynamometer," *Experimental Mechanics*, Vol. 30, No. 1, 1990, pp. 40–48.
- [14] Cunningham, E. P., *Digital Filtering: An Introduction*, Boston: Houghton Mifflin, 1992.
- [15] Hull, M. L., "Survey of Actively Controlled (Electronic) Snow Ski Bindings," *Skiing Trauma and Safety: Fifth International Symposium, ASTM STP 860*, R. L. Johnson and C. D. Mote, Jr., Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 238–257.

- [16] Lautier, D. J., Maeder, L. L., and Mayer, P. E., "Controllably Self-Releasable Safety Fastener and Method of Unlocking Same," U.S. Patent No. 3,919,563, November 1975.
- [17] Lieu, D. K. and Mote, C. D., Jr., "An Electronic Ski Binding Design with Biofeedback," *Proceedings, International Conference on Medical Devices and Sports Equipment*, San Francisco, 1980, American Society of Mechanical Engineers, Vol. 103, No. 3, 1981, pp. 138-145.