Part II
Ski Bindings

Interactions of Tech Bindings with AT Boot Toe Inserts: Part I, Binding Toe-Piece Mechanics

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Abstract Alpine touring (AT) is a subdiscipline of alpine skiing where skiers ascend and descend snow slopes under their own power. Specialized equipment has been developed for AT skiing, including Tech/Pin bindings that rely on metal inserts molded into AT boots to rigidly couple the boot to the binding. The current lack of standardization has resulted in significant variation in tech insert geometry between boot manufacturers. It is hypothesized that the constraint forces from the tech binding on AT boots are highly sensitive to variations in tech insert geometry.

The dimensions of tech inserts in toe region of AT boots were measured from five manufacturers' boots. The constraint force applied by the toe pieces throughout their travel was measured quasi-statically using custom-built fixture on ten models of tech bindings from five manufacturers. In addition, the retention and release characteristics for an applied twisting torque were measured for the AT boots in the Tech/Pin binding toe pieces using an ASTM F504 test apparatus. Linear statistical models were developed to predict the measured retention-release behavior using the clamping force and tech insert geometry as predictor variables. The relative importance of each predictor variable from the linear model was then calculated.

The compressive forces applied to the AT boots were significantly different between bindings for the same boot, but not significantly different for the AT boots

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in any particular binding ($p < 0.001$). Across all AT boots tested, the twisting release torque was not significantly different between bindings for a given boot ($p = 0.81$); however, significant differences in release torque were found between boots in any particular binding (*two-way ANOVA, Tukeys Post Hoc,* $p < 0.001$). Boot dimensions at the toe had the largest influence on release torque (~85%) while the compressive force had the smallest influence (~15%).

Tech/Pin binding toe pieces are sensitive to small changes in tech insert geometry. This study only examined toe-piece kinematics and forces of tech bindings. Based on the data presented, a companion study will test Tech/Pin boot-binding systems with both the toe and heelpieces.

Keywords Skiing • Alpine touring • Ski bindings • Tech inserts

1 Introduction

Conventional alpine boots and bindings rigidly couple the skiers' boot to the ski to allow skiers to perform maneuvers while skiing downhill and to release the ski from the boot before loads to the lower leg become injurious. Alpine touring (AT) is a subdiscipline of skiing in which the skier uses the skis to ascend, traverse, and descend snow-covered terrain in the backcountry on unmaintained trails and sometimes rough terrain. Conventional alpine skiing equipment lacks functionality to allow skiers to ascend slopes under their own power during alpine touring. As a result, ski boot and binding manufacturers have developed specialized alpine touring equipment.

As a system, AT boots and bindings have two functional modes:

- Downhill (Ski) mode: the toe and heel of the boot are both rigidly fixed to the ski by the binding to allow the skier to perform maneuvers as they ski down snow slopes.
- Uphill (Walk) mode: the binding allows the heel of the boot to be decoupled from the ski, and the toe of the boot is free to pivot to allow the skier to walk up hill on skis, providing both flotation in deep snow and efficiency.

1.1 Alpine Touring Bindings

There are currently two alpine touring binding designs on the market, AT Frame Bindings and Tech/Pin bindings. AT Frame bindings are extrapolations of established alpine binding technology that incorporate an alpine binding toe piece and heelpiece mounted on a hinged chassis. A locking mechanism can secure the chassis to the ski for skiing and unlock for walking uphill. A hinge at the toe of the chassis allows the binding to pivot on the ski. The functional interface of AT frame bindings with AT boots is nearly identical to alpine bindings. AT frame bindings have release value settings that are controlled on the toe piece for twist and heelpiece for forward lean of the binding. These bindings are defined here for clarity but not the subject of the current study.

Tech/Pin bindings were developed by Fritz Barthell in the 1980s but were not widely adopted by AT skiers until the mid-2000s. Since the expiration of Barthell's patent in 2005 (Austria, NR. 376577), the growth in the AT boot sector has been explosive. Their name is derived from Barthell's first model, the "Low-Tech" binding. The boot-binding interface and retention-release mechanisms of these bindings function on completely different principles from alpine and AT frame bindings.

Commonly referred to as "mouse-trap bindings," Tech/Pin bindings have two stable equilibrium positions, open or closed (Fig. 1). The toe and heelpiece of the binding interface with metal inserts molded into the toe and heel of AT boots (Fig. 2). The toe piece commonly consists of a spring-loaded cam mechanism that has two conical pins that clamp into the inserts of the boot toe. For downhill skiing, the heelpiece commonly has two pins that engage into slots in the heel of the boot. For walking, the heelpiece pins can be retracted or rotated 90 degrees such that the rear pins do not engage the boot heel and the boot pivots about the toe piece to allow the skier to walk uphill (Fig. 2). Traditionally, the toe piece does not have any release value adjustment. In 2016, two tech-binding models incorporated release mechanisms in the toe and heelpieces to more adequately respond to combined loads. However, these models have little market share; tech-binding models with the largest market share control twist and forward lean release values are still controlled by the heelpiece.

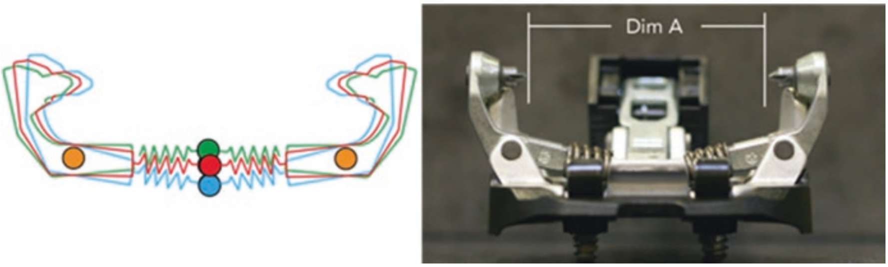

Fig. 1 (*Left*) Open and closed equilibrium positions of the Tech/Pin binding toe piece. (*Right*) Dim A is denoted as the pin-to-pin dimension when the binding is closed

Fig. 2 (**a**) Heel inserts, (**b**) toe inserts molded into ski boots, (**c**) Tech/Pin binding-boot in ski model, with the toe and heel of the boot engaged, (**d**) heel of the boot engaged, (**e**) toe of the boot engaged, (**f**) walk mode with the heelpiece disengaged and only the toe piece of the binding engaged with the boot

1.2 The State of Alpine Touring Equipment

Mesolithic humans are estimated to have begun using skis for locomotion over snowy terrain as far back as 9000 BC [1, 2]. However, the development and standardization of recreational AT equipment is still in its infancy compared to alpine skiing equipment. AT equipment is continually evolving in an effort to meet consumer demands for light-weight equipment that allows efficient uphill performance, while simultaneously providing reliable retention and release functionality skiers have come to expect from their conventional alpine ski equipment. However, the release-retention performance of many of these systems is a secondary design function to their uphill performance.

Safety standards have long been established for alpine ski equipment and have been proven to be effective in reducing the incidence of skiing-related lower leg injuries since the 1980s [3–6]. It wasn't until the early 2000s that international standards began to address the safety considerations of AT equipment with standards adapted from alpine ski equipment for AT equipment. The rapid pace of development of AT equipment has quickly outpaced the international standards organization's ability to address many new issues presented by evolving equipment designs. The interface geometry of AT boot soles with AT Frame bindings was standardized by ISO 9523:2006 and the retention-release requirements of AT bindings were defined by ISO 13992:2014 [7, 8]. However, these standards were largely derived from alpine boot-binding standards and have little bearing on how Tech/Pin boot-binding systems function.

No standard currently defines the interface geometry or properties of AT boots with Tech/Pin bindings. A common perception among consumers is that Tech/Pin bindings have unpredictable retention characteristics that produce inadvertent releases, which occur when a binding releases prematurely, when loads transferred from the ski to the skier are not at risk of injuring the lower leg. Consequently, many consumers ski with the toe piece of their Tech/Pin bindings in walk mode, which effectively locks out any release capability of the toe-piece mechanism. In the event of a fall with the toe piece in walk mode, the likelihood of the binding releasing is virtually nonexistent. The likelihood of a lower leg fracture using alpine ski bindings has been shown to increase three-fold if a binding does not release in a fall [9–11].

There are no known epidemiological studies for injury rates using AT equipment. However, examining injury rates in alpine skiing, inadvertent releases cause slightly less injuries than those caused by bindings not-releasing, 0.89 vs. 1.15% of all injuries, respectively [12]. Manufacturers have begun to recommend use of their boots with specific bindings and not others based on inter-manufacturer differences in boot geometry to address consumer perceptions of inadvertent releases. If consumer's perceptions are correct, then the risk of injury from an inadvertent release or from a non-release because the toe piece is locked out, is a concession of safety that must be addressed. To our knowledge, no previous work exists addressing the retention-release characteristics of AT boot-binding systems.

The purpose of the current study is to examine parameters critical to the retention-release performance of the AT boot-Tech/Pin bindings system and quantify the amount of inter-manufacturer variability in AT boot geometry and Tech/Pin binding performance. It is hypothesized that the dimensions of the boot inserts will be the largest source of release torque variability. From this analysis we hypothesize that several parameters can be identified for standardization to improve the reliability of the retention-release performance of Tech/Pin boot-binding systems.

2 Methods

When an AT boot is inserted into the toe piece of a Tech/Pin binding, the pins of the toe piece engage and come to rest at the inner most conical point of the inserts, defined as Dim A for the purposes of this study (Figs. 1 and 3). As load is applied to the ski, the pins of the toe piece will move apart, and the overall distance between them will increase until the toe piece snaps open.

2.1 Boot Measurements

Two linear dimensions, Dim A and Dim B, were measured three times each from the inserts on one pair of boots from nine boot models from seven manufacturers (Table 1) using a micrometer fitted with conical tips (Mitutoyo, Resolution ±0.001 mm). Dim A is defined as the inner most point between the two inserts (Fig. 3). Dim A is defined as the largest distance, in the horizontal plane, of the

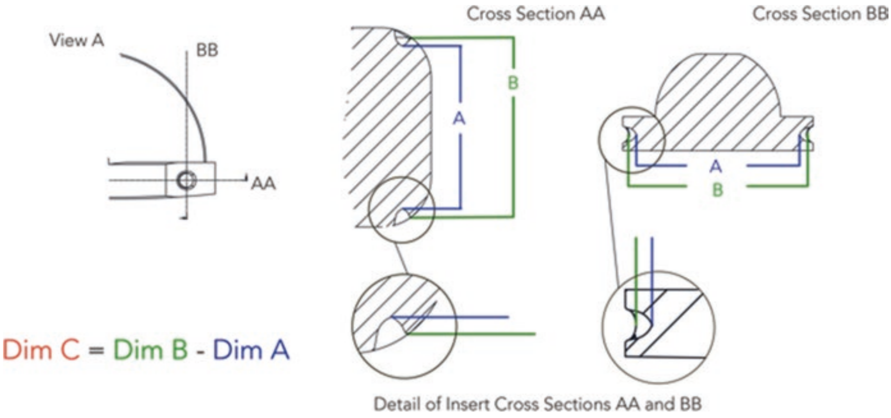

Fig. 3 AT boot dimensions measured at the toe inserts. View (A) is looking at a boot toe from the side. Cross section (AA) is a horizontal cut through the plane of the insert and boot sole. Cross section (BB) is a cut through the vertical plane of the boot toe; the view is towards the boot toe

Table 1 Descriptive statistics for three linear boot dimensions

Manufacturer	Model	Dim A (mm)	Dim B (mm)	Dim C (mm)
A	A1	58.13 ± 0.07	63.80 ± 0.38	5.15 ± 0.36
B	B1	58.17 ± 0.03	63.24 ± 0.20	5.07 ± 0.22
	B2	58.13 ± 0.03	63.69 ± 0.01	5.45 ± 0.04
C	C1	57.97 ± 0.06	63.91 ± 0.07	5.94 ± 0.13
	C2	58.09 ± 0.00	64.24 ± 0.02	6.15 ± 0.02
D	D1	58.47 ± 0.13	62.24 ± 0.23	3.95 ± 0.10
E	E1	57.85 ± 0.20	63.66 ± 0.28	5.81 ± 0.08
F	F1	57.85 ± 0.20	63.37 ± 0.13	5.52 ± 0.32
G	G1	57.60 ± 0.02	63.15 ± 0.02	5.55 ± 0.00
MN ± SD		58.03 ± 0.24	63.45 ± 0.51	5.42 ± 0.63
[Min, Max]		[57.58, 58.56]	[62.25, 64.25]	[3.89, 6.17]

insert on the anterior most position of the insert (Fig. 3). A third dimension, Dim C was calculated as the difference between Dim A and Dim C.

2.2 *Binding Measurements*

The force–displacement of the toe piece was measured using a custom force-displacement transducer (Fig. 4). The transducer incorporated a custom strain gage-based compression load cell (Range: 300 N, Resolution: 0.3 N ± 0.1 N) and custom linear displacement transducer (Range 12 mm, Resolution: 0.1 mm ± 0.01 mm)

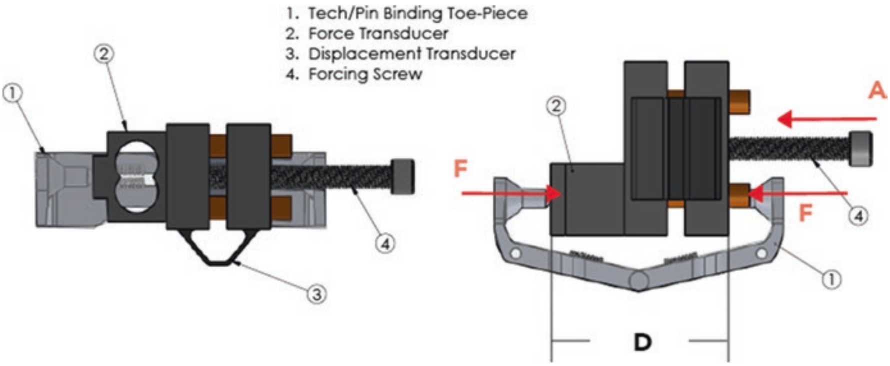

Fig. 4 Force–displacement transducer for measuring the clamping force–displacement curve of toe pieces. (*A*) The direction of the forcing bolt. (*F*) Arrows show the resulting compressive force measured by the force transducer. (*D*) The linear displacement of the binding pins measured by the displacement transducer

(J2A-06-S047G-350/SP62 Strain Gages, Vishay Measurements Group, Raleigh, NC). The custom force transducer was calibrated against a NIST-traceable six-axis load cell (Model 4526, Humanetics, Plymouth, MI) and the custom linear displacement transducer was calibrated using a micrometer (Mitutoyo, Resolution ±0.001 mm). The force-displacement transducer incorporated a forcing screw mechanism to push the pins of the toe piece from the closed to open position while measuring the corresponding force-displacement relationship (Fig. 4). Force-displacement was measured on a total of 10 pairs of bindings from five manufacturers using a 16-bit data acquisition device while data were sampled at 250 Hz (SLICE NANO, Diversified Technical Systems, Seal Beach, CA). Tests were repeated six times on each binding toe piece.

2.3 Release Torque Measurements

The release characteristics of Tech/Pin boot-binding systems were tested in a laboratory setting using a lower leg surrogate that conformed to standards ISO 9462:2012 Appendix B [5] and ASTM F504–05 [13] (Fig. 5). The ten models of Tech/Pin bindings measured in Sect. 2.2 was mounted to their own test skis; all test skis were the same make, model, and 167 cm in length (AMP Rx, K2 Sports, Seattle, USA). Five models of AT boots measured in Sect. 2.1 (models A1, B1, C2, D1, E1 from Table 1) with boot sole lengths between 306 and 310 mm were prepared for testing. In order to measure the effect of boot design features, it was necessary to create a rigid coupling between the portion of the boot that interacts with the ski binding and a torque transducer. To this end, each test boot shell was cut below the pivot point of the upper shell and an aluminum adapter plate was secured to the foot area by filling

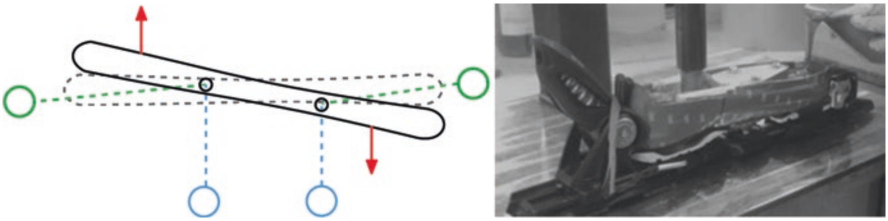

Fig. 5 Schematic of test apparatus that conforms to ASTM F504–05. The system applied forces (*red arrows*) to the ski using a motor-driven system of cables and pulleys. A load cell measures the torque on the simulated leg along the axial and transverse axes

the interstitial space with aluminum-filled epoxy (Rencast® 4037, Huntsman, The Woodlands, TX) (Fig. 5).

Ski/boot/binding systems were rigidly affixed to a transducer located in a lower leg surrogate via the adapter plate mounted in the boot; torque was applied to the ski using a system of motors, cables, pulley, and pneumatics which is measured by the transducer about the axial and transverse axes, as defined in ISO 9462–2012 (Fig. 5). All bindings released at very small angular displacements; therefore, a correction for the torque was not necessary. The range of the load cell was ±400 Nm (resolution: 0.29 Nm) and ±700 Nm (resolution: 0.17 Nm) along the axial and transverse axes. The load cell was calibrated against a NIST-traceable six-axis load cell (Model 4526, Humanetics, Plymouth, MI) and had less than 0.5% error at full scale. The data were collected at 1,000 Hz using a 16-bit data acquisition system (Model 6210-USB, National Instruments, Austin, TX) with a 200 Hz low-pass, anti-aliasing filter. Labview 14.0 software (National Instruments, Austin, TX) was used to collect and filter digitally the data using with a four pole, zero phase shift, low-pass Butterworth filter with a cut-off frequency of 10 Hz. A pure twisting couple, or torque, was applied to the ski with only the toe piece engaged in the ski position. Tests were performed dry, at 21 °C.

2.4 *Statistical Analysis*

Two-way ANOVAs were employed to test for statistical differences in constraints between bindings and boots, with a significance level of 0.05.

2.4.1 Multiple Linear Regression (MLR) Analysis

Independent variables quantified from boot-binding constraints were used predict release torque in multiple linear regression (MLR) models (***R***, *Foundation for Statistical Computing, Vienna, Austria, Fox, 2003*). Data were centered about their mean and scaled by one standard deviation. The Kolmogorov-Smirnov test was employed to test for skewness [14]. MLR analyses were used to predict release torque based on unique combinations of independent variables for each load case. The likelihood ratio test compared models using different independent variables and tested for interactions between independent variables. Variance inflation factors (VIF > 5) were used to identify regressors with high collinearity [15]. Regressors were not used if they were not significant contributors to the model, with a significance level of 0.05, or if they were redundant.

2.4.2 Relative Contribution of Regressors to MLR Models

The percent contribution to variation in release torque of each regressor in the MLR models was calculated using the *lmg* metric from the *relaimpo* statistical package in ***R*** [16]. The *lmg* metric normalizes R^2 to 100% and the contribution of each regressor is calculated as a percentage of the R^2 from the linear model. The variance of percent contribution was calculated by bootstrapping the MLR models at 1000 bootstrap intervals, holding the regressors fixed and bootstrapping the residuals. The 95% bootstrap confidence intervals for regressors are reported.

3 Results

3.1 Boots

Descriptive statistics for measured dimensions of AT boot inserts are tabulated in Table 1. The distribution of measurements of Dim A, Dim B, and Dim C were positively (Dim A: 0.849) and negatively skewed (Dim B: −0.147, Dim C: −1.12), respectively (Fig. 6). However, skewness was not significant enough to require data transforms according to a Kolmogorov-Smirnov test. The variation in Dim A, ±

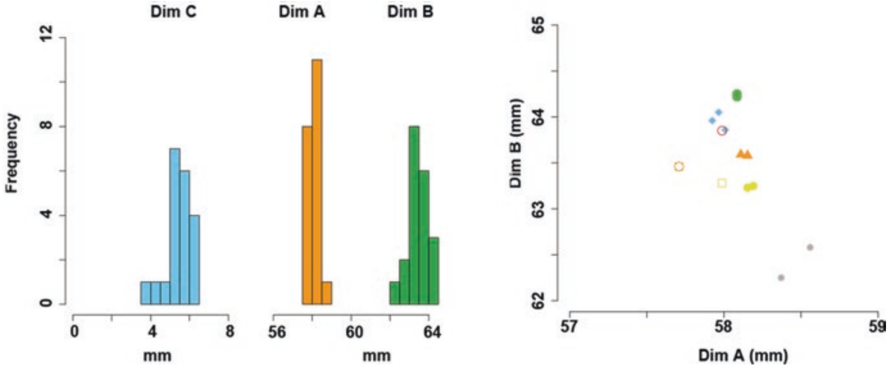

Fig. 6 Histogram of the distribution of Dim A, Dim B, and Dim C. Dim A vs. Dim B from nine boot models (*right*). No trend or scaling of Dim A vs. Dim B is apparent, meaning Dim C varies across manufacturers

0.24 mm, and Dim B, ± 0.51 mm, appeared to contribute to tolerance stacking as the standard deviation in the Dim C dimension, ±0.73 mm, is approximately equal to the sum of the standard deviations of Dim A and Dim B.

3.2 Bindings

Force–displacement curves were generated for ten binding models from five manufacturers. Each curve showed significant variation in magnitude (Fig. 7a). Three representative clamping force-displacement curves are shown in Fig. 7 with the standard deviation from six repeated measurements of the force–displacement curve. The peak clamping force each binding was capable of generating varied significantly between models, ranging from 125N up to 225N.

3.3 Boot-Binding Compressive Force

In Fig. 7, the points corresponding to Dim A for all boots measured lie on the uphill side of the force–displacement curve. Their location on this curve represents the amount of initial compressive force holding the boot in the binding. The positive slope of the curve results in differences in the magnitude of the preload applied to different boots, depending on the value of Dim A for a given boot. To release from

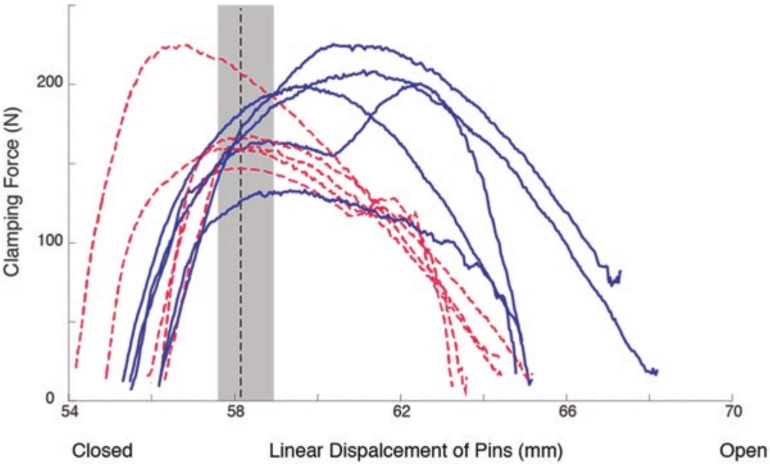

Fig. 7 Average force–displacement curves from all toe pieces measured moving from the closed position (*left*) to open position (*right*). The *shaded rectangle* delineates where Dim A from the nine boots measured lie on each force–displacement curve. *Dashed lines* indicate bindings where the boots lie on the curve past the binding's energy barrier. *Solid lines* indicate bindings where boots lie on the curve before the energy barrier

the toe piece, these loads transmitted from the ski to the boot must overcome the energy barrier that corresponds with the peak of the force-displacement curve, moving from left to right in Fig. 7.

Curves shown in Fig. 7 with dashed lines are significantly different; their shape indicates that the toe piece closes on all boots at points along the curve that are already past the peak, or energy barrier, of that particular binding. As the pins of the toe piece open in response to loads transmitted from the ski to the boot, the binding toe piece will apply a smaller and smaller compressive force until the toe piece snaps open.

An analysis of variance on the clamping force yielded significant variation between bindings, $F(9,170) = 80.69$, $p < 0.001$. A post hoc Tukey test showed significant differences between all but 39 of the clamping forces generated by five of the binding toe pieces were significantly different from the remaining five (*two-way ANOVA, Tukey's Post Hoc Test,* $p < 0.001$).

3.4 *Twisting Release Torque: Toe Piece Only*

An analysis of variance on the release torque yielded significant variation among boots and bindings, $F(39,140) = 12.94$, $p < 0.001$. A post hoc Tukey test showed significant differences in release torque in all but three boots (Fig. 8). A post hoc Tukey test also revealed the release torque from one binding toe piece to be significantly different from six other bindings (Fig. 8).

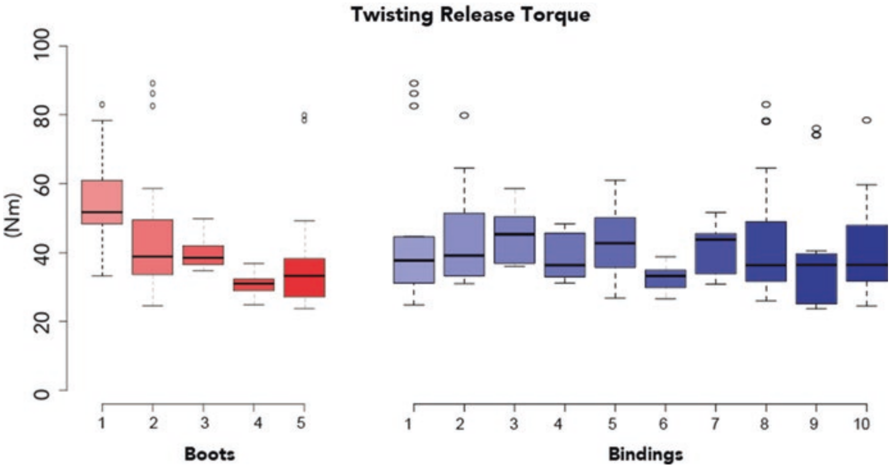

Fig. 8 Boxplots of release torque of the toe piece of bindings grouped by boots (L) and bindings (R)

3.5 Predicting Release Torque from Boot-Binding Constraints

With independent variables of clamping force and boot dimensions, Dim A and Dim C, a significant MLR model was found for all binding toe pieces ($F(4,175) = 22.55$) that accounted for approximately 34% of the variance in release torque for all bindings ($\textit{Multiple-}R^2 = 0.340$, $\textit{Adjusted-}R^2 = 0.325$, $p < 0.001$). However, significant MLR models were found for each individual binding toe piece that accounted for approximately 84.7% ± 19.1% of the variance of Pure Twist release torque (Appendix, Table A.1).

The MLR models predicted the boot dimensions, Dim A and Dim C control ~85% of the variability in release torque in each binding toe piece (Table 2, Fig. 9). In contrast, the clamping force exerted by the binding on the boot accounts for only ~15% of the variability in release torque. A significant interaction between the starting positions of the pins, Dim A, and the amount of displacement required to release in twist, Dim C, was found 20.4% [8.8%, 32%]. Finally, the clamping force from the binding contributed the least amount to variance in release torque 14.9% [13.1%, 16.7%]. Results from the MLR predict that increases in Dim A will decrease the release torque and increases in Dim C will increase release torque (Appendix, Table A.2).

Table 2 Percent relative contribution and the 95% CIs [LL, UL] of boot-binding constraints to release torque variation for a pure twist release

Binding	Dim A	Dim C	DimA|DimC	Clamping force	R^2	p
1	22.2% [20.9, 23.7]	18.8% [17.8, 19.9]	9.9% [8.7, 11.1]	48.7% [47, 50.8]	0.995	<0.001
2	26.2% [23.6, 28.1]	35.4% [31.7, 38.4]	10.5% [7.2, 13.7]	28% [24, 31.1]	0.976	<0.001
3	25.4% [23.5, 27.9]	44.0% [39.1, 50.2]	4.6% [1.7, 9.9]	21% [16.2, 27.8]	0.930	<0.001
4	33.9% [33.1, 34.8]	46.1% [44.7, 47.6]	7.7% [6.6, 8.8]	12% [11, 13.4]	0.996	<0.001
5	33.1% [26.2, 44.2]	33.5% [25.4, 44.7]	10.4% [4.3, 20.5]	11.7% [8.6, 18.6]	0.841	<0.001
6	8.2% [5.6, 11.8]	9.3% [6.3, 13.3]	66.4% [60.2, 72]	13.3% [11.6, 16]	0.961	<0.001
7	22.9% [18.6, 28.0]	37.5% [29.2, 46]	5.9% [1.2, 14.1]	7.4% [4.3, 14.8]	0.709	<0.001
8	31.4% [30.8, 32.1]	53.1% [52, 54.3]	8.4% [6.7, 10.1]	6.7% [6.3, 7.3]	0.995	<0.001
9	26.4% [25.9, 26.9]	58.3% [57.1, 59.6]	8.4% [6.9, 10.1]	6.5% [6, 7.1]	0.600	<0.001
10	28.1% [8.4, 49.7]	12.8% [4.9, 25.5]	16.6% [1.2, 44.4]	4.5% [1.1, 25]	0.467	<0.001

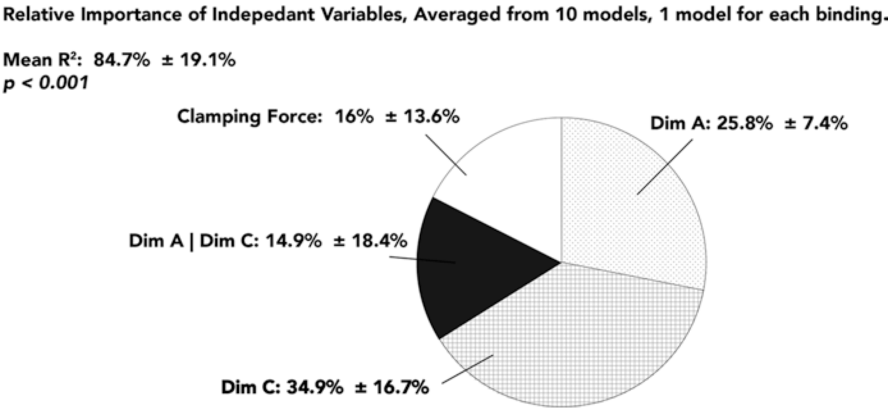

Fig. 9 Average relative importance of independent for the ten models from each binding

Dim A of the boot controls the initial clamping force; however, the potential energy to release is controlled by the slope of the force–displacement curve. The effect of the shape of the force–displacement curve has not been captured by the MLR models reported here. The toe piece with the highest compressive (clamping) force (Fig. 7) is very symmetrical and has a peak at a specific displacement value such that the values of Dim A lie on the positive slope of the curve.

In contrast, no matter what boot is used in the bindings corresponding dashed lines to in Fig. 7, there is no potential energy barrier to resist an inadvertent release. It follows that the available energy dissipation from each of these bindings is significantly different. Not only is the available potential energy, the area under each curve, very different, but also the variation in geometry found across all boots will alter considerably, the amount of energy a binding has to dissipate energy and prevent an inadvertent release. Furthermore, bindings represented by the dashed lines in Fig. 7 are closer to the middle equilibrium position shown in Fig. 1. The closer to this position the binding starts, the more unstable, and prone to prerelease it will be.

4 Discussion

International standards for alpine and AT boot geometry specify the geometry and tolerances for key interface dimensions to provide repeatable retention-release characteristics as consumers mix and match boots and bindings from different manufacturers. International ski boot standards specify allowable deviations from standardized boot geometry at the boot-binding interface that range between 0.5 mm and 2 mm, or approximately 5–20% of the target dimensions [5, 7].

Although the geometry of the AT boot toe inserts is not standardized, the variance measured in Dim A, Dim B, and Dim C between boots from ten manufacturers was relatively small, ± 0.25 mm, ±0.55 mm, and ±0.73 mm, respectively.

However, these small variations significantly altered the release torque of boots from the toe piece in twist. For example, in Fig. 9, mean release torque of Binding 2 from a sample of ten boots was 36.5 Nm, but the maximum torque recorded from a boot was 78.44 Nm, a 215% increase in release torque resulting from the use of different boots in the same binding. The MLR models predicted that 85% of this variability is a product of the small variations in boot geometry. These results highlight Dim A and Dim B as dimensions that highly influence the behavior of Tech/Pin boot-binding systems and that if standardized across manufacturers, a significant portion of the variation in release torque could be reduced. However, if a standard were to be developed for the insert geometry, the dimensions would likely require significantly tighter tolerances than what manufacturers are accustomed to.

The amount of variation in release torque found between boots and bindings may give credence to the perception among consumers that the release torque of Tech/Pin boot-binding systems is variable and unpredictable. This may tempt skiers to lock out the release mechanism of the toe piece while skiing, particularly when the consequences of a fall could lead to serious injury or death. If the variability in release torque found in this study is an indicator of retention-release function of Tech/Pin bindings under skiing conditions, consumers may be at a higher risk of injury than they are accustomed to when using typical alpine skiing equipment, whether they lock out the release mechanism or not, due to an inadvertent release, or a non-release of a boot-binding system [12].

The current study has investigated the effect of geometric variations of boot insert geometry on release torque. Other factors not explored in the current study, but may also significantly affect release torque, include the surface roughness of the boot inserts, the hardness of the metal used in the binding pins and boot toe inserts, wear of these metal components over time, and debris that enters the system from being used in a mountainous environment.

This study was limited to an examination of the interactions of the boot-binding interface with the toe inserts of the boot and toe piece of the binding. The goal of this study was to understand the fundamental mechanics of the interaction of AT boot insert geometry and Tech/Pin binding toe pieces. The energy barriers of the toe piece have been reported from quasi-static tests. The slope of these quasi-static energy barriers provides valuable insight into the stability of a toe piece under dynamic loading; readers should note that under dynamic loading conditions, with the heelpiece engaged, the effects of boot geometry reported here might change. Our study examines the contribution of the toe piece to variation in release torque. Other than a pure twisting release, the current study did not examine any other load cases. Future studies will also examine how the contributions of the heelpiece and boot dimensions affect variations in release torque under other loading scenarios simulating forward and backward twisting falls.

5 Conclusion

Anecdotally, skiers have reported locking the release mechanism of the binding toe piece due to a consumer perception that Tech/Pin boot-binding systems have unreliable retention performance. However, this exposes skiers to a higher risk of injury in the event of a fall when the binding should release from the boot. The consumer perception may have some merit since large variations in release torque were measured in this study. The consumer perception may have some merit since large variations in release torque were measured in this study stemming from the differences in boot insert geometry between manufacturers. If boot insert geometry were standardized across all manufacturers, the variation in release torque would decrease significantly.

A. Appendix

Table A.1 MLR fit metrics for release torque from ten bindings

Binding	$F(4,10)$	Multiple R^2	Adjusted R^2	p
1	645.1	0.996	0.995	<0.001
2	143	0.983	0.976	<0.001
3	47.3	0.950	0.930	<0.001
4	892.5	0.997	0.996	<0.001
5	19.57	0.887	0.841	<0.001
6	86.41	0.972	0.961	<0.001
7	27.84	0.736	0.709	<0.001
8	693.1	0.996	0.995	<0.001
9	6.247	0.714	0.600	<0.001
10	4.066	0.619	0.467	<0.001

Table A.2 Scaled MLR coefficients (β_n), standard errors (SE), and fit metrics for independent variables: Dim A, Dim C, the interaction of Dim A and Dim C (Dim A|Dim C), and the clamping force (CF)

Bindings		MLR: Independent variables					R^2	p
		Intcpt.	Dim A	Dim C	DimA|DimC	CF		
All	***βn***	−0.29	***0.44***	***1.11***	***−0.32***	***−0.08***	0.325	<0.001
	SE	0.10	***0.06***	***0.15***	***0.14***	***0.09***		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.182*		
1	***βn***	−0.25	−0.58	−0.20	−0.28	−0.76	0.996	<0.001
	SE	0.04	0.09	0.06	0.05	0.05		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		
2	***βn***	−0.52	−0.20	1.06	−0.59	−0.09	0.976	<0.001
	SE	0.09	0.11	0.19	0.14	0.10		
	p	*<0.001*	*0.31*	*<0.001*	*<0.001*	*0.43*		
3	***βn***	−0.28	0.98	1.83	−0.32	−0.24	0.930	<0.001
	SE	0.16	0.32	0.23	0.1642	0.18		
	p	*0.109*	*0.0124*	*<0.001*	*0.080*	*0.211*		
4	***βn***	−0.43	2.12	2.78	−0.49	−0.14	0.996	<0.001
	SE	0.04	0.08	0.05	0.04	0.04		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		
5	***βn***	−0.98	−2.20	0.31	−1.18	1.26	0.841	<0.001
	SE	0.30	0.52	0.24	0.34	0.28		
	p	*0.009*	*0.002*	*0.226*	*0.006*	*0.001*		
6	***βn***	−1.83	−4.09	−1.0647	−2.0661	1.85	0.961	<0.001
	SE	0.12	0.24	0.17	0.12	0.14		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		
7	***βn***	−0.37	3.02	3.77	−0.40	−0.55	0.709	<0.001
	SE	0.14	0.36	0.40	0.12	0.11		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		
8	***βn***	−0.43	3.26	4.20	−0.48	−0.49	0.995	<0.001
	SE	0.03	0.08	0.09	0.03	0.03		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		
9	***βn***	−0.42	1.82	2.86	−0.49	−0.48	0.600	<0.001
	SE	0.03	0.03	0.06	0.06	0.03		
	p	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*		
10	***βn***	−0.62	1.32	1.79	−0.72	0.44	0.467	<0.001
	SE	0.33	0.49	0.57	0.32	0.24		
	p	*0.090*	*0.023*	*0.010*	*0.050*	*0.099*		

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Interactions of Tech Bindings with AT Boot Toe Inserts: Part II Binding in Skiing Mode

Jeffrey R. Campbell, Irving S. Scher, David Carpenter, Bruce J. Jahnke, and Randal P. Ching

Abstract Alpine touring (AT) is a subdiscipline of alpine skiing where skiers ascend and descend snow slopes under their own power. Specialized equipment has been developed for AT skiing, including Tech/Pin bindings that rely on metal inserts molded into AT boots to rigidly couple the boot to the binding. The current lack of standardization has resulted in significant variation in tech insert geometry between boot manufacturers. A companion study examined the effects of inter-manufacturer variation of boots and bindings on the release characteristics of the toe piece of Tech/Pin bindings. This study continues this work and examines how inter-manufacturer variability affects the Tech/Pin boot-binding system as a whole, when both the toe and heelpiece are engaged.

The retention and release characteristics for an applied twisting torque were measured for the AT boots in the Tech/Pin binding toe pieces using an ASTM F504 test apparatus. Linear statistical models were developed to predict the measured retention-release behavior using the clamping force and tech insert geometry as predictor variables. The relative importance of each predictor variable from the linear model was then calculated.

Tech/Pin boot-binding systems have variations in release torque that exceed the minimum-maximum allowable release envelope prescribed by international standards. These variations stem from using boots from different manufacturers in a given binding. The indicator settings in these bindings do not change the release torque at the same proportional rate as other AT and alpine ski equipment. Skiers

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should not assume that Tech/Pin bindings will provide the same retention-release characteristics as alpine ski equipment, nor that the numerical indicator settings on Tech/Pin bindings are equivalent to alpine bindings. Homogenizing boot geometry would reduce the amount of variation in release torque from these boot-binding systems, but would not eliminate the problem completely, and could exacerbate the problems for users on one far end of the binding setting scale or the other.

Keywords Skiing • Alpine touring • Ski bindings • Tech inserts • Skiing mode

1 Introduction

Alpine touring (AT) is a subdiscipline of skiing in which the skier uses skis to ascend, traverse, and descend snow-covered terrain in the backcountry on unmaintained trails for which ski boot and binding manufacturers have developed specialized alpine touring equipment. For ascending uphill, skiers' boots are attached to the ski by two pins on the binding toe piece that apply a compressive force to metal conical inserts in the boot toe. The toe piece can be locked during the ascent to eliminate the binding toe piece releasing from the boot. The binding heelpiece is engaged to secure the boot heel for descending slopes while performing alpine turns. In most Tech binding models, the retention-release performance for twisting and forward lean falls is controlled on the heelpiece. A spring-loaded cam mechanisms control the release torque. The preload on the spring is adjusted to indicator values (IV) that correspond to release torque values specified by international standards and are determined based on a skiers height, weight, boot size, and skier classification [1].

Anecdotal evidences suggests that many skiers leave the toe piece locked during the descent, against manufacturers recommendations, to eliminate the risk of an inadvertent release of the binding when a fall could result in injury or death. International standards have not yet been developed for the interface geometry of a subset of AT equipment, called Tech/Pin boot-binding systems. It is hypothesized that variations in boot-binding interface geometry diminishes their compatibility causing their release characteristics to be unpredictable. In turn skiers react to this unpredictability by locking the toe piece out, essentially blocking the release mechanism of the binding, and increasing the risk of injury in the event of a fall.

In a companion study, the relationship between variations in the interface geometry between the boot and binding toe piece, the resulting variations in release torque by quantifying the amount of variation in interface geometry, and constraint forces of the binding were explored. A twisting release torque was applied to the ski-boot-binding system with only the toe piece of the binding engaged with the boot. The amount of variation in boot geometry and binding constraint forces between manufacturers significantly affected the release torque of these systems. The geometry of these inserts are not defined in international equipment standards [2]. This study found that ~85% of the variation in release torque between AT boots

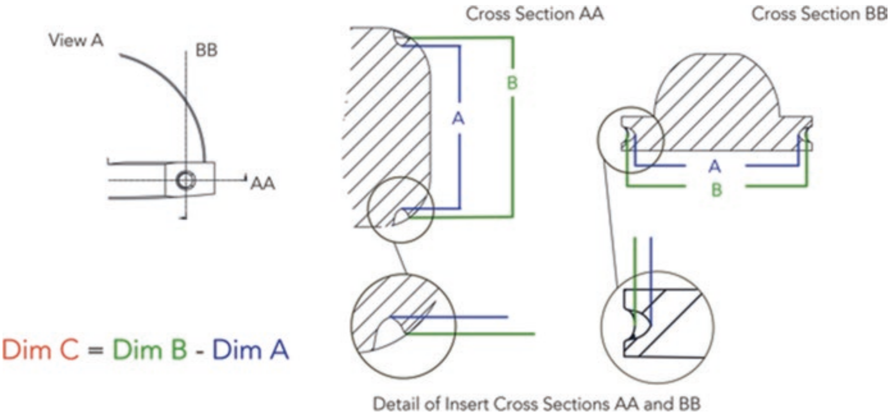

Fig. 1 AT boot dimensions measured at the toe inserts. View (A) is looking at a boot toe from the side. Cross section (AA) is a horizontal cut through the plane of the insert and boot sole. Cross section (BB) is a cut through the vertical plane of the boot toe, the view is towards the boot toe

from different manufacturers could be attributed to difference in two critical dimensions of the boot geometry, namely Dim A and Dim C (Fig. 1). The other ~15% of variation was a result of differences in the amount of clamping force the toe piece of the binding imposed on the boot.

This initial study provided a foundation for examining features critical for understanding the variation in release torque of Tech/Pin boot-binding systems. However, it was limited to the performance of the toe piece and serves as the motivation for the current study; to measure the effect of differences in boot-binding features on the variation in release torque of Tech/Pin boot-binding systems as a whole, with the toe and heelpieces are engaged.

2 Methods

The release characteristics of Tech/Pin boot-binding systems were tested in a laboratory setting using a lower leg surrogate that conformed to standards ISO 9462:2012 Appendix B [3] and ASTM F504–05 [4]. For a complete description of the test methods and setup, please refer to our companion study. Three models of Tech/Pin ski bindings were selected for testing as representative of the principal toe piece mechanism currently on the market. Each binding was mounted to its own test ski; all test skis were the same make, model, and length 167 cm (AMP Rx, K2 Sports, Seattle, USA). Five models of AT boots with boot sole lengths between 306 and 310 mm were acquired for testing. A pure twisting couple or torque was applied to the ski-binding-boot system with the binding in four configurations tabulated in Table 1. The indicator setting marked on each binding was used to set each configuration. Each configuration was tested three times. Tests were performed dry, at 21 °C.

Table 1 A pure twisting torque was applied to the ski in four-test configurations

Test configuration	1	2	3	4
Toe-piece setting	Ski mode	Ski mode	Ski mode	Ski mode
Heelpiece setting	Not engaged	IV = minimum	IV = median	IV = maximum
Binding 1	~ 0	IV = 5	IV = 8.5	IV = 12
Binding 2	~ 0	IV = 4	IV = 7	IV = 10
Binding 3	~ 0	IV = 5	IV = 7.5	IV = 10

Note: IV = indicator value marked on the heelpiece of the binding was used to set the release torque for each configuration

2.1 Multiple Linear Regression (MLR) Analysis

Independent variables, boot dimensions Dim A and Dim C and the clamping force associated with each boot-binding combination, were quantified in the previous study and used predict release torque in multiple linear regression (MLR) models for each binding and configuration listed in Table 1 (***R***, *Foundation for Statistical Computing, Vienna, Austria, Fox, 2003*). Data were centered about their mean and scaled by one standard deviation. The Kolmogorov-Smirnov test was employed to test for skewness. MLR analyses were used to predict release torque based on unique combinations of independent variables for each test configuration. The likelihood ratio test compared models using different independent variables and tested for interactions between independent variables. Variance inflation factors (VIF > 5) were used to identify regressors with high collinearity [5].

2.2 Relative Contribution of Regressors to MLR Models

The percent contribution to variation in release torque of each regressor in the MLR models was calculated using the *lmg* metric from the *relaimpo* statistical package in ***R*** [6]**.** The *lmg* metric normalizes R^2 to 100%, and the contribution of each regressor is calculated as a percentage of the R^2 from the linear model. The variance of percent contribution was calculated by bootstrapping the MLR models at 1000 bootstrap intervals, holding the regressors fixed and bootstrapping the residuals. The 95% bootstrap confidence intervals for regressors are reported in Appendix A, Table A.1.

2.3 MLR Coefficients

Coefficients from the MLR models were rescaled to observe how the sensitivity of the boot-binding to the independent variables changed as the binding heelpiece settings were increased.

3 Results

3.1 Release Torque

Release torque for configuration 1 (IV = 0, toe piece only) varied significantly between Binding 1 and Binding 3 (two-way Anova, Tukey's Post Hoc Test, $p < 0.001$). The release torque for the other test configurations with the heelpiece at the minimum, median, and maximum settings increased linearly for all three bindings. However, they did not increase proportionally at the rate defined by international standards. A boxplot of the release torque from the three bindings and five boots in all four-test configurations is shown in Fig. 2. The shaded region defines the minimum-maximum release torque envelope for a given IV setting per ISO 13992:2014 [1]. The indicator settings of all three bindings do not increase the release torque at the same proportional rate as prescribed by international standards. A linear regression on the release torque vs. Indicator Value (not including test configuration 1, IV = 0), revealed that torque for Bindings 1, 2, and 3 increased at 35.4%, 55.9%, and 84.7% the rate prescribed by international standards, respectively (Appendix A, Table A.2).

The largest variance in release torque for Binding 1 was with the heelpiece setting at the maximum IV. Bindings 2 and 3 both had the largest variation in release torque when the heelpiece was not engaged (toe piece only). However, across the five boots tested in each binding, the variation in release torque at each indicator setting with the heelpiece engaged exceeded the minimum-maximum variation prescribed by the envelope shown in Fig. 2.

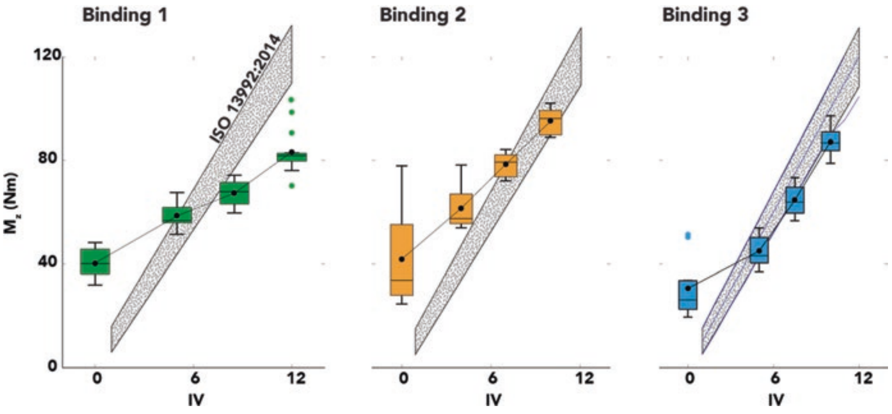

Fig. 2 Boxplots of the release torque of three bindings for configurations 1–4 overlaid with the minimum-maximum release envelope defined by ISO 13992:2014 for a twisting release torque. Boxplots at IV = 0 correspond to tests performed without the heelpiece engaged (toe piece only). Other plots are located on the *x*-axis corresponding to their IV setting (minimum, median, or maximum) for the heelpiece of each binding

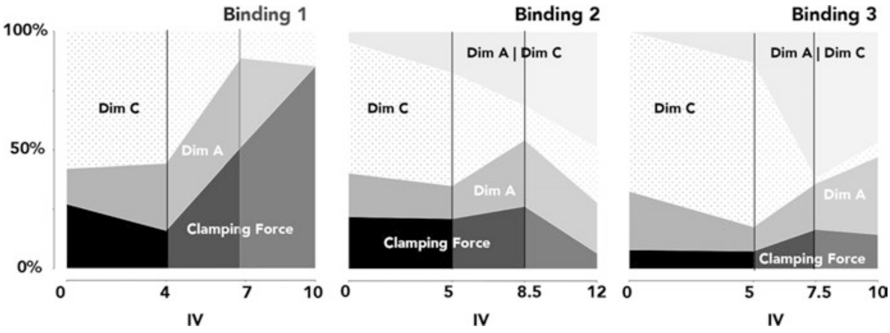

Fig. 3 The relative contribution of each independent variable to the total variance in release torque for each configuration scaled to 100%. The notation “DimA|DimC” denotes the significant interaction between Dim A and Dim C from the MLR model

3.2 Predicting Release Torque from Boot-Binding Constraints

Using independent variables of clamping force and boot dimensions Dim A and Dim C, significant MLR models were found for each binding and configuration tested (Appendix A, Table A.3). The relative contribution of each independent variable is reported in Table A.3 and shown graphically in Fig. 3. The relative contribution of each independent variable is dependent on the heelpiece. As the indicator setting is increased, the heelpiece contributes more resistance to the release torque and the toe-piece dynamics change. The relative contribution to the variance in Torque of each independent variable was scaled to its contribution to the standard deviation, and the overall standard deviations with the absolute contribution of each boot-binding parameter overlaid in Fig. 4.

3.3 Binding Sensitivity to Boot-Binding Features

The effects or sensitivities from the MLR models are designated by the symbol β_n, of each linear fit correspond to how the change in release torque, dT, is affected as a function of the change in each independent variable $dDimA$, $dDimC$, dF. The β_ns of each MLR describe sensitivity of the release torque to changes in each of the parameters the coefficients are derived from. Figure 5 shows an exemplar MLR for the independent variables Dim A, Dim C, and Clamping Force regressing on the twisting release torque for all four-test configurations for Binding 3. Each β_n outlined in Eqs. (1)–(3) represents the slope of the linear fit of the independent variable and response variable, torque.

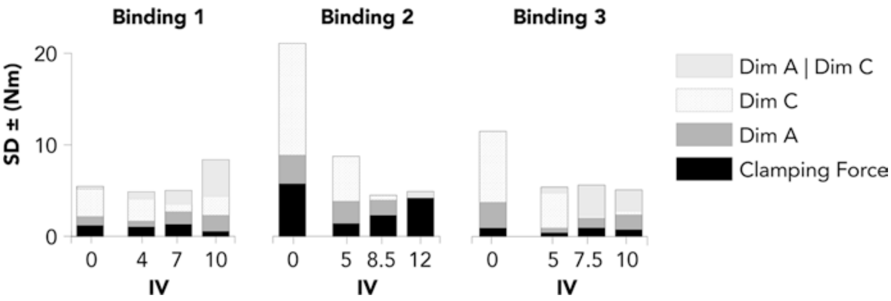

Fig. 4 The standard deviation from each binding tested in each configuration, toe only (IV = 0), followed by IV = [Min, Median, Max] for each binding. The relative contribution of boot dimensions and the clamping force of each binding shown in Fig. 3 are scaled and plotted for each configuration. The notation "DimA|DimC" denotes the significant interaction between Dim A and Dim C from the MLR model

$$\beta_{\mathrm{DimA}} = \frac{dT}{d\mathrm{DimA}} \tag{1}$$

$$\beta_{\mathrm{DimC}} = \frac{dT}{d\mathrm{DimC}} \tag{2}$$

$$\beta_{F} = \frac{dT}{dF} \tag{3}$$

Of particular interest is the change in each β_n as the IV values were increased on the heelpiece. In Fig. 6, β_{DimA} is plotted against β_{DimC} for each test configuration and each binding. The origin of each plot represents the point at which the release torque of a binding would be invariant to changes in Dim A or Dim C; in other words, the slope β_n would equal zero. Figure 6 shows that as the IV of the heelpiece increases, the overall sensitivity to changes in boot geometry decreases. In fact, for Binding 1, the sensitivity curve between IV = 5 and IV = 8.5 passes through the origin at IV = 7.5, assuming a linear relationship. Theoretically, at this discrete value of IV = 7.5, any of the five boots tested would all release at the same release torque value from Binding 1. However for any settings above IV = 7.5, the variation in Dim A and Dim C will have the opposite effect on release torque since the sensitivity curve passes from the upper left quadrant to the lower right quadrant. This could explain why the largest variation in release torque for Binding 1 was at the highest IV setting (Fig. 2).

Extrapolating these observations to the plots for Binding 2 and Binding 3, the sensitivities of both bindings decrease and trend towards the origin, but do not intersect the origin at any point. The sensitivity curve for Binding 2 remains in the upper left quadrant but approaches the origin. Similarly for Binding 3, the sensitivity

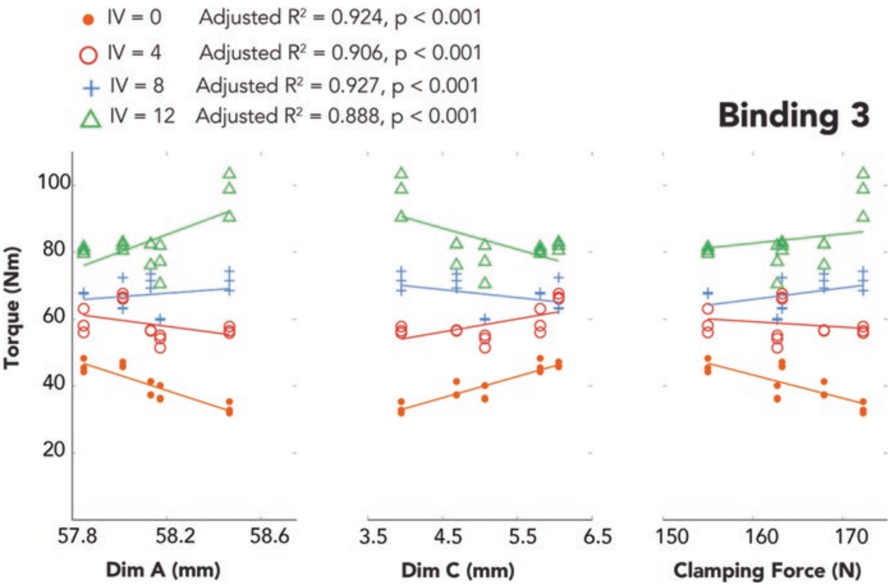

Fig. 5 An MLR for Binding 3, with independent variables Dim A (*left*), Dim C (*center*), and clamping force (*right*) regressing on the twisting release torque for all four-test configurations. Fit metrics for the four MLR models corresponding to each IV setting are given in the legend

curve actually circles close to the origin, but never intersects it. Therefore, the variation in release torque will not be as significant between boots at higher IV settings for Bindings 2 and 3.

4 Discussion

The purpose of this two-part study aimed to quantify the amount of inter-manufacturer variability in release torque and determine specific parameters of the Tech/Pin boot-binding system that could possibly be optimized to performance of Tech boot-binding systems. Consumers perceive that Tech/Pin boot-binding systems have unreliable retention characteristics and often react by locking out the release function of their bindings. Given the amount of variation in release torque between boots shown in Fig. 2, this perception might have some merit. Lower leg injury rates stemming from an inadvertent release of a binding are slightly lower than rates associated with no-release of a binding during a fall [7]. However, both options (an inadvertent release or non-release) are considered to increase the risk of injury than if the release function of a binding adheres to international standards [8]. Furthermore, the results presented here in Fig. 2, show that indicator values marked on the Tech/Pin bindings tested did not correspond to the prescribed release torque

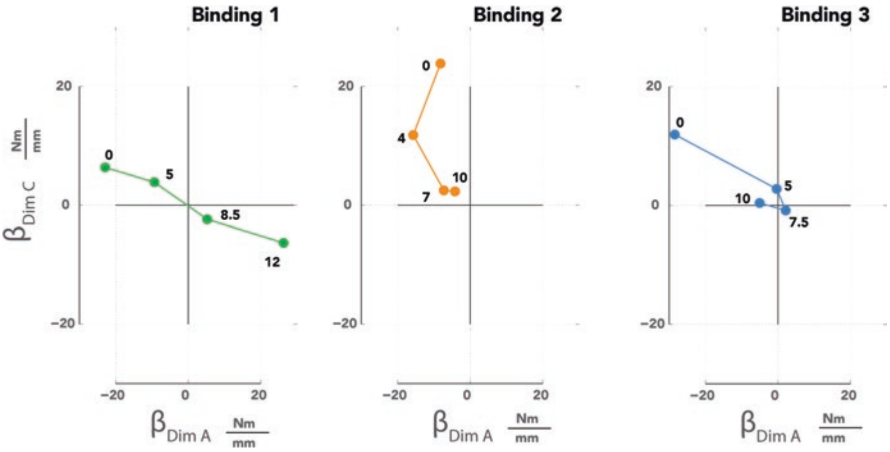

Fig. 6 The MLR coefficient β_{DimA} (x-axis) is plotted against β_{DimC} (y-axis) for each of the three bindings. The numbers aside each point indicate the corresponding Indicator Value of the binding (IV). IV = 0 indicates a test performed without the heelpiece engaged (toe piece only). Other numerical values represent the IV setting (minimum, median, or maximum) for the heelpiece of each binding

by international standards. Consumers and professional ski mechanics should refer to ski binding test devices that conform to ISO 11110:2015 to set and verify proper binding release torque to the individual skier's requirements, rather than assume the marked indicator settings will provide the appropriate release values.

Our previous companion study identified two boot measurements, Dim A and Dim C, as well as the clamping force from the binding that are strong predictors of release torque variability of the toe piece. This study has shown that while the boot parameters are still responsible for the bulk of the variability in release torque when the heelpiece of Tech/Pin bindings is engaged with the boot, the effect of these parameters changes as the indicator values on the heel are changed.

The sensitivity of each binding to differences in boot dimensions complicates an otherwise simple optimization problem due to the fact that the sensitivities themselves did change as a function of binding settings (Fig. 6). The lack of adjustability in most Tech/Pin binding toe pieces would limit the effectiveness of an optimization routine that identified values for Dim A and Dim C (among other possibilities) undertaken to reduce the amount of variation in release torque. If only boot dimensions are to be considered, one set of boot dimensions found to be optimal for lower IV settings would not be optimal for higher IV settings.

It is hypothesized that for Tech/Pin boot-binding systems to have retention-release characteristics similar to alpine ski boot-binding systems, improvement on current designs or new mechanisms for the toe piece will be necessary. There are currently two models of Tech/Pin bindings that utilize different mechanisms than the majority of bindings that incorporate indicator settings into the toe piece as well as the heelpiece. These designs are new do not have significant market share, and one of them utilizes different heel inserts than other bindings. Therefore, they were not considered by the authors to be representative of a sample of bindings on the market, and the authors do not speculate on their performance. However, it is likely that some ability to adjust the clamping force preload of the toe piece, the release load of the toe piece, and the dynamics of the toe piece based on the corresponding heelpiece dynamics will be necessary to reduce the variation in release torque in Tech/Pin boot-binding systems.

This study has not examined the effect of material hardness or loading conditions other than a pure twisting release. It is possible that other boot dimensions and binding features studied here are critical in other release modes or loading conditions. Furthermore, it will likely be impossible to optimize these systems until reaction forces transmitted from the ski to the boot through Tech/Pin bindings is directly measured such that the functional retention-release requirements of Tech/Pin boot-binding systems is clearly defined. Future laboratory testing on this subject could include dynamic impact tests to elucidate how the variables explored in our current study behave under dynamic loads of varying frequency and magnitude.

The mating interface geometry between alpine boots and bindings were homogenized by international standards in the 1980s; in turn, this normalized the retention/release characteristics. As a result, any alpine ski boot conforming to ISO 5355:2006 [9] from any manufacturer can be used with any alpine binding conforming to ISO 9462:2006 [3] from any manufacturer, without sacrificing retention/release performance. The results presented here show that retention/release characteristics of the Tech/Pin bindings tested, one of which was certified to ISO 13992:2014 by the Technischer Überwachungsverein, or TÜV, vary widely depending on which specific boot is being used and that Tech/Pin boot-binding systems do not provide the same retention/release characteristics as their Alpine boot-binding counterparts.

5 Conclusion

In summary, Tech/Pin boot-binding systems have variations in release torque that exceed the minimum-maximum allowable release envelope prescribed by international standards. These variations stem from using boots from different manufacturers in a given binding. The indicator settings in these bindings do not change the release torque at the same proportional rate as other AT and alpine ski equipment. Skiers should not assume that Tech/Pin bindings will provide the same retention-release characteristics as alpine ski equipment, nor that the numerical indicator settings on alpine bindings are equivalent to Tech/Pin bindings. Homogenizing boot geometry would reduce the amount of variation in release torque from these boot-binding systems, but would not eliminate the problem completely, and could exacerbate the problems for users on one far end of the binding setting scale or the other.

Appendix A: Statistical Tables

Table A.1 Percent relative contribution and the 95% CIs [LL, UL] of boot-binding constraints to release torque variation for pure twist releases

	Config	Clamping force	DimA	DimC	DimA|DimC
Binding 1	C1	15.7% [14.35, 18.83]	33.2% [28.2, 40.2]	39.2% [32.9, 48.0]	3.1% [0.1, 10.1]
	C2	18.7% [11.8, 29.0]	13.1% [10.3, 17.6]	41.8% [31.1, 53.6]	15.3% [5.5, 29.5]
	C3	23.7% [10.9, 40.8]	12.7% [7.1, 22.0]	13.0% [3.5, 28.2]	28.0% [9.2, 50.9]
	C4	4.5% [3.2,13.8]	24.9% [13.6, 41.6]	15.9% [8.7, 28.8]	33.4% [15.7, 54.7]
Binding 2	C1	27.0% [22.7, 32.4]	14.6% [14.1, 15.4]	57.0% [51.2, 61.8]	0% [0, 0]
	C2	18.5% [13.8, 24.4]	14.7% [13.7, 16.9]	63.8% [58.2, 70.1]	0% [0, 0]
	C3	43.5% [33.7,57.1]	32.3% [25.6, 43.6]	9.5% [5.7, 19.6]	0% [0, 0]
	C4	53.0% [46.8, 60.0]	31.8% [27.6, 38.3]	9.1% [6.8, 15]	0% [0, 0]
Binding 3	C1	7.8% [6.6,10.5]	19.3% [18.3, 21.6]	65.4% [61.7, 69.8]	0% [0, 0]
	C2	5.8% [4.5, 9.8]	24.0% [19.6, 30.0]	53.2% [45.4, 60.3]	10.2% [3.9, 19.1]
	C3	17.6% [10.8, 26.5]	7.9% [5.0, 12.3]	2.2% [1.4, 5.8]	65.0% [54.7, 76.8]
	C4	14.8% [8.2, 26.0]	20.3% [13.2, 29.7]	6.0% [3.3, 11.7]	47.7% [33.3, 63.9]

Table A.2 Linear regression of indicator values on release torque for test configurations 2–3 corresponding to tests with the heelpiece settings at the minimum, median, and maximum indicator values. One linear regression was performed for each binding model tested. The reference slope of the indicator value-release torque curve prescribed by ISO 13992:2006 is 10 Nm/IV

Binding	Slope (Nm/IV)	F		Mult. R^2	Adj. R^2	p
1	3.54	$F(1,58)$	374	0.8657	0.8634	<0.001
2	5.59	$F(1,46)$	138.3	0.7504	0.745	<0.001
3	8.47	$F(1,58)$	284.2	0.8305	0.8276	<0.001

Table A.3 MLR metrics with standardized coefficients

		β_n						
	Config	Interc.	β_F	β_{DimA}	β_{DimC}	$\beta_{\text{DimA\|DimC}}$	Adj. R^2	p
Binding 1	C1	0.00	0.12	1.02	1.83	0.00	0.90	<0.001
	C2	0.39	−0.24	2.31	2.13	0.47	0.91	<0.001
	C3	0.92	0.24	0.11	−0.24	1.10	0.90	<0.001
	C4	0.77	0.45	−0.85	−0.69	0.92	0.84	<0.001
Binding 2	C1	−0.20	0.44	−0.79	0.66	−0.24	0.88	<0.001
	C2	−0.46	1.37	−0.61	1.41	−0.55	0.84	<0.001
	C3	−0.62	1.63	−2.37	−0.89	−0.74	0.68	0.003
	C4	−0.65	0.15	0.18	−0.06	−0.77	0.70	0.002
Binding 3	C1	0.00	0.92	−0.07	1.07	0.00	0.98	<0.001
	C2	0.00	0.80	−0.14	1.08	0.00	0.96	<0.001
	C3	0.00	2.02	−2.17	−0.24	0.00	0.80	0.001
	C4	0.00	2.15	−2.17	−0.23	0.00	0.92	<0.001

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Special Design of Ski Plates May Improve Skiing Safety

Matej Supej and Veit Senner

Abstract Background: Alpine skiing is a popular winter sport that is confronted with high injury rates. Ski bindings are often mounted on ski plates, which can positively affect the release consistency of ski bindings and thus improve skiing safety. The aim of the study was to explore, if a new ski plate design of which the middle main part was "floating" on rocker arms improved the release consistency of ski bindings when the ski was deflected.

Method: In order to test the new ski plate, three pairs of equal slalom skis were equipped with identical ski bindings. They were mounted: (1) directly to the ski, (2) on the original ski plate, and (3) on the new ski plate. The forward bending release and the torsion release behaviour of these three ski-plate-binding set-ups were tested on a standardized testing device under three conditions: a flat ski, ski-deflection according to the ISO-standard and an extreme ski-deflection.

Results: One-way ANOVA with Tukey post hoc test revealed that all comparisons among different mountings of the binding under three conditions, except in three occurrences when comparing no plate versus new plate, were significantly different. In addition, the new ski plate demonstrated a more consistent torsion release behaviour with almost no shift in the release load (~ −1.5%) for both tested ski-deflections. The majority of relative differences ranged between 6.9 and 8.2% between the three tested mounting conditions with respect to the forward release.

Conclusion: Mounting ski bindings on specially designed ski plates may result in an improved release behaviour and thus potentially increase skiing safety.

Keywords Alpine skiing • Ski plates • Ski bindings • Injury prevention • Tibia fractures

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1 Introduction

Alpine skiing is a popular outdoor winter sport in many countries with approximately 400 million skier visits worldwide [1]. In competitive alpine skiing, skiers, on the one hand, strive to optimize their skiing by optimizing several different mechanical predictors such as time, speed, turn radius and energy dissipation [2–4]. Several of these parameters are, on the other hand, recognized as major risk factors for injuries in competitive skiing [5–8]. It is therefore no surprise that injury rates for competitors are very high [9].

The injury rates are very high also in recreational alpine skiing with a range from 2.4 to 7.0 injuries per 1000 activity days [10]. Alpine skiing was stated to be "the riskiest sport undertaken by adults on a routine basis" [11]. Both, in competitive as well as in recreational skiing the highest rate of injuries is connected to the knee joint [12–14]. The injury rate in the knee joint remains at a high level since the mid-nineties [15], only the MCL (medial collateral ligament)-knee injuries seem to have slightly decreased over the 18 investigated seasons [16]. The reduced ski length generally explains this levelling-off since the introduction of carving skis [15, 17].

With the background of this unchanged high knee injury rate a recent study investigated the potential role of the ski-binding-boot functional unit to decrease the injury risk of lower extremities [18]. It concluded that the biggest potential to decrease the injury rate was to develop more sophisticated safety release bindings, i.e. introducing a mechatronic design. Among others, it was pointed out that the reduction in the influence of constraining forces on the release behaviour of the bindings could be achieved by the intervention in the appropriate design of sliding elements and bearings.

In order to explain the relationship between the inadvertent release and no release when necessary, a Signal Detection Theory (SDT) has been introduced [19]. SDT describes normal load (NL) and injury load (IL). The NL represents the area when no release is needed and the IL when the release is needed. In addition, there is also a probability when (1) a failure to release and (2) the inadvertent release appears. In general, these two probabilities are desired to be as small as possible in order to yield safer bindings for a target population group. Therefore, any attempt that can help providing a decrease in the inadvertent release without affecting the appropriate release is considered beneficial for skiing safety.

Ski plates have been primarily propagated to influence a bending line and the damping behaviour of the ski as well as the boot-out at large ski inclinations [18]. Recently, a platform for mounting the binding on a ski (Allflex plate, Allflex ski and snowboard plates, Slovenia) with a unique patented construction [20] has been introduced to the market. It has been designed in such a way that the middle rigid part holding the ski bindings is connected to the ski with two rigidly anchored vertical rocker arms at the front and at the back as well as two horizontal rocker arms in the middle of the plate (Fig. 1). Vertical rocker arms at the front and at the back function as compensatory parts, cancelling the shortening of the ski's upper surface when the ski is deflected. The two double horizontal rocker arms in the middle part

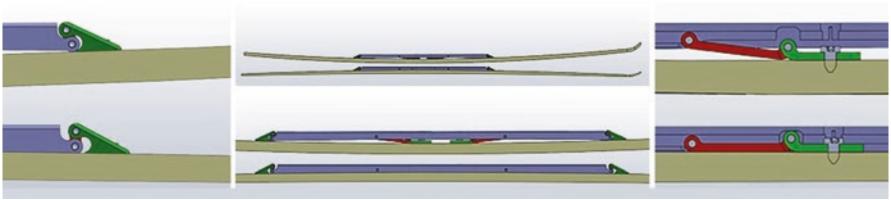

Fig. 1 A new ski plate (*middle*) with two vertical rocker arms at the front and at the back (*left*) as well as two horizontal rocker arms in the middle (*right*). In all parts of the figure, the bottom drawing represents a plate mounted on an unloaded ski (stretched ski) and the top one mounted on ski which is loaded and consequently deflected

act synchronously with the vertical rocker arms and avoid moving the middle rigid part of the plate forward and backward along the skis. This construction of ski plate intends to decrease the constrained forces on the ski binding when the ski is deflected and should—according to the SDT theory—improve the release behaviour [19, 21].

Therefore, the aim of this study was to explore, if the new ski plate design where the middle main part of the plate was "floating" on rocker arms, improved the release consistency of ski bindings when the ski was deflected.

2 Methods

An alpine ski binding should fulfil two main functions. It should ensure a firm connection between the ski boot and the ski and release the ski if there is an excessive load that could potentially cause an injury to the leg. In practice, the ski binding is exposed to three-moment and three-force components. Ideally, the ski bindings should have a release mechanism that can be triggered by any of these mechanical parameters at excessive (injury level) loads [18]. The official requirements and test methods for the ski bindings are described by the International Standardization Organization (ISO) under the ISO 9462:2014 standard.

In order to test the new ski plate, three pairs of equal Elan Slalom skis (Race SLX World Cup M52, length 165 cm—FIS approved) selected based on their mechanical properties (<1 mm tolerance in camber height of the unloaded ski and <3% difference in the ski-deflection distance in as standard bending test with 300 N applied force) were equipped with the identical Elan (ER 17.0 Free Flex PRO) ski bindings. The bindings were mounted in three different ways (Fig. 2):

- Directly to the ski without any additional ski plate (no plate)
- On the (supplemental) "original ski plate" (Tyrolia Raceplate RDX)
- On the "new ski plate" (Allflex plate)

The new ski plate was considerable differed from the original ski plate and consisted of two pieces per ski. Each piece of the original plate was on a distal side fixed by using a screw over the oblong hole. This allowed movements/flexibility of the ski under the plate as it is common in "classic" plate designs.

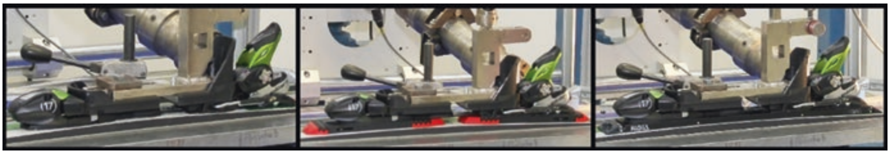

Fig. 2 The bindings mounted directly to the ski without any additional ski plate (*left*), on the original ski plate (Tyrolia Raceplate RDX; *middle*) and on the new ski plate (Allflex plate; *right*)

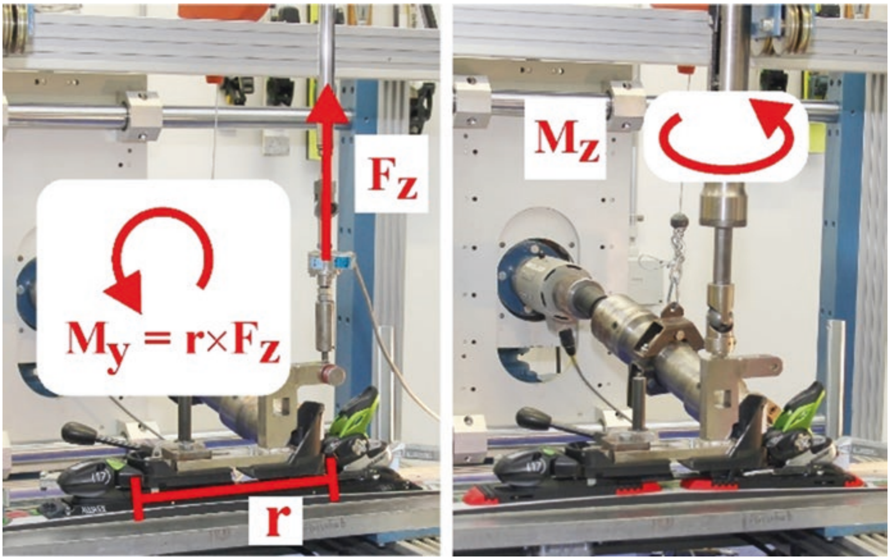

Fig. 3 The forward bending release (*left*) and torsion release (*right*) test on an ISO 9462 Method A testing device at TÜV Product Service GmbH, Munich, with a ski clamped to the ground (flat ski). *Fz* vertical force; *r* lever (sole length); *My* forward bending release torque; *Mz* torsion release torque

In order to smooth the bearings to run the systems at minimum friction, these three ski-plate-binding set-ups were skied 5 days for 10–15 runs by a ski tester, former member of the Slovenia Alpine Ski Demo Team prior to the release behaviour tests.

The release behaviours were tested on a standardized testing device (TÜV Product Service GmbH, Munich, Germany; Fig. 3), where the ski was rigidly connected to the test frame and the quasi-static torque or force were progressively applied to the sole until the binding released (Test Method A, ISO 9462:2014). First, the release values on all ski-plate-binding set-ups were set to the same value ($Z = 8$) according the standard on the bindings scale. Thereafter, the reference values were verified and adjusted by a series of tests on a flat ski according to the standard procedure in order to achieve the same “true” initial settings for all ski bindings. Thereafter, two tests were performed (Fig. 3):

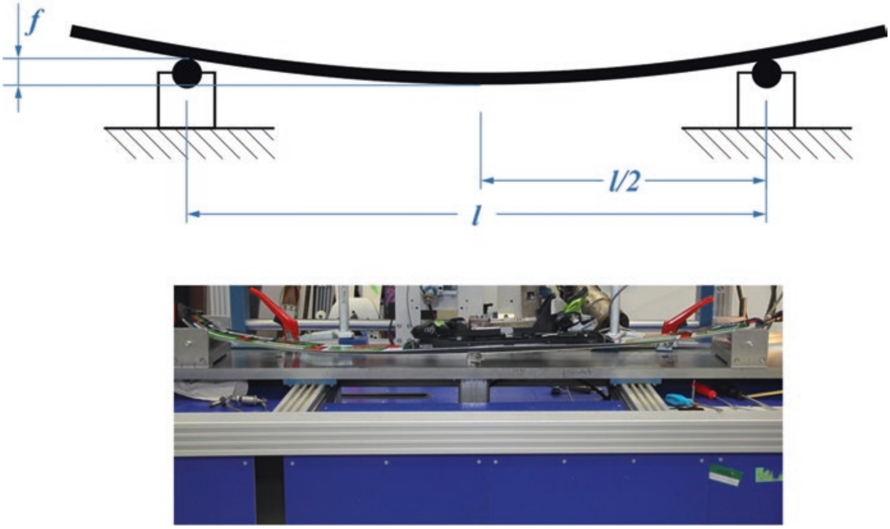

Fig. 4 ISO 9462 Method A testing device (TÜV), during a modified forward bending release test with standard ski-deflection of the ski equipped with the new ski plate (*bottom*) and the corresponding scheme of the support and deflection distance (*top*). *l*, distance between the supports; *f*, deflection distance

1. A modified “forward bending release test”: applying vertical force Fz at the heel part of the binding resulting in a combined loading of torque My about the horizontal (medio-lateral) axis and a vertical (upright directed) force
2. The ISO compliant standard “torsion release test”: applying the torque Mz about the vertical axis

The reason for the modified ISO forward bending release test (note that in the ISO 9462 procedure, only pure moments without any extraneous forces have to be applied) was that this was expected to be the worst-case scenario for the new plate. The vertical force in this test pulled the plate away from the ski under such loading.

Both tests were conducted under three conditions:

1. A flat ski (clamped and thus pressed to the ground; zero deflection)
2. The standard ISO ski-deflection (a distance between the supports of 150 cm and a deflection of 6 cm; Fig. 4)
3. An extreme ski-deflection (a distance between the supports of 110 cm and a deflection of 6 cm; Fig. 4)

Each test was repeated until three consecutive measurements with equivalent release values were achieved. Only consistent tests were used for further analysis. In practice, no more than one additional “pre-test” was necessary to yield consistency. Consistency was visually judged from the measurement curves that were plotted one over another in real time.

The vertical force and the heel displacement were recorded for the forward bending release. In the torsion release test, the torque and the toe piece angle were recorded. The vertical force and the lever of 0.31 m (sole length) were used to calculate the present forward bending torque (My) as shown on Fig. 3. For both torque parameters, peak values were calculated in each test. In addition, the tests were alternatively recorded at high speed (200 Hz) or Full High definition (50 Hz) video recording for visual inspection.

Results are reported as mean and standard deviations. Statistical analysis was performed by one-way Analysis of variance (ANOVA), followed by multiple-comparison Tukey post hoc test. The level of statistical significance was set to $p < 0.05$. Data were analysed in Matlab 7.5 software environment (MathWorks, Natick, MA, USA).

3 Results

3.1 Forward Release

The binding's releases occurred at the peak force values (Fz) in force–displacement data (forward bending release) for the three different mountings of bindings at three different deflection conditions. The descriptive statistic along with one-way ANOVA and Tukey's post hoc test for the release values are presented in Table 1. The mean Fz values ranged from 1019.6 N (flat ski, original plate) to 1114.7 N (ISO-standard deflection, no plate) with standard deviation ranging from 0.6 N to 2.9 N. The analysis of variance revealed significant effect of mounting types (no plate, original and new plate) on forward bending release. Post hoc comparison using Tukey's test indicated that the mean score among all pairs, except no plate versus new plate under flat ski and extreme-deflection conditions, were significantly different.

The relative differences (mean and standard deviation) between the peak My values for the flexed versus the flat ski are presented in Fig. 5. The observed mean differences range from 6.9 to 8.1% for the standard ISO ski-deflection and from 3.3 to 8.2% for the extreme ski-deflection.

With an increase in the release load being less than 9% for all three mounting conditions and for both ski-deflections, it becomes obvious that neither the first nor the second variables are of major importance for the release characteristics of the binding tested. This interpretation is supported by the fact that a deviation of up to 15% in the release load is accepted in all corresponding ISO standards in the official retailer setting procedures ("inspection tolerance"). It is interesting to see in Fig. 5 that the best performance (lowest difference compared to the test condition "flat") is shown for the binding mounted without any plate under the extreme bending condition.

Table 1 Comparison between mean values of forward bending release (My) and torsion release (Mz) under three different deflection conditions for three different mountings of the binding

Test	Deflection condition	No plate $n = 3$	Original plate $n = 3$	New plate $n = 3$	F	p	Tukey post hoc
My (Nm)	Flat ski	319.64 (0.18)	316.01 (0.41)	320.91 (0.9)	56.53	<0.001	1,3
	ISO	345.56 (0.87)	337.89 (0.61)	344.99 (0.55)	115.13	<0.001	1,3
	Extreme	330.15 (0.32)	341.81 (0.64)	344.31 (0.56)	617.49	<0.001	1,2,3
Mz (Nm)	Flat ski	79.46 (0.37)	80.69 (0.38)	82.89 (0.24)	78.59	<0.001	1,2,3
	ISO	80.27 (0.12)	87.17 (0.25)	81.59 (0.3)	736.63	<0.001	1,2,3
	Extreme	81.62 (0.38)	85.45 (0.06)	81.62 (0.16)	252.62	<0.001	1,3

Means and standard deviations (in parentheses), ANOVA results and significant differences based on Tukey's post hoc analysis. n = sample size; F = ANOVA F-statistics; p = level of significance for ANOVA; ISO = ISO deflection condition (150 cm); Extreme = extreme-deflection condition (110 cm); Significant differences based on Tukey post hoc test between the three mounting conditions are indicated by numbers: 1 = no plate versus original plate; 2 = no plate versus new plate; 3 = original plate versus new plate

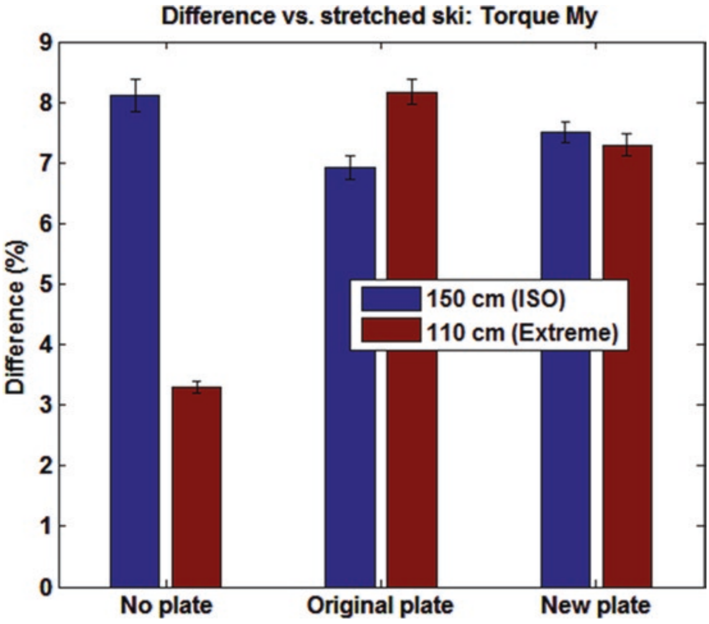

Fig. 5 Mean relative difference (ski-deflected versus stretched ski) in peak My torque values for the binding mounted directly on the ski (no plate), on the original and on the new ski plate under the two testing conditions: ISO-standard ski-deflection (a support distance of 150 cm) and an extreme ski-deflection (a support distance of 110 cm). The error bars represent standard deviations

3.2 Torsion Release

Similarly as in forward bending release test, the binding's torsion releases occurred at the peak torque values (Mz) in torque-angle data (forward bending release) for the three different mountings of bindings at three different deflection conditions. The descriptive statistic along with one-way ANOVA and Tukey's post hoc test for the torque release values are also presented in Table 1. The mean Mz values ranged from 79.46 Nm (flat ski, no plate) to 87.17 Nm (ISO-standard deflection, original plate) with standard deviation ranging from 0.06 to 0.39 Nm. The analysis of variance revealed significant effect of the mounting condition (no plate, original and new plate) on torsion release. Post hoc comparison using Tukey's test indicated that the mean score among all pairs, except no plate versus new plate under extreme-deflection condition, were significantly different.

The relative differences (mean and standard deviation) between the peak Mz values for the deflected versus the flat ski are presented in Fig. 6. The observed mean differences range from −1.6 to +8.0% in the standard ISO ski-deflection, while they range from −1.5 to +5.9% for the extreme ski-deflection. The relative peak difference was overall highest for the original plate in both testing conditions and lowest for the new ski plate.

4 Discussion

The main findings of the study are that the new designed ski plate, where the middle main part of the plate is "floating" on rocker arms, (1) improves the torsion release consistency of the ski binding when the ski is deflected, and (2) has no positive effect on the forward release.

The study examined an effect of the specially designed "Allflex" ski plate on the release behaviour of an *Elan ER 17.0 Free Flex PRO* ski binding. In order to elucidate the effect, the mounting of the ski bindings on the above-mentioned plate was compared to the mounting without any additional ski plate and to the mounting on the original supplemented ski plate. For this purpose, an ISO-standard loading device for testing ski bindings release was used. Three ski-deflection conditions (1) flat ski, (2) ski deflected according to ISO 9462:2014, and (3) ski-deflection exceeding the ISO condition were distinguished.

All three different ski binding mounting conditions resulted in release values which remained within the tolerances given by the ISO-standard for both release tests. This also holds true for the extreme deflected ski test condition, which is not a part of the ISO-standard. Despite that, one-way ANOVA with Tukey post hoc test (Table 1) revealed that all comparisons among different mountings of the binding under three conditions, except no plate versus new ski plate in forward bending release (ISO and extreme-deflection) and in torsion release (extreme ski-deflection), were significantly different from each other. These results should be interpreted that

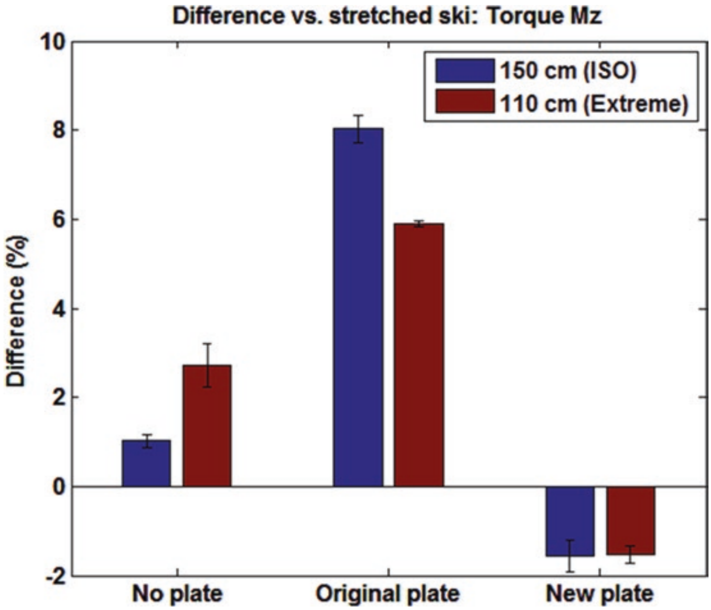

Fig. 6 Mean relative difference (ski-deflected versus flat ski) in peak torque Mz values for the binding mounted directly on the ski (no plate), on the original and on the new plate under the two testing conditions: ISO-standard ski-deflection (a support distance of 150 cm) and an extreme ski-deflection (a support distance of 110 cm). The error bars represent standard deviations

bindings in the same conditions (mounting and deflection) behaved very consistently, i.e. with small variance.

Despite the procedure of adjusting the bindings' releases by a series of test, significant differences in the baseline were observed, i.e. comparing the release values when the ski was set flat on the ground on both tests (Table 1). However, these differences were small, <5 Nm in forward bending and <3.5 Nm in torsion release, which is in the range of possible manipulation in the manual settings. Still, the differences in the baseline may influence the interpretation of the results comparing release consistency among mounting types. For this reason, relative differences between the releases values for the flexed versus the flat ski were more intensely analysed (Figs. 5 and 6) and some important differences between the mountings in the results were observed, especially with respect to the torsion release.

Torsion release under both, ISO and extreme-deflection, was very consistent with the binding mounted on the new ski plate, showing a negligible reduction of ~ − 1.5% compared to the flat condition. Interestingly, mounting directly on the ski was the second most consistent and superior to the mounting on the original (supplemented) ski plate. This result demonstrated that the ski plate may either improve or even spoil the release consistency.

Even though the detected improvements in relative torsion release consistency of bindings mounted on the new plate design were small, they still can be interpreted as a contribution to binding safety. As severe combined loading conditions were not tested in the current study, i.e. ski being deflected and at the same time twisted about its longitudinal axis (due to edging moment or "roll loading"), the safety gain by the new plate design might even be higher.

Based on the message of the Signal Detection Theory [19, 21], an increase in release consistency can be interpreted as a decrease in the probability of both inadvertent and also of the false release under the condition that the binding settings are appropriate [18]. This finding regarding the torsion release is of great importance because it is known that in both, recreational as well as competitive skiing, the largest number of injuries is related to the lower extremities, particularly to the knee joint [12–14]. For the knee joint it was found that both, internal and external rotations of the ski, are associated with knee injury mechanisms [22–24].

Even though all three mountings of the bindings under the ISO-standard deflection condition in forward bending release test demonstrated almost identical relative differences, their absolute values in most cases differed significantly. In contrast to torsion release, the specially designed ski plate did not improve the forward bending release consistency to a meaningful magnitude compared to other two types of mountings. A video analysis of the release behaviour revealed that the (upward directed) Fz vertical force (during forward bending release) caused to bend and stretch the middle floating part of the new ski plate away from the ski. This observation was in line with the fact that the set-up used in the current study with pulling at the heel does not adequately simulate typical real situation in skiing, as it neglects the body weight component. This however is also true for the test procedure according to ISO 9462:2014 (section 6.3.3). It is not well known even among experts that this release test with ski under deflection contains a rather critical simplification, which might significantly change the behaviour of the system. In real skiing, the force that deflects the ski is applied through the boot to the binding and then to the ski, whereas in the current ISO test, the deflection of the ski is forced *"… by a strap or clamp, which does not interfere with the binding*" (ISO 9462:2014, section 6.3.3.2 Testing). To the authors' knowledge, there is still no standard test procedure available offering satisfactory external validity.

Interestingly, the mounting of the binding with its own inbuilt "Free Flex system" directly on the ski outperformed the other two in an extreme-deflection condition. This indicates that adding ski plates does not necessarily improve the overall release behaviour. Even more, the overall results (relative differences) for the bindings mounted on the original plate were less consistent compared to the mounting directly on the ski.

The main limitation of the study was that only one type of skis, namely, Elan slalom skis, were used for all three mountings of the ski bindings in the testing protocol. It can be expected that at least the forward bending release could be dependent on the skis' longitudinal stiffness. This means that a less longitudinally stiff ski may flex more when the Fz vertical force is applied (forward bending release) compared to a stiffer ski and thus alter the results. However, the difference can be estimated as small, if not negligible according to the fixation of the ski in the testing procedure (see Fig. 4). Hence, possible effect of the small differences in the selected skis for the current study can be concluded to be even smaller. In addition, one type of ski bindings was used for tests, and it is possible that other binding models and/or brands may behave differently. However, these bindings are a standard set together with the skis used in the current study.

Another limitation of the study was the problems of drawing conclusions based on laboratory tests when compared to real skiing situations where numerous factors may play a role and very different injury mechanisms are possible [6, 18, 25–27]. Nevertheless, a state-of-the-art measuring and testing device at an experienced and certified test house was employed for the experiment to ensure reliable and valid measurements.

The test protocol in this study did not investigate the effect of combined loads, which may be present in case of a twisted forward fall. For that reason ISO 9462: 2014 foresees a release test under combined loading (section 6.3.4). According to this standard, the influence of a forward lean of the body should not exceed 35%, the influence of a backward lean no more than 25%, the influence of a "roll loading" no more than 20% and the influence of an axial force no more than 15% of the reference value (a single axis loading condition). Interestingly, these ISO tests for combined loads are not united with those tests for the ski under deflection. In practice however, this situation may occur, for instance when a skier runs into a bump falling forward with a rotational component and the ski being strongly flexed at the same time. It is very likely that the new ski plate might demonstrate its additional safety margin under such extreme (but not rare) conditions.

In conclusion, mounting of ski bindings on specially designed ski plates may result in an improved release behaviour and thus potentially increase skiing safety. However, it should be noted that optimizing the consistency of one type of the release behaviour does not necessarily improve the overall ski bindings release behaviour. Even more, mounting of ski bindings on the ski plates can even decrease the release consistency (and skiing safety) as it was the case with the original (supplemented) ski plate. We suggest caution to skiers when combining different brands and types of skis, ski plates and ski bindings in order to avoid compromising skiing safety.

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Self-Release of Ski Bindings: A Sex Comparison

Markus Posch, Gerhard Ruedl, Robert Eberle, and Martin Burtscher

Abstract Background: Among recreational skiers, ACL injury risk is about three times greater in females compared to males and female skiers suffering from ACL injury reported about 20% points more frequently a failure of binding to release compared to male skiers with an ACL injury. Performing a daily self-release test of ski bindings, however, can prevent skiing-related injuries of the lower extremity.

Aim: To evaluate to what extent uninjured male and female skiers are able to self-release their ski bindings which were recently adjusted to the ISO 11088 standard.

Methods: A total of 15 male and 15 female healthy and physically active young adults with a mean age of 23.0 ± 1.7 years and without any previous injury of the lower extremities participated in this study. Subjects had to perform an isometric leg test and the self-release test of ski bindings with both legs on a Kistler force plate. For each attempt to release the binding, torques calculated via the force plate were normalized to torques calculated by a binding adjustment system (Relative Release Torques—RRT) and represented by percentage values.

Results: Sexes significantly differ regarding body mass and BMI, but not regarding relative maximum isometric leg strength. Eleven out of the 15 male subjects (73%) and three out of the 15 female (20%) subjects released their ski bindings at least once with both legs. Regarding a total of 90 self-release trials among each sex (3 trials × 2 legs × 15 subjects), failure of binding release was significantly higher among female compared to male trials (84 vs. 54%, $p < 0.01$). The mean relative release torques (RRT) of the 76 female trials of failure of binding release were significantly lower compared to the 49 male trials of failure of binding release (40.9 ± 20.2 vs. 50.6 ± 20.1%, $p = 0.009$).

Conclusion: Three times more females than males were unable to self-release their ski bindings although their bindings were correctly adjusted according to the ISO 11088 standard for binding setting values. In addition, females reached about 20% lower RRT values within failure of binding release trials although males and females did not differ with regard to relative isometric leg strength.

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Keywords Ski binding release • Self-release test • Alpine skiing • Prevention • Knee injury

1 Introduction

Recreational alpine skiing is one of the most popular winter sports annually enjoyed by several 100 million skiers worldwide [1, 2]. Despite the large number of skiers, the currently calculated injury rate in Austria is less than one injury per 1000 skier days [3]. The knee joint represents the most commonly injured body part accounting for about one-third of all injuries in recreational skiers, however with a distinctive difference between sexes [3–5]. Female recreational skiers have twice the knee injury prevalence of male skiers and the ACL injury risk is three times greater in female skiers [4–6]. This sex difference of knee injuries among recreational alpine skiers may be partly related to hormonal, anatomical, and/or neuromuscular risk factors which distinguish females from males [7, 8]. Another decisive sex difference among knee-injured skiers concerns the amount of failure of binding to release at the moment of accident [9–12]. For instance, a total of 55–67% male skiers reported a failure of the ski bindings to release compared to 74–88% of female skiers suffering from an ACL injury [9–12]. This difference in binding non-releases percentages occurred even though there was no difference in the date of last binding adjustment [11], whether the bindings were adjusted correctly [13], or self-reported types of falling [11, 12]. In a very recent study among a cohort of about 500 male and female recreational skiers suffering from an ACL injury, Ruedl et al. [12] showed that binding release was independently associated with forward falling with rotation. This so-called forward twisting fall [12] corresponds well with the self-release test of ski bindings where skiers try to release their bindings by an inward twist of their leg [14]. Previous studies by Ekeland et al. [15] and Jørgensen et al. [16] found that performing daily the self-release test of ski bindings can prevent skiing-related injuries of the lower extremity. Keeping in mind that female skiers with an ACL injury reported about 20% points more failures of binding to release compared to male skiers with an ACL injury, the aim of this study was to evaluate to what extent uninjured male and female skiers are able to self-release their ski bindings that were recently adjusted according to the ISO 11088 standard for binding setting values. As the ISO 11088 standard for binding setting values does not consider sex-specific differences, we hypothesized that there are no differences between male and female skiers performing the self-release test.

2 Material and Method

2.1 Subjects

A total of 15 male and 15 female healthy and physically active young adults without previous injury of the lower extremities were asked to participate in this study. Most participants were students from the Department of Sport Science in Innsbruck/Austria with an advanced skiing skill level.

The study was performed in conformity with the ethical standards of the 2008 Declaration of Helsinki. Informed written consent was obtained from all subjects prior to the beginning of this research. In addition, the study was approved by the Institutional Review Board.

2.2 Study Protocol

After subjects performed a standardized warming up, maximal isometric leg strength of both legs were tested. Then subjects had to perform three trials with each leg to release their bindings adjusted according to the ISO 11088 standard.

2.3 Ski Binding Adjustment

Each subject used his/her own skies and ski boots. The day before the tests took place the skies and ski boots were taken to a ski rental shop where the ski bindings were correctly adjusted according to the ISO 11088 standard using a Wintersteiger Speedtronic adjustment system. Release values of the bindings according to the ISO 11088 standard are determined using individual age, height, weight, skiing type, and sole length of ski boots. In addition, skiers have to differentiate between skiing speed (slow to moderate vs. fast), terrain (gentle to moderate vs. steep), and skiing style (cautious vs. aggressive) to classify themselves into one out of three skiing types. The Wintersteiger Speedtronic adjustment system then calculated the required release torques for the toe and heel piece of the ski binding.

2.4 Isometric Leg Strength Test

Prior to the isometric leg strength test all participants had to do a 7 min warming-up programme on a stationary cycle ergometer. Regarding the determination of leg dominance, subjects were asked which leg they would prefer to kick a ball. According to a study by Raschner et al. [17], participants performed three one-leg isometric leg extensions on each leg. The greater trochanter, lateral intercondylar notch, and lateral malleolus were used as landmarks to ensure that a knee angle of 100° was reached (180° = fully extended knee). The calculated strength parameters were the mean absolute leg force and the mean relative leg force which was got when dividing the absolute leg force by body weight [17].

2.5 Self-Release Test

For the self-release test of the ski binding a wooden plate was fixed on a Kistler force plate (Fig. 1). Then, the ski was fixed with metal bars on the wooden plate in a way that the participants were not able to move their skis neither in vertical nor in horizontal direction. The fixation of the ski was necessary in order to make the measured values of self-release trials comparable with the testing results of the Wintersteiger Speedtronic device. The subjects were given detailed instructions and a demonstration by the first author how to perform the self-release test by simultaneously avoiding a rotation of the hips and/or valgus position of the knee. Subjects were not allowed to practice self-releases before the testing started. In order to provide a ski-specific position all participants were told to wear both ski boots and to use their ski poles (Fig. 1). Participants tried to release the toe piece of their ski bindings by an inward twist of their foot and leg, but without an inward movement of the knee. Each leg was tested three times. For each attempt to release the binding, torques calculated via the force plate were normalized to torques calculated by the Wintersteiger binding adjustment system (Relative Release Torques—RRT) and represented by percentage values.

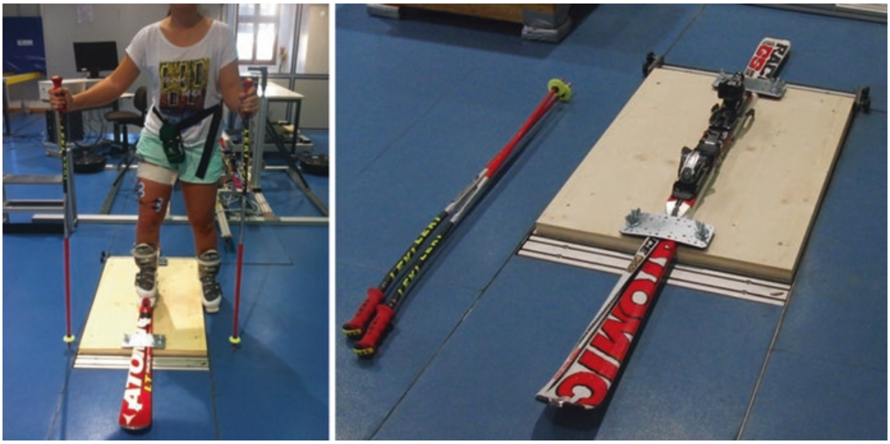

Fig. 1 Self-release test on a Kistler force plate

3 Statistics

Data are presented as means, absolute, and relative frequencies. Differences in mean age, height, weight, BMI, and dominant leg strength with regard to sex were evaluated by independent *t*-tests and Mann-Whitney *U*-tests. Differences in ski binding release frequencies were evaluated by χ^2 tests. Sex-specific differences in isometric leg strength, ski binding release torques were investigated by independent t-tests and Mann-Whitney *U*-tests. Statistical analyses were performed by the use of SPSS 23.0. All *P* values were two-tailed and values less than 0.05 were considered to indicate statistical significance.

4 Results

A total of 15 males and 15 females with a mean age of 23.0 ± 1.7 (range: 20–28) years participated in this study. With regard to leg dominance, 29 subjects reported dominance of their right leg and one subject of his left leg.

The sex comparison in Table 1 shows significant differences regarding age, height, weight, BMI, but not concerning the relative isometric leg strength of both legs.

Eleven out of the 15 male subjects (73%) and three of the 15 female subjects (20%) released their ski bindings at least once with both legs. Regarding the total of 90 trials of the self-release tests among each sex (3 trials × 2 legs × 15 subjects), failure of binding release was significantly higher among female compared to male trials (84 vs. 54%, $p < 0.01$).

Mean relative release torques of the 14 female trials of binding release did not significantly differ compared to the 41 male trials of binding release (99.0 ± 19.4 vs. 88.0 ± 26.0%, $p = 0.132$).

Mean relative release torques of the 76 female trials of failure of binding release were significantly lower compared to the 49 male trials of failure of binding release (40.9 ± 20.2 vs. 50.6 ± 20.1%, $p = 0.009$).

Table 1 Baseline characteristics of participants

	Males ($n = 15$)	Females ($n = 15$)	p value
Age [years]	23.6 ± 1.1	22.4 ± 2.0	0.017
Height [cm]	180 ± 0.1	167 ± 0.1	<0.001
Weight [kg]	77.0 ± 4.4	60.2 ± 5.6	<0.001
BMI [kg/m^2]	23.9 ± 1.9	21.6 ± 1.4	0.001
Relative isometric strength of the dominant leg [N/kg]	16.4 ± 2.5	15.0 ± 2.1	0.107
Relative isometric strength of the non-dominant leg [N/kg]	15.7 ± 2.2	14.4 ± 2.0	0.094

Data are mean values ± SD

5 Discussion

The aim of the present study was to evaluate to what extent uninjured male and female skiers are able to self-release their ski bindings that were recently adjusted according to the ISO 11088 standard for binding setting values. The main finding was that significantly more females were not able to self-release their ski bindings compared to males.

In our tests, 84% of female trials and 54% of male trials showed a failure of self-release of their ski bindings. These sex-specific values seem in line with findings observed among ACL-injured recreational skiers where 74–88% of female skiers compared to 55–67% male skiers reported a failure of binding to release [9–12]. This conformity might be somewhat surprising as the self-release test was performed in a stationary laboratory setting in contrast to the self-reported amount of failure of binding release during skiing on the slope leading to an ACL injury. However, it may become understandable considering the findings by LaPorte et al. [10] who showed that a total of 44% of lower leg injuries (50% of all tibia fractures, 44% of all MCL injuries, 47% of all complex knee sprains, and 43% of all ACL injuries) occurred at low speed or in a stationary position indicating the potential problem of ski binding release at low speed.

Relative release torques (RRT) of female and male trials of failure of binding release were about 41 and 51%, respectively, indicating a huge difference to the recommended binding setting values. In a field experiment, Scher and Mote [18] analysed forces among a cohort of 12 recreational skiers (two females, ten males) during skiing by using two six-load component dynamometers which were attached under the toe and the heel binding of the left ski. They found that the ASTM (American Society for Testing and Materials) recommended release settings were significantly higher than the forces required to ski normally on varied terrain from hard snow to soft spring snow for ten of the 12 skiers [18]. With regard to the lateral release setting at the toe, ten of the subjects skied within 67% of the current settings and could have lowered this setting by 33% without signalling for inadvertent release [18]. In addition, for inexperienced, lightweight skiers, the release setting at the toe could have been lowered by 38%. Interestingly, the only subject who fell two times and released from the ski was a female beginner skier whose measured minimum retention setting at the toe was found to be 61% of the ASTM recommended setting [18]. Scher and Mote [18] concluded from their results that forces generated during skiing depend more on a skiing style variable than on anthropometrical parameters and that, therefore, binding standards that depend on weight, height, and age cannot predict accurately the minimum retention settings for individual skiers. According to the ISO 11088 standard for binding values, skiers have to differentiate between skiing speed (slow to moderate vs. fast), terrain (gentle to moderate vs. steep), and skiing style (cautious vs. aggressive) to classify themselves into one out of three skiing types. Studies, however, found that female skiers are skiing on average at significant lower speeds compared to male skiers [13, 19] and that females, less skilled and cautious skiers perceived their actual speed as fast, moderate, and slow when skiing up to 10 km/h significantly slower compared males, more skilled skiers, and risky skiers [20]. As the ISO 11088 standard for binding setting values does not consider any sex-specific factor so far and to get more insight in needed retention settings of male and female recreational skiers, we would strongly recommend replicating the study design by Scher and Mote [18], however, aiming at comparing potential differences between males and females.

The observed RRT difference of about 20% between male and female trials of failure of binding release might be also considered when discussing the implementation of a sex factor within the ISO 11088 standard. In previous years, a lower binding setting among female skiers has been discussed by LaPorte et al. [21]. In a case-control study, they found that lower binding release values in female skiers set 15% lower than those recommended by the ISO 11088 standard would clearly reduce knee injuries in these persons. No increase in injuries from inadvertent binding release through reduced binding settings has been found [21]. However, these findings mean an association, and not definitely "cause and effect" relationship, because another study at the same time showed a decrease in ACL injury risk without reducing binding settings [22] which might be due to the introduction of the short and shaped carving skis at this time [11]. Interestingly, the ISO 11088 standard accepts a deviation of 15% between the measured release moment ("reference moment") determined according to the setting tables in ISO 8061 and ski binding settings may also be lowered by the same magnitude upon request of the skier [23]. However, this fact is generally unknown in the overall skier population, but could represent a potential preventive measure, especially for female recreational skiers.

A study by Werner and Willis [14] found that muscle strength is highly correlated with the ability to release the binding in a self-release test. Assume that a male and a female skier of equal age, height, weight, and ski boot sole length classified themselves as type-3 skier (fast speed, steep terrain, aggressive style). They both would get the same binding setting values without considering sex. With regard to the equal weight of the male and female skier in the mentioned example, it has to be considered that the weight-to-strength ratio is negatively influenced by the higher fat mass in females [24] may be partly explaining the sex difference within the lack of binding release among ACL-injured recreational skiers due to less muscular strength among females. Participants of the present study were young healthy and physically active males and females. Although sexes significantly differ regarding body mass and BMI, no significant differences were detected within relative maximum isometric leg strength when normalized by body weight. Therefore, one would assume that both sexes are able to self-release their bindings to the same amount.

As performing the self-release test seems to prevent skiing injuries [15, 16], male and female skiers should be able to self-release their ski bindings to the same extent, if their bindings are correctly adjusted according to the ISO 11088 standard. However, compared to about 70% of males only one fifth of females in this study were able to self-release their ski bindings with both legs. Therefore, the question arises whether a lowering of the binding settings for females by, e.g. 15% would be relevant in order to decrease the risk of female knee injuries without an increase of inadvertent releases. However, to answer this question, more research in laboratory as well in field settings is needed.