Engineering a Ski-Bindings Test Apparatus

A Major Qualifying Project Report
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Degree of Bachelor of Science in Mechanical Engineering

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Abstract

The objective of this Major Qualifying Project was to design and construct a load bearing frame capable of supporting the loads when testing ski-bindings in response to tibia torque and valgus moment with respect to the location of the applied loads. This was done in order to provide a standardized starting point for future designs. The team designed a device that required minimal experience in manufacturing and was able to be constructed using off the shelf parts. The final product is capable of supporting and redirecting the loads specified by ASTM F504 to test ski-bindings to the point of release.
Acknowledgements

For their assistance in the completion of this project, without whom this project would not have been possible, I would like to thank the following people. Paulo Matos for his hard work and dedication in the design and building aspects of this project. Rick Howell for the detailed explanations of regarding the testing methods of ski bindings and the hands on testing experience provided by him. William Sanguinet for his assistance in transportation and refining of design elements. Samuel Johnston for his help editing and proofreading. Finally, Professor Christopher Brown for his guidance throughout the entire project.
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1 Introduction

1.1 Objectives

The objective of this project is to use Axiomatic Design to prototype a device that is capable of supporting the loads when testing ski-bindings in response to tibia torque and valgus moment with respect to the location of the applied loads. An objective of this write-up is to investigate why it was not possible to design and build a working prototype in 12 weeks, which is examined in the discussion, section 5.

1.2 Rationale

In order to evaluate the risk various ski bindings pose to the consumer it is important to perform tests that measure the peak forces being transmitted to the user by the bindings prior to release. The design solution provides the base, frame, safety precautions, and load redirection sections of a new design. The work outlined in this design solution provides a first generation design for developing a new testing apparatus that is capable of measuring valgus moments, tibia torques, as well as forward and rearward bending loads. Ultimately the tests completed with a future iteration of the design solution will lead to safer bindings that reduce the chance of injury to the skier under normal operating conditions.

1.2.1 Risk moderation

The majority of ski-related injuries occur in the lower extremities; with MCL, ACL, and tibia injuries being among the primary concerns. Many of these injuries occur when bindings do not release under excessive torsional loads applied to the user under normal operating conditions of the skis. Looking at the data of the past 32 years, it is easy to conclude that ACL injuries should receive more attention. In 1973, the skier-days between ACL injuries were 6600 days. This indicates that the average number of days that a skier would spend without injuring their ACL is 6600. For tibia-fractures, the number of days was 600 back in 1973. Looking at the data for 2013, the numbers reveal a great reduction in tibia-fractures: 20000 days between injuries. But the days until a skier ruptures the ACL didn't increase as much, up to only 2500 days of skiing before an ACL injury would occur on average. (Kim et al. 2012)

1.2.2 Cost

Ski-related injuries have significant costs, including medical bills, missed work or inability to work resulting in lost income, insurance costs, and possible legal fees for the injured party as well as the binding manufacturer. Reducing the frequency of lower extremity injuries will mitigate some of the costs for all parties.
1.2.3 Multiple testing sites

According to expert in the ski-binding and binding testing field Rick Howell, there are only a handful of locations globally that have the capability to test ski-bindings for release moments in accordance with the ASTM F504 standard. In order to increase the confidence interval, as well as the overall availability of testing, more testing locations are necessary. A limiting factor in the creation of additional testing sites is the cost of prototyping a new apparatus for testing that is able to obtain data consistent with current testing apparatuses. There is a clear need for a standardized and clearly defined apparatus that conforms to all applicable standards. Multiple testing locations provide the opportunity to test for reproducibility between testing sites.

1.3 State of the art

This section examines standards and methods currently in use in the ski binding testing industry used to measure release moments.

1.3.1 ASTM F504

The America Society for Testing and Materials (ASTM) develops and publishes voluntary consensus standards for materials, products, systems, and services. The specific standard ASTM F504, “covers a procedure for the measurement of release moments of ski bindings under conditions where inertia loadings of the ski binding system are not significant”.

ASTM F504 defines several key criteria for use in ski binding testing apparatuses, listed below.

- Frame of reference
- Testing conditions
- Ski loading locations
- Angles of interaction
- Pull rates
- Preloads
- Load transmission methods
- Load application methods
- Measurements
- Definitions

1.3.2 ISO 9462

The International Standardization Organization (ISO) is an independent and non-governmental organization that develops and promotes internationally accepted industrial and commercial standards. The specific standard ISO 9462 “Specifies the main characteristics of ski bindings” and also describes two example methods, A and B, for testing ski bindings. Method B
describes a test nearly identical to those in ASTM F504. Whereas method A describes a testing procedure in which the test ski is rigidly secured to the frame such that release does not occur.

1.3.3 Rick Howell’s testing methods

Howell’s testing methods conform to the key criteria of ASTM F504 using almost entirely mechanical testing methods. Through the use of torque wrenches, mechanical connections and bearings Howell tests for tibia torque in compliance with ASTM F504. Howell’s methods expand on ASTM F504 by adding additional loading locations between existing test points, as well as in areas closer to the ski binding which are expressly excluded from ASTM F504. Howell’s methods also incorporate a secondary testing apparatus for measuring the torque through the femur when the knee is at 90 degrees. This is accomplished with a free hanging test sole attached through a shaft to a simulated knee made from circular steel plates. The mock knee transmits the force to a ‘femur’ shaft which is positioned perpendicular to the ‘tibia’ shaft and is supported by bearings. Valgus moment data is then acquired by measuring the torque through the femur shaft with a torque wrench.

1.4 Approach

The design solution advances the state-of-the-art by allowing for testing valgus moments as well as including new testing locations close to the sole/binding interface. This is accomplished through the use of axiomatic design in order to decompose the problem. The design solution also aims to standardize the overall design of the load bearing mechanisms through the use of off the shelf parts when applicable and with clear blueprints for replication. Finally, the mechanism will be designed with the intention of adding electronic load generation and measurement elements in future iterations in order to accommodate further state-of-the-art advancements.

1.4.1 Explanation of Axiomatic Design

Axiomatic design is a method of decomposing complex problems into functional requirements that can be satisfied using specific features referred to as design parameters. The following table defines key terms related to Axiomatic Design.

<table>
<thead>
<tr>
<th>Terms</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axiom</td>
<td>Core truth for which there can be no opposition</td>
</tr>
<tr>
<td>CEME</td>
<td>Collectively Exhaustive, Mutually Exclusive</td>
</tr>
<tr>
<td>Child</td>
<td>Either an FR or DP that further supports the parent FR or DP in conjunction with its siblings</td>
</tr>
<tr>
<td>Constraint</td>
<td>Requirements that don’t need a DP.</td>
</tr>
</tbody>
</table>
This project utilized Axiomatic Design to develop the final design solution. Customer needs were first identified and decomposed into functional requirements (FRs) which were then assigned design parameters (DPs). The FRs and DPs were further broken down into parent/child relationships when applicable in order to fully define the design solution for the testing apparatus while remaining collectively exhaustive and mutually exclusive (CEME).

This project utilizes the two core axioms of AD to guide the overall design process. The first axiom states that FRs are to maintain independence from one another; that is to say that the FRs do not exhibit coupling such that altering one FR changes another FR or causes it to become invalid. The second axiom states that the decomposition must contain only the minimum amount of required information, with no excess in limitations on the solution space (Suh 1990). Through these axioms, AD allows for an alternative method of approaching a problem that leads to a wide variety of design solutions that could potentially be overlooked in other design processes, thereby reducing or eliminating the need for iterations later in the design process.

1.4.2 Compare/Contrast to ASTM F504

The design solution will satisfy all criteria defined in ASTM F504. Specific aspects include accommodating a pull rate of 2cm/second, supporting the applied load, maintaining the loading orientation, and ensuring that all relevant data is able to be acquired. These aspects will be satisfied in order to ensure that any testing devices built utilizing this design will conform to currently accepted standards, resulting in statistically similar data when compared to existing ASTM F504 compliant testing apparatuses. The design solution will also adopt axis conventions, depicted in figure 1 as well as key terminology provided in ASTM F504.

In addition to meeting the specifications provided, the design solution will provide the capability of measuring valgus, forward, and rearward bending loads. The design solution also aims to fully define, a mechanism that can be built with off the shelf parts with minimal tools or fabrication expertise required. This is done in order to reduce the cost and complexity of prototyping an ASTM F504 compliant testing apparatus for ski binding testing.
The design solution also will accommodate more testing locations in addition to those specified in ASTM F504. Where ASTM F504 specifies six points shown in figure 2, locations closer to the test sole and in between existing load locations will be added at 10 cm intervals, originating from the test sole, to address the lack of data available in those regions. It will also be possible to bridge two adjacent load locations to collect data at 5cm intervals. It is key to note that the load locations close to the test sole are important because they are more prone to ACL damaging valgus loads without inducing the necessary torques to cause a release.

Overall, the design solution aims to comply and further the ASTM F504 standards and testing procedure, include new metrics for testing and to provide a standardized starting point for future testing partners to iterate from.
1.4.3 Compare to ISO 9462

The design solution, having set out to modify ASTM F504 and not ISO 9462 standards will not address ISO 9462 at all. While there may be overlap in testing procedures that are compliant with method B of ISO 9462’s procedure they are all purely incidental and will not be utilized to gauge success. Since method A depicts a testing procedure that does not incur release, none of this method will be used at all, this is because the testing process in this project specifies testing bindings to release.

1.4.4 Compare/Contrast with Howell’s Testing Apparatuses

The design solution is similar to Howell’s testing apparatuses in that it tests both the tibia torque and valgus moments. Several items such as the shaft and test ski will be identical to Howell’s designs having been donated from Howell’s spare parts. Unlike Howell’s apparatuses however, the goal of this design is to combine both tests into a single mechanism and allow the tests to be performed simultaneously. The design solution also aims to reduce the number of moving parts in the design in an attempt to simplify the overall function and minimize the potential for failure.

An additional goal of the design solution is to introduce electronic sensors as a replacement for the mechanical sensors currently used in Howell’s design. This allows for quicker data acquisition and increased resolution in the data. Furthermore, the addition of electronic sensors will reduce the possibility for human error in the reading and data recording aspects of testing. Finally the design solution aims to include the use of a motor and a feedback loop in an attempt to both regulate and measure the speed of the pulls. This will allow for increased repeatability of the testing as well as provide a new metric to further evaluate the risks associated with various ski bindings.

2 Decomposition

The top level CN was to decrease the potential for injury while skiing. The method chosen to address this CN was to provide data on torsional loads and bending moments acting on the human body prior to binding release. This method led to the FR0: Test ski bindings for transmission of valgus loads and tibia torques during binding release. Which gave the DP0: Mechanism that measures torque and bending moments.

Constraints:
1. Allow 360 degree uninhibited movement of the ski about the binding
2. Cause no damage to the work space
3. Easily Manufactured
4. Provide capabilities to use strain gauges
5. Resist Plastic Deformation
6. Allow elastic deformation measureable by electronic strain gauges
7. Accommodate Various Ski Bindings

2.1 FR1 and DP1

<table>
<thead>
<tr>
<th></th>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maintain the loading direction/orientation during testing</td>
<td>Base that holds the shaft stable and allows the ski to rotate freely relative to the shaft</td>
</tr>
<tr>
<td>1.1</td>
<td>Prevent sliding of the mechanism</td>
<td>Weights/braces to resist X,Y, and Z translation</td>
</tr>
<tr>
<td>1.2</td>
<td>Prevent the mechanism from tipping over</td>
<td>Weights/Braces to resist rotation about the X, Y, and Z axes</td>
</tr>
<tr>
<td>1.3</td>
<td>Resist Deflection</td>
<td>Base Thickness</td>
</tr>
<tr>
<td>1.4</td>
<td>Provide Attachment location for Shaft</td>
<td>Surface area sufficient to accommodate the tibia shaft</td>
</tr>
</tbody>
</table>

*Table 2 - FR/DP 1 Decomposition*

2.1.1 Discussion of Parent FR/DP

The purpose of FR1 is to ensure that the design solution remains stationary during the testing process in accordance with ASTM F504 section 4.2. This feature is necessary so that the results are not skewed due to changes in the loading orientation. This FR also inhibits any damage to the work space. The accompanying DP was selected to ensure that the shaft is held stable and able to measure the induced forces without interfering with testing procedures.

2.1.2 Discussion of Children FRs/DPs

The purpose of FR1.1 is to ensure that the design solution is unable to slide during the testing process. This is important in order to maintain stability during release. This serves to preserve the workspace, reducing the possibility of scratching or gouging the floor that may occur if the apparatus were to slide across it. DP1.1 provides two possible solutions, adding weights or bracing the apparatus. The first possible solution would increase the frictional force and thereby resist the release forces to prevent sliding. The second possible solution would allow any release forces to be transferred to the walls.

The purpose of FR1.2 is to ensure that the design solution is unable to tip over during the testing procedure. This is important because the impact from tipping, specifically resulting loads through the sensors, would require recalibration of the sensors. Furthermore, the impact also has the potential to damage the design solution or the work space. DP1.2 provides two possible solutions either adding weights or braces. The first solution would increase the down force and prevent the device from tipping over. The second solution would transfer the induced loads to the wall and resist any movement.

The purpose of FR1.3 is to limit the deflection of the base/frame during the testing procedure. This is important because deflecting results in changes in the loading orientation which can compromise the results of the test. DP1.3 accomplishes this by increasing the rigidity
of the base. This serves to increase the force required to bend the base beyond its allowable deflection to more than those that will be applied during normal testing procedures.

The purpose of FR1.4 is to provide ample space that the tibia shaft can be attached to the base. This is important because if the shaft is unable to interface it will be able to rotate freely and will result in no measurable deflections. DP1.4 accomplishes this by ensuring sufficient surface area to accommodate mounting the test shaft to the base.

2.2 FR2 and DP2

<table>
<thead>
<tr>
<th></th>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Transmit loads from ski to sensors and base</td>
<td>Steel Shaft that connects test sole to base</td>
</tr>
<tr>
<td>2.1</td>
<td>Secure to test sole</td>
<td>Interface plate welded to top of shaft that matches test sole hole pattern</td>
</tr>
<tr>
<td>2.2</td>
<td>Secure to base</td>
<td>Interface plate welded to bottom of shaft with holes for bolts/screws</td>
</tr>
<tr>
<td>2.3</td>
<td>Provide attachment locations for strain gauges</td>
<td>Shaft length and Diameter selection</td>
</tr>
</tbody>
</table>

Table 3- FR2/DP2 Decomposition

2.2.1 Discussion of Parent FR/DP

The purpose of FR2 is to ensure that the loads applied to the test ski, act on the sensors and are transmitted to the base. This is important so that the design solution can measure torque and bending moments accurately. DP2 accomplishes this by providing all of the necessary attachment points for the test sole, base, and sensors.

2.2.2 Discussion of Child FRs/DPs

The purpose of FR2.1 is secure the test sole to the shaft so that forces are transmitted to the sensors. This is important because without a secure connection the test sole and ski would spin freely. DP2.1 accomplishes this by interfacing with the test sole, which is connected to the test-ski, where the loads are applied. The called for interface plate matches the hole patterns already present in the test sole and allow the sole to be secured to the tibia shaft.

The purpose of FR2.2 is to secure the shaft to the base. This is important so that the shaft deflects under applied loads instead of rotating freely. The resulting deflections can then be measured via strain gauges affixed to the shaft. The accompanying DP accomplishes this by providing an interface plate between the shaft and the base allowing the two pieces to be secured together. This serves to allow all loads to be transferred to the base and thus act as a load frame.

The purpose of FR2.3 is to provide ample surface area for mounting the strain gauges. This is important as without all of the strain gauges, data would either be missing or incorrect. DP2.3
accomplishes this by ensuring that the outer diameter of the shaft provides a circumference which is able to accommodate four strain gauges mounted at the same height. DP2.3 also stipulates the shaft length so that there is ample space to mount a minimum of two tiers of strain gauges. One tier for measuring torsional loads, the other for measuring bending moments.

### 2.3 FR3 and DP3

<table>
<thead>
<tr>
<th></th>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Transmit generated load to ski in compliance with ASTM F504</td>
<td>Rope/Pulley/redirection system</td>
</tr>
<tr>
<td>3.1</td>
<td>Transmit load</td>
<td>Sailing Rope</td>
</tr>
<tr>
<td>3.2</td>
<td>Redirect the load</td>
<td>Pulleys</td>
</tr>
<tr>
<td>3.3</td>
<td>Maintain load application angle</td>
<td>Multiple attachment locations to maintain load orientation relative to ski</td>
</tr>
</tbody>
</table>

*Table 4 - FR4/DP4 Decomposition*

### 2.3.1 Discussion of Parent FR/DP

The purpose of FR3 is to receive the generated load and transmit it to the test-ski. This is important as without transmitting the loads, binding release and all relevant data therein cannot be obtained.

### 2.3.2 Discussion of Child FRs/DPs

The purpose of FR3.1 is to support the generated load and transmit it to the test-ski. This is important as the load needs to be applied to the test ski in order to induce binding release and have the forces reach the sensors. DP3.1 accomplishes this with sailing rope. This serves to receive the load in tension, and transmit it the load to the test ski. It is key to note that ASTM F504 specifies ‘cable’ to be used in load transmission which is why other load transmission methods were not addressed.

The purpose of FR3.2 is to change the direction of the load. This is important in order to ensure consistent direction of force application on the ski in compliance with ASTM F504 standards regardless of the location of force generation. DP3.2 accomplishes this by providing pulleys to redirect the rope so that the ski is always pulled in the proper direction. Furthermore, the pulleys ensure a smooth application of force and inhibits binding of the rope during redirection.

The purpose of FR3.3 is to ensure that the loads are always perpendicular to the test-ski load locations. This is important because if the applied loads are not perpendicular to the ski load location at the time of release, the test will not be compliant with ASTM F504 6.7.1 and will be
invalid. DP3.3 accomplishes this by providing multiple load redirection locations. This serves to provide an accompanying redirection location for every application location present on the test-ski in order to maintain the orientation angle.

### 2.4 FR4 and DP4

<table>
<thead>
<tr>
<th></th>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Protect operators and Equipment During Release</td>
<td>Safety system</td>
</tr>
<tr>
<td>4.1</td>
<td>Absorb force from binding release</td>
<td>Bungee Cords</td>
</tr>
<tr>
<td>4.2</td>
<td>Prevent ski from leaving the testing area</td>
<td>Hard stop/backup Mechanism</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Prevent X direction displacement outside the frame</td>
<td>Netting/mesh on the front and back of the frame</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Prevent Y direction displacement outside the frame</td>
<td>Netting/mesh on the left and right of the frame</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Prevent Z direction displacement outside the frame</td>
<td>Netting/mesh on top of the frame</td>
</tr>
<tr>
<td>4.3</td>
<td>Mitigate damage to sensitive components inside the testing area</td>
<td>Padding</td>
</tr>
</tbody>
</table>

*Table 5 - FR4/DP4 Decomposition*

#### 2.4.1 Discussion of Parent FR/DP

The purpose of FR4 is to protect the operators as well as the equipment from any damage that may occur during a violent release in testing. This is important as safety of the operators is a prime concern. Additionally, protecting the equipment will reduce part failure and cost therein. DP4 accomplishes this through the use of bungees to absorb energy, netting to stop the skis should the bungees fail, and padding to protect sensitive components within the containment netting.

#### 2.4.2 Discussion of Child FRs/DPs

The purpose of FR4.1 is to slow the transfer of energy from the ski to the frame in order to reduce the impact momentum. This is important because it reduces the destructive potential of the ski upon release. DP4.1 accomplishes this through the use of bungie cords, which absorb and store energy as they undergo elastic deformation; this energy is then released over time, in a safer manner, as the system returns to equilibrium.

The purpose of FR4.2 is to provide a secondary safety measure in the event that the bungee cords fail or become insufficient. This is important as it provides an extra layer of safety for the operators as well as the work space. DP4.2 accomplishes this by attaching netting to the extremes of the frame/base assembly. The netting serves to prevent the ski from leaving the
operating area in the event that the bungee fails. The children of FR4.2 and DP4.2 serve to ensure that all possible directions of release have protective netting.

The purpose of FR4.3 is to inhibit damage to the mechanical and electronic systems of the design solution. This is important as many of the more expensive pieces of the design solution must be located within the netting and thereby would be subject to damage during binding release without sufficient safety precautions. DP4.3 accomplishes this through the use of foam padding placed over the shaft, sensors, and base. The foam padding serves to cushion and distribute the forces of any key area that is hit in order to mitigate damage.

### 2.5 FR5 and DP5

<table>
<thead>
<tr>
<th></th>
<th>FR</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Support safety and load redirection features</td>
<td>Frame superstructure and interfaces</td>
</tr>
<tr>
<td>5.1</td>
<td>Envelop test area</td>
<td>Vertical Support members which extend above test ski</td>
</tr>
<tr>
<td>5.2</td>
<td>Attach safety features</td>
<td>Eye bolts</td>
</tr>
<tr>
<td>5.3</td>
<td>Secure frame to base</td>
<td>Corner brackets</td>
</tr>
</tbody>
</table>

*Table 6- FR5/DP5 Decomposition*

#### 2.5.1 Discussion of Parent FR/DP

The purpose of FR.5 is to provide a supporting structure in order to mount the netting/bungee cords from FR4. This is important to ensure that the safety measures are in a location to function properly and that they are stable when forces are applied to them. DP5 accomplishes this by creating a separate superstructure for supporting and interfacing with the safety features.

#### 2.5.2 Discussion of Child FRs/DPs

The purpose of FR5.1 is to provide the frame work to enclose the work area. This is important to ensure that when the netting from FR4 is attached the test ski is properly separated from the work space and contained in the testing area. Furthermore this is necessary to allow the redirection locations to be positioned parallel to the test ski. DP5.1 accomplishes this by adding vertical supports, placed at the extremes of the base, which are taller and wider than the shaft/ski assembly.

The purpose of FR5.2 is to provide an interface that allows the netting and bungees to be attached. This is important so that the superstructure can properly hold up the bungees and allow any forces in the bungees or netting to be transferred to the frame. DP5.2 accomplishes this by adding eye bolts in the frame superstructure to which bungee cords and netting can be tied or clipped to.

The purpose of FR5.3 is to secure the frame to the base and transmit any forces that act on the frame to the base. This is important because if the frame were to move when the ski hit it
upon release, damage to the work space or personnel injury. DP5.3 accomplishes this by using corner brackets to provide an interface between the base and the vertical support members.

3 Physical implementation

This section serves to show the layout intent for the designed physical components as a visual representation of how they satisfy the DPs. Furthermore, this section provides an example for load generation and sensors for illustrative purposes. A complete model of the designed device can be seen in figure 3.

3.1 Base and Support frame
The supporting base frame shown in figure 4 provides ample space in the XY plane to encapsulate the required testing area. The selected 4”x4” members also add sufficient weight and rigidity to satisfy FR1.1 and FR1.2. The addition of a middle cross brace satisfies FR1.3 by preventing the rectangular frame from easily distorting into a parallelogram under load. It also serves to reduce the distance between supports for the base plate.

The base plate shown in figure 5 satisfies FR1.4 by adding a large surface area to be used in attaching the shaft assembly. The base plate covers the entire supporting base structure allowing it to also increase rigidity by securing it to all support members further securing their relative orientations. While the base plate is larger than required to accomplish FR1.4, space is left to attach future components such as the suggested motor spool assembly.
3.2 Vertical Frame and Safety Attachment locations

The vertical support members shown in figure 6 are located at the corners of the base in order to properly encapsulate the XY plane testing area. They extend above the height of the test shaft assembly to encapsulate the Z axis direction.

The corner brackets in Figure 7 show the connection interface between the vertical support members and the base. These satisfy FR5.3 by securing the vertical members to the base and transmitting loads acting on the vertical members to the base.
The eyebolts depicted in Figure 8 satisfy FR5.2 by providing attachment locations for the safety features. The top and outward facing eyebolts allow the safety netting to be attached by either tying them to the bolts or using methods such as carabineers for quick attachment. The internal eye bolts provide attachment points for the bungee cords to be attached using a similar method.

3.3 Load Redirection Components
The eyebolts and supporting bar depicted in Figure 9 shows the load redirection locations. These satisfy FR3.3 by providing locations at 10cm intervals, matching locations to those found on the test ski provided by Rick Howell, depicted in figure 10. The use of eyebolts allows for quick changing of load locations as well as utilizing two adjacent attachment locations simultaneously to provide 5cm intervals if necessary.
3.4 Shaft Assembly

Figure 11 – Shaft Assembly

Figure 11 shows the entire shaft assembly with attached test ski. FR2 depicts the steel shaft used to support the loads. FR2.2 Shows the shaft base interface that allows the loads to be transmitted to the base plate and supporting frame.

Figure 12 – Torque Transmission Assembly

Figure 12 depicts the test sole and attachment location which satisfies FR2.1 by transmitting loads from the test sole to the shaft also depicted. Also shown in figure 11 is suggested locations and orientations for strain gauges used to measure tibia torque and bending moments. This is done to show that FR2.3 is satisfied and that ample space for mounting the sensors is provided.
3.5 Not Depicted

Some components were deemed basic and were not added into the cad model due to the disproportionately large amount of time that would be required to model them. This includes all wire and cables, pulleys, bungee cords, and safety netting.

4 Prototype Production

This section describes the production of the prototype assembly, shown in figure 13, specifically the materials used, tooling selection and specific methods for assembly.

![Figure 13 - Actual Load Frame construction](image)

4.1 Base and Support frame Support

The base support is constructed using 6’ x 4” x 4” lumber for the support frame and internal bracing. The joints are held together using 2” x 2” steel corner brackets affixed using 2.5” deck screws. The base sheet is 4’ x 6’ x .75” plywood. It is affixed to the frame using the same 2.5” deck screws at the corners, along the perimeter, and along the supporting central brace member for reinforcement. Tooling for assembly is an electric drill and #2 Philips driver.

4.2 Vertical Frame

The vertical frame members, sample shown in figure 14, are 3’ x 4” x 4” lumber, affixed to the base support using 2” x 2” steel corner brackets affixed with 2.5” deck screws, located at all four corners.
of the base support. Each vertical frame member has a 1” threaded eye bolt on each internal face 2” from the top of the vertical frame member. Tooling for assembly is an electric drill, #2 Philips driver, and a 1/8” drill bit used to predrill holes for the eye bolts.

![Figure 14 - Actual Vertical Support Member](image)

### 4.3 Load Redirection

The load redirection sites are 1” diameter threaded eye bolts screwed into a 6’ x 2” x 4” piece of lumber affixed between two of the vertical frame members at a height of 1’ from the top of the base plate using 2.5” deck screws. The 1” threaded eye bolts are spaced at 10cm intervals. Tooling for assembly is an electric drill, and a #2 Philips driver, and a 1/8” drill bit used to predrill holes for the eye bolts.

### 5 Discussion

This section summarizes the accomplishments of the project and offers commentary on constraints, the design process, and possibilities for further work. This section also offers critical analysis on why the project was unable to build a complete working prototype.

The final design is a robust loadbearing frame that conforms to existing ASTM F504 standards in being able to support and redirect the loads required to test ski bindings for release. The design is simple enough that it can be built with off the shelf parts available at a local hardware store using an electric drill with common bit attachments, requiring no specialized training. The final design expands on ASTM F504 by adding safety features to protect the mechanisms and operators. It serves as a platform for expanding ASTM F504 by allowing the use of electronic sensors for measuring valgus moments, tibia
torque, and forward/rearward bending moments. Additionally, it provides additional testing locations closer to the binding.

Axiomatic Design played a major role in the success of this project by defining clear functions and providing a logical method for gauging the effectiveness of various designs. Specifically AD allowed for identification of over-complicated designs, such as those similar to Howell’s, leading to a simpler final design. Lack of experience with AD meant that there was a steep learning curve for creating the decomposition. For this reason, AD may have initially slowed down the project, though considering the advantages of using AD, it is unclear whether there was a net gain or loss of time because of this. Overall, using AD on this project was a useful learning experience.

Based on the experience of using AD for the course of the project, there are several recommendations for future projects utilizing AD. First, utilizing AD in a controlled environment prior to starting the project could be beneficial. A sample problem to apply AD to, which has already been decomposed properly, could be utilized as a discussion tool in order to examine and address project members’ misconceptions and issues with implementing AD. Secondly, starting the project with a blank slate, or otherwise not exposing project teams to other solutions to similar problems may help remove bias and allow more open thinking when decomposing the problem. For example, in this project, the team was exposed to Howell’s designs prior decomposing the problem. Due to this exposure, early decompositions mimicked Howell’s designs rather than developing CEME-Min FRs. Thirdly, writing the decomposition section of the paper during the decomposition process could help identify issues as they arose. Writing the explanation for the approach and choices made in the decomposition helped identify errors that were previously overlooked. Finally, further decomposing the problem into the “nuts and bolts”, both literally and figuratively, would have aided in transitioning into the build phase and ultimately led to an improved final product.

The project originally set out to build an entire working prototype this goal was ultimately not met in the final design. The project addressed skiing, a subject which was foreign to project members, as a result, a disproportionately large set time was spent understanding the problem. There was also an overestimation of the ability of project members in relation to the timeframe of the project, which led to unrealistic goals being set. Particularly goals set requiring electronic or programming components such as the motor and feedback loop lay out of the skill set of project members. In an attempt to compensate for this deficit in skills and meet the initial goals, excessive time was spent researching electronics that could have been better spent finalizing or assembling the mechanical components. Suboptimal communication during the project, between members, to the advisor, and to other assisting parties also served to slow the project down. The project also never made it to the testing phase for the aforementioned reasons and round robin testing would have been a good way to ensure the device performed close to other existing devices.

The final design met most of the constraints. The location of the shaft, as well as the design of the base and frame allows for 360 degree uninhibited movement of the ski about the binding. The weight of the base and the safety netting adequately protects the work space. Using off the shelf parts and only an electric drill requires little to no experience in manufacturing to build the test apparatus. Through using a test sole the design is able to accommodate most modern alpine ski bindings. There were a few constraints not fully addressed due to time constraints. Testing was not done to ensure that the design
would properly resist plastic deformation, or to ensure that the shaft configuration would provide elastic deformation measurable by strain gauges.

While the load frame is capable of supporting the applied loads, material choices were made based on immediate availability and personal preference. For instance, the support base is constructed using pressure treated 4x4’s due to local availability. Further work could be done using finite element analysis to evaluate material choices to more properly reflect expected stress concentrations.

6 Concluding Remarks

6.1 Accomplishments
- Designed a loadbearing frame that satisfies ASTM F504 and can accommodate electronic sensors
- Frame is easy to assemble with off the shelf parts
- Frame redirects loads to provide a consistent testing environment

6.2 Criticism
- Project suffered due to lack of proper communication
- Unable to add electronic sensors
- Unable to perform tests
- Design is over built

6.3 Recommendations
- Future projects could focus on adding and calibrating sensors
- Round robin testing could be done to ensure the device performs adequately
7 References


