Worcester Polytechnic Institute
Digital WPI

March 2013

# Torque-Displacement Binding Tester

Bradley William Merrill
*Worcester Polytechnic Institute*

Justin Lagassey
*Worcester Polytechnic Institute*

## Repository Citation

Merrill, B. W., & Lagassey, J. (2013). *Torque-Displacement Binding Tester*. Retrieved from https://digitalcommons.wpi.edu/mqp-all/1123

# Torque-Displacement Binding Tester

ME-CAB-1206

Design of a ski binding test device with torque and displacement sensing

A Major Qualifying Project Report

Submitted to the faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

in Mechanical Engineering

by

Bradley Merrill

In cooperation with

Justin Lagassey

Date: 3/12/2013

Keywords:
1) Alpine Ski Binding Tester
2) Torque Sensing
3) Displacement

Approved:

Prof. C A Brown, Major Advisor

# Abstract

Inadvertent release of a ski binding occurs when the ski binding releases the skier under non-injurious loading conditions and has been known to cause loss of control leading to severe upper body injury and death. Work required to release the ski boot from the ski binding is a parameter that influences the tendency for inadvertent release. The project utilized Suh's Axiomatic method for the design of a device that measures work to release through the simultaneous measurements of torque and displacement. The optical mouse is tested and recommended as a low cost displacement sensor.

## Acknowledgements

We thank:

Robert Johnson, Jasper E. Shealy, and Carl Ettlinger for their dedication to skier safety,

Rick Howell, for enlightening us on ski binding design,

and Professor Christopher A. Brown, for advising us through to the completion of our project's success.

# Table of Contents

Abstract ..... i

Acknowledgements ..... ii

Table of Figures ..... v

1. Introduction ..... 1

  1.1 Objective ..... 1

  1.2 Rationale ..... 1

  1.3 State of the Art ..... 2

  1.4 Approach ..... 4

2. Design Decompositions and Constraints ..... 4

  2.1 Zero level Decomposition Theme ..... 5

  2.2 First Level Decomposition Theme ..... 5

    2.3.0 General Statement First Level Decomposition ..... 6

    2.3.1 FR1 – Functional Requirement 1 ..... 6

    2.3.2 DP1 – Design Parameter 1 ..... 6

    2.3.4 FR2 ..... 7

    2.3.5 DP2 ..... 7

    2.3.6 FR3 ..... 7

    2.3.7 DP3 ..... 7

    2.3.8 FR4 ..... 7

  2.4 Second Level Decomposition Theme ..... 7

    2.4.0 General Statement Second Level Decomposition ..... 8

    2.4.1 FRi.1 ..... 8

    2.4.2 DPi.1 ..... 8

    2.4.3 FRi.2 ..... 9

    2.4.4 DPi.2 ..... 9

    2.4.5 FRi.3 ..... 9

    2.4.6 DPi.3 ..... 9

3. Physical Integration ..... 9

  3.1 Introduction of New Constraints ..... 10

  3.2 Displacement Sensing ..... 10

3.3 Displacement Calibration ........ 13
3.4 Torque Sensing ........ 13
3.5 Combining Signals ........ 14
4. Testing of the Final Design ........ 15
4.1 Displacement testing ........ 15
4.1.1 Materials ........ 16
4.1.2 Jig Preparation ........ 16
4.2 Linearity Testing ........ 17
4.3 Precision Testing ........ 18
5. Discussion ........ 20
5.1 Accomplishments ........ 20
5.2 Societal Context ........ 20
5.3 Deficiency in Prior art and Considerations ........ 20
5.3.1Program Design ........ 20
5.3.2 Multiple Mice ........ 21
5.3.3 Mechanical Considerations ........ 21
5.4 Commercial Use ........ 21
6. Concluding Remarks ........ 21
7. Works Cited ........ 23
8. Appendix A ........ 25

## Table of Figures

Figure 1: Signal Detection:  (Heeger, 1998) ........ 3
Figure 2: Test Axes (ASTM, 2005) ........ 5
Figure 3: First level decomposition ........ 5
Figure 4: Design is decoupled and therefore satisfies independence axiom ........ 6
Figure 5: The second level of axiomatic decomposition, notice the FR repetitiveness ........ 8
Figure 6: Displacement VI ........ 11
Figure 7: Mouse Settings ........ 12
Figure 9: Strain Null and Shunt Calibration ........ 13
Figure 10: Strain output ........ 14
Figure 11: Testing Apparatus ........ 15
Figure 12: Jig for displacement testing ........ 16
Figure 13: Pixel vs. Real Displacement ........ 17
Figure 14: Displacement Calibration ........ 18
Figure 15: Sample Distribution ........ 19
Figure 16: Random Number Distribution ........ 19

# 1. Introduction

## 1.1 Objective

The objective of this Major Qualifying Project is to design a device that can evaluate the susceptibility for inadvertent release of alpine ski bindings by measuring the work required to release the ski boot from the binding. Inadvertent release is defined as a release of the ski binding under loads that are not injurious to the skier.

## 1.2 Rationale

Testing susceptibility for inadvertent release is important because inadvertent release can lead to loss of control at high velocity and cause life threatening collisions. During high velocity collisions, a greater impact force is required to slow the skier, increasing the risk for serious or fatal injury. According to the National Ski Areas Association, in 2011 there were 31 fatal skiing injuries (Hawks, 2011). The most prevalent mechanism of skier death involved impact with an object or person (Langran, 2012). Loss of control due to inadvertent release is a contributing factor in some of these collisions, and is especially likely when the skier fights for control and maintains velocity after losing one ski.

Inadvertent release is not well understood or recognized by most recreational skiers. Although inadvertent release is reported as causing only 1% of skiing injuries (Shealy, Ettlinger, & Johnson, 2005), the rate of inadvertent release injuries is likely underreported due to lack of awareness by the general public. Most skiers do not know what inadvertent release is, so it likely goes undetected as a cause for many accidents. Another cause of underreporting is that the casualty of an inadvertent release accident may be unable to recall the specific order of events surrounding the injury, especially when the casualty suffers a traumatic brain injury.

Identifying bindings that are prone to inadvertent release is also important because users who experience inadvertent release often react by increasing their retention settings beyond the settings recommended by the ASTM standard F 939 – 05a (ASTM, 2005). Increased settings may lead to greater risk for lower extremity equipment related (LEER) injury. One study found that bindings failed to release in 96% of all LEER injuries and that advanced skiers have higher binding retention settings than intermediate and novice skiers, even when controlling for weight and skier type (Urabe, Ochi, Onari, & Ikuta, 2002). The tendency to increase release settings in response to inadvertent release has been nicknamed the "ratchet effect" because skiers who increase their settings rarely lower the settings (Ettlinger, 2010). It would be beneficial for ski technicians to have a device that can better detect bindings prone to release problems so that corrective action can be taken before retention settings are increased beyond reason.

## 1.3 State of the Art

Detecting and measuring binding response to force profiles is an important goal of this project. Two functional requirements of a binding are to filter out injurious loads, and transfer control loads. Thus a binding must be able to successfully differentiate between injurious and non-injurious loads and release only under injurious loads. A recent publication by Shealy, Ettlinger, and Johnson focuses on using signal detection theory to analyze the release and retention criteria for alpine bindings (Shealy, Ettlinger, & Johnson, 2005). For alpine ski bindings, a signal is the collective description of the forces and moments that are transmitted through the boot-binding interface. Signal detection theory posits that there are two types of signals that a binging can see, injurious and non-injurious, and that the binding has two responses, release and retain. The two undesirable response scenarios occur when the binding response is to either retain during an injurious signal (miss) or to release when a non-injurious signal is applied (false alarm). The response criterion is the retention setting on the toe and heel piece as defined by the ASTM standard F 939 – 05a (ASTM, 2005). By setting the release setting higher than recommended, the probability of a false alarm is decreased but the probability of a miss is increased; likewise, lowering the retention settings incurs the opposite effect. The authors argue that the ASTM standard balances the risk of a miss or false alarm because the risk of injury from either event is about equal in the skiers whose bindings are set according to the standard (Shealy, Ettlinger, & Johnson, 2005). Development of the signal detection model to describe ski binding release and retention functions is important because it serves as a basis for this project; better bindings are better able to distinguish between signals, and should reduce probability of misses and false alarms.

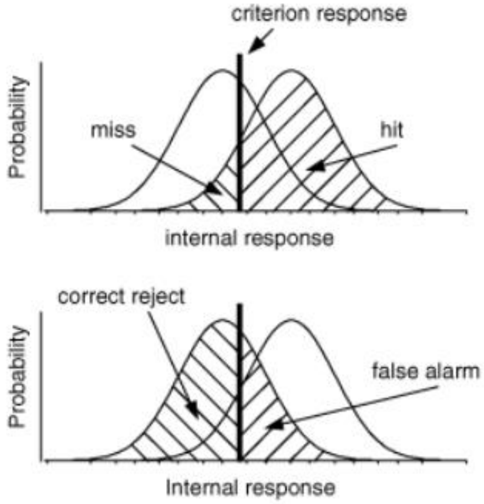


*Figure 1: Signal Detection: (Heeger, 1998)*

The binding testing device developed by this project seeks to improve on the current testing devices that service technicians use to measure the release peak torque values. An understanding of the functional requirements and design parameters of current devices is thus critical to this project's success. Vermont Ski Safety offers a binding release calibrator that tests the peak torque in both the forward bending and twisting toe release tests (Ettlinger, Vermont Ski Safety Equipment Inc., 2010). The testing device is constructed of three main parts; the foot, the arm, and the leg. The foot rests inside the boot and transfers torque applied to the arm to the boot. The leg is used in the forward bending test and extends the foot along the tibia. The arm functions as both a torque measuring device and a lever, where a torque is manually applied to release the boot from the binding. The cost of this device is quoted as $3,750 - $4,750, depending on the model and includes the three parts of the testing device mentioned above as well as a vice to secure the ski for testing. This project will develop a device which interfaces with the existing Vermont Binding Calibrator and will advance the state of the art by adding torque-displacement measuring capabilities to the current tester.

Inadvertent release is often seen as an issue that is confined to the binding, but there are other mechanisms between the ski and the boot that can reduce inadvertent release. Recent work at Worcester Polytechnic Institute has focused on stopping signals that could cause inadvertent release in the plate between the binding and the ski (Havener, 2009). One project used a shock absorbing plate that was designed to increase the work required for a forward bending release. By increasing the displacement up to the release point, the binding can absorb more energy, thus mitigating inadvertent release caused by high magnitude, short duration torques. Our project aims to build on this work through the development of a reproducible testing procedure that will encourage the measurement of work to release as a standard metric.

### 1.4 Approach

The current ASTM standard for maintenance level ski binding testing is focused on two parameters; torque required for lateral toe release, and torque required for vertical heel release (ASTM, 2005).These two parameters measure only maximum torque, however the rate at which energy is absorbed by the binding (work-to-release), and the ability to return to center are crucial for determining the safe performance of a binding.  Bindings that can absorb more energy prior to release likely have a lower tendency for inadvertent release.

Although currently possible, it is prohibitively expensive for most retailers to test the displacement of a boot in a ski binding while simultaneously measuring the applied torque. This testing is typically only performed to gain certification for new bindings, and costs thousands of dollars per test (Howell, 2012; International Standard, 2006).  Most skiers are therefore unaware if their bindings may have a tendency to release inadvertently.

The primary objective of this project is to complete a prototype device that can measure work to release of a ski boot from a ski binding at an affordable cost to most ski shops; under $500. The decomposition for a device that satisfies this functional requirement was realized using Suh's axiomatic design method. The testing apparatus will consist of two major components, a torque wrench, and a displacement sensor.  By measuring these two parameters simultaneously and integrating the area under the torque/displacement curve, the work to release can be calculated.

## 2.  Design Decompositions and Constraints

Axiomatic design was used to organize the design of the binding tester. The collectively exhaustive principal of axiomatic decomposition ensures that the problem was thoroughly reviewed and described completely. The mutually exclusive principal organizes the design to minimize the information content and make the problem as simple as possible.

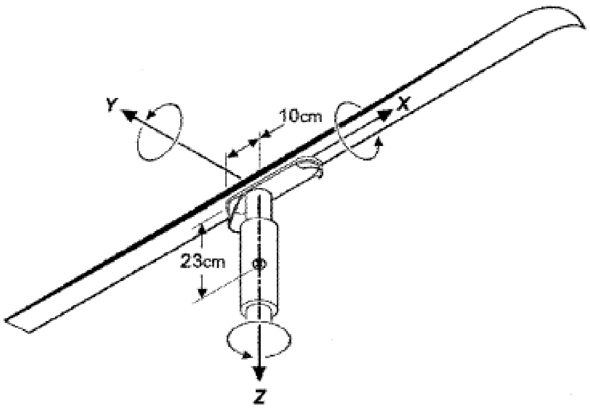


FIG. 2 Test Equipment

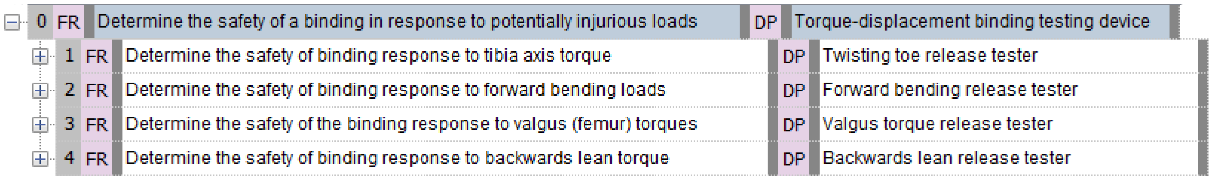
*Figure 2: Test Axes (ASTM, 2005)*

## 2.1 Zero level Decomposition Theme

The assumption of this project is that binding safety and performance can be evaluated by a set of parameters that together will identify good and bad bindings. Thus the fundamental functional requirement is that the design should determine the safety of a binding in response to loading.

## 2.2 First Level Decomposition Theme

The theme for top level decomposition was to test each component of the ski binding so that the independence axiom could be best satisfied. The major functions of a binding are to retain the boot in the binding while the skier performs controlled maneuvers and to release the boot when torque values exceed a control limit defined by ASTM standard F 339 – 05a (ASTM, 2005).The functions of retention and release are met by different binding design elements for different loading scenarios. Therefore the first level functional requirements were specified to address the functionality of each major binding component.



| | | | | |
|---|---|---|---|---|
| 0 | FR | Determine the safety of a binding in response to potentially injurious loads | DP | Torque-displacement binding testing device |
| 1 | FR | Determine the safety of binding response to tibia axis torque | DP | Twisting toe release tester |
| 2 | FR | Determine the safety of binding response to forward bending loads | DP | Forward bending release tester |
| 3 | FR | Determine the safety of the binding response to valgus (femur) torques | DP | Valgus torque release tester |
| 4 | FR | Determine the safety of binding response to backwards lean torque | DP | Backwards lean release tester |

*Figure 3: First level decomposition*

|  | DP1 | DP2 | DP3 | DP4 |
|---|---|---|---|---|
| FR1 | X | 0 | 0 | 0 |
| FR2 | 0 | X | 0 | 0 |
| FR3 | 0 | 0 | X | 0 |
| FR4 | 0 | 0 | 0 | X |

*Figure 4: Design is decoupled and therefore satisfies independence axiom*

### 2.3.0 General Statement First Level Decomposition

FRi "Determine the safety of the binding response to (z, +y, x through knee, -y) type of torque" for i = {1,2,3,4}, respectively. This form of functional requirement has three statements. "Determine the safety" means that the test must be able to distinguish between safe and unsafe bindings and that the parameters used are good indicators of field performance. "Of the binding response" means that the binding reacts appropriately in an unsafe loading scenario, and that this response is repeatable. "(z, +y, x through knee, -y) type of torque" identifies the axis about which torque is applied and the direction of the torque. This approach assumes that torque is the primary cause of injury.

### 2.3.1 FR1 – Functional Requirement 1

The first of two primary release mechanisms that almost all bindings have incorporated since the 1960's is the twisting toe release for torques applied about the z-axis, commonly called tibia torque (Beyl, 1962). Danger associated with inadvertent release in the toe piece is well-documented and has been reported in the literature (Brown, Hoffman, & Heinzmann, 1996). The effectiveness of binding response to tibia axis torques is critical to the function of the binding.

### 2.3.2 DP1 – Design Parameter 1

The binding testing apparatus for tibia torque is generalized at this level, although the concept is expanded to include continuous torque and displacement monitoring of the boot-binding system. The design suffers from a small degree of coupling because certain components are reused in the forward bending tester. This coupling is not a major issue because the components are used in different configurations and the transitions between configurations is necessary for existing designs (Ettlinger, Vermont Ski Safety Equipment Inc., 2010). The coupling becomes an issue if testing multiple loads simultaneously.

### 2.3.4 FR2

The other major release mechanism is the vertical heel release for positive torques applied about the y-axis, commonly known as forward bending torque. This release mechanism is designed to prevent injury to the tibia such as boot-top fractures or a rupture of the Achilles tendon. Popularized in the 1970's, releasable heels have been in use almost as long as toe pieces (Brown C. A., 2006). The same concerns for the releasable toe piece apply to the heel; the binding must transmit control loads and not transmit injurious loads, from the ski to the skier.

### 2.3.5 DP2

The forward bending tester is similar to the tibia torque tester, but is aligned such that the torque and angular displacement is measured about the y-axis. Like the tibia torque tester there is continuous monitoring of the torque and the displacement of the boot-binding system.

### 2.3.6 FR3

Some newer bindings, such as Tyrolia's diagonal bindings, have incorporated vertical toe release to respond to negative torque applied about the y-axis (backward bending torque) (Tyrolia, 2013). The incorporation of this moment in the design criteria is in anticipation that the availability of a binding tester for these loading scenarios will encourage binding companies to improve current designs.

### 2.3.7 DP3

The binding tester follows the same procedure as the forward bending procedure but in the opposite direction.

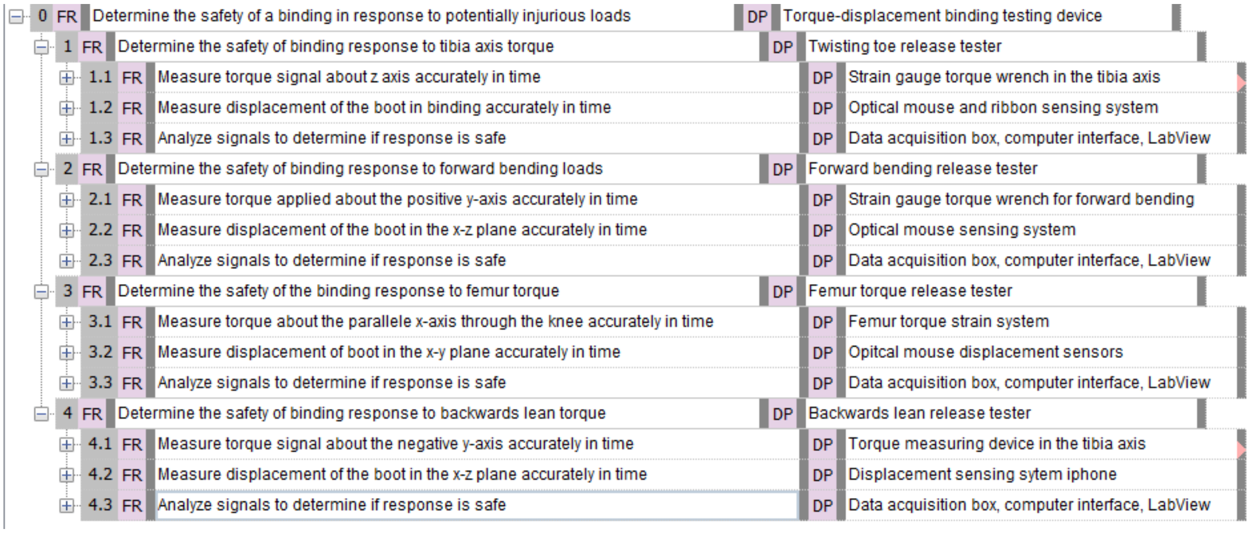
### 2.3.8 FR4

One manufacturer, Knee Binding, has introduced a lateral heel release function to address force applied directly underfoot that produces a torque about an axis parallel to the x-axis and through the knee (Pure Lateral, 2013). Many bindings are not designed to protect skiers from these loading scenarios and the availability of this testing device might pave way towards safer bindings.

## 2.4 Second Level Decomposition Theme

The theme for second level decomposition is release-retention criteria. The release criterion is that the binding release the boot when the acted upon by an injurious torque. The retention criterion is that the binding absorb non-injurious loads that momentarily exceed the control limit. During normal skiing maneuvers, especially in racing, the applied load to the ski will momentarily exceed the control values for release. This is measured by the amount of energy that the binding can absorb before a release. In application, the energy absorbed is the integral of torque with respect to the angular displacement. The binding absorbs energy by allowing the boot to displace in the binding for a short distance, and returns to center when the applied load drops below the control limit.

The release criterion for the binding test is defined by a metric that measures the tolerance on the maximum torque transmitted to the boot during release. The retention criterion for the binding tester is based on the amount of energy absorbed before a release occurs and should be maximized. These two metrics are linked by the measurement of torque so the decomposition was decomposed by torque, displacement and analysis. This satisfies the independence axiom by decoupling release and retention in the analysis functional requirement. The decomposition is exhaustive and mutually exclusive.



| | | | | |
|---|---|---|---|---|
| 0 | FR | Determine the safety of a binding in response to potentially injurious loads | DP | Torque-displacement binding testing device |
| 1 | FR | Determine the safety of binding response to tibia axis torque | DP | Twisting toe release tester |
| 1.1 | FR | Measure torque signal about z axis accurately in time | DP | Strain gauge torque wrench in the tibia axis |
| 1.2 | FR | Measure displacement of the boot in binding accurately in time | DP | Optical mouse and ribbon sensing system |
| 1.3 | FR | Analyze signals to determine if response is safe | DP | Data acquisition box, computer interface, LabView |
| 2 | FR | Determine the safety of binding response to forward bending loads | DP | Forward bending release tester |
| 2.1 | FR | Measure torque applied about the positive y-axis accurately in time | DP | Strain gauge torque wrench for forward bending |
| 2.2 | FR | Measure displacement of the boot in the x-z plane accurately in time | DP | Optical mouse sensing system |
| 2.3 | FR | Analyze signals to determine if response is safe | DP | Data acquisition box, computer interface, LabView |
| 3 | FR | Determine the safety of the binding response to femur torque | DP | Femur torque release tester |
| 3.1 | FR | Measure torque about the parallele x-axis through the knee accurately in time | DP | Femur torque strain system |
| 3.2 | FR | Measure displacement of boot in the x-y plane accurately in time | DP | Opitcal mouse displacement sensors |
| 3.3 | FR | Analyze signals to determine if response is safe | DP | Data acquisition box, computer interface, LabView |
| 4 | FR | Determine the safety of binding response to backwards lean torque | DP | Backwards lean release tester |
| 4.1 | FR | Measure torque signal about the negative y-axis accurately in time | DP | Torque measuring device in the tibia axis |
| 4.2 | FR | Measure displacement of the boot in the x-z plane accurately in time | DP | Displacement sensing sytem iphone |
| 4.3 | FR | Analyze signals to determine if response is safe | DP | Data acquisition box, computer interface, LabView |

*Figure 5: The second level of axiomatic decomposition, notice the FR repetitiveness*

## 2.4.0 General Statement Second Level Decomposition

There are three generizable second level requirements described below: “Measure torque about..., Measure displacement of…, and Analyze signals to...”.

## 2.4.1 FRi.1

“Measure the torque about the (z, +y, x through knee, -y) axis accurately in time”. This torque measurement must be accurately timed so that torque data can be synchronized with displacement data.

## 2.4.2 DPi.1

The torque wrench from the Vermont Ski Safety torque wrench was modified by the addition of a strain gauge. The surface preparation for the strain gauge mounting follows Micro-Measures’ strain gauge preparation guide (Vishay Precision Group, 2011). First the metallic surface was degreased, and wet abrased using progressively finer silicon carbide paper. The surfaced was then neutralized with M-Prep neutralizer, and Loctite 496 was used to bond the strain gauge to the surface. Lead wires were soldered onto the strain gauge and the whole unit was submersed in hot glue to prevent the gauge and solder from damage.

### 2.4.3 FRi.2

“Measure the displacement of the boot in the (z, +y, x through knee, -y) plane accurately in time”. The displacement measurement, like torque, must be accurately timed so that the data can be synchronized.

### 2.4.4 DPi.2

The displacement sensing involved a rigid target of carboard attached to the boot such that the optical mouse could be held against it. The exact configuration of the mouse and target changed considerabley depending on the type of release being tested, but the setup worked through maintaining pressure between the target and the mouse, while keeping the mouse fixed during boot displacement.

### 2.4.5 FRi.3

“Analyze signals to determine if the response is safe”. The analysis functional requirement deals with the computation of the release and retention metrics. This is the final treatment of the data and determines work-to-release.

### 2.4.6 DPi.3

The signals were acquired and digitalized through a data acquisition box and were processed in LabView software with final analytics completed in excel.

## 3. Physical Integration

For a device to successfully evaluate the susceptibility for inadvertent release of alpine ski bindings, the device must be capable of differentiating between high-performing and poor-performing bindings. The tolerance provided by the torque sensor should satisfy the performance requirements set forth in ANSI F1061 – 97, and the tolerance provided by the displacement sensor should satisfy the ISO 9462 return-to-center test. Torque and displacement sensing options that meet the preceding standards were explored. The difficulty in measuring work-to-release arises with synchronizing the displacement and torque time signals. Although these two parameters can be observed relatively easily as separate analog signals, it becomes challenging to process this data simultaneously without the use of digital signal processing. After failed attempts of using a high speed camera to physically couple a torque and a displacement reading, it was realized that other digital methods need be explored. Consequently, LabView provides a user friendly option for data acquisition and data manipulation.

## 3.1 Introduction of New Constraints

New constraints were generated when LabView was selected as the interface for data acquisition. The sensors that be chosen must be able to convert physical displacement and torque signals to electrical signals; the analog electrical signals must then be converted to digital signals so that they can be read by a PC. Different transducers, which convert mechanical energy into electrical energy, were explored for their use as torque and strain sensors.

Programming knowledge now constrained the feasibility of fulfilling most of the functional requirements described in chapter 2. The time constraint thus had the greatest influence on the overarching functional requirements of this project. Programming knowledge can be improved over time but more importantly it takes time to complete the project. Inherently there is functional coupling that would influence the direction of the project. The process integration described below aims at collecting the data necessary to measure work-to-release, however design suggestions that adhere to the original FR-DP matrix are listed in the discussion section.

## 3.2 Displacement Sensing

Due to high volume production, the optical mouse offers a high resolution displacement sensing option at nearly 2% the cost of conventional displacement sensors, such as LVDT (linear variable differential transformer) and RVDT (rotary variable differential transformer) sensors. Unlike mechanical-electrical displacement transducers, an optical mouse converts an electromagnetic signal, light, to an electrical signal by reflecting LED light off of a surface onto a CMOS (complementary metal-oxide semiconductor) sensor and compares surface images thousands of times per second in a DSP (Digital Signal Processor) (Ng, 2003). Its position is determined relative to how well the previous image matches up to the current. Although not a suitable displacement transducer for all applications, namely when taking measurements on reflective surfaces or over large distances, the optical mouse was investigated for displacement measurements of ski boots during ski-binding torque tests.

In a 2003 study by T.W. Ng of The National University of Singapore, it was determined that an optical mouse can function as an effective two-dimensional displacement sensor when measuring small distances on opaque surfaces (Ng, 2003). In this study an optical mouse was displaced 1mm horizontally and 1mm vertically: The mean square error calculated was .018mm$^2$ and the mean $R^2$ value was .9914. Before physical integration with the ski-binding testing device, further testing was performed to determine whether this high repeatability could be reproducible during mouse displacements correlating with distances a ski boot travels during binding torque tests. The results of these tests can be found in chapter 4.

An optical mouse, although capable of measuring displacement, is intended to provide interface for human interaction, hence the acronym HID (human interface device). Therefore, it is necessary to reverse engineer the mouse to an extent where displacement data can be acquired. The original displacement Virtual Instrument (VI) that was created for displacement sensing can be seen below in Figure 6.

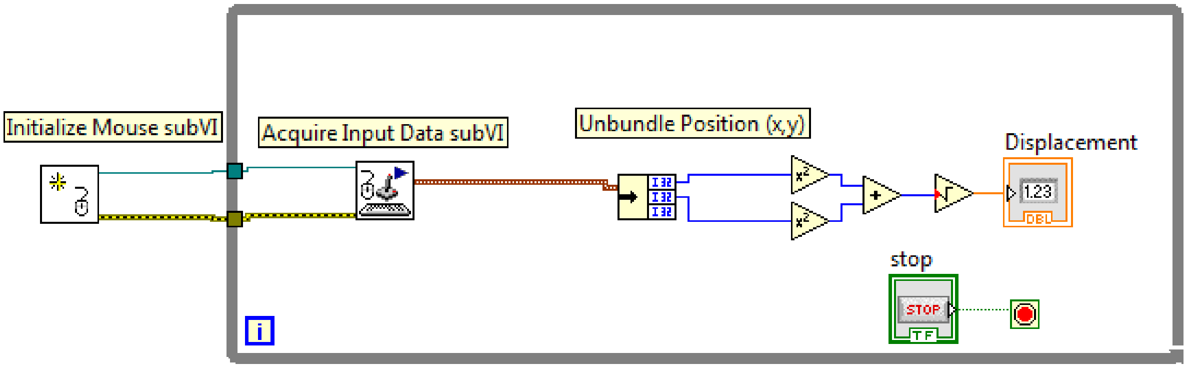
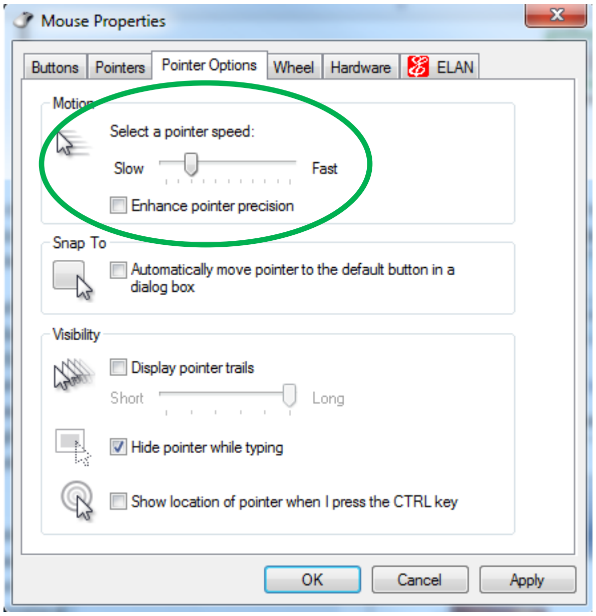


*Figure 6: Displacement VI*

The x,y position of the cursor relative to the upper left hand corner on the monitor is obtained with built-in LabView Virtual Instruments, (Initialize Mouse, and Acquire Input Data sub VI's). The function $|s|(t)= (dx^2+dy^2)^{1/2}$ is evaluated in the while loop above yielding the displacement, in pixels, relative to the upper left hand corner of the monitor.

In the above VI, the position of the mouse is coupled with the position of the cursor on the monitor. One issue with this design is that the position of the mouse cannot be evaluated when the cursor comes in contact with the edge of the monitor. As stated earlier, position is measured with respect to the upper left hand corner of the monitor, so the mouse must be initially displaced down and right to achieve any reasonable displacement measurement. To fully decouple this system it would be necessary to analyze the mouse data before it reaches the mouse driver; for the purpose of this project, sufficient complexity is removed by allowing displacement to be measured on a user keystroke. By taking measurement on a keystroke, the user does not need to interact with the mouse which could potentially result in faulty measurements.

In the final displacement VI, Figure 8, two-dimensional mouse displacement can be measured in any direction when the cursor is initially located towards the center of the monitor. From observation, the displacement of a ski boot in a ski binding is on the order of 1-10cm and the cursor will not come in contact with the edge of the monitor so long as the cursor sensitivity is turned down sufficiently, and the cursor acceleration is turned off. The correct settings can be seen below in Figure 7.



Motion

Select a pointer speed:

Slow Fast

☐ Enhance pointer precision

Snap To

☐ Automatically move pointer to the default button in a dialog box

Visibility

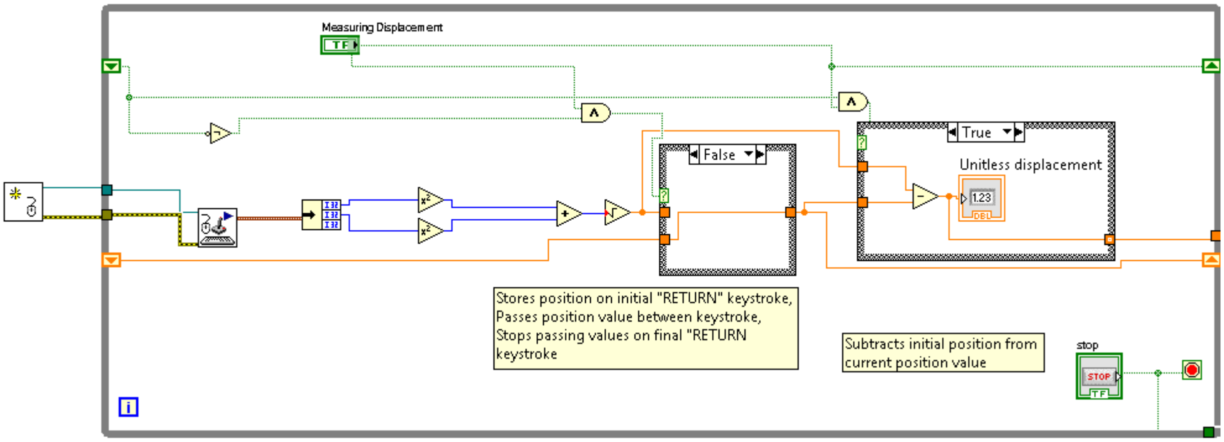
☐ Display pointer trails

Short Long

☑ Hide pointer while typing

☐ Show location of pointer when I press the CTRL key

*Figure 7: Mouse Settings*



Stores position on initial "RETURN" keystroke, Passes position value between keystroke, Stops passing values on final "RETURN keystroke

Subtracts initial position from current position value

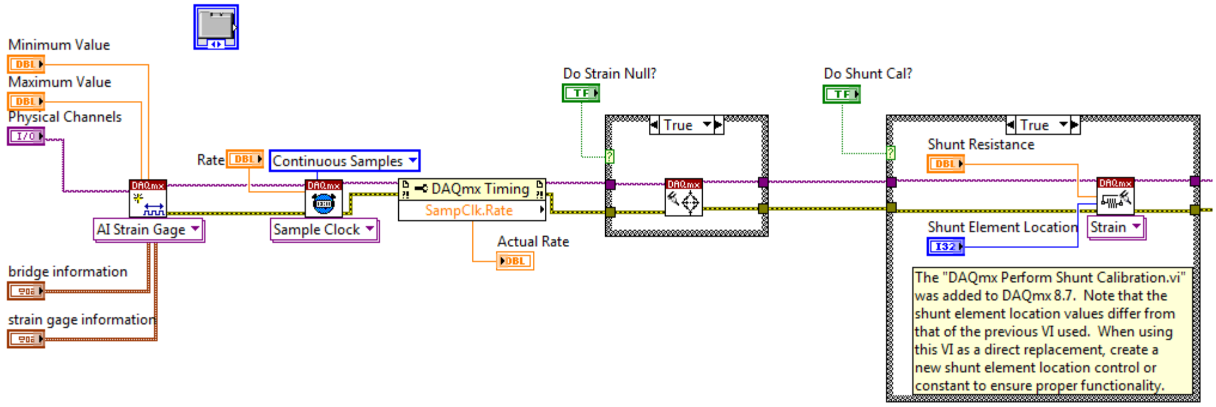
*Figure 8: Revised Displacement VI*

## 3.3 Displacement Calibration

The displacement VI measures the cursor's displacement in pixels; thus the pixel displacement needs to be converted to a unit displacement for measuring work. By displacing the optical mouse a known distance, a function relating pixel displacement to the known displacement can be calculated. By nature of optical mouse operation there is a degree of systematic, as well as random error that exists in its measurements. Methods for improving the accuracy and repeatability of the measurements were explored. By using the same or a similar surface for calibration as for taking measurements the systematic error can be decreased. Likewise, if the measurement surface is displaced linearly such that the CMOS operates on nearly an identical trajectory, random error caused by surface irregularities should recur across multiple measurements, increasing the repeatability of the results.

## 3.4 Torque Sensing

For measuring torque, a Micro-Measures 120 Ohm strain gauge was outfitted to the Vermont Ski Safety tester as shown in Figure 11. The final iteration consisted of a Quarter-Bridge I (National Instruments, 2012) configuration used in conjunction with a Vishay 2310B Signal Conditioning Amplifier, and a USB-6229 BNC for analog to digital signal conversion. Hardware strain nulling and shunt calibration were performed due to availability of the 2310B signal amplifier, however these operations can also be performed in software; Strain Null and Shunt Calibration Sub-VI's can be found in the help drop-down menu in LabView, and are shown in the case structures in Figure 9.



The "DAQmx Perform Shunt Calibration.vi" was added to DAQmx 8.7. Note that the shunt element location values differ from that of the previous VI used. When using this VI as a direct replacement, create a new shunt element location control or constant to ensure proper functionality.

*Figure 9: Strain Null and Shunt Calibration*

Strain data is sampled continuously, indexed as an array, and sent to an excel spreadsheet when the while loop has completed executing. If it is desired to graph the strain data while it is outputting, a wire can connect the DAQread sub-VI to a waveform graph within the while loop. The code in Figure 10 shows how strain data is indexed, and outputted as an array to the destination spreadsheet.

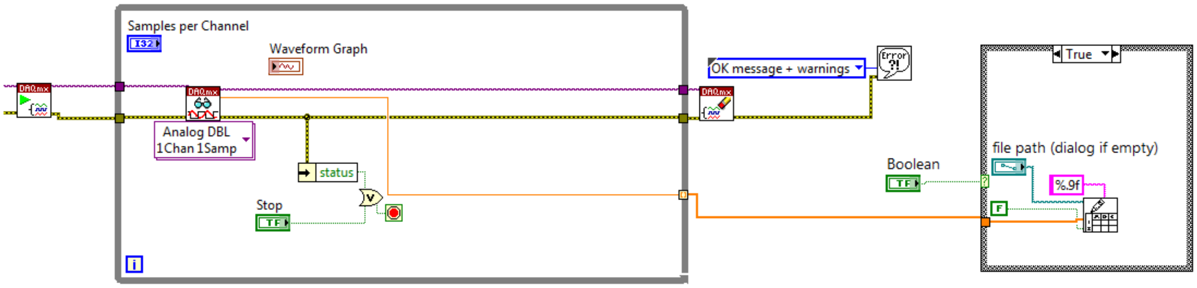


*Figure 10: Strain output*

## 3.5 Combining Signals

Attempts were made at combining the two signals. Before sending data to external analysis software the data must be first indexed as an array. Difficulty in indexing the mouse displacement data ensued, prohibiting the ability to couple the torque and displacement time signals and successfully analyze work-to-release. Data from both the mouse and strain gauge were able to be read simultaneously, however mouse movement data could not be indexed; further investigation is needed to understand what inhibited mouse data storage.

*Figure 11: Testing Apparatus*

## 4. Testing of the Final Design

The optical mouse was tested for feasibility as a displacement sensor.

### 4.1 Displacement testing

Parameters that were tested in the feasibility study were linearity and repeatability. The device must be able to differentiate between high-performing and poor-performing bindings; therefore repeatability across multiple tests using the same equipment is most important. Linearity shows how accurate the data is without a correction factor. Tests were performed using the jig in Figure 11. Note that Figure 11 shows the mouse positioned vertically; however the tests were performed while moving the mouse horizontally. Measurements were taken in a way to mimic how data would be acquired during ski binding testing.

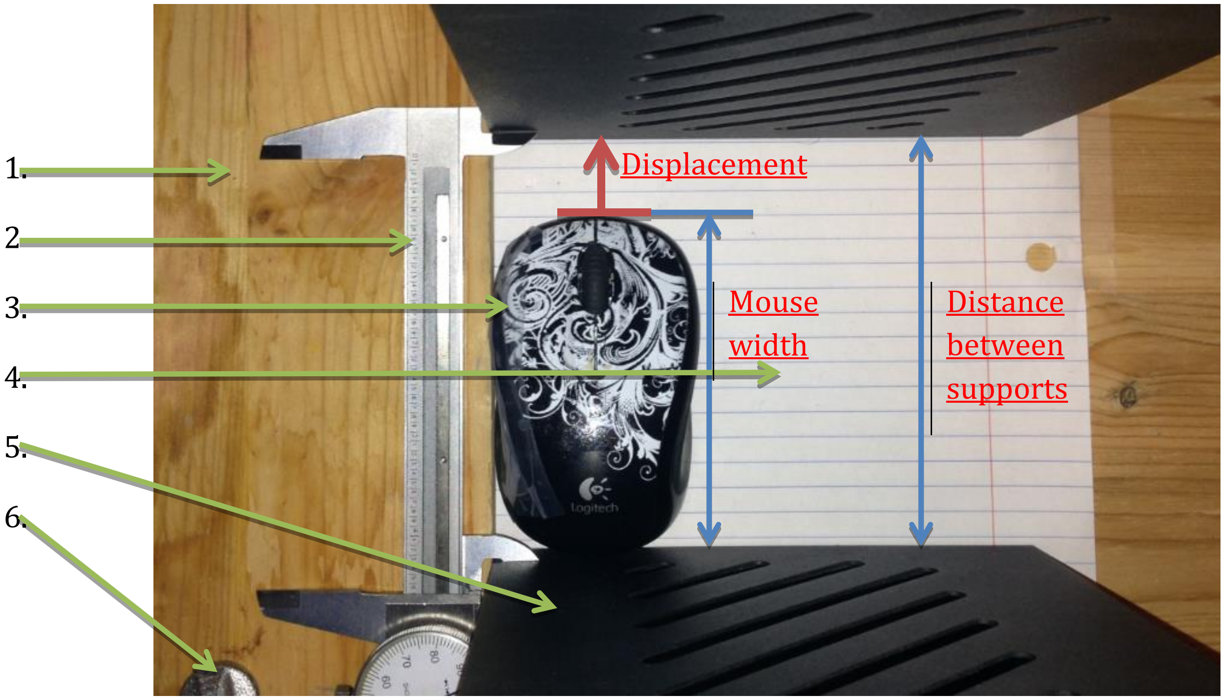


*Figure 12: Jig for displacement testing*

### 4.1.1 Materials

LabView is opened and the displacement VI from Figure 8 is ran. The following materials were used in this experiment:

1. 2 X .5” thickness wood sheet
2. 1 X Vernier Caliper with .001” graduations
3. 1 X Logitech M305 wireless mouse
4. 1 X Sheet of paper
5. 2 X 90° steel supports
6. 3 X C-Clamps,
7. 1 X PC

### 4.1.2 Jig Preparation

To prepare the jig, the lower steel support is clamped down to the base wood, with the paper in between. The second wood piece is placed at a right angle against the steel support and clamped down, also to the base wood. The Vernier caliper is then clamped in a way that the outer jaw closest to the dial is secure against the steel support, and the free jaw extends collinearly with the edge of the top wood sheet.

## 4.2 Linearity Testing

The second steel support is set an unknown distance away from the clamped steel support, forming a right angle with the top wood piece. This distance is measured with the Vernier caliper and recorded in Excel. The width of the mouse is also measured and recorded.

The mouse is then moved linearly from the first steel support until it contacts the second support. The displacement in LabView is recorded. This is performed twice more, and the mean of the three displacements is calculated. This procedure is repeated 14 more times, gradually increasing the distance between the steel supports. The final distance the mouse moves is 1.645”. The mouse width is subtracted from the measured distance between the supports, yielding the actual distance that the mouse moved. The pixel displacement (optical mouse measurement) is then plotted as a function of the actual displacement (Vernier Caliper measurement). The results in Figure 13 below indicate linear correlation between pixel displacement and actual displacement.

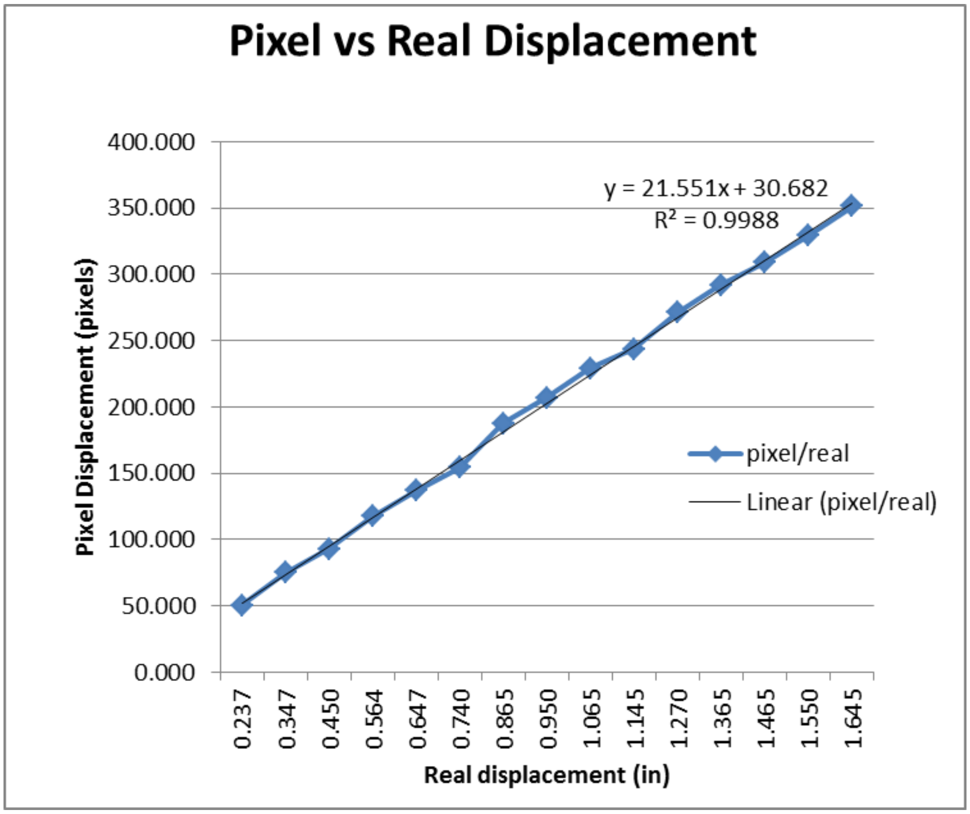


*Figure 13: Pixel vs. Real Displacement*

Note that the mouse was moved from the same initial position on each test. Moving the mouse intermittently, such that it only moves in one direction, never returning to the initial position was attempted; however the results were very non-linear. This is likely due to error propagation of the initial acceleration and final deceleration on every measurement. Performing the experiment using the first testing procedure is representative of how the mouse would measure displacement during binding torque tests, as displacement of the ski boot is also continuous during these tests.

## 4.3 Precision Testing

Next, the optical mouse was tested for measurement repeatability. In this test the mouse was displaced 10 times, a distance of 2.634" (caliper measurement). The mean of this sample was calculated and a function converting the mean to the actual displacement was generated. This same function was applied to every measurement (mouse measurement), and it was observed how closely the measured values (mouse measurement) correlated with the accepted values (caliper measurement). The chart below, Figure 14, indicates that the measured values were very close to the accepted. The percent error of the value furthest from the mean was .535%.

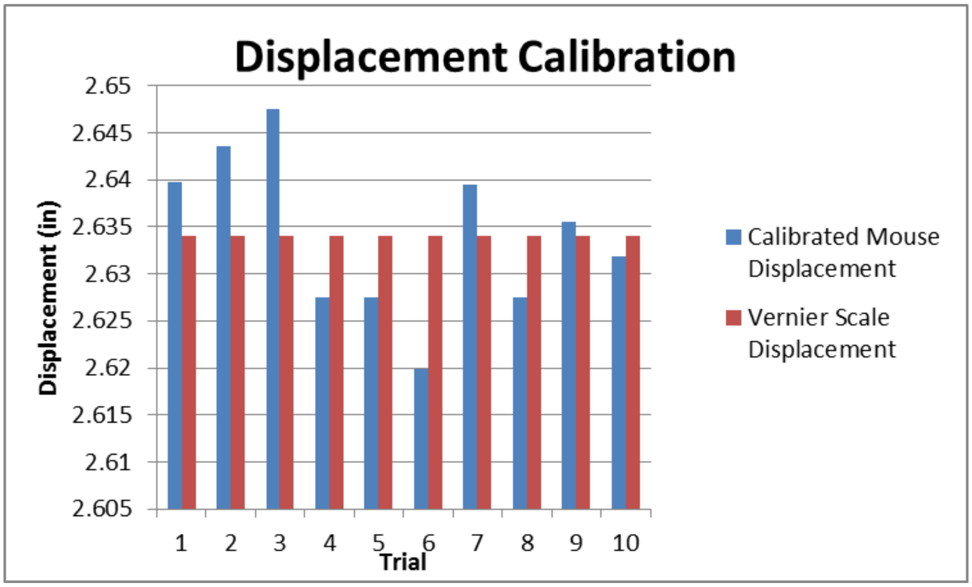
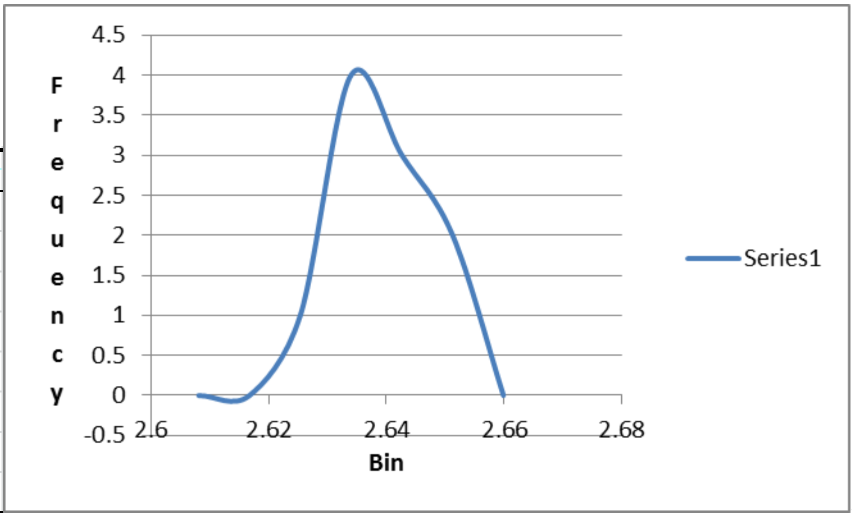


*Figure 14: Displacement Calibration*

The data was then tested for normal distribution. The standard deviation was calculated and subsequently the data was normalized and plotted in a histogram; Figure 15. Using this same model, 2000 random numbers were generated and plotted; Figure 16. The distribution in the sample satisfied the normal distribution model. According to the three-σ-rule, 99.73% of all normally distributed data will fall within three standard deviations of the mean. Thus with a .008615” standard deviation, 99.73% of all data will be within .0258” of 2.634”. The precision of the optical mouse is therefore sufficient for use in ski binding torque tests.

| *Bin* | *Frequency* |
|---|---|
| 2.608155 | 0 |
| 2.61677 | 0 |
| 2.625385 | 1 |
| 2.634 | 4 |
| 2.642615 | 3 |
| 2.65123 | 2 |
| 2.659845 | 0 |
| More | 0 |



a

*Figure 15: Sample Distribution*

| *Bin* | *Frequency* |
|---|---|
| 2.608155 | 7 |
| 2.61677 | 37 |
| 2.625385 | 279 |
| 2.634 | 677 |
| 2.642615 | 678 |
| 2.65123 | 262 |
| 2.659845 | 55 |
| More | 5 |

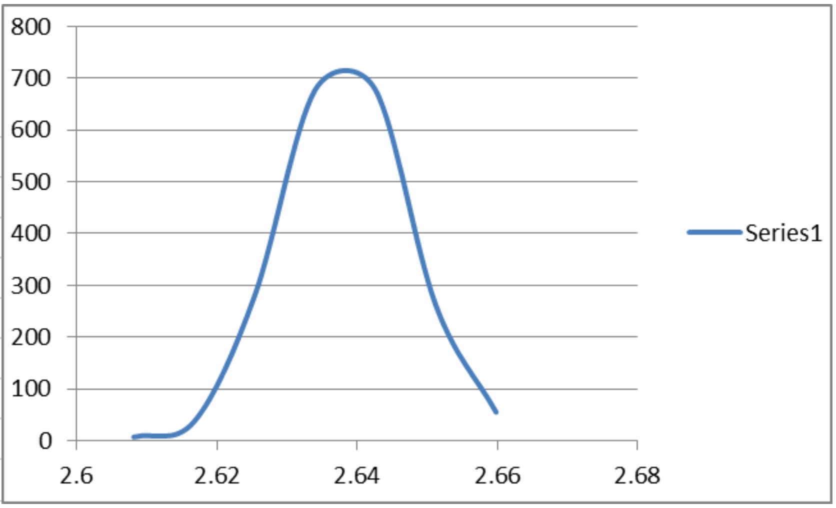


*Figure 16: Random Number Distribution*

# 5. Discussion

## 5.1 Accomplishments

The objective of this Major Qualifying Project was to design a device that can evaluate the susceptibility for inadvertent release of alpine ski bindings by measuring the work required to release the ski boot from the binding. Due to programming difficulties the team was unable to acquire the data necessary for calculating work-to-release; the project was successful in other aspects.

Recognizing the need for a ski binding work-to-release testing device is a significant step towards better ski binding design. Value is defined by a device's functional requirements; a method for quantifying the functional requirements is therefore essential for recognizing a device's value. Work-to-release is an indication of a ski binding's performance; however no device is currently available for measuring this parameter.

A major accomplishment of this project was identifying and verifying the optical mouse as a viable displacement sensor in ski binding testing. Optical mice may be overlooked as displacement sensors; they are not displacement transducers in of themselves, but electromagnetic transducers.

## 5.2 Societal Context

The first Fundamental Engineering Canon states that, "Engineers shall…hold paramount the safety, health, and welfare of the public" (NCEES, 2013). Engineering Standards play a pivotal part in protecting our role as engineers. A National Standards Body will normally determine a market need for a standard (ISO, 2009). Market need may be qualified for a number of reasons; in the context of this project, the market need is safeguarding the interests of the skiing public. The most outreaching goal of the torque-displacement binding sensor is to prevent skier death. The probability of severe skier injury or death is low, but it is present nonetheless. Without the introduction of a standard requiring ski binding companies to disclose work-to-release, there is low market potential for this this device.

## 5.3 Deficiency in Prior art and Considerations

Deficiency in the prior art and considerations for eliminating said deficiency are listed below.

### 5.3.1Program Design

By minimizing the user-information required to iterate the work-to-release measurements, the device becomes more intuitive. LabView has capability for every calculation to be performed in its own code without the need for external data analysis software; sending data to Excel is an extra step that can be avoided through improved code. Graphing the displacement/torque curve and numerically integrating the curve all in LabView is the best solution because it embraces Axiom 2 of Axiomatic Design.

### 5.3.2 Multiple Mice

The possibility of using two or three mice was investigated, and although there is currently software available to allow for multiple mice to control multiple cursors on one PC, i.e. Plural Input (Gulden, 2013), LabView does not integrate with this software to our knowledge. LabView integrates with the Windows mouse driver, and Plural Input removes this driver from any non-primary mouse so that the position can be retrieved. Analyzing the mouse data before it reaches the driver, and then sending the position to LabView is one possible way to circumvent this issue, but it would require familiarity with USB protocol. A configuration which allows for one dedicated PC mouse and two measurement-taking mice is ideal because it would decouple the calibration and measurement functional requirements.

### 5.3.3 Mechanical Considerations

A two-handled torque wrench such as the Epitaux binding tester would help direct the axis of rotation down the tibia axis during lateral toe release testing (Epitaux, 1989).

ISO 9462 calls for more extensive testing than ASTM F 1062 – 97(ASTM, 2005; ISO, 2006) and integration with ISO test sole (ISO, 2006) could allow for more exhaustive testing; however, also resulting in a costlier device if strain is to be measured across more axes.

## 5.4 Commercial Use

There is currently no work-to-release ski binding requirement; the target market is therefore limited to skiers and ski service technicians who wish to identify bindings prone to inadvertent release. With an ability to differentiate between safe and unsafe bindings, ski shops and ski binding companies may see this device as an opportunity to drive customers to purchase new and safer bindings.

# 6. Concluding Remarks

Work required to release the ski boot from the ski binding is a parameter that influences the tendency for inadvertent release. The project sought to utilize Suh's Axiomatic method for the design and testing of a device that measures work-to-release. Although unsuccessful in achieving work data, the project was successful in other ways; recognizing need for the device and identifying and verifying the optical mouse as a viable displacement sensor were the project's greatest successes.

Skiers would likely pay to know if their bindings have a tendency to release inadvertently however most skiers do not even know what inadvertent release is. The first step towards safer binding design is therefore educating the skiing public. The work-to-release binding tester could accelerate the development of better bindings, by helping to recognize imperfections in current bindings.

In the context of ski bindings, quantitative data should be more important to the consumer than its qualitative characteristics. By current standards, the only quantitative metrics widely accessible to consumers are the peak torque range, and number of release modes. With the advent of a work-to-release binding tester, skiers will be able to tell if their bindings are prone to inadvertent release; the device would have a real opportunity to prevent severe injury and save skiers' lives.

## 7. Works Cited

ASTM. (2005). Standard Practice for Selection of Release Torque Values for Alpine Ski Bindings. *ASTM Standards*. Pennsylvania, United States of America: American Society for Testing and Materials.

ASTM. (2005, Febuary 1). Standard Test Method for Measuring the Quasi-Static Release Moments of Alpine Ski Bindings. *ASTM Standards*. West Conshohocken, Pennsylvania, United States: ASTM International.

Beyl, J. J. (1962). *Patent No. 3027173.* United States.

Brown, C. A. (2006). *Axiomatic Design and the Evolution of Conventional Alpine Ski Bindings.* Retrieved March 8, 2013, from Axiomatic Design: http://www.axiomaticdesign.org/docs/AxiomaticDesignandSkiBindings.pdf

Brown, C., Hoffman, A., & Heinzmann, R. (1996). Skier Trajectories after Loss of Control. *Skiing Trauma and Safety: Tenth International Symposium* (pp. 186-195). American Society for Testing and Materials.

Ettlinger, C. (2010). *FAQ #5 for Skiers/Riders*. Retrieved November 8, 2012, from Vermont Ski Safety: http://www.vermontskisafety.com/vsrfaq5.php

Ettlinger, C. (2010). *Vermont Ski Safety Equipment Inc.* Retrieved November 9, 2012, from Vermont Ski Safety: http://www.vermontskisafety.com/

Havener, D. M. (2009). *Design of a Spring Loaded Tiliting Binding Plate.* Worcester, MA: Worcester Polytechnic Institute.

Hawks, T. (2011, September 1). *NSAA Fact Sheet.* Retrieved November 8, 2012, from National Ski Areas Association Website: http://www.nsaa.org/nsaa/press/NSAA-Facts-Ski-SnowB-Safety-9-11.pdf

Heeger, D. (1998). *Signial Detection Theory Handout*. Retrieved February 28, 2013, from stanford.edu: http://www-psych.stanford.edu/~lera/psych115s/notes/signal/

Howell, R. (2012, July 16). (J. Lagassey, & B. Merrill, Interviewers)

International Standard. (2006, February 15). ISO 9462. *Alpine ski-bindings - Requirements and test methods*.

Johnson, R., Ettlinger, C., & Shealy, J. (1989). Skier Injury Trends. *Skiing Trauma and Safety* (pp. 25-31). Philadelphia: American Society for Testing and Materials.

Julich, U. (2012). *Fitness Testing Assingment: Alpine Skiing.* Bently, AU: Curtin University School of Physiotherapy.

Langran, M. (2012). *Head Injuries on the Slopes*. Retrieved December 5, 2012, from Ski Inujry: http://www.ski-injury.com/specific-injuries/head

New York Times. (2004, March 4). *Mens World Cup*. Retrieved November 8, 2012, from The New York Times: http://www.nytimes.com/2008/03/04/sports/04iht-alpine4.10693330.html

Ng, T. W. (2003). The optical mouse as a two-dimensional displacement sensor. *Sensors and Actuators*, 21-25.

Shealy, J. E., Ettlinger, C. F., & Johnson, R. J. (2005). Using Signal Detection Theory as a Model to Evaluate Release/Retention Criteria in Alpine Ski Bindings. *Journal of the ASTM International*, 3-11.

Shealy, J., Ettlinger, C., & Johnson, R. (1999). Signal Detection Theory: A Model for Evaluating Release/Retention Criterea in Alpine Ski-Binding-Boot Systems. *Skiing Trauma and Safety*, 120-131.

Suh, N. (1998). Axiomatic Design Theory for Systems. *Research in Engineering Design*, 189-209.

The Associated Press . (2008, May 4). *Researchers work to make skiing easier on the knees*. Retrieved November 8, 2012, from Summit Daily: http://www.summitdaily.com/article/20080504/SPORTS/325265816

Tyrolia. (2013). *Ski Binding Safety Features*. Retrieved February 6, 2013, from Tyrolia: http://www.tyrolia.com/index.php?id=140

Urabe, Y., Ochi, M., Onari, K., & Ikuta, Y. (2002). Anterior cruciate ligament injury in recreational alpine skiers: analysis of mechanisms and strategy for prevention. *Journal of Orthopaedic Science*, 1-5.

Vishay Precision Group. (2011, December 19). *Surface Preparation for Strain Gage Bonding*. Retrieved March 2013, from VishayPG.com.

Young, L. (1989). Elevated Racer Binding Settings and Inadvertent Releases. *Skiing Trauma and Safety*, 222-227.

## 8. Appendix A

Examples of release and retention failures

One example of the ratchet effect is illustrated in Matthias Lanzinger's world cup super-giant slalom crash on March 2nd, 2008. During this crash Lanzinger sustained severe injury to his lower left leg including open fracture of his tibia and fibula. His lower left leg was amputated two days after the crash due to damage to the circulatory system and prolonged ischemia of the lower leg (New York Times, 2004). It is probable that the non-release of the vertical heel release mechanism, as shown in Figures 1 and 2, caused the initial fracture. Once broken, the fractured leg did not provide the resistance needed for lateral toe release, which is why twisting well beyond the normal range of motion between figures 2 and 3 can be seen. World Cup skiers' bindings are often set to extraordinarily high release settings to avoid inadvertent release, which can thus influence extremely severe LEER injuries.

Figure one: Lanzinger braces for impact with gate after coming off a jump in the wrong direction, the impact causes the fall.

Figure two: The left ski makes contact with the snow and forward bending moment is applied to lower leg. The binding fails to release, causing a severe tibia-fibula boot top fracture.

Figure three: With no resistance offered by the broken leg, the foot rotates a full 180°. This leads to massive internal bleeding and later requires the amputation of the lower leg.

Lanzinger's fall demonstrates an extreme instance of non-release however injuries sustained during an inadvertent release have the potential to be life-threatening. An example of a dangerous inadvertent release occurred in the 2008 Lake Louise Super-G to athlete Bode Miller. Although Bode managed to ski away from this accident, the potential for sever upper body injury during a high speed inadvertent release like this is very high. The inadvertent release was likely caused by a vertical heel release because the released binding apparently has the heel piece in the down position. In one study, vertical heel inadvertent releases such as this were self-reported as more common in giant slalom and speed events, and is purportedly caused by two mechanisms; Brown's Bow, or a sudden unweighting of the ski (Young, 1989).