Use And Applications Of The F504 Tester In Existing And Emerging Ski Technologies

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USE AND APPLICATIONS OF THE F504 TESTER IN EXISTING AND EMERGING SKI TECHNOLOGIES

A Thesis Presented

by

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ABSTRACT

Skiing injuries to the lower leg have drastically decreased since the 1970's. This is largely due to standardization around the release and retention characteristics of recreational ski bindings. The 504 tester, developed by Carl Ettlinger, exists in the University of Vermont's Ski Safety Laboratory and presents itself as a useful tool for quantifying the release and retention characteristics of ski bindings and helps to quantify the risk associated with their use, particularly in terms of lower leg fractures. Although, standardization around binding release has lowered the occurrence of lower leg fractures greatly, there is an opportunity to create a performance standard to inform the release of ski bindings in preloaded scenarios, most closely resembling real-world conditions that occur on hill. Beyond this, there is an opportunity to utilize the 504's testing capabilities to investigate the release and retention characteristics in new and emerging technologies.

The purpose of this research is two-fold: contribute to a performance standard for traditional alpine bindings in preloaded scenarios and compare the behavior of traditional alpine bindings in these scenarios to new technologies such as multi-norm compatible bindings and GripWalk soles. The release and retention characteristics of traditional alpine bindings in front and rear preloaded scenarios were tested and a standard for their performance was suggested. The performance of multi-norm bindings was then tested using various ISO certified boot soles. It was found that multi-norm compatible bindings behaved differently depending on the boot sole they are paired with. Additionally, multi-norm bindings were found to have release behavior that was significantly different than that of alpine bindings. The risk of putting non-compatible GripWalk soles into alpine bindings was also quantified. It was found that this boot-binding combination puts the user at risk for an inadvertent or early release. Overall, it was found that user experience can vary greatly depending on the boot-binding combination and the recommendation remains that all boot-binding combinations be tested by a professional.

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CHAPTER 1: INTRODUCTION

1.1 History of Ski Safety

In 1970 it was reported that two-thirds of all serious skiing injuries were to the lower body, the most common of this being tibia/fibula fractures. Of those serious injuries, it was found that 75% of those were due to a binding not releasing [1]. The effort to reduce the occurrence these injuries in the mid 1970's led to the ski bindings and the standardization around them that skiers have today. At present, ski bindings have two functions: the first being to secure the skier in their ski while they maneuver and the second to release the skier when the loads transferred to the lower leg pose a risk for severe injury. From 1972 to 2006, the overall injury rate dropped by 55%, reflecting on overall occurrence of 1.9 injuries for every thousand skier visits. Injury rates for a twisting related fall dropped by 87% and injury rates for bending related falls dropped by 77%. Additionally, a 37% reduction of upper body injuries was seen [2]. Today injury due to a binding releasing too early and injury due to a binding not releasing make up only 1% of injuries respectively [3]. These injury reductions can be attributed to standardization of binding release, advancements in ski/boot/binding systems, and education of skiers to avoid high risk scenarios [4].

Although injuries to the lower leg have decreased significantly, the same 1972-2006 study found a three-fold decrease in the MDBI (mean-days-between-injury) of anterior cruciate ligament (ACL) sprains, reflecting a 268% increase in occurrence over the before mentioned time interval [2]. Modern bindings as designed were intended to protect against ankle and tibia and or fibula fractures, not knee ligament injuries [4]. The release function of bindings across groups with ACL sprains and those that were uninjured show that particular injury rate is not impacted by the release function of the binding [5]. There have been no improvements in binding technologies to reduce ACL injuries and reductions in prevalence of ACL injuries have been seen only with education of skiing technique, rather than equipment modifications [6].

1.2 Binding Release

Modern alpine ski bindings today are equipped with two spring-loaded cam systems (Figure 1), one in the toe piece and one in the heel piece. In his 2016 Dissertation conducted at the University of Washington, Campbell describes the mechanics of the release of these two cam systems [8]. In the case of a forward leaning fall, the cam mechanism in the heel releases vertically in response to the force that is produced by the anterior aspect of the lower leg against the top of the ski boot, F_X^{Skier}. In the case of a twisting fall, the cam mechanism releases laterally as result of the force created by the toe edge of the boot (Figure 2).

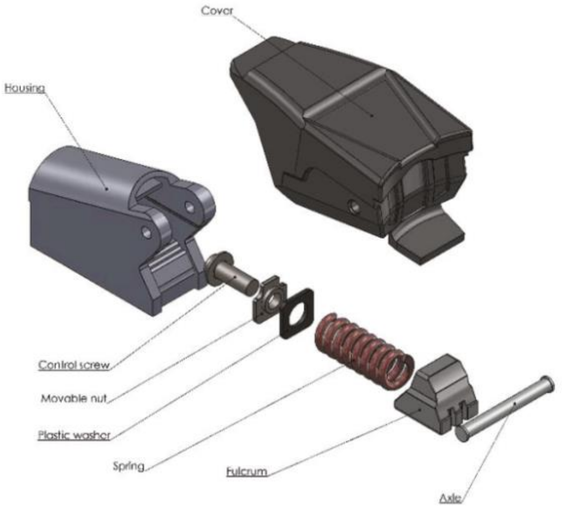

Figure 1: 3D model design of binding heel piece spring loaded cam system created by Jeli et al. [7]

The force produced by each cam mechanism, $F_Z^{Heel,Binding}$ or $F_Y^{Toe,Binding}$, for a forward or twisting release respectively is a function of the spring constant, k, the cam profile, and the preload applied to the spring, δ^{IV}.

Figure 2: Traditional modern alpine bindings release laterally at the toe (a) or vertically at the heel (b)

Campbell then continues to define the sum of the moments producing a bending moment in a forward leaning fall as,

$$\boldsymbol{\sum M_Y = M_Y^{Binding} + M_Y^{Tibia}\ where,} \tag{1}$$
$$M_Y^{Tibia} = F_X^{Skier} L_{Boot}\ and\ M_Y^{Binding} = F_Z^{Heel,Binding} L^{Heel}$$

Where L_{Boot} represents the height of the boot from the base of the ski and L^{heel} represents the distance to the heelpiece along the length of the ski from the tibial long axis of rotation. In a twisting fall, the sum of the moments can be defined as,

$$\sum \boldsymbol{M_Z} = \boldsymbol{M_Z^{Binding}} + \boldsymbol{M_Z^{Tibia}}\ \boldsymbol{where,} \tag{2}$$

$$M_Z^{Tibia} = F_Y^{Toe} L^{Toe}\ and\ M_Z^{Binding} = F_Y^{Toe,Binding} L^{Toe}$$

Where L^{Toe} represents the distance of the toe piece along the ski from the tibial axis.

In Ettlinger's 1970 thesis, he proposes a threshold where bindings should release the skier when M_Y and M_Z are greater than the torque required to break a bone while bindings should retain the skier if the torques are lower than those required to successfully maneuver the skis [1]. The lower constraint of the threshold, or the torque required to successfully maneuver the skis without an early, or inadvertent release, later become what is now referred to as the minimum retention requirement (MRR). In his thesis Ettlinger found skier weight, the proximal width of the tibia, skier ability, and age to be predictors of the MRR of ski bindings. Ettlinger also found that the effects of icing, moisture, wear and corrosion impacted the bindings release torque [1]. A few years later, ASTM F939, Standard Practice for Selection of Release Torque Values for Alpine Ski Bindings, was adopted using the MRR method. In contrast to the work by Ettlinger, research by Sher and Mote in 2000 found that skier age, height, and ability were not sufficient predictors of MRR. In their research it was found that the ASTM F939 standards for binding MRR allowed forces that far exceed those needed to safely maneuver the skis [10].

Nevertheless, current standards ASTM F939 and ISO 8061 employ the MRR method for recommend release torque values based on weight, height, age, and skier ability. The standard ISO 9462:2014 specifies the test method for measuring release torque of alpine bindings and correlates release values to Z-values [11]. The Z-scale corresponds to the printed numeric values on the heel and toe piece of the binding that indicate the amount of preload applied to the spring in the cam mechanism, δ^{IV} . The Z-value is also commonly referred to as the Indicator Value (IV).

In addition to the guidance provided in ISO 9462:2014 most ski manufacturers provide a chart to ski shops with recommended release and IV values based on skier type, skier height, weight, boot sole length, and ability. Skier ability is defined in ASTM F939 and ISO 11088 and split into three categories: Type 1 is considered beginner; Type 2 intermediate; and Type 3 advanced [12]. The combination of height and weight inform what is called a “skier code”. Skier codes typically range from A to P and correspond to greater release torques and IVs with each additional letter down the alphabet. For example, a skier weighting 126-147 pounds of height 5’2” to 5’5” would qualify as a skier code J. A skier weighing 175 to 209 pounds of height 5’11” to 6’4” would be a skier code L. Once skier code is established, boot sole length is taken into consideration. In a normal ski shop environment, once skier code and target release torque are determined, the bindings then are set to the recommended IV, and the binding release is tested per ISO 11088 [12]. If the binding releases within range of the skier code the binding is considered fit for use. If the binding releases out of range, the binding IV is adjusted. In the case that the adjustment needed falls out of the manufacturer’s allowable adjustment, troubleshooting procedures must be followed to determine the cause of failure [5].

1.3 University of Vermont Ski Safety Test Laboratory

The University of Vermont Ski Safety Test Laboratory was built in 2021. The main piece of equipment in the laboratory is colloquially known as the “504” machine (Figure

3).Developed originally by Carl Ettlinger, the 504 machine provides a means for testing bindings according to the ASTM F504- Standard Test Method for Measuring the Quasi-Static Release Moments of Alpine Ski Bindings [13].

Figure 3: University of Vermont 504 Ski Binding Release Tester in the Ski Safety Test Laboratory consisting of two motors, a system of cables, and load cell.

The 504 machine consists of a system of cables and pulleys arranged to accommodate the different loading scenarios outlined in the standard. The center of the 504 contains a load cell capable of measuring torques in the y and z direction. Figure 4 below outlines the orientation of the axes on the 504 tester. With the z-axis running along the length of the skier's tibia, a torque in the y-direction represents torques in a forward leaning fall and torques in the z-direction representing torques in a twisting fall.

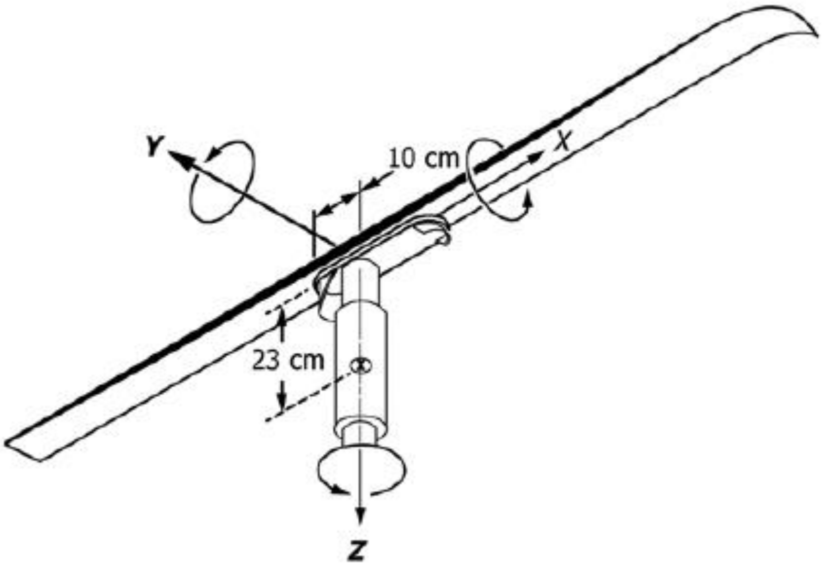

Figure 4: Axis orientation of the 504 tester as outlined in ASTM-F504 standard [13]

The load cell represents the skier's tibial axis and is therefore able to detect the representative loads transferred to a skier's lower leg during a fall or binding release. The second motor can be seen in Figure 5. This motor rotates around the center of the load cell and provide a downwards force on either the rear or front of the ski.

Figure 5: The 504 tester's smaller preload motor and spring system rotates around the center axis to provide front or rear preload.

The digital readout system mounted on the outside of the cage (Figure 6) displays the torque on the load cell and outputs the value continuously. Once the binding has released the user is able to display the maximum torque that was applied during the run. This readout box also includes buttons to zero the load cell after each test.

Figure 6: The digital readout system displays maximum torque during a release in the bending and twist directions.

1.4 Research Objectives and Outline

The objectives of this thesis fall into two categories: 1) contributing to a performance standard for the release and retention characteristic of classic alpine bindings in front and rear preload scenarios and 2) investigating the release and retention characteristics of novel ski boot and binding technologies.

Chapter 2 of this thesis will focus on collecting data to contribute to a performance standard for release and retention characteristics of ski bindings under loaded scenarios. Beyond Chapter 2, this thesis will focus on the comparison of novel technologies in loaded scenarios informed by the performance of traditional alpine bindings. Chapter 3 describes an investigation of the performance of new, multi-norm compatible bindings combined with various ISO approved boot soles. Chapter 4 provides information on the release and retention behavior of multi-norm compatible bindings in comparison with traditional alpine bindings. Finally, Chapter 5 describes a study of the release characteristics of unapproved GripWalk and alpine binding combinations and provides an assessment of the risk associated with their use.

CHAPTER 2: ALPINE BINDING PERFORMANCE DATA AND STANDARD

2.1 Introduction

The decrease in lower leg fractures due to ski bindings not releasing can be largely attributed to the research and standardization of binding release and retention in unloaded configurations. While the release characteristics of bindings in unloaded configurations have been standardized, binding release in preloaded scenarios associated with body weight, muscle contraction, and skiing conditions most closely resembling falls that occur on hill remains an open question. Ski shops adjust binding release to meet manufacturers recommended release for forward lean and pure twist, leaving skiers unaware of how their bindings will respond on hill in real world scenarios. Factors such as skiing intensity and the slope of the hill require the skier to introduce various levels of forward and backward lean which produce corresponding changes in the load and torques that are transmitted across the boot-binding-ski system. [14]. It is important to understand the release and retention characteristics of alpine bindings under these loading scenarios to more thoroughly understand how alpine bindings perform in on-hill scenarios and the loads and torques that transfer to a skier's leg at specific binding settings. The purpose of this investigation is to understand how alpine binding release and retention performance changes when load is introduced and to contribute to the creation of a performance standard based on this behavior of alpine bindings. This research was conducted under the direction of Guidance Engineering (GEAR) in Seattle, WA to supplement their data set with data from an independent ski-safety test laboratory. After understanding the behavior of alpine bindings under forward and backward load, Guidance Engineering will propose an international standard, setting a minimum requirement for binding release and retention for forward and backward twisting binding releases.

2.2 Methods

The release characteristics of alpine boot-binding systems in a front and rear preloaded configuration were tested on five different alpine bindings from various manufacturers. Each of the bindings was mounted onto its own ski of the same make and model. The alpine sole used for testing, referred to throughout this document as the "test sole", conforms to ISO 9838:2023 as a test stole that is representative of an ISO 5355 compliant alpine boot (Figure 7).

Figure 7: Test sole that is used as a representative of ISO 5355 alpine boot soles during alpine binding release testing

2.2.1 Loading Scenarios

Four independent tests, comprising three different separate load scenarios were performed on each binding. The scenarios were set-up as outlined in ASTM-F504 [13]. Figure 8 below outlines the locations of the reference points on the ski in centimeters from the tibial axis, or center line, where the load is to be applied.

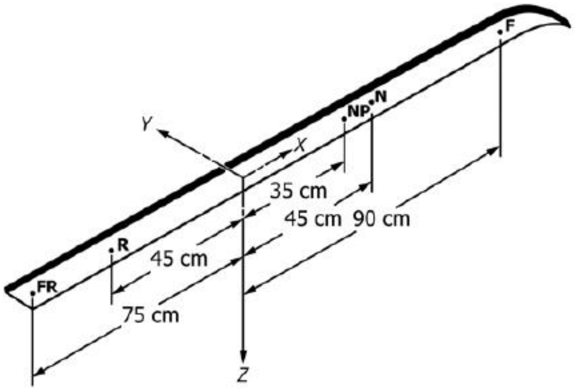

Figure 8: Reference points on the test ski and their distance from the tibial-axis (z-axis) as outlined in the ASTM-F504 standard [13]

The first test performed, referred to throughout this document as Test 1.1 Pure Twist, applies an axial twisting moment to the ski that replicates the moment applied about the long axis of the lower leg (Figure 9a). Cables are connected to the ski 45 cm from the center of the testing shaft to the front of the ski and to the rear of the ski. This first test is performed in a dry ski and binding environment. The second test performed is a repetition of Test 1.1 Pure Twist, but the ski and binding are both sprayed with room temperature water to mimic wet conditions. Sprays of water from a standard household spray bottle were applied to the ski and binding until droplets are visible on the equipment. The next test performed, Test 1.6 Front Preload Twist (Figure 9b), applies a downward preload to the front of the ski, 35 cm in front of the center line of the test shaft, before applying a twisting moment to the front of the ski 45 cm in front of the center line. The final scenario, Test 1.10 Rear Preload Twist, applies a preload 45 cm from the center line at the rear of the ski before applying a twisting moment at the back of the ski from the same rear point (Figure 9c). Both Test 1.6 and Test 1.10 were performed under wet conditions. Additional water was applied every three runs to ensure moisture levels were maintained. All tests were performed at ambient, room, temperature.

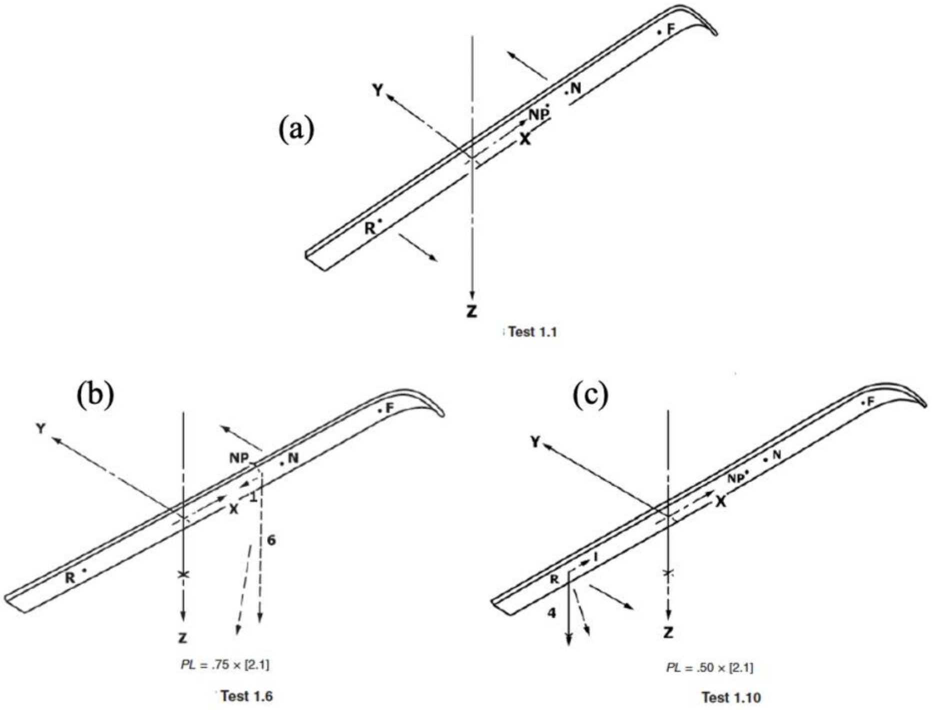

Figure 9: (a) Test set up for Test 1.1 Pure Twist (b) Test set up for Test 1.6 Front Preload (c) Test set up Test 1.10 Rear Preload [13]

The preloads applied are a function of forward lean release toque of ASTM-F504 Test 2.1 (Figure 10).This test, meant to simulate a skiers release at the heel when a forward directed bending moment is applied, applies an downward force 45 cm from the center line towards the front of the ski and an upward force 45 cm from the center line towards the rear of the ski.

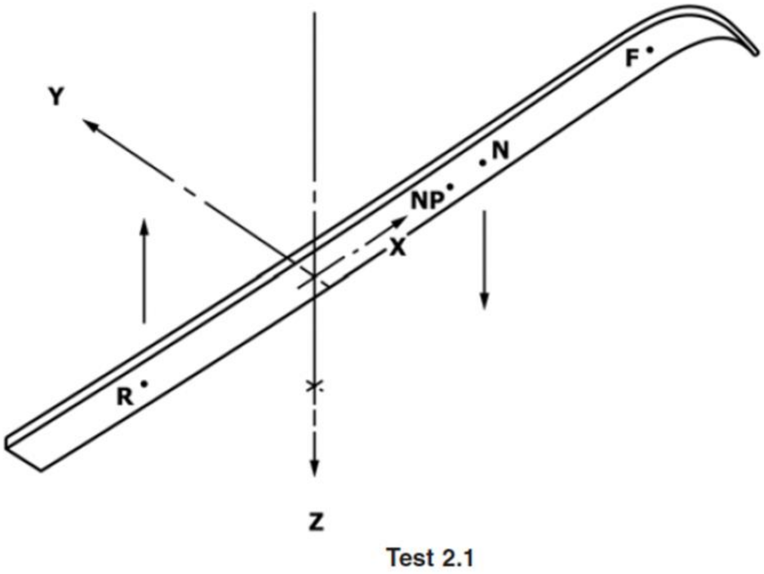

Figure 10: Forward lean (Test 2.1) release set up as per ASTM-F504 guidelines [13]

Although forward lean release torque was not tested in this investigation, this value was derived from the skier code being tested per the manufacturers binding adjustment guide and is generally correlated with skier weight. Per ASTM-F504, the preload used in Test 1.6 Front Preload Twist is to be 0.75x the forward lean release torque and the preload used in 1.10 Rear Preload Twist is to be 0.5x the forward lean release toque (Table 1).

Three separate skier codes were selected for analysis: Skier code J, skier code L, and Skier code N. For each of the three skier codes each test was repeated 5 times per loading scenario with each of the 5 skis, totaling 300 tests completed.

Table 1: Preload torque values for skier codes J, L, N, P as a function of forward lean release values given on the manufacturers binding adjustment guide.

Skier Code	Test 1.6- Front Preload Twist Preload (Nm)	Test 1.10- Rear Preload Twist Preload (Nm)
J	123.8	82.5
L	171.8	114.5
N	240	160
P	339	226

2.2.2 Setting Reference Value and Calibration

Between each ski test the load cell was zeroed in the z and y (twist and bending) directions without the ski and binding and only the mounted boot sole. To begin the tests of each skier code the bindings were set to the recommended IV per the manufacturer guidelines. Per this guideline for skier code J the bindings were initially set to an IV of 4.5, 6.5 for skier code L, and 9.5 for skier code N. Once set to the recommended value Test 1.1 Dry was performed. If the binding did not release within ± 2% of the targeted release torque value the binding indicator value was then adjusted higher or lower iteratively until the target release value was reached. Once this target value was reached, an additional 4 runs of Test 1.1 Dry were performed and the IV was not adjusted for the duration of the testing. The method of setting of consistent reference values was agreed upon with GEAR. This method was chosen due to its similarity to the process that would be undergone for setting release torque values at a ski shop. Additionally, because the preload values are a function of forward lean release, which was not performed, it was necessary to align all bindings at release value included in the manufacturer's adjustment chart to determine the appropriate preload values.

2.2.3 Statistical Analysis

The maximum release torque during each binding release run was recorded. Unpaired, t-tests for means were run between the preloaded release torques (Test 1.6 and Test 1.10) and the maximum release torque for 1.1 Pure Twist in wet conditions for each skier code in JMP with a significance level of .05.

2.3 Results

Unpaired t-tests between preloaded test release torque and unloaded pure twist Test 1.1 release torques all resulted in p-values <.0001 (Table 2). The maximum, mean, and standard deviation for release torque in front and rear preloaded configurations for each selected skier code run at University of Vermont's Ski Safety Lab are displayed below in Table 3.

Table 2: P-values from unpaired t-tests between mean release torques of preloaded configurations compared to 1.1 Pure Twist (Wet) release torques

	Skier Code J	Skier Code L	Skier Code N
Test 1.6	<.0001	<.0001	<.0001
Test 1.1	<.0001	<.0001	<.0001

Table 3: Maximum, mean, and standard deviation for preloaded scenarios for test sole-alpine bindings combination at UVM Ski Safety Laboratory separated by skier codes J, L and N

	Alpine Binding (Code J)		Alpine Binding (Code L)		Alpine Binding (Code N)	
	Max (Nm)	Mean ± SD (Nm)	Max (Nm)	Mean ± SD (Nm)	Max (Nm)	Mean ± SD (Nm)
1.1 Dry	44.9	43.3 ± 1.1	59.2	57.6 ± 0.7	79.6	77.7 ± 1.5
1.1 Wet	46.5	43.9 ± 2.2	61.6	58.8 ± 1.3	84	79.2 ± 2.5
1.6 Wet	54.8	51.5 ± 2.4	74.8	70.2 ± 2.3	100.4	95.8 ± 2.3
1.10 Wet	76.0	60.1 ± 6.8	93.7	80.2 ± 7.2	119.7	108.2 ± 6.7

Table 4: % increase from 1.1 Wet Release Torque for skier codes J, L, and N

	Code J	Code L	Code N
1.6 Wet	15%	18%	16%
1.10 Wet	39%	34%	30%

The percent increase of release torque from Test 1.1 Wet is included for both front and rear loading scenarios (Table 4). Based on the alpine bindings tested it was observed that rear pre-loaded twist releases resulted in a higher release torque than front pre-loaded twist releases. It was seen that alpine bindings with a front preload can release at a significantly higher torque than unloaded pure twist release, up to 18% higher than an unloaded twisting release depending on the skier code chosen. Similarly, alpine bindings with a rear preload can release at significantly higher torque than unloaded twisting release, up to 39% higher than an unloaded twisting release depending on the skier code.

The results of this testing were communicated with GEAR. GEAR supplied a boxplot comparing the data collected at the University of Vermont in comparison to the data collected at GEAR (Figure 11) using the same bindings, skier codes, and test method. GEAR did not supply their raw data for statistical comparison. In the below figure the plotted data are separated for each skier code and boxplots are provided with minimum, maximum, mean, upper and lower quartile ranges. The dashed line on the box plot represents the target release pure twist release value for the given skier code per the manufacturer's adjustment chart. While some variation can be seen in mean release torques for the pre-loaded scenarios across laboratories, the increases from Test 1.6 to Test 1.10 are observed to be similar across laboratories.

2.4 Discussion

During testing it was observed that there was significant difference in the release torques of preloaded twisting releases when compared to unloaded twisting releases, bolstering the need for a performance standard for preloaded releases. Upon completion of this testing, ASTM-F372 *Standard Specification for Release Characteristics of Ski-Binding-Boot (S-B-B) Systems for Recreational Skiing* was created and released in December of 2024 [15]. This standard outlines a performance requirement for any recreationally used boot-binding-ski combination for unloaded and preloaded scenarios such as those tested in this analysis

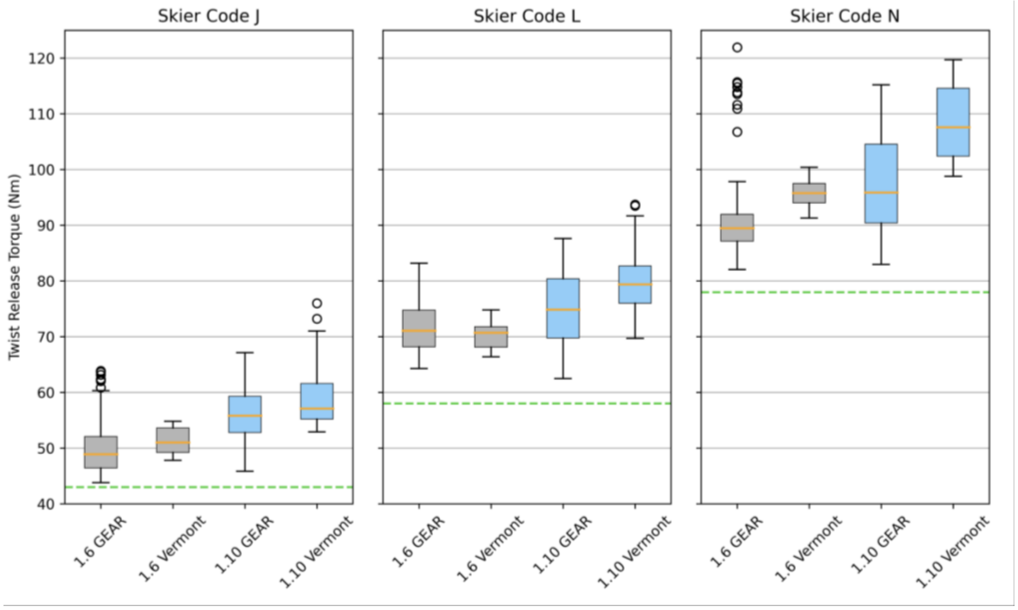

Figure 11: Release data for alpine ski bindings with front and rear preload by the University of Vermont in comparison with data gathered at GEAR separated by skier code. Boxplot displays maximum, minimum, median, first quartile range, and third quartile range. Dots represent outliers.

The performance standard provides acceptable ranges for preload tests based on a reference value of Test 1.1 Pure Twist and Test 2.1 Forward Lean release values. Table 5 below determines the acceptable range of release torques for Test 1.6 and Test 1.10 based relative to the target reference value of Test 1.1 Pure Twist depending on skier code selection.

Based upon this standard, one of the five alpine bindings tested would have failed the Test 1.10 standard on skier codes L and N. The failing ski, labeled Ski 1, released at a torque 55% higher than the 1.1 Twist reference value for skier code L and 49% higher for skier code N.

Table 5: Acceptable range of front preload and rear preload twist release tests in Newton-meters based on given target values outlined in ASTM-F372 for skier codes J, L, N, and P.

Skier Code	1.1 Reference Value (Nm)	1.6 Min (Nm)	1.6 Max (Nm)	1.10 Min (Nm)	1.10 Max (Nm)
J	43	38.7	58.05	38.7	62.35
L	58	52.2	78.3	52.2	84.1
N	78	70.2	105.3	70.2	113.1
P	105	94.5	141.75	94.5	152.25

2.5 Summary

Data gathered in this testing contributed to the creation of a minimum performance standard for bindings under front and rear loaded twisting falls. The standard accepts a large range of release values. The implementation and adherence to this standard will better inform skier and manufacturers of the release and retention characteristics of their bindings under load and improve the safety of skiers whose skis conform to these guidelines. In addition, the comparison of release torque values with those of GEAR solidify the accuracy of the 504 in UVM's Ski Safety laboratory and bolster the repeatability of the test methods used.

CHAPTER 3: RELEASE CHARACTERISTICS OF MULTI-NORM BINDINGS

3.1 Introduction

In a 2024 article for Ski Magazine Derek McClellan, Category Manager and technical director for Marker-Dalbello-Völkl, stated “alpine soles will disappear except from racing and [multi-norm systems] will be the new norm in the next three years” [16]. McClellan is referencing the emergence of new technology in the ski boot and binding space such as Multi-Norm Compatible Bindings (MN, formerly MNC). Up until the release of the first MN binding in 2018, skiers needed to choose a binding that was compatible with their specific boot sole, requiring them to purchase separate bindings for each different boot sole.

Figure 12: Multi-Norm ski binding, as denoted by “MNC” in the toe piece, used in multi-norm binding testing

Current MN bindings on the market are said to be compatible with traditional alpine (ISO 5355), GripWalk (ISO 23223), and touring (ISO 9523) soles (Figure 12). While the bindings are said to be compatible, little research exists comparing the retention and release characteristics of different boot soles in the same binding.

3.1.1 New Technologies

This chapter seeks to evaluate the release and retention characteristics of two new pieces of equipment: Multi-norm ski bindings and GripWalk (GW) boot soles. Multi-norm compatible ski bindings became available to the consumer in 2018. The intention of these bindings is to be compatible with a variety of different boot soles by incorporating an adjustable toe piece or Anti-Friction Device (AFD). The adjustability of the AFD enables the binding to be adjusted depending on boot-sole thickness while the boot-sole still maintains appropriate contact with the binding. The AFD was originally introduced in the 1970's when it was observed that bindings were not releasing reliably under vertical loads. Modern AFDs incorporate low friction materials and/or mechanical rollers to decrease the friction between the boot and binding under load [17]. Most multi-norm bindings incorporate mechanical AFDs, that slide laterally at the toe during a release.

GripWalk soles were first introduced in 2016. The rockered, slip-resistant soles are marketed as easier to walk in when not skiing than traditional alpine boot [18]. In 2022, Marker, the original manufacturers of GripWalk soles, offered up their patent to be used without royalties by other manufacturers allowing international standardization under ISO 23223 [16]. Due to this, GripWalk soles are becoming ubiquitous in recreational skiing. However, the rockered geometry of GripWalk boot soles impacts the soles' ability to contact traditional alpine bindings AFD properly and therefore is only approved for use in GripWalk approved bindings such as MN bindings.

3.2 Methods

To acquire data about the retention and release characteristics of multi-norm bindings, a multi-norm compatible binding was acquired and mounted onto a ski per the manufacturer's guidelines. The release characteristics of three separate boot soles were used in testing of the release characteristics of this binding: the test sole (as described in Chapter 2), a potted alpine boot sole, and a GW sole. To create a compatible GW sole, a GW boot was purchased and then cut at the sole. After cutting, a piece of aluminum was set into the sole with steel reinforced epoxy and drilled to mate with the test mount (Figure 13).

Figure 13: GripWalk sole after being cut and removed from boot housing and set with reinforcement plate and steel-reinforced epoxy. Holes drilled with mate with boot mount.

Figure 14 below shows the three soles used in this testing. Although both the test sole and the potted alpine sole are both representative of ISO 5355 soles, their topology and geometry differ providing useful insight into the differences in interaction of the soles with the binding. It has been noted that even boots of the same ISO perform differently across manufacturers [16].

A similar methodology was employed in this section as in Chapter 2. The boot-binding systems in this section were tested in accordance with ASTM-F504 [13]. Each boot-binding system was tested in the configurations of Test 1.1 Pure Twist Dry, Test 1.1 Pure Twist Wet, Test 1.6 Wet, and Test 1.10 Wet.

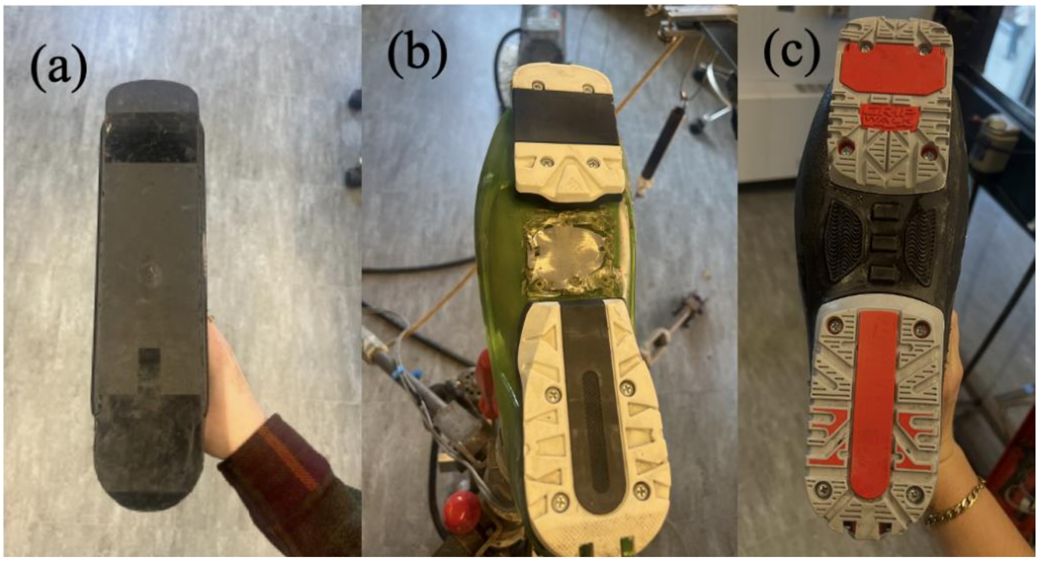

Figure 14: Boot soles used in combination with the multi-norm binding, (a) Test sole (ISO 5355 compliant) (b) Potted sole (ISO 5355 compliant) (c) GripWalk sole (ISO 23223 compliant)

The test configurations used can be seen in Figure 9. Each boot-binding system was tested entirely through two skier codes: skier code L and skier code N. Both iterations of Test 1.1, wet and dry, as well as Test 1.6 were performed on all three boot soles at skier code P. Test 1.10 Wet was not tested at skier code P due to the increased release torques associated with this skier code and rear preload configuration. This was done to protect lab equipment and binding integrity. The preloads used during front and rear preload tests can be found in Table 1. All boot-sole lengths fell within the same category for binding adjustment. Therefore, all bindings were set to an IV of 6.5 for skier code L, 9.5 for skier code N. A recommended adjustment for the given boot sole length was not given for skier code P. An estimate of an IV of 12 was deemed appropriate for this skier code and used as starting point for IV adjustment to reach the target reference release torque for Test 1.1 Dry. The boot-binding combinations were first run using Test 1.1 Dry. If the bindings did not release within ± 2% of the manufactures guideline then the IV was adjusted iteratively until the target was reached.

The load cell was zeroed in the y and z direction (bending and twist) with only the boot sole attached with the changeover of each boot sole. Owing to the adjustable nature of multi-norm bindings, the AFD height was adjusted per the manufacturer's guidelines for each boot sole. The forward pressure of the boot was also adjusted to accommodate any minor differences in boot sole length. Each test was run five times per boot sole, totaling 165 tests.

3.2.1 Statistical Analysis

The maximum release torque during each binding release run was recorded. A two-way analysis of variance (ANOVA) was conducted to determine if there was significant difference between the means in preloaded release torques for each boot sole using a significance level of .05. Using JMP, the sole type was set as the independent variable and release torque as the dependent variable [19]. Data was separated by loading scenario (front or rear preload) and skier code.

3.3 Results

A box plot of the resulting release torques from testing the three different boot-binding combinations are displayed below in Figure 15. The data are separated by skier code and display the maximum, minimum, median, first quartile and third quartile of the release values. As can be seen from the plot, Test 1.10 resulted in much larger release torques than Test 1.6. The release torques for Test 1.6 were generally close to the Test 1.1 targeted release torque as denoted by the green dashed line on the graph. This was true for all binding combinations. The potted sole released at the highest torque for Test 1.6 Wet across skier codes.

A p-value of less than .05 was obtained for all ANOVAs indicating that at least one of the three boot soles exhibited significant difference in release torque and suggesting the need for pair-wise post-hoc testing to determine which specific means were significantly different [20]. A Tukey Honestly Significant Difference (HSD) was performed in JMP to determine which pairwise combinations exhibited significant difference in mean release torque using a p-value of .05 [19]. The p-values for each pairwise combination are displayed in Table 6 for front preload and Table 7 for rear preload. A summary of the Tukey HSD results can be seen below in Table 8 for Test 1.6 Front Preload and Table 9 for Test 1.10 Rear Preload using a connecting letters report for readability. In the connecting letters reports below the boot sole release torques within the same skier code that are not connected by the same letter are significantly different. For all skier codes and preload configurations there is at least one pair of boot soles that exhibit significant difference. All boot soles release at statistically different values for Test 1.6 for skier code N.

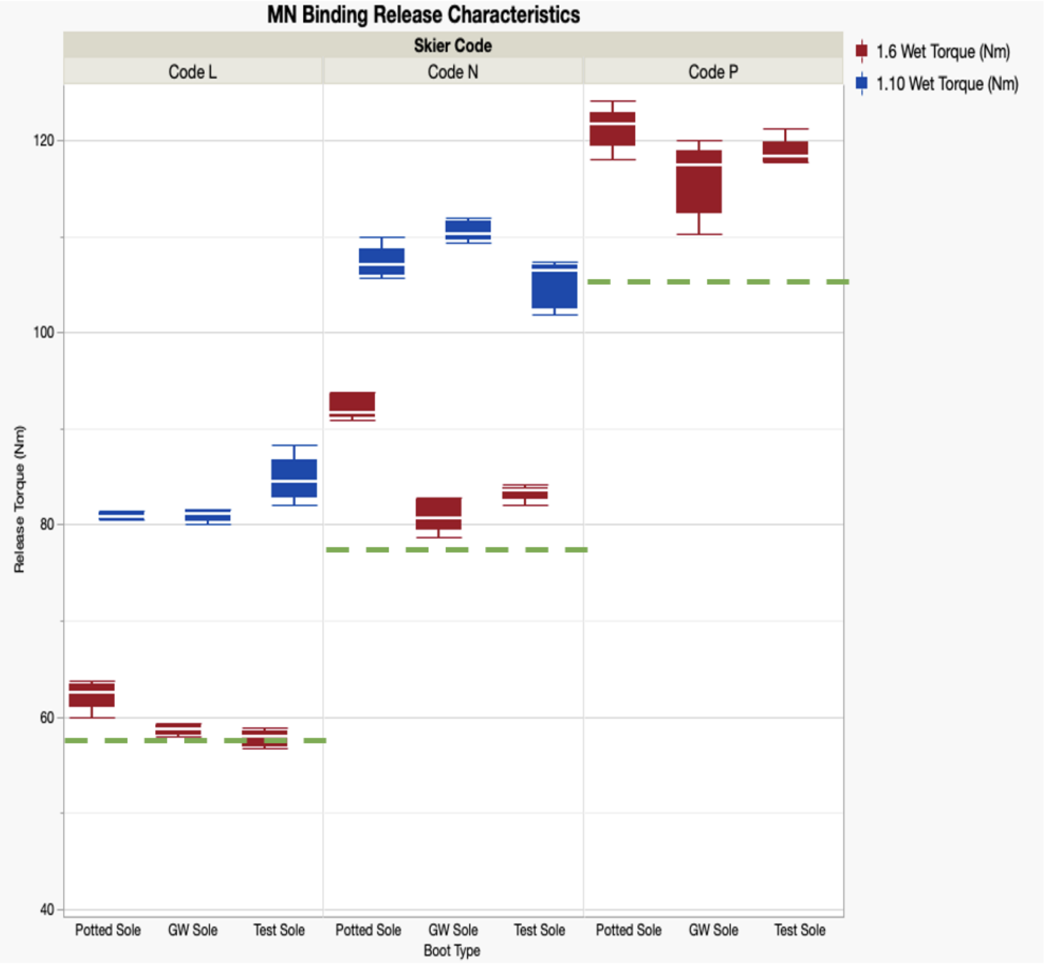

Figure 15: Boxplot displaying maximum, minimum, median, first quartile range, and third quartile range for each boot tested in combination with the multi-norm compatible binding separated by skier codes L, N, and P.

Table 6: P-values for each pairwise comparison of release torques for Test 1.6 using Tukey HSD

	Skier Code L		Skier Code N		Skier Code P	
	Test Sole-MN	GW Sole- MN	Test Sole-MN	GW Sole- MN	Test Sole-MN	GW Sole- MN
Potted Sole-MN	<.0001	0.0004	<.0001	<.0001	0.3200	0.0223
Test Sole-MN		0.3851		0.03		0.2749

Table 7: P-values for each pairwise comparison of release torques for Test 1.10 using Tukey HSD

	Skier Code L		Skier Code N	
	Test Sole-MN	GW Sole-MN	Test Sole-MN	GW Sole-MN
Potted Sole-MN	0.0024	0.9899	0.1851	0.0365
Test Sole-MN		0.0031		0.0013

Table 8: Connecting letter plot for Test 1.6 Front Preload release torque in Newton-meters. Boot soles of the same skier code that do not share the same letter were found significantly different in a Tukey HSD.

	Code L		Code N		Code P	
	Mean (Nm)	Letter	Mean (Nm)	Letter	Mean (Nm)	Letter
GW	58.7	B	81	A	116	B
Test	57.8	B	83.3	B	118.8	A B
Potted	62.3	A	92.3	C	121.3	A

Table 9: Connecting letter plot for Test 1.10 Rear Preload release torque in Newton-meters. Boot soles of the same skier code that do not share the same were found significant in a Tukey HSD.

	Code L		Code N	
	Mean (Nm)	Letter	Mean (Nm)	Letter
GW	81	B	110.6	A
Test	84.8	A	105.2	B
Potted	80.9	B	107.3	B

3.4 Discussion

Multi-norm bindings are certified and marketed as being compatible with a variety of different boot soles. After testing a pair of multi-norm bindings with three separate boot compatible boot soles it was found that multi-norm bindings do not behave consistently across compatible boot soles. The behavior of the test sole and potted alpine boot also behaved significantly different, emphasizing the impact of unique boot geometry even amongst boots of the same ISO categorization. It is important to highlight the variation of IVs that were used to achieve the targeted reference value (Figure 16). Binding indicator values to achieve the same Test 1.1 Pure Twist release torque varied across bindings. Only when set at varying IVs did the bindings release at the same reference torque with the largest variation of indicator values being present for code P testing where all bindings were set to different IVs. It can be deduced that the difference in release torque in preloaded configurations would be even larger if the IVs were not adjusted and the binding's release was tested at the same IV for all boot soles.

3.5 Summary

Multi-norm bindings do not exhibit consistent behavior across compatible boot soles, and their release and retention characteristics are not consistent across a standard IV. While the allure of a multi-norm binding might be its compatibility with a variety of boot soles, a skier cannot use a new or different boot in their multi-norm bindings and expect a similar release profile. The recommendation remains that all boot-binding combinations are tested and adjusted by a professional and this adjustment must occur in between each addition of a new or different boot sole.

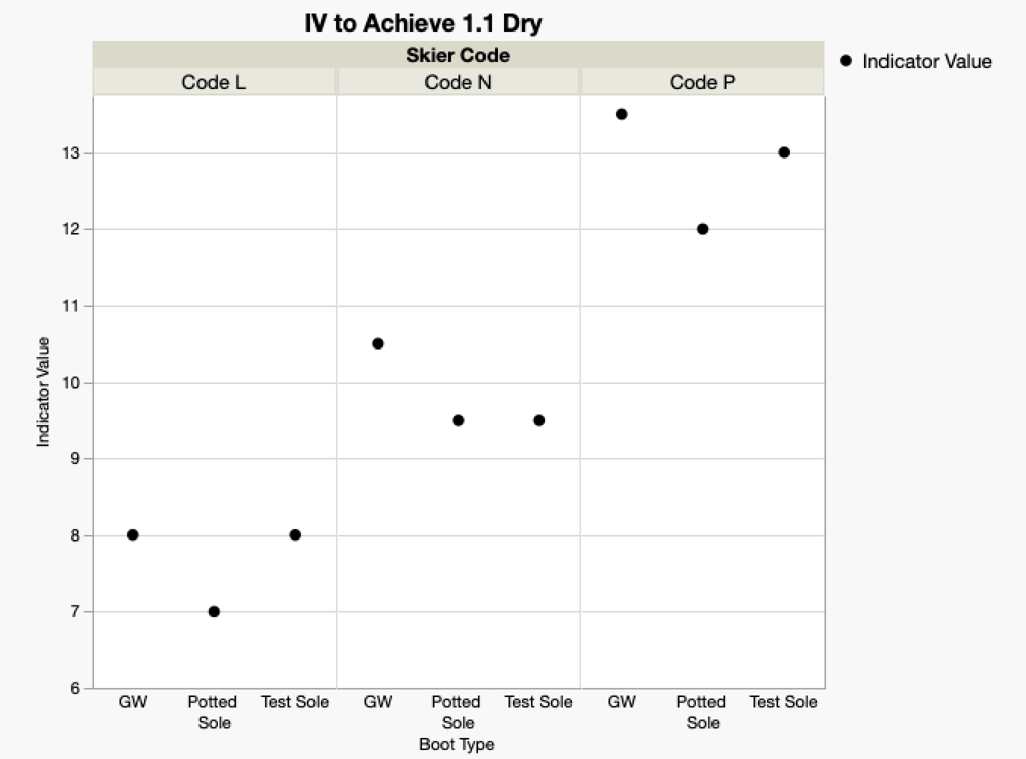

Figure 16: Dot plot of the indicator values the multi-norm binding was set to reach the 1.1 Pure Twist reference torque for each boot sole tested separated by indicator value

CHAPTER 4: RELEASE OF MULTI-NORM BINDINGS VS ALPINE BINDINGS

4.1 Introduction

With the release and increase in popularity of multinorm style bindings, it is critical to understand how multi-norm bindings behave in comparison to traditional alpine bindings for both the user and those creating release and retention standards. Due to multi-norm bindings' novelty, very little research exists comparing the retention and release characteristics of these newer style bindings with the characteristics of more extensively researched alpine bindings. ASTM-F3728 applies to "all recreational snow skiing bindings" [15]. This includes multi-norm bindings. To ensure this standard's validity with multi-norm bindings we must analyze the differences in release and retention behavior. It is also important to research the differences in the retention and release characteristics between these two types of bindings for the consumer, who may be switching over from one binding kind to another in the changing equipment landscape.

4.2 Methods

The analysis of the retention and release characteristics in multi-norm bindings vs. alpine bindings was conducted using the data gathered in Chapters 2 and 3. To limit the number of variables related to boot geometry, analysis was only performed on the multi-norm and alpine bindings with the test sole. Skier codes L and N were chosen for analysis as both boot-binding combinations were tested on those codes.

4.2.1 Statistical Analysis

The maximum release torque during each binding release run was recorded. Unpaired, t-tests for means between the release torques in preloaded scenarios were conducted between the test sole-alpine and test sole-MN boot-binding combinations in JMP with a significance level of .05. Data were separated by skier code.

4.3 Results

Below in Figure 17 is a boxplot displaying the differences in release torque for the test sole-alpine binding and the test sole-multi-norm binding combinations.

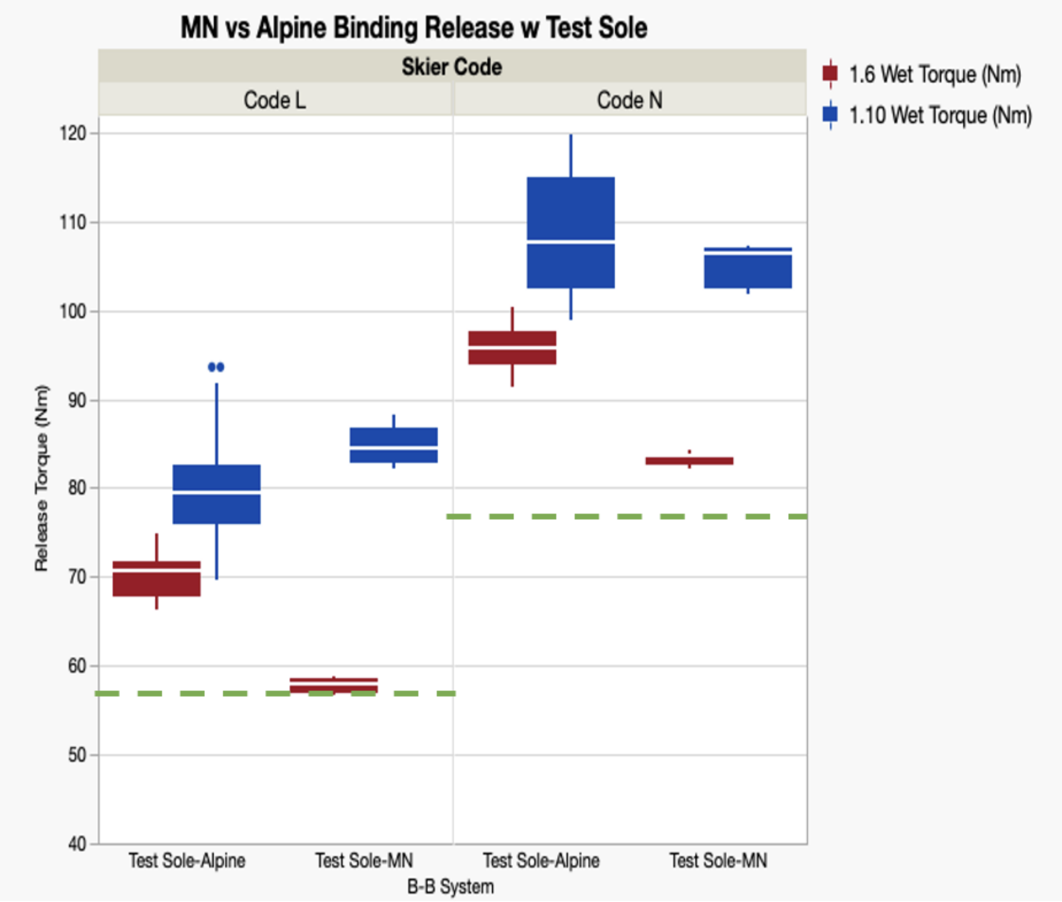

Figure 17: Boxplot displaying maximum, minimum, median, first quartile range, and third quartile range for release values of the test sole-alpine binding combination vs the test sole-multi-norm binding combination separated by skier code. Dots are outliers

The data are separated by skier code and display the maximum, minimum, median, first quartile and third quartile of the release values. The target reference torque for Test 1.1 wet is shown by the dotted green line.

For both skier codes L and N, all runs of Test 1.6 resulted in lower release torques for the multi-norm binding. For both skier codes significant difference was seen in 1.6 Wet release torques (p<.001), with the multi-norm bindings releasing at a significantly lower torque. For skier code L only was the difference in 1.10 Wet release torque significantly different (p=0.019), with multi-norm bindings releasing at a significantly higher torque.

Table 10: Maximum, minimum, mean, standard deviation, and percent increase from 1.1 Wet for test sole-alpine binding combination vs test-sole-multi-norm binding combination for skier code L. Includes p-value from unpaired t-test.

	Test Sole/Alpine Binding			Test Sole/MN Binding			
	Max (Nm)	Mean ± SD (Nm)	% Increase	Max (Nm)	Mean ± SD (Nm)	% Increase	p- value
1.1 Dry	59.2	57.6 ± 0.7		57.5	57.2 ± 0.4		
1.1 Wet	61.6	58.8 ± 1.3		58.6	58.2 ± 0.3		
1.6 Wet	74.8	70.2 ± 2.3	18%	58.9	57.8 ±0.9	-1%	<.001
1.10 Wet	93.7	80.2 ± 7.2	34%	88.3	84.7 ± 2.3	31%	0.019

Table 11: Maximum, minimum, mean, standard deviation, and percent increase from 1.1 Wet for test sole-alpine binding combination vs test-sole-multi-norm binding combination for skier code N. Includes p-value from unpaired t-test.

	Test Sole/Alpine Binding			Test Sole/MN Binding			
	Max (Nm)	Mean ± SD (Nm)	% Increase	Max (Nm)	Mean ± SD (Nm)	% Increase	p- value
1.1 Dry	79.6	77.7 ± 1.5		79.3	78.6 ± 0.5		
1.1 Wet	84	79.2 ± 2.5		80.1	78.2 ± 1.5		
1.6 Wet	100.4	95.8 ± 2.3	16%	84.2	83.3 ± 0.8	7%	<.001
1.10 Wet	119.7	108.2 ± 6.7	30%	107.3	105.2 ± 2.4	26%	.096

4.4 Discussion

This study examined the differences between the retention and release behavior of alpine bindings and multi-norm bindings with the same boot sole. Significant differences were seen in their behavior, especially in front preloaded cases. In front preload tests, multi-norm bindings released at a significantly lower release torque. The bindings released similarly, and in some cases at higher torques (skier code L) in the rear preload test.

The front preload release torques for multi-norm bindings are significantly lower than the release torques for alpine bindings and therefore do not pose a significant risk for exposing the leg to excessive torques causing lower leg injury. Similarly, all release values conform to the performance standard as outlined in ASTM-3728. However, these differences do have the potential to impact the user. Upon mounting and testing the given boot-binding combinations in a ski shop, the user would expect similar behavior from each set of bindings. However, multi-norm and alpine bindings could have an entirely different release profile on hill when forward and backward lean are incorporated. In one scenario, a user with multi-norm bindings may experience a perceived inadvertent release in a forward leaning scenario due to the lower release torques for this orientation. This could lead a user to believe the IVs on their binding are too low. However, increasing the IV would then increase the release torque in a rear leaning fall, putting the skier at risk for lower leg injuries.

4.5 Summary

Through this testing it has become apparent that a skier may take an ISO approved boot sole, put it into two separate binding technologies, have it mounted and adjusted by a professional, and have two very different experiences with its release in real-world on hill scenarios. While the differences themselves do not indicate any large risks to safety, it is important that users do not take these differences as an opportunity or reason to adjust their bindings to a higher IV. Multi-norm bindings tend to release at torques significantly lower than alpine bindings in the front-loaded configuration, likely due to the incorporation of mechanical sliding AFDs. However, a proportionate reduction of release torque is not seen in the rear-loaded position.

CHAPTER 5: IMPACT OF INCOMPATIBLE BOOT-BINDING COMBINATIONS

5.1 Introduction

Per ISO compatibility guidelines Grip Walk (ISO 23223) boot soles are not compatible with standard alpine bindings. However, anecdotal evidence shows this combination being used by skiers. A number of skiers have been observed to believe that if a boot sole "fits" in a binding, then compatibility is guaranteed. This research looks to quantify the risk associated with the incompatible pairing of GripWalk rockered soles and alpine bindings and seeks to understand the geometric reasons for any discrepancies. While it will never be recommended that skiers disregard compatibility requirements, it is important to understand what level of risk is present. To identify this risk the retention and release behavior of GW Sole-alpine binding combinations was compared with the retention and release behavior of all other boot-binding combinations investigated throughout the previous chapters of this manuscript.

5.2 Methods

To compare the retention and release characteristics of incompatible boot-binding combination with those of ISO certified combinations, the GW boot sole was tested in the five alpine bindings from Chapter 2. The release and retention characteristics of the GW soles in alpine bindings were tested using 1.1 Dry, 1.1 Wet, 1.6 Front Preload, and 1.10 Rear Preload configurations and maximum release torque was recorded. See Figure 9 for these configurations. The boot-binding combinations were tested at skier code L and skier code N owing to favorable overlap with previously collected data. Before testing began the skis were set to a target reference value for 1.1 Dry per the manufacturer's guidelines. The load cell was zeroed with only the boot mounted. The forward pressure was adjusted on each ski to accommodate the GW boot sole length. For any binding with additional toe adjustment, such as wing adjustment, these adjustments were made. Each test was repeated 5 times. The preload values for Test 1.6 Wet and 1.10 Wet can be found in Table 1.

5.3 Results

Figure 18 below includes a boxplot displaying the maximum, minimum, mean, first quartile range, and third quartile range. The boxplot is split by skier code and boot-binding system and includes all boot-binding systems that were investigated in this paper. Observation shows that the GW sole-alpine binding system had release torques for 1.10 Wet that were below any observed value in any of the other boot-binding systems (excluding the outlier values in skier code L). A direct comparison of maximum, minimum, mean, standard deviation, and percent increase from 1.1 Wet for preloaded release torques between of the GW-alpine and GW-multi-norm boot binding combination is made in Table 12. The increase of release torques for the approved GW-multi-norm combination is greater than 20 Nm from Test 1.6 to Test 1.10. The increase in release torques between these same tests is less than 2 Nm for the GW-alpine combination at the same skier code L. The percent differences in Test 1.6 and Test 1.10 from Test 1.1 Wet were determined for all boot-binding combinations for skier codes L and N (Table 13). Notably, the GW-alpine combination saw an increase of > 3% in release torques from Test 1.6 to Test 1.10 for skier code L. All other boot-binding combinations saw an increase in release torques for these tests of at least 8%. The GW-alpine combination resulted, on occasion, in release torques for Test 1.10 that were less than the reference torque. For two skis in particular, Ski 2 and Ski 5, the mean release torque for Test 1.10 was less than the mean release torque for Test 1.6. Such results were not observed for any other boot-binding combination.

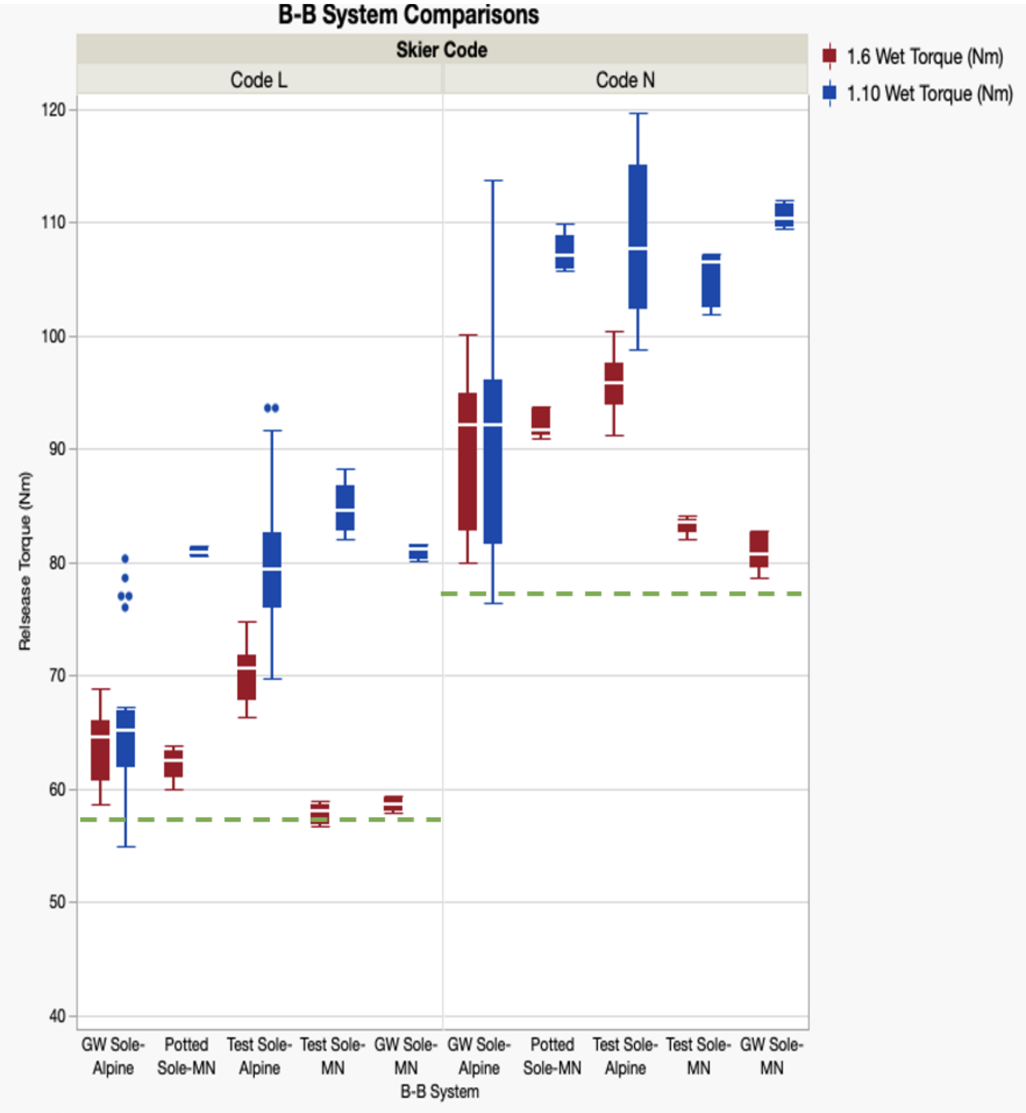

Figure 18: Boxplot displaying maximum, minimum, median, first quartile range, and third quartile range for incompatible GW sole-alpine binding combination vs. all other boot binding combinations tested. Dots represent outliers.

Table 12: Maximum, minimum, mean, standard deviation, and percent increase from 1.1 Wet for release torques for GW Sole-alpine binding combination vs GW sole-multi-norm binding combination for skier code L

	GW Sole/Alpine Binding			GW Sole/MN Binding		
	Max (Nm)	Mean ± SD (Nm)	% Increase	Max (Nm)	Mean ± SD (Nm)	% Increase
1.1 Dry	60.1	58.4 ± 0.9		59.2	58.4 ± 0.8	
1.1 Wet	63.4	58.0 ± 1.9		60.0	58.5 ± 0.8	
1.6 Wet	68.9	63.9 ± 3.1	9%	59.4	58.7 ± 0.6	0%
1.10 Wet	80.3	65.8 ± 7.1	12%	81.6	81.0 ± 0.3	28%

Table 13: Percent increase from 1.1 Wet for all boot-binding combinations separated by skier code

	Code L					Code N				
	GW Sole-Alpine	Potted Sole-MN	GW Sole-MN	Test Sole-Alpine	Test Sole-MN	GW Sole-Alpine	Potted Sole-MN	GW Sole-MN	Test Sole-Alpine	Test Sole-MN
1.6 % Increase	9.2%	7.6%	0.2%	16.3%	-0.8%	10.1%	17.6%	3.1%	17.4%	6.2%
1.10 % Increase	11.9%	28.8%	27.7%	26.7%	31.3%	13.6%	29.1%	29.1%	26.8%	25.7%

5.4 Discussion

In this study the release and retention behavior of incompatible boot binding combinations was compared with the same behavior of compatible boot binding combinations. It was seen that incompatible combinations released at a much lower torques in the rear loaded position when compared the other data of the same skier code. Although the release values of Test 1.10 still meet the performance standard described in ASTM-F3728 this value is significantly lower than seen for any other boot-binding system in the analyses and experimentation completed throughout this manuscript. If the results of Ski 1, which released outside of ASTM-F3728 limits for Test 1.10 in Chapter 2, are excluded from the above analysis, the Test 1.10 % increase from Test 1.1 Wet in Table 13 decease to 8% for both skier codes L and N, reflecting a negative change in mean release torque when compared to Test 1.6. Inadvertent or early release of bindings in a backward lean scenario have been discussed by Etlinger. In such falls where an inadvertent release occurred as the skier approached a mogul was determined that weight shift to the back of the ski causes the boot to move into the heelpiece and forward pressure can no longer be maintained. It was determined that increasing the IV would not prevent this inadvertent release as is bolstered by the findings above where the release torque is low across both skier codes tested [21]. It is hypothesized that this early release mechanism is exacerbated by the rockered design of the GW boot sole. Releasing at lower torques than other boot-binding combinations suggests that putting GW soles into alpine bindings puts the skier at risk for an inadvertent release. Although the severity of injuries in inadvertent releases is not well documented, they have been found to be just as common as injuries caused by failure to release, both accounting for about 1% of ski injuries. Injuries due to inadvertent releases commonly impact the head, neck, and shoulders [3].

5.5 Summary

GripWalk soles used during this testing were able to fit into alpine bindings and forward pressure indicators were able to be adjusted to manufacturer guideline satisfaction. However, incompatible boot-binding combinations do not release similarly to approved combination under load. Although the bindings were released during Test 1.1 Pure twist without issue, the incompatibilities became apparent when the bindings were in rear loaded configurations. This is a shortcoming that would not be detected during standard ski shop assessment of binding release. It is recommended that only compatible approved boot-binding combinations are used to minimize risk of injury.

CHAPTER 6: CONCLUSIONS

In conclusion, all the boot-binding combinations tested throughout this paper adhered to the ASTM-F3728 performance standard. However, although these bindings met this performance standard this does not change the differences in performance and user experience a skier might have with retention and release on the slopes. With boots and bindings having a half-life about 2.5 years, many seasoned skiers are being thrust into a landscape where their new boot and binding combinations may not perform the same way as their old tried and true combinations [5]. It has been found that yearly inspection of binding release reduces the risk of injury [22]. Adherence to ASTM and ISO standards as they apply to ski binding release testing by a professional has been shown to reduce risk of lower leg fracture when compared to countries who do not adhere to these standards [23]. In no circumstances should skiers be adjusting their own bindings IV, even after an inadvertent release as this could put the skier at higher risk for a no-release in a different weight distribution configuration. To reduce the risk of early release related injuries skiers should only use ISO approved boot binding combinations.

6.1 Limitations and Recommendations

This study was limited by the number of non-alpine pieces of equipment that could be acquired for testing. This analysis only includes one multi-norm ski binding and one GripWalk sole. Further research into this area should include a greater variety of equipment from a variety of manufacturers. Additionally, because the MN binding is designed for a more advanced skier, the MN binding was unable to be adjusted to low release values satisfying skier code J. Conversely, the alpine bindings were unable to satisfy the high release values of skier code P. This reduced the number of skier codes that could be used for comparison. An additional limitation was the exclusion of forward lean testing. This test is used to determine the preload in Test 1.6 and Test 1.10 and typically correlated with release values in a forward leaning fall. Largely this study investigated the release and retention characteristics of binding release at the toe.

Although all tests were repeated in wet conditions, all the testing was performed at ambient room temperature. Further investigation should investigate the impact of temperature on binding release as it has been seen that icing has an impact on release characteristics [1]. Impact of icing and temperature should be examined in terms of both the friction on the AFD as well as the stiffness of the binding's release spring. The impact of wear should also be investigated. Though many of the bindings used in this testing were subjected to many release cycles for testing, the impact of repeated release and wear of bindings was not considered.

Finally, the investigations in this manuscript defined risk as the probability of a lower leg bone fracture or probability of an inadvertent release. However, due to the test methods and limitations of the 504 tester currently, an estimation of risk for knee ligament injuries could not be made. Current literature suggests a mechatronic style binding as the most promising for reduction of ACL injuries [22]. Any such advancements in binding technologies should utilize the 504 as a tool for measuring retention and release of the binding and would especially benefit from 504s ability to verify sensed forces. Further investigation into the prevalence of ACL injuries should not overlook the differences in male and female binding release and anatomies. Studies have reported that females are at three times greater risk for ACL injuries than male counterparts [24].

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