Sit Ski by Axiomatic Design

A Major Qualifying Project Report

Submitted to the faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

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Degree of Bachelor of Science

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Abstract

Current adaptive skiing devices fail to provide many of the controls that non-disabled skiers have such as fore-aft movement of CG, edge angle, and vertical articulation of skis. Due to these limitations it can be difficult to satisfy Euler's equations for stability in 3-D and thereby exit turns cleanly. This project creates an adaptive skiing device that can better replicate normal skiing techniques which may enable better skiing and lessen the strength and balance demands required to operate it. A rigorous, structured innovation process following axiomatic design theory and methods is used to develop viable solutions. From this we have come to a solution that can better replicate a non-disabled skier with independent fore-aft, lateral-medial, vertical, edging, and steering of each ski.

Acknowledgments

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1.) Introduction

1.1.) Objective

The objective of this project is to provide a solution for adaptive skiing that properly recreates the true skiing experience for individuals with disabilities. This will be achieved by creating an adaptive skiing device that enables a disabled skier to mimic the technique of non-disabled skiers better than current adaptive skis. This device will achieve this by providing the user with greater control over ski and body position through controls that allow dynamic movement in more directions than current adaptive devices. The device may enable individuals with greater disability to ski more easily and independently through reduced strength and balance requirements.

1.2.) Rationale

Adaptive skiing technology has remained relatively unchanged for many decades and while current technology does allow some individuals the ability to ski again, it fails to recreate the same “body mechanics and control” achieved by non-disabled skiers (Brown & LeMaster, 2012). Current adaptive skis are also limiting in that only certain individuals with less severe disabilities can effectively use them because they require strong torso and upper body strength and control. A more intuitive and less physically demanding skiing device would allow a wider range of individuals with disabilities to experience skiing (Warren Cleary). With an increase in individuals participating in adaptive sports yearly, there is a growing market for this device. A new adaptive skiing device such as this would be sought after by both current athletes and those who couldn't participate in the sport prior (Eliane Mauerberg-Decastro, Debra, & Carolina, 2016). It is also hypothesized that the device would be of interest to individuals without disabilities who are suffering from an injury or are seeking a unique skiing experience. A device that fulfills this customer need would have great market viability as a consumer product through direct purchase and rental. Ski slopes could provide the device for rental to any and all individuals and sale of the device online would allow access to the global market.

1.3.) State-of-the-Art

As previously mentioned, the technology of adaptive skiing has remained relatively unchanged in recent years. Currently there are only two manufacturers working to improve the adaptive skiing experience through novel designs. The Hydra mono-ski is a newly developed device that claims to: “assist with fore/aft center of gravity (CG) movement, assisting in powerful yet smooth turns with perfect edge grip” (Solomon, 2018; Tokura, 2016). This CG movement is achieved through a newly developed suspension system, Fig 1, with unique kinematics that, though user tests, has generated a claim that “the Hydra is as close as a monoski will get, so far, [to] reproducing the control an able bodied skier of very high caliber has" (Chris Devlin-Young, DynAccess)

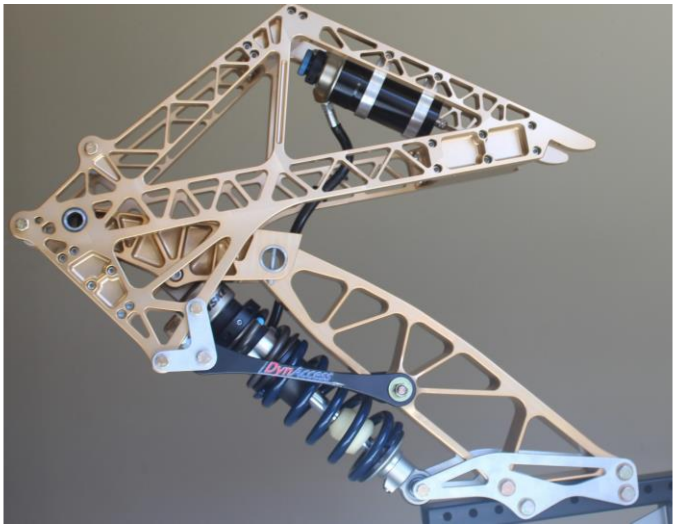


Figure 1: *Hydra suspension design by DynAccess*

Tessier Adaptive Sports Equipment is a second manufacturer working to improve adaptive skiing. They currently have two devices, the Snow'Kart and the Dualski, that address issues of past devices. The Snow'Kart is a unique adaptive skiing device that is "designed [for] people who have a lack of strength in the upper body and/or who don't have enough balance to ski with Uniski or Dualski"(Tessier, 2018).

Figure 2: *Tessier Snow'Kart (left) and Dualski four-bar mechanism (right)*

The Snow'Kart is controlled by two independent handles that allow the rider to adjust edge angle and yaw of each ski. The Dualski is stated to "allow skiing independently with remarkable performances like the best able-bodied skiers. It is much more than a biski" with two skis on four-bar mechanisms that allows for carving when leaning the ski (Tessier, 2018).

1.4.) Approach

By satisfying the objective of creating an adaptive skiing device that enables a disabled skier to mimic the technique of non-disabled skiers, the design resulting from this project will advance the state-of-the-art by better incorporating multiple dynamic movements into one system. By utilizing a rigorous, structured innovation process following axiomatic design (AD) theory a viable solution will be developed. AD theory states that all good design solutions must comply with two axioms: maintain the independence of the functional elements and minimize the information content. Functional requirements (FRs) are formulated to satisfy customer needs (CNs) then the physical solution, i.e., design parameters (DPs) are selected to fulfil the FR's. These are mapped in parallel hierarchical decompositions from abstract to detailed, checking at each level for compliance with the axioms (Suh, 2001). CN's are formulated from research on comparing techniques between adaptive and traditional skiing and interviews conducted with individuals experienced in adaptive skiing. FR's are then formulated with accompanying DP's within a software program called Acclaro. A full decomposition can be found in Appendix A.

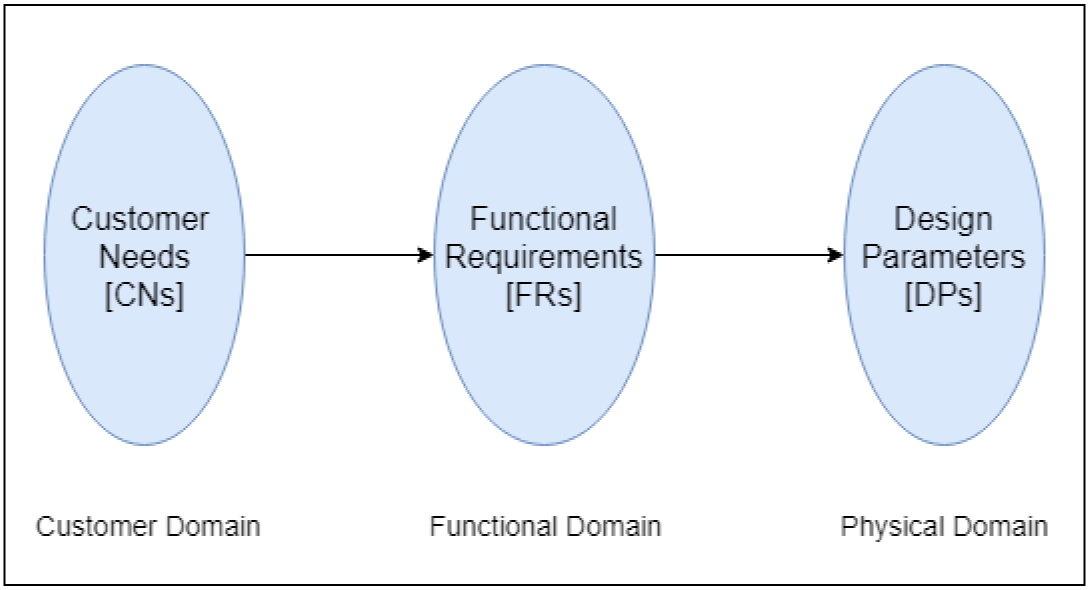


Figure 3.) *Flow Between Domains of Axiomatic Decomposition*

2.) Design Decomposition and Constraints

In this section the important FRs and DPs of the decomposition will be discussed. All of the FRs and DPs of the major design decisions will be outlined and justified. Once a DP of a major design decision is discussed and justified it will not continue to be discussed in the succeeding decomposition levels for brevity, even though it may have many more levels of children. A full decomposition can be seen in Appendix A.

2.1.) Design Purpose and FR 0

The main goal of the project is defined by the top-level FR, FR 0, stating that the project will enable disabled skiers to mimic non-disabled skiing techniques while using an accessible skiing device. The accessible skiing device will fulfill all the customer needs set forth in the introduction to this paper.

2.2.) Project Constraints

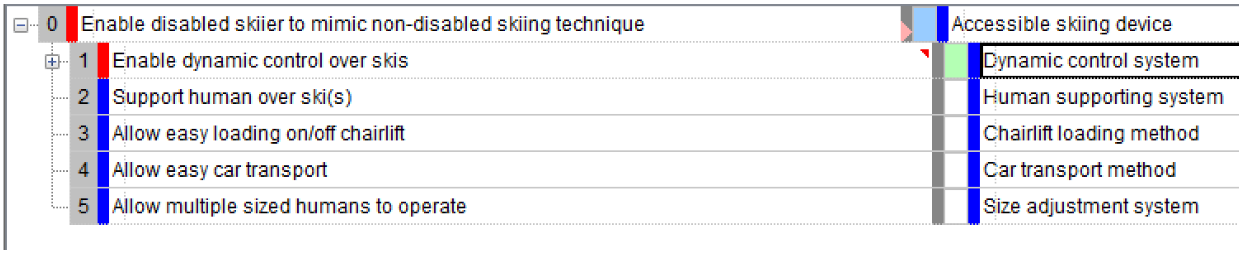
The following constraining factors were taken into consideration while completing the design for this project:

- Budget: The team had to stay within the budget provided by the two sponsors, Robert Nuemeister, and the Tinkerbox Organization, as well as the money allocated to each of the students by the ME department at WPI. The total money for the project totaled \$8500.
- Construction: When completing the physical integration and prototype production, the team only had access to waterjet technology, CNC Machines, 3D printers, and hand tools to produce their product
- Electrical/Software: All the members of the project team were ME students and had limited knowledge of electronic and software systems. Simple systems that required little software or electrical knowledge were favored over more involved systems.
- Size/Shape: The design had to be able to physically accommodate a human rider and adapt to their size. In addition, the weight had to be minimized because momentum increases with weight, which could make stopping difficult.

2.3.) Level One

2.3.1.) Functional Requirements (FRs)

The first level defined the main design constraints of the accessible skiing device, as shown below in Figure 4. Together these five FRs encompass the five minimum requirements that the device must fulfill before it can be fully tested and then put into production, making the system collectively exhaustive. In addition, all the requirements are separate from one another and will not have any coupling, making the system mutually exclusive.



0	Enable disabled skiier to mimic non-disabled skiing technique	Accessible skiing device
1	Enable dynamic control over skis	Dynamic control system
2	Support human over ski(s)	Human supporting system
3	Allow easy loading on/off chairlift	Chairlift loading method
4	Allow easy car transport	Car transport method
5	Allow multiple sized humans to operate	Size adjustment system

Figure 4. *Decomposition level one view*

2.3.1.1.) FR 1

FR 1 states that the device will enable dynamic control over the skis. This is the most detailed FR because it defines how the dynamic control system will operate on the accessible skiing device. This dynamic control system will allow the sit skier to perform the actions that normal skier can complete.

2.3.1.2.) FR 2

FR 2 states that the skiing device must be able to support a human rider over the skis so that they can arrive at the bottom of the mountain safely.

2.3.1.3.) FR 3

FR 3 states that the device must have easy loading on and off the chairlift. It is important that the device can reach all types of terrain that a normal skier could, and to do this, the device must be able to be loaded onto a chairlift. In addition, it is important that the system can be loaded quickly to avoid delaying the chairlift.

2.3.1.4.) FR 4

FR 4 states that the skiing device must be able to be easily transportable by car. It is important that individuals who use one of these devices do not have to rely on separate means of transportation to get their device to the mountain.

2.3.1.5.) FR 5

FR 5 states that multiple sized humans must be able to operate the device. Riders will range greatly in height and weight, so the device must be able to accommodate a sufficient range of individuals.

2.3.2) Design Parameters (DPs)

At this level, the design parameters do not have specific components yet because the FRs of the device do not define the system well enough yet. Instead, the DPs are very general and are as such:

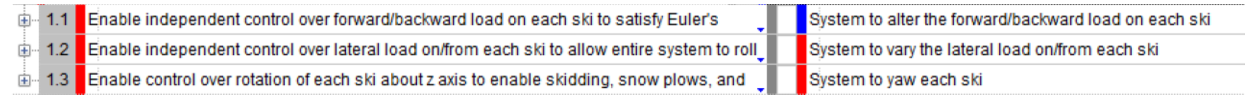
- DP 1: Dynamic control system
- DP 2: Human supporting system
- DP 3: Chairlift loading method
- DP 4: Car transport method
- DP 5: Size adjustment system

2.4.) Level Two

As the decomposition continues, only FR1 is going to be discussed. This is because FRs 2-5 have not been further decomposed. The main goal of this project and decomposition was to understand the feasibility of using a dynamic control system to help disabled and non-disabled skiers to better mimic non-disabled skiing techniques. FRs 2-5 were determined to not be in the scope of this project but are still essential in completing before the device can be put into production.

2.4.1.) Functional Requirements

As can be seen in Figure 5, there are three functional requirements in this level. Together these three FRs cover the full range of motion that the user has control over with the accessible skiing device to complete the same techniques that non-disabled skiers use, making the list collectively exhaustive. In addition, all the ranges of motion are specified by different FRs and will be separate from each other to minimize coupling and continue to make the skiing device mutually exclusive.



1.1	Enable independent control over forward/backward load on each ski to satisfy Euler's	System to alter the forward/backward load on each ski
1.2	Enable independent control over lateral load on/from each ski to allow entire system to roll	System to vary the lateral load on/from each ski
1.3	Enable control over rotation of each ski about z axis to enable skidding, snow plows, and	System to yaw each ski

Figure 5. *Decomposition level two view*

2.4.1.1.) FR 1.1

FR 1.1 states that the dynamic control system will enable the independent control over the forward and backward load on each ski to satisfy Euler's Equations. Controlling the forward and backward load on each ski is the main method for entering and exiting turns on skis. It is important that the user can precisely control their forward/backward center of gravity (CG) so they successfully complete turns and link them together.

2.4.1.2.) FR 1.2

FR 1.2 states that the dynamic control system will enable the independent control over lateral load on/from each ski to allow the entire system to roll about a central point. This is very important because the rolling of the system is essential in turning, as well as stabilization of the device over varying terrain and conditions.

2.4.1.3.) FR 1.3

FR 1.3 states that the dynamic control system will enable the control over the rotation of each ski about the z-axis. In order to properly skid turn, hockey stop, and snowplow, the skis must be able to yaw about the z-axis. These techniques are extremely important because they are the main tool that non-disabled skiers use to control speed and stop.

2.4.2.) Design Parameters

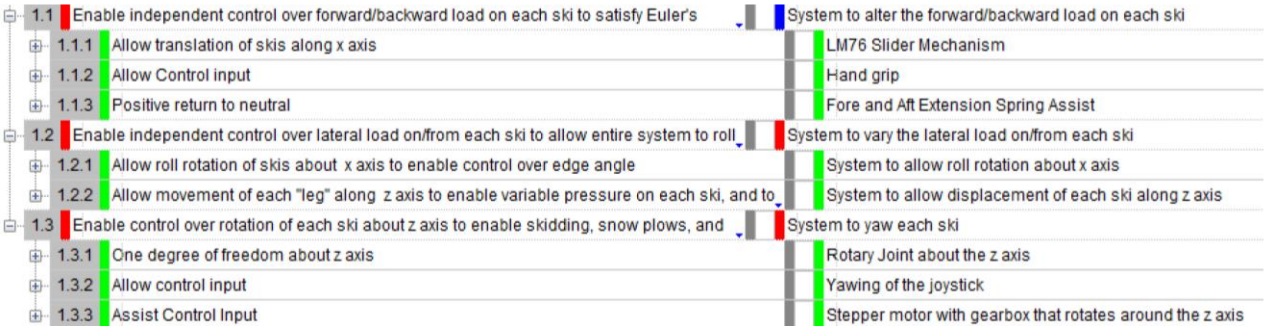
Again, at this level, the design parameters do not have specific components yet and are still at the system level because the FRs of the device do not define the system well enough yet. The DPs are as follows:

- DP 1.1: System to alter the forward/backward load on each ski
- DP 1.2: System to vary the lateral load on/from each ski
- DP 1.3: System to yaw each ski

2.5.) Level Three

2.5.1.) Functional Requirements

There are eight different functional requirements in this level. Together these FRs take each of the motions that the device is trying to mimic and define how each of them will be achieved thus making the system collectively exhaustive. In addition, the requirements for the user input begin to get defined in this level. As can be seen in Figure 6, all the systems are independent from each other as a result of being mutually exclusive.



	FR	DP
1.1	Enable independent control over forward/backward load on each ski to satisfy Euler's	System to alter the forward/backward load on each ski
1.1.1	Allow translation of skis along x axis	LM76 Slider Mechanism
1.1.2	Allow Control input	Hand grip
1.1.3	Positive return to neutral	Fore and Aft Extension Spring Assist
1.2	Enable independent control over lateral load on/from each ski to allow entire system to roll	System to vary the lateral load on/from each ski
1.2.1	Allow roll rotation of skis about x axis to enable control over edge angle	System to allow roll rotation about x axis
1.2.2	Allow movement of each "leg" along z axis to enable variable pressure on each ski, and to	System to allow displacement of each ski along z axis
1.3	Enable control over rotation of each ski about z axis to enable skidding, snow plows, and	System to yaw each ski
1.3.1	One degree of freedom about z axis	Rotary Joint about the z axis
1.3.2	Allow control input	Yawing of the joystick
1.3.3	Assist Control Input	Stepper motor with gearbox that rotates around the z axis

Figure 6. *Decomposition level three view*

2.5.1.1.) FR 1.1.1

FR 1.1.1 states that the system to alter the forward/backward load on each ski will allow translation of the skis along the x-axis with respect to the rider. This translation of the skis along the x-axis will provide the forward or backward change in the CG of the rider, that will help enter and exit turns, as well as help with general stability of the rider using the skiing device.

2.5.1.2.) FR 1.1.2

FR 1.1.2 states that the system to alter the forward/backward load on each ski will have control input that the user can use to control the motion.

2.5.1.3.) FR 1.1.3

FR 1.1.3 states that system to alter the forward/backward load on each ski will have a positive return to neutral. This is important because when the device is a rest, the forward/backward load system should be centered on each ski. This FR will ensure that it doesn't take the rider any physical effort to maintain a neutral position on the device.

2.5.1.4.) FR 1.2.1

FR 1.2.1 states that the system to vary the lateral load on each ski will allow roll rotation of the skis about the x-axis. In a case where an alternate edge angle must be used to maintain proper traction, but rolling the entire system would cause an imbalance, this FR ensures that the edge angle can be altered independent of the skiing device's lean angle.

2.5.1.5.) FR 1.2.2

FR 1.2.2 states that the system to vary the lateral load on each ski will allow vertical movement of each "leg" along the z-axis to enable variable pressure on each ski. When a non-disabled skier turns, they have varying pressures on their two skis because they will move their CG more over one ski than the other. This effect becomes even more drastic when turns are taken at higher speeds or with a smaller radius. It is essential that the device can control this varying load to properly balance and maintain traction during turns.

2.5.1.6.) FR 1.3.1

FR 1.3.1 states that the system to yaw each ski will allow one degree of freedom around the z-axis. It is important that this system only allows one degree of freedom to minimize coupling between the different systems on the skiing device.

2.5.1.7.) FR 1.3.2

FR 1.3.2 states that the system to yaw each ski will have a control input that user can use to control the yaw of each of the skis.

2.5.1.8.) FR 1.3.3

FR 1.3.3 states that the system to yaw each ski will have some form of assisted control input, meaning that there will be some type of mechanical or electrical system to help assist with this movement. This movement will require an assist of some form because the to yaw each of the skis takes a considerable amount of force and holding torque, and this can be hard to do for individuals who may not have a large amount of upper body control or strength. An assist will make the movement attainable by the largest portion of individuals.

2.5.2.) Design Parameters

2.5.2.1) DP 1.1.1

DP 1.1.1 states that an LM76 linear sliding mechanism will be used to control the translation of skis along the x-axis. Other ideas were to use a four-bar linkage to control this movement, but a four bar would couple the vertical and horizontal movement of the system which would violate axiom one. There are some concerns that debris could get lodged into the linear sliding system and bind it up, but a shield around the mechanism could solve this and should have minimal performance risk.

2.5.2.2) DP 1.1.2

DP 1.1.2 states that a hand grip will be used to control the input of the forward/backward load system. The team decided to make this motion electrically unassisted because it would not take a lot of force to pull and push an individual's weight fore and aft. The team believed that a mechanical lever arm could be used to accomplish this. In addition, by making the motion electrically unassisted, it would allow for tactile feedback to the user and cut down on the overall weight of the skiing device. If it becomes apparent that it requires too much physical effort to alter the forward/backward load on each ski during testing, then an electronic system may be considered in the future.

2.5.2.3) DP 1.1.3

DP 1.1.3 states that fore and aft extension springs will assist in returning the system to a neutral position. This will allow the individual to only exert a force on the forward/backward load translation mechanism when trying to change their CG. Otherwise the user would have to use constant force to hold their position even when not turning.

2.5.2.4) DP 1.2.1

DP 1.2.1 states that there will be a system to roll the ski about the x-axis in order to allow roll rotation about the x-axis to give control over ski edge angle.

2.5.2.5) DP 1.2.2

DP 1.2.2 states that there will be a system to allow the displacement of each ski along the z-axis to have vertical movement of each "leg". This will enable the skiing device to create variable pressure on each ski.

2.5.2.6) DP 1.3.1

DP 1.3.1 states that there will be a joint that creates a rotation about the z-axis. This rotation will be only one degree of freedom in order to minimize coupling of systems.

2.5.2.7) DP 1.3.2

DP 1.3.2 states that by yawing the joystick, the user can control the motion of the system that yaws the skis. This motion was chosen because the team wanted the system to be as intuitive as possible. Thus, the team wanted to keep the motion of the joystick similar to the motion that the skis would make.

2.5.2.8) DP 1.3.3

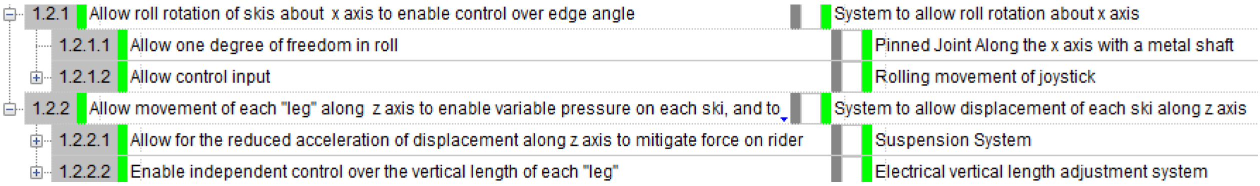
DP 1.3.3 states that there will be stepper motor and gearbox that will assist the control input of the yawing motion. The stepper motor was chosen because they have high torque at low rotational speed, have high rotational acceleration, and their position can be precisely controlled very easily. The other option was to use a servo motor, but when compared, they provided less torque and had a lower rotational acceleration, thus the system would be less responsive than a stepper motor.

2.6.) Level Four

In this section, only the fourth levels associated with FR 1.2.1 and FR 1.2.2 will be discussed, because in level three the DPs were still only at a system level, and to properly discuss the major design decisions associated with both, a fourth level must be introduced in this report. The other FRs will not be discussed further because the decomposition has already defined the DP that will satisfy the FR and further levels just continue to define the DP further.

2.6.1.) Functional Requirements

Underneath FR 1.2.1 and FR 1.2.2, there are four different functional requirements in the fourth level. At this level, the edge angle system gets defined in greater detail and the vertical displacement system gets split up into two distinct systems. As shown in Figure 7, all the systems are separate from each other and include all of the components that will be present in the design, making the system collectively exhaustive and mutually exclusive.



1.2.1	Allow roll rotation of skis about x axis to enable control over edge angle	System to allow roll rotation about x axis
1.2.1.1	Allow one degree of freedom in roll	Pinned Joint Along the x axis with a metal shaft
1.2.1.2	Allow control input	Rolling movement of joystick
1.2.2	Allow movement of each "leg" along z axis to enable variable pressure on each ski, and to	System to allow displacement of each ski along z axis
1.2.2.1	Allow for the reduced acceleration of displacement along z axis to mitigate force on rider	Suspension System
1.2.2.2	Enable independent control over the vertical length of each "leg"	Electrical vertical length adjustment system

Figure 7. *Decomposition level four view*

2.6.1.1.) FR 1.2.1.1

FR 1.2.1.1 states that the edge angle assembly will allow only one degree of freedom in roll (about the x-axis). It is important that the system only moves in one degree of freedom to ensure that it is not coupled with another system.

2.6.1.2.) FR 1.2.1.2

FR 1.2.1.2 states that the system to allow roll rotation about the x-axis will have a way for the user to control the input.

2.6.1.3.) FR 1.2.2.1

FR 1.2.2.1 states the system to allow the displacement of the skis along the z-axis will have a method of reducing the acceleration of displacement along the z-axis in order to mitigate the force on the rider. In order to ensure a comfortable and enjoyable riding experience, the system must be able to absorb the force imparted on the device and user from the terrain.

2.6.1.4.) FR 1.2.2.2

FR 1.2.2.2 states that the system to allow the displacement of the skis along the z-axis will enable the user independent control over the vertical length of each leg. When turning, it is important to be able to alter the vertical length of each leg because depending on the sharpness of the turn, as well as the angle of the terrain, the legs may need to be different lengths to get optimal traction.

2.6.2.) Design Parameters

2.6.2.1.) DP 1.2.1.1

DP 1.2.1.1 states that in order to allow one rotational degree of freedom about the x-axis, the ski will be pinned along the x-axis with a metal shaft. This shaft will restrict motion to only one degree and ensure that no coupling exists.

2.6.2.2.) DP 1.2.1.2

DP 1.2.1.1 states that a rolling movement of the joystick will act as the control input of the system and enable the user to control the roll and edge angle of the device. It is important that the joystick uses a movement that is similar to the movement of the ski to make the device more intuitive to control.

2.6.2.3.) DP 1.2.2.1

DP 1.2.2.1 states that a suspension system will be used to mitigate the force exerted on the rider along the z-axis. If a suspension system were not used, the frame and the rider would have to take the full force that the terrain exerts on the skiing device. In order to properly protect the rider and the device from these forces a spring and damper suspension system will be used.

2.6.2.4.) 1.2.2.2

DP 1.2.2.2 states that an electric powered vertical length adjustment system will be used to enable independent control over the vertical length of each leg. A powered system must be used because it will take a very large amount of force to extend and retract each leg, and an average human would not have the upper body strength to control the system for extended periods of time.

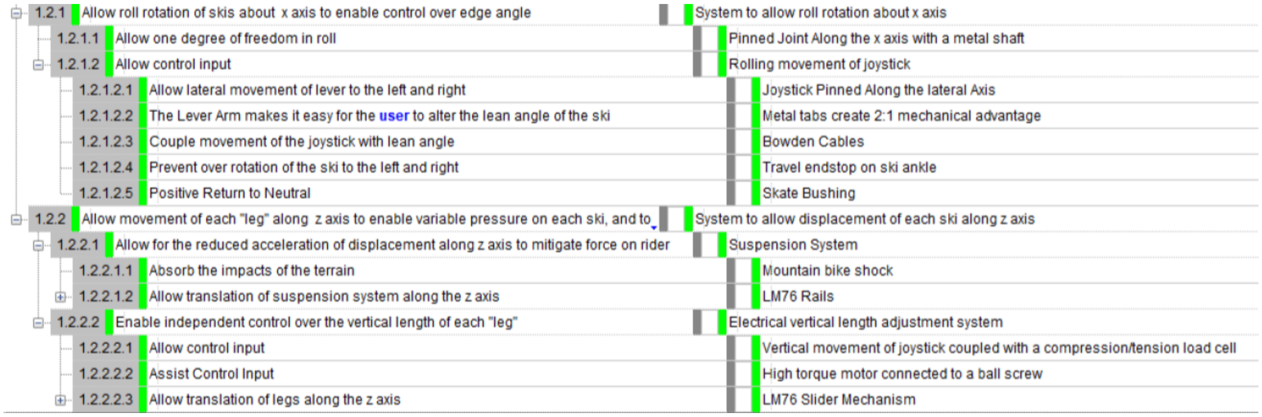
2.7.) Level Five

In this section, only the fifth levels associated with FR 1.2.1.2, FR 1.2.2.1, and FR 1.2.2.2 will be discussed because they still have several major design decisions to be explained and justified.

2.7.1.) Functional Requirements

Underneath FR 1.2.1.2, FR 1.2.2.1 FR 1.2.2.2, there are ten different functional requirements in the fifth level. At this level, the user control input for the roll mechanism and the vertical displacement system is defined in greater detail. In addition, the design decisions associated with the powered vertical length adjustment system and the suspension system are discussed. As shown in Figure 8, all the systems are separate from each other and include all of the systems that will be present in the design, making the system collectively exhaustive and mutually exclusive.

Figure 8. *Decomposition level five view*



1.2.1	Allow roll rotation of skis about x axis to enable control over edge angle	System to allow roll rotation about x axis
1.2.1.1	Allow one degree of freedom in roll	Pinned Joint Along the x axis with a metal shaft
1.2.1.2	Allow control input	Rolling movement of joystick
1.2.1.2.1	Allow lateral movement of lever to the left and right	Joystick Pinned Along the lateral Axis
1.2.1.2.2	The Lever Arm makes it easy for the **user** to alter the lean angle of the ski	Metal tabs create 2:1 mechanical advantage
1.2.1.2.3	Couple movement of the joystick with lean angle	Bowden Cables
1.2.1.2.4	Prevent over rotation of the ski to the left and right	Travel endstop on ski ankle
1.2.1.2.5	Positive Return to Neutral	Skate Bushing
1.2.2	Allow movement of each "leg" along z axis to enable variable pressure on each ski, and to	System to allow displacement of each ski along z axis
1.2.2.1	Allow for the reduced acceleration of displacement along z axis to mitigate force on rider	Suspension System
1.2.2.1.1	Absorb the impacts of the terrain	Mountain bike shock
1.2.2.1.2	Allow translation of suspension system along the z axis	LM76 Rails
1.2.2.2	Enable independent control over the vertical length of each "leg"	Electrical vertical length adjustment system
1.2.2.2.1	Allow control input	Vertical movement of joystick coupled with a compression/tension load cell
1.2.2.2.2	Assist Control Input	High torque motor connected to a ball screw
1.2.2.2.3	Allow translation of legs along the z axis	LM76 Slider Mechanism

2.7.1.1.) FR 1.2.1.2.1

FR 1.2.1.2.1 states that the joystick will allow lateral movement to the left and right to provide the input for the rolling mechanism.

2.7.1.2.) FR 1.2.1.2.2

FR 1.2.1.2.2 states that the lateral movement of the joystick must allow for the easy altering of the edge angle of the ski. The user may not have enough fore-arm strength to properly control the lean angle of the ski, so a system that creates a mechanical advantage will be used for the control input.

2.7.1.3.) FR 1.2.1.2.3

FR 1.2.1.2.3 states that the lateral movement of the joystick will be coupled to the movement of the edge angle, maintaining intuitive control.

2.7.1.4.) FR 1.2.1.2.4

FR 1.2.1.2.4 states that the device will prevent over-rotation of the ski to the left and right so that the rider maintains edge angles that are of reasonable values.

2.7.1.5.) FR 1.2.1.2.5

FR 1.2.1.2.5 states that there will be a positive return to neutral of the roll mechanism. This FR will ensure that it doesn't take the rider any physical effort to maintain a neutral position on the device when at rest.

2.7.1.6.) FR 1.2.2.1.1

FR 1.2.2.1.1 states that the suspension system will be able to absorb impacts of the terrain. A skier can experience a large range of impact forces depending on the terrain, so the device must be able to absorb all the impact forces without damaging itself or rider.

2.7.1.7.) FR 1.2.2.1.2

FR 1.2.2.1.2 states that the device must allow for the translation of the suspension system along the z-axis. The suspension system will be designed such that it only moves in the z direction to prevent coupling with other mechanisms. In addition, the suspension system will need to translate independent of the electronic vertical length adjustment system to ensure that it is not only decoupled, but also so that it does not become over constrained.

2.7.1.8.) FR 1.2.2.2.1

FR 1.2.2.2.1 states that the length adjustment system will have a method for the user to control its input.

2.7.1.9.) FR 1.2.2.2.2

FR 1.2.2.2.2 states that the length adjustment system will have a component to assist with the control input. This is necessary because the rider may not have enough upper body strength to maintain varying leg lengths, so an electrical assist will have to be used.

2.7.1.10.) FR 1.2.2.2.3

FR 1.2.2.2.3 states that the length adjustment system will need to translate independent of the suspension system to ensure they do not become coupled.

2.7.2.) Design Parameters

2.7.2.1.) DP 1.2.1.2.1

DP 1.2.1.2.1 states that in order to allow lateral movement of the joystick left and right, the joystick will be pinned along the x-axis.

2.7.2.2.) DP 1.2.1.2.2

DP 1.2.1.2.2 states that metal levers will create a 2:1 mechanical advantage to help the user control the lean angle of the ski. By creating metal levers on the roll mechanism that are twice the length of the actuating component on the joystick, a mechanical advantage of 2:1 is created. Other options include having a pulley system to increase the mechanical advantage, but it would become bulky and more complicated, adding to the information content of the system.

2.7.2.3.) DP 1.2.1.2.3

DP 1.2.1.2.3 states that in order to couple the movement of the joystick with the lean angle, bowden cables will be used.

2.7.2.4.) DP 1.2.1.2.4

DP 1.2.1.2.4 states that to prevent the over-rotation of the skis to the left and right, travel end stops on the ankle will be installed. These end stops will be mounted such that when the lean angle becomes too drastic, it will hit a plastic bump stop.

2.7.2.5.) DP 1.2.1.2.5

DP 1.2.1.2.5 states that a skate bushing will be used as a positive return to neutral. Skate bushings are very easy to install and come in varying resistances allowing for varying levels of positive return. Springs were also considered as a method for the positive return to neutral, but they can be larger and less reliable than a skate bushing would be.

2.7.2.6.) DP 1.2.2.1.1

DP 1.2.2.1.1 states that a mountain bike shock will be used to absorb impacts from the terrain. Mountain bikes undergo many of the same impact forces that the skiing device will experience, so using a mountain bike shock was chosen. Another option was to have a custom-made long travel suspension made for the design, but this would be much more expensive.

2.7.2.7.) DP 1.2.2.1.2

DP 1.2.2.1.2 states that to allow the translation of the suspension system along the z-axis, LM76 linear rails would again be used, just like in the x-axis translation mechanism.

2.7.2.8.) DP 1.2.2.2.1

DP 1.2.2.2.1 states that the rider will control the input of the length adjustment system by putting vertical forces on the joystick. The joystick will have a compression and tension load cell mounted within that will be able to detect vertical forces and convert it to an electrical signal. Another option was to have the joystick move up and down vertically and use an optical sensor to detect the change in position but using a load cell allows the system to stay more rigid and be less complicated, minimizing the information content.

2.7.2.9.) DP 1.2.2.2.2

DP 1.2.2.2.2 states that a high torque motor attached to a ball screw will help assist the control input. Another option was to use a scissor lift to control the change in height, but actuation with such a device would be too slow and not function as well as a ball screw.

2.7.2.10.) DP 1.2.2.2.3

DP 1.2.2.2.3 states that to allow the translation of the suspension system along the z-axis, LM76 linear rails would again be used. These rails would be completely independent of the other vertical rails used in the suspension system.

3.) Physical Integration

3D models of the axiomatic systems were created to facilitate physical integration. SolidWorks CAD software was used to draft each part of the design, which enabled computer analysis of interference, strength, and mass. A simplified 3D model of an adult human male was included in the draft assembly to verify the ergonomics of the design. The human model, ballscrew, and joystick models were used from GrabCAD (McMahon 2015, Miroslavov 2014, and Appleby 2017). 3D Models from part suppliers were used, and all other parts were custom designed.

3.1.) Overall Integration

The physical design resulting from the axiomatic design generally consists of a seat and seat frame, with a left and right side assembly each consisting of a joystick, leg, ankle, and ski. The joysticks are fixed to their respective leg and enable the user to control the position and orientation of the respective ski. Each leg enables translational movements longitudinally and vertically, and each ankle enables rotational movements in roll and yaw. Computer renders of the overall physical design are shown in Figure 9 below.

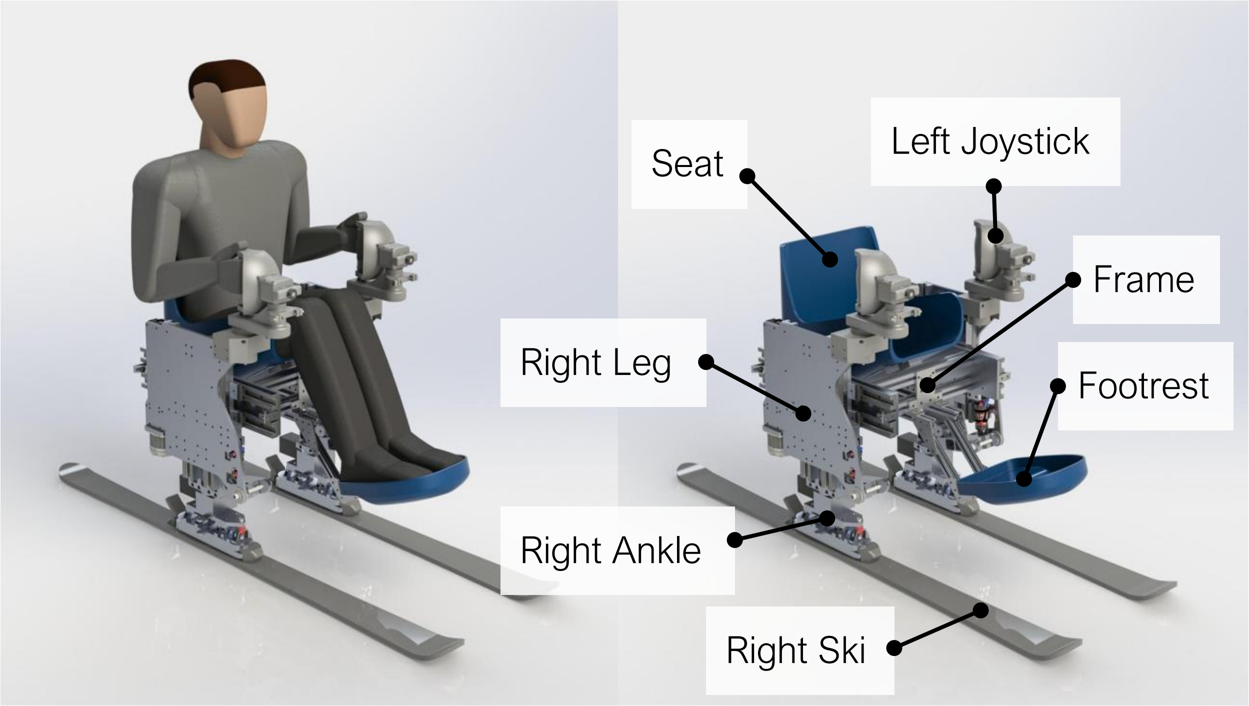


Figure 9.) *Overall Physical Integration Renders with and without Human Model*

3.2.) Frame Integration

The seat frame was viewed as an easier design challenge and was saved to be designed at the end of the project. Due to time constraints, the frame was not fully developed in the axiomatic decomposition and was left at a low FR-DP level. The seat frame fulfills FR 2, which is to "support human over ski(s)." The seat and footrest were reused from decommissioned Yetti monoskis, which were generously donated by Attitash Mountain Resort.

The main function of the frame is to rigidly connect the left and right legs to the seat and footrest, shown below in Figure 10. The frame was designed using extruded T-slot aluminum to simplify drafting and assembly, and to be more adaptable. The T-slots allow accessory components such as electronics to be easily attached anywhere, and the distance from the seat to the footrest can quickly be modified to adapt for taller or shorter users.

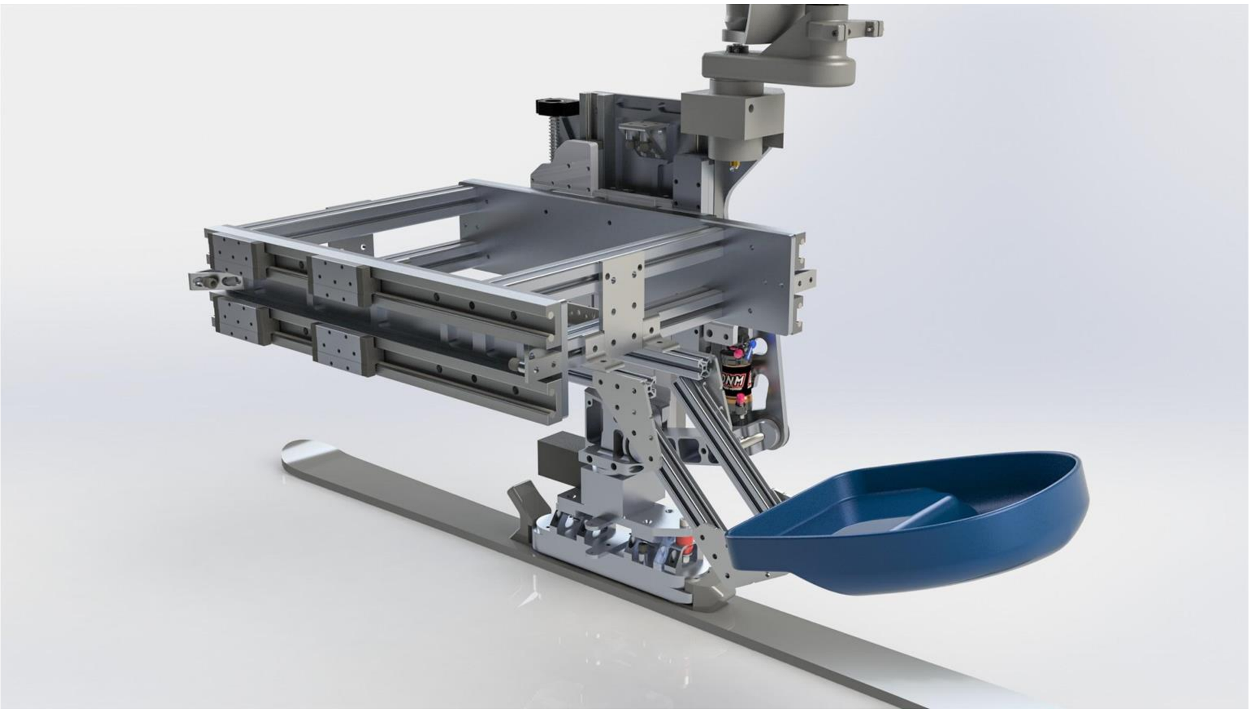


Figure 10.) *Frame Integration Render*

3.3.) Leg and Ankle Integration

The left and right legs and ankles are the most integral parts of the design. These systems enable all the translational and rotational movements of each ski.

The first stage of movement from the seat frame is the fore-aft translation, fulfilling FR 1.1.1, “Allow translation of skis along x-axis.” The translation is allowed on each leg using two linear roller slides with two carriages on each, which are labelled in Figure 11 below but are more visible in Figure 10 above. Linear roller bearings were selected because frictionless linear motion is required with potentially large moments and deflection. Linear plain bearings have a much higher resistance to environmental conditions such as water and dirt, however due to the “binding ratio” they cannot support large moments without seizing movement (Schroeder, 2017). Linear ball bearings can be more affordable due to their abundance in CNC manufacturing equipment; however, they require tight tolerances and low deflection for frictionless movement. Linear roller bearings generally consist of a rail and a carriage block, with the carriage block having multiple rollers which ride along the rails. A single carriage block is constrained in all axes other than the desired linear translation, so only one carriage is required to allow the intended motion, however it could potentially experience high moment loads. These moment loads can be eliminated by using four carriages on two rails, so that each carriage only sees an applied force rather than a torque when a moment is applied to the system. The system can hold a higher moment load when the carriages are spaced further apart.

LM76 was a local supplier for linear motion components and had a large selection of roller bearings available, so the roller bearings were purchased from them. The SGB-20N-3 bearings were selected based on the load strength required to hold the moment of an average person with the slides in the rearmost position. These style slides were used on all other linear axes for design simplicity. The rails were chosen to be 600mm long to allow the leg to have a significant travel of 300mm, and so that the rails did not extend too far ahead of the user, and were chosen to have centerlines spaced about 75mm apart to hold the moment created from a lateral force of 200N at the base of the ski (Euro Bearings 2018).

The second stage of movement is the leg extension, fulfilling FR 1.2.2, “Allow movement of each ‘leg’ along z-axis to enable variable pressure on each ski.” The carriages were spaced vertically just enough to straddle the horizontal slides and spaced horizontally enough to leave room for the next stage, discussed below. A large force is required to actuate the leg extension system and lift the user up, so an assist motor is used, fulfilling FR 1.2.2.2, “Assist control input.” A hybrid servo-stepper motor from Clearpath Motion was chosen to drive a ball screw and assist this movement because of the large force, speed, and accuracy required (Clearpath 2019).

Within the second stage is another set of independent vertical slides, which are passively controlled by an air shock. This system fulfills FR 1.2.2.3, “Reduce acceleration of displacement along z-axis to mitigate force on rider." Air shocks were chosen because of their simplicity and adaptability. Regular spring shocks have a narrow envelope of weight compatibility, but air shocks can simply be pumped up to a pressure that supports the desired load. Air shocks are abundant and proven within the sport of mountain-bikes, so a top-rated shock available on Amazon was chosen. It has a short travel of 35mm, but the linear slides have a travel of 140mm, so a 4 to 1 lever was used, and a short linkage was added to interface with the linear motion. This type of suspension linkage also creates a progressive motion, meaning that the spring force from the damper onto the leg increases exponentially with suspension displacement rather than linearly, giving better resistance to bottoming out (Collins, 2018).

The third controlled axis of movement is the yaw rotation of each ski, fulfilling FR 1.3.1, "Enable control over rotation of each ski about z-axis." This system is controlled by a stepper motor and a worm gearbox, fulfilling FR 1.3.3.1. The worm gearbox prevents the motor from being back driven, reducing the required holding torque of the motor and increasing precision. The shaft from the worm gearbox is internally threaded and constrained vertically inside the mounting block above by a screw. The potentially large moment loads are transmitted around the shaft through an oversized thrust bearing.

Finally, the last controlled axis is the roll rotation of each ski, fulfilling FR 1.2.1. This system uses sets of radial bearings which support 8mm shafts, allowing the rotation. The axis of rotation is positioned roughly half the ski waist width above the ski so that a large force is not required to roll the ski. A standard skateboard truck bushing is used near the toe of the binding to provide damping and a positive return to center.

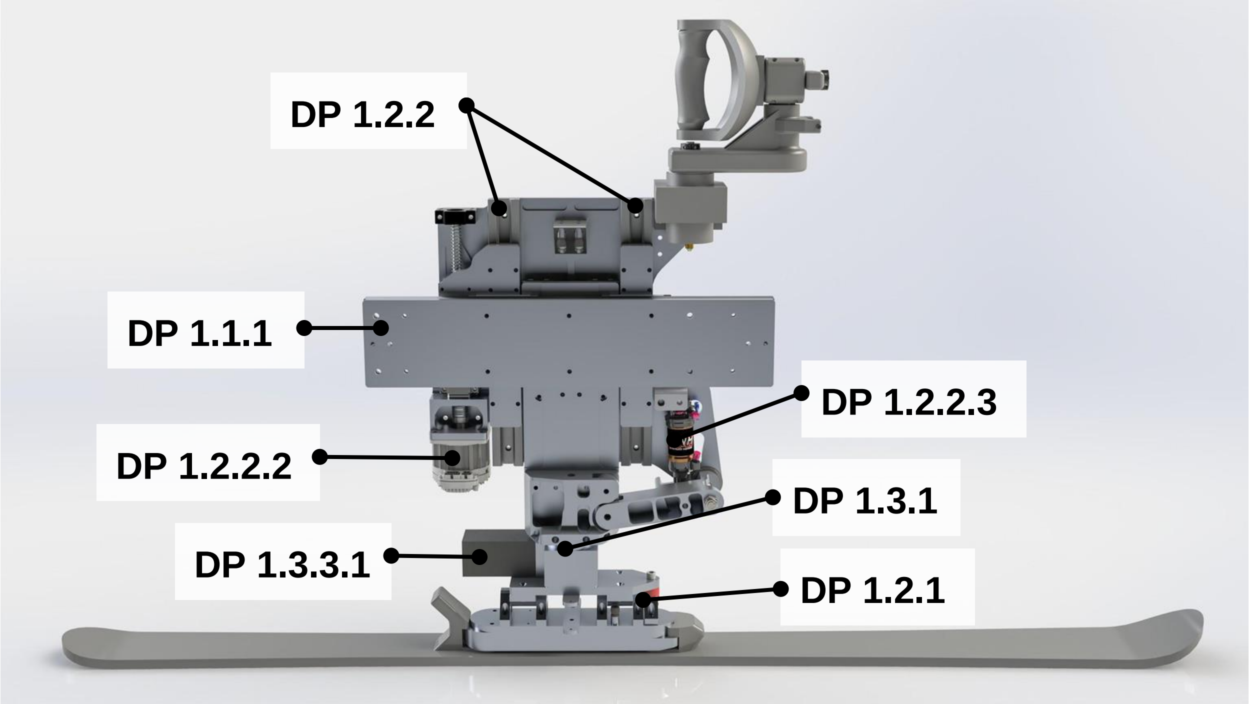


Figure 11.) *Leg and Ankle Integration Render*

3.4.) Joystick Integration

All the controllable movements of each ski are controlled by their respective joystick. A close-up of the left joystick is shown in Figure 12 below. FR 1.1.2 is to “Allow control input” for the fore-aft translation of each ski, and FR 1.2.2.1 is to “Allow control input” for the vertical translation of each leg, which are both fulfilled by having the handle grip secured directly to the stage of the leg which can freely translate fore, aft, up and down. Additionally, FR 1.2.2.2 is to “Assist control input” for the vertical translation of each leg, which is achieved by first sensing the vertical force applied to the joystick with a load cell located inside the first stage of the joystick. FR 1.3.2 is to “Allow control input” for the yaw rotation of each ski, which is fulfilled by allowing the handle to twist an encoder protruding from the bottom of the joystick. FR 1.2.1.2 is to “Allow control input” for the roll rotation of each ski, which is fulfilled by allowing the handle to twist a lever at the front of the joystick that extends and contracts bowden cables connected to similar levers about the axis of roll rotation.

Similar to the frame, much of the joystick design was left until the end of the project because it was not viewed as a difficult design challenge. The joystick became more complicated than anticipated after working to maintain independence of control inputs, which would have been coupled with a more traditional looking joystick. Traditional joysticks rotate about axes below the handle grip, which would create a moment when forces for FR 1.1.2 and 1.2.2.1 are applied directly to the handle grip. For example, if the user rolled a traditional handle to create an edge angle, then applied a force to translate the leg forward, a yawing moment would be created and the user would likely yaw the ski by accident. To solve this, joystick was designed in a gimballed format so that the axes of rotation were aligned with the center of the handle grip. The center of rotation was then aligned with the point where forces for FR 1.1.2 and 1.2.2.1 are applied, decoupling the inputs and eliminating any unintended interactions.

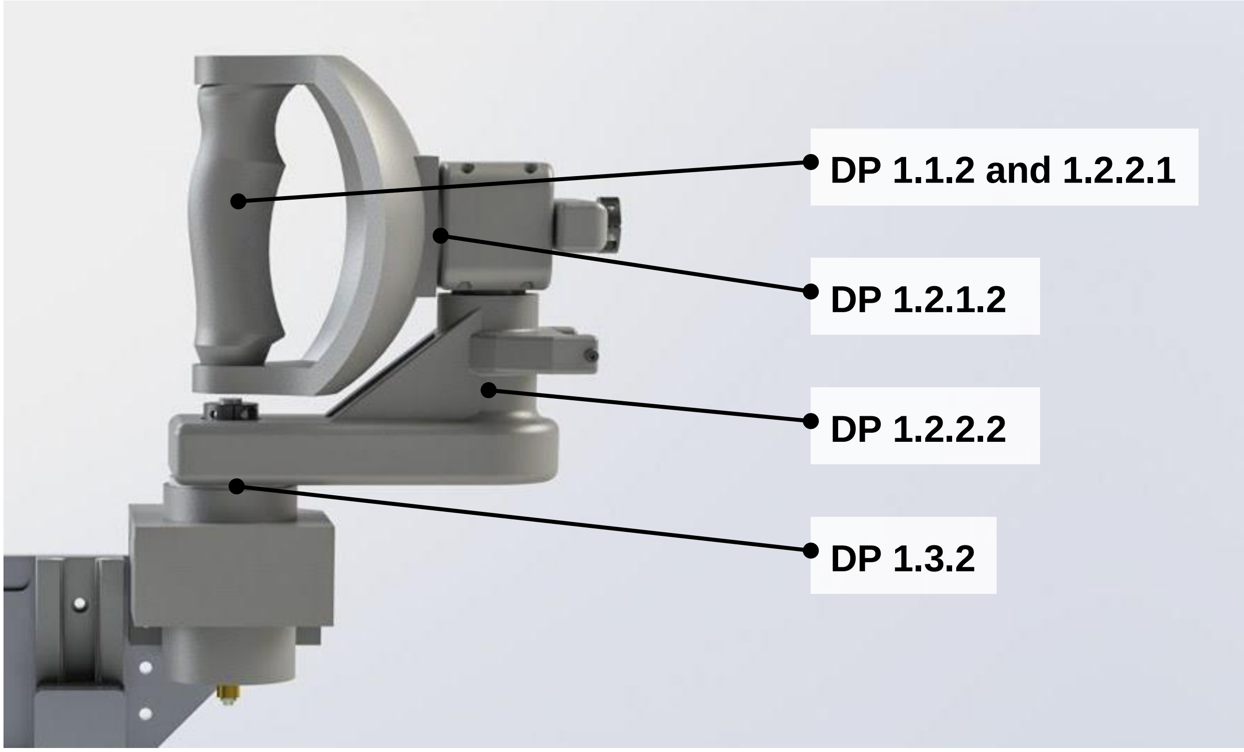


Figure 12.) *Joystick Integration Render*

4.) Prototype Production

The production of the prototype was completed using various manufacturing tools. The physical design uses many plate-shaped parts to interface between the linear slides, which were determined to be manufactured most easily through waterjet cutting. The other custom metal parts were CNC machined out of 6061 aluminum at WPI Washburn Shops using a Haas VM2 for large parts, and a Haas Super Mini Mill for small parts. The toolpaths for the CNC machining was created using Autodesk Fusion 360 software. The joysticks were manufactured using multiple FDM 3D printers, including a Prusa i3, pictured in Figure 13 below.

Figure 13.) *FDM 3D Printer (Left), Haas VM2 Mill (Center), Haas Super Mini Mill (Right)*

4.1.) Computer Aided Manufacturing

The toolpaths for CNC machining was chosen to be created in Autodesk Fusion 360 because of the software's intuitive interface, numerous resources, collaborative features, and proven use within Washburn Shops. The workflow within Fusion 360 included directly importing each SolidWorks part to be machined then switching to the manufacturing workspace and defining each setup required to machine the part. Figure 14 below shows an example of a light weighting operation performed on one of the large mounting plates in Fusion 360. The pockets were created in SolidWorks based off the locations of the mounting holes and locations of the mounted parts. In Fusion 360, roughing, finishing, and chamfering operations were created for all features where possible. The roughing was performed using Adaptive Clearing, which automatically created trochoidal moves to keep a consistent chip load for the tool, and more efficiently remove material.

A valuable feature in Fusion 360 is the intuitive auto-probing operation. The interface allows the user to set up a part's origin and pre-program any probing macro desired, so that probing macros do not need to be manually generated on the machine over and over for parts with similar origins. This feature was used extensively when more than two of the same parts had to be made, because the origin of the first part still had to be located manually for the auto-probing procedure to probe in approximately the correct location for the next part. Parts which used auto-probing included the single setup light-weighting for the linear rails and the three setups required for all the roll shaft supports.

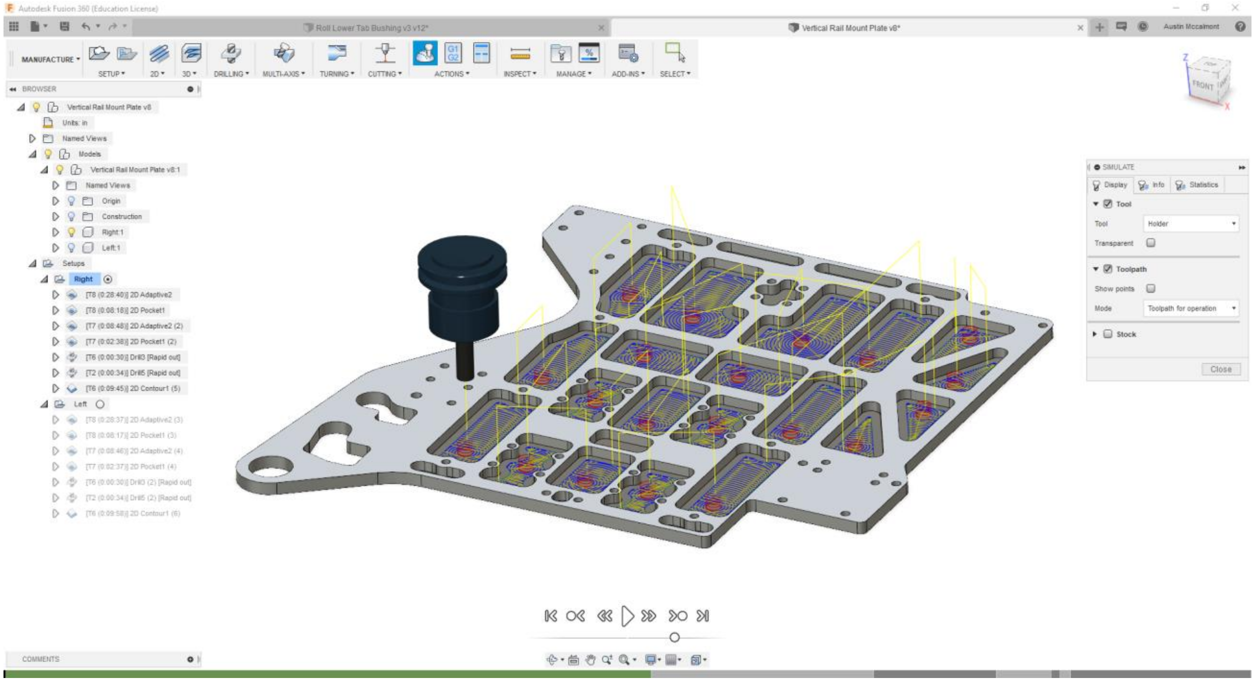


Figure 14.) *Screenshot of Machining Operations Created in Fusion 360*

4.2.) CNC Fixturing

Multiple types of part fixturing were used while machining. When possible, parts were fixtured using a vice to reduce the time required to fixture each part. When a vice was installed, it only needed to be trammed once on its fixed side, then all parts fixtured in the vice did not need to be trammed. Many of the parts which were machined and light weighted were able to be fixtured in a vice, but were too long to be properly supported by a single device, so two vices were used to fixture the part, which were trammed together by clamping a steel block in both vices, and tramming across its side.

An example of double-vice fixturing is shown below in Figure 15, with single setup light weighting for the 600mm long linear rails. The Renishaw electronic probe is visible in the spindle, ready to auto probe the part. With this setup, cycle times were reduced to around five minutes while removing almost 350g of material, including the time required to manually remove one part and fixture the next.

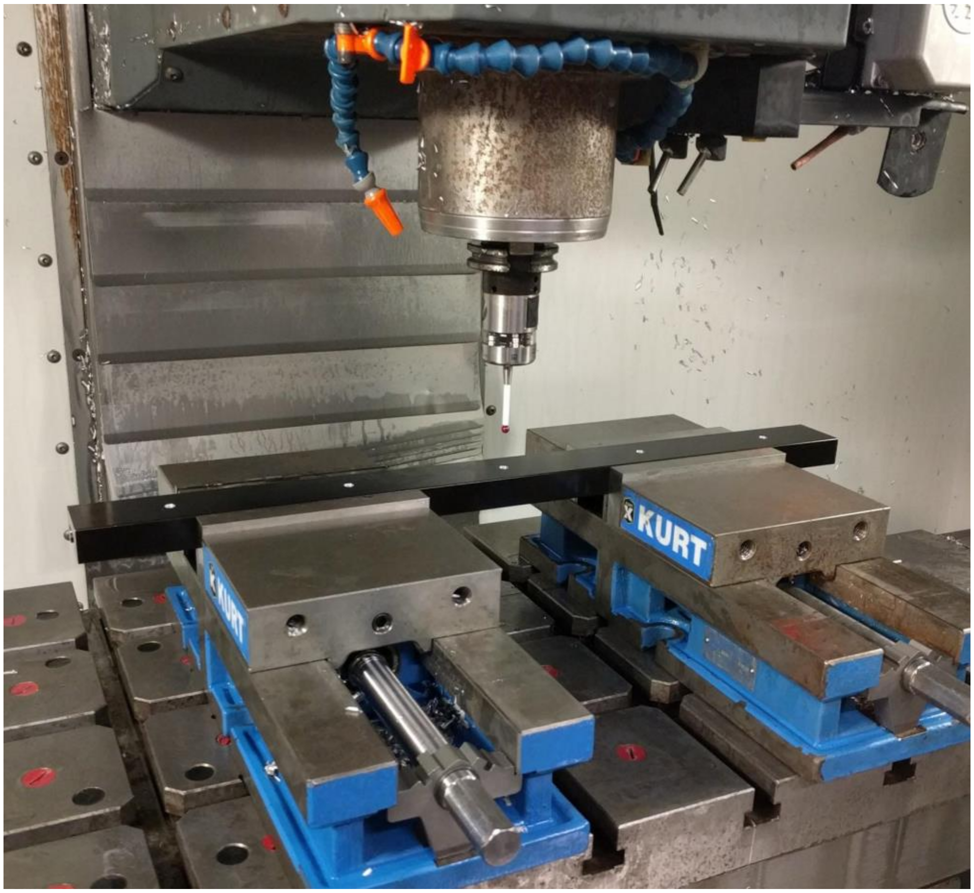


Figure 15.) *Setup for Light weighting of 600mm Linear Rail*

All the waterjet parts also required light weighting, yet often had odd-shaped perimeters or were simply too big to be fixtured in a vice, so toe-clamps were used. Figure 16 below shows an example of a toe clamp setup for a ⅝” thick waterjet part. That operation also used a sacrificial plate to allow drilling operations to go full depth. To clamp the part, a flat reference edge was first pushed against two vertical dowel pins placed in the T-slot to get the edge close to parallel with the machine, and after lightly clamping was then trammed in with a dial indicator as shown in the figure. In addition to light weighting, a few functional features were added to the waterjet parts including pockets for bolt heads, blind nuts, and areas requiring more clearance.

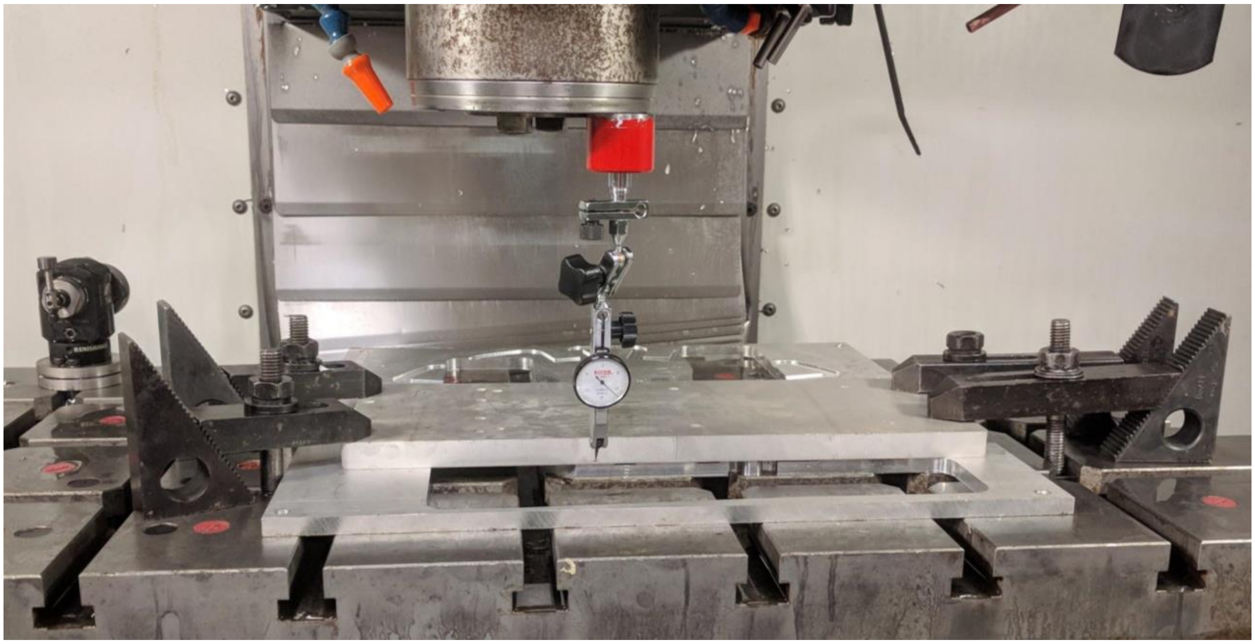


Figure 16.) *Toe-clamp Setup with Sacrificial Plate for Waterjet Part*

4.3.) Assembly

Most of the assembly for the prototype occurred over a few days leading up to WPI MQP project presentation day. Figure 17 below shows a spread of the parts ready for assembly at the time. All the screws and bolts were organized into plastic bins for easier location and access. The first step in assembling one of the rail systems included setting the eccentric roller on the carriage to the proper pretension, which was done by mounting the carriage on the rail and rotating the eccentric roller until increased sliding friction was noticed. The eccentric roller set screws were then tightened.

An unforeseen phenomenon experienced during assembly was cold welding of the bolts to the lock nuts. The fasteners were all made of 18-8 stainless steel to have better corrosion resistance in environmental conditions, but this ended up creating an ideal scenario for cold welding as was experienced (Bolt Depot 2019). Fortunately, a marine-grade anti-seize compound had also been purchased due to concerns of galvanic corrosion between the stainless fasteners and the aluminum parts, which also worked well to eliminate problems with cold welding.

The assembly was not fully completed at the time of this report, but what had been assembled can be seen below in Figure 18. Parts not finished included the yaw mounts which connects the ankles to the legs, and the suspension linkages. In total, the full assembly has 218 major parts excluding fasteners. Many parts, such as the linear carriages and dampers, each have multiple sub-components which are not included in that number.

Figure 17.) *Parts Ready to be Assembled*

Figure 18.) *Final Prototype Nearly Assembled*

5.) Testing of design

Our adaptive skiing concept is still in its final production phase, testing has been limited to checking the function of each motion system as they are completed. As each motion system is completed it is checked to make sure it can pass through all the positions needed to fulfil its functional requirement. Systems that use similar methods of achieving motion are tested in similar ways. Once tested for basic function the parts will be tested to ensure that there is no unintended coupling occurring once the individual components are assembled. Testing on the full system will begin once all parts have been completed and checked for their individual function.

Testing on the linear slides was completed to make sure that they were properly aligned to make sure that there is no added friction. The carriers were also checked to make sure that they fit the sliders correctly. To make sure the sliding parts were fully constrained, the bump stops were also tested to make sure that they could withstand the forces applied by the sliders. Through this testing we found that the parts could all handle the applied loads, but after experiencing vibrations we found that some parts tended to work their way loose. In order to improve on the longevity of our design solution we recommend increasing the amount of thread-locker used or switching to full use of nylon locknuts. The roll system was tested to make sure it was able to rotate between both extremes of the motion without binding, along with making sure the selected bushings provided appropriate return to center.

Future testing of our design solution will include testing the roll cable system to make sure it provides the proper mechanical advantage to the user, along with testing of the damper and spring system to ensure proper force absorption, and testing of all electrical components to make sure they provide outputs that are properly calibrated to the inputs of vertical force and yaw. Once the individual parts are certified to function as designed, testing of the full assembly will begin. This testing will include vertical and horizontal load testing, vibration testing, control testing, and testing to make sure all axes are decoupled.

6.) Discussion

The completion of this project revealed several notable conclusions. First, that Axiomatic Design is a viable design theory that encourages novel ideas and robust systems. We were also able to conclude that through the Axiomatic Design process, we were successful at creating a device that provides users with more control, better means of fulfilling 3D dynamics involved in turning as described by Euler's equations, and a more accessible adaptive skiing experience. Future improvements can be made to make the device cheaper to manufacture and easier to use, along with finally taking the device to market.

6.1.) Axiomatic Design Analysis

Axiomatic design separates the system requirements into individual functional requirements (FRs) each with a matching design parameter (DPs). This method was used to design the systems independently of our preconceived notions as to how to design an adaptive skiing device. Since the functional requirements of our system could be laid out independently of one another, it allowed us to decide upon the ideal design parameter for each motion. When designing each system, only the requirements of that system needed to be considered, allowing us to focus on creating a fully decoupled motion in each axis. Approaching this design problem through Axiomatic Design allowed us to fine tune each individual control method without altering the others. Each of the functional requirements were satisfied through the corresponding design parameters, as Axiomatic Design allowed for the rigorous development of each concept before moving to prototype production.

6.2.) Constraints

The prototype design solution meets all customer needs and constraints set forth above. In theory, the device does not limit the level of ability of the rider, allowing anyone to use it, and does not pose significantly higher risk to the rider compared to current devices. All of this was achieved within the budget we were given. The device could be lightened significantly as it is currently much heavier than standard adaptive skiing devices and is likely stronger than required.

6.3.) Analysis of Design Objectives

Current adaptive skiing devices mostly consist of seats with passive suspension connected directly to the control surface. This leaves all control of turning to the rider through manipulation of body position. Our design solution provides 4 axes of direct control to the rider in order to complete natural skiing motions while only requiring inputs from the riders arm. Users have control over leg extension in two axes, vertical and horizontal, along with ski rotation in two axes of roll and yaw. These four motions were selected because they most accurately encompass the required movements to complete standard skiing techniques. Our design solution provides fully independent control over movements that are currently unavailable on any other accessible skiing device.

The design solution fulfils FRs that directly relate to motions utilized when skiing naturally. The adaptive skiing concept utilizes vertical control (along the z-axis) and longitudinal control (along the x-axis) over the location of the center of gravity of the rider. These control axes mimic the function of the human upper leg muscles, altering the torque created while turning. These linear motions create the shift in center of gravity that natural skiers use to cleanly enter and exit carve turns. The other two axes of dynamic control influence the roll and yaw characteristics of the ski, motions created at the knee of traditional skiers. Allowing the rider control over the orientation of the ski opens up more skiing techniques that require finer adjustment of ski attitude. Having this control over the ski allows for the rider to utilize techniques such as the pizza turn, skid, and hockey stop. Through these four motions, our design solution will be better able to exhibit most techniques utilized while skiing naturally down a slope.

Due to the lack of active control, prior adaptive skiing designs rely on the rider being able to shift their center of gravity around in order to enter and exit turns. Movement of the center of gravity requires upper body strength that is not present in people with high level spinal injuries, which limits potential users. Requiring this additional movement means that most introductory adaptive skiers, or those without necessary abdominal strength, require additional guides or handlers to ensure safety. Through use of our control axes, adaptive skiers will now be able to adjust their center of gravity even without great abdominal strength. Our design solution can fulfil the motions needed to turn while requiring less core strength, an improvement that will allow people with higher level injuries to complete proper skiing technique. Adaptive skiers who required assistance in the past will now be able to ski more independently.

We succeeded in fulfilling our objective of creating a design solution that provides the user with more control over ski position and center of gravity changes, mimics the motions used by non-disabled skiers in order to fulfill Euler’s equations, and allows for individuals of more levels of disability to ski independently.

6.4.) Future Work

The adaptive skiing prototype achieves the objectives of providing more dynamic controls to the user in order to better mimic non-disabled skiing technique. The prototype provided a good starting point for a consumer device but there are several future iterations that could be made to improve on the design and overall functionality of the device.

Material selection should be considered in future iterations in order to maximize the weight to strength ratio. Composite materials like carbon fiber could be utilized to maintain strength while reducing weight. Other metals than aluminum such as titanium could also be incorporated in finite areas to further improve the strength to weight ratio.

Additional features for the device not explored in the first prototype but included in the filed IP include a motor to assist with traversing flat terrain with a regenerative braking feature to charge the system while reducing speed on downhills, and a fifth axis of dynamic control that allows the user to adjust the adjacent distance between each ski to increase stance and achievable yaw angles. With the already included electrical components, additional sensors such as a gyroscope and accompanying software could be included to allow for assistive piloting. More advanced electrical components incorporating robotics could also be included to further improve the dynamic nature of the device but may couple functions, reducing independence of components.

7.) Conclusions

- Axiomatic Design provided a rigorous design method that was successful in creating a system that fulfills our customer needs
- The design solution created was then produced through the use of CNC machining, 3-D printing, and water jet cutting of parts
- Design parameters were analyzed to insure their completion of the associated functional requirements
- We created a device that better mimics non-disabled skiing techniques when compared to current state of the art adaptive skiing devices and allows its user to better recreate proper skiing technique
- Our adaptive skiing concept provides the user with more control over both position and orientation of the skis and user
- The axiomatically designed adaptive skiing device will allow people to ski more easily and independently despite greater levels of injury
- Future work on this project could include improvements in material selection to maximize strength to weight ratio, increased axes of control, powered acceleration and regenerative braking, or assisted piloting software

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Appendices

Appendix A: Acclaro Decomposition

0	Enable disabled skiier to mimic non-disabled skiing technique	Accessible skiing device
1	Enable dynamic control over skis	Dynamic control system
1.1	Enable independent control over forward/backward load on each ski to satisfy Euler's	System to alter the forward/backward load on each ski
1.1.1	Allow translation of skis along x axis	LM76 Slider Mechanism
1.1.1.1	Allow One Degree of Freedom In Pitch	Rail and Coupler
1.1.1.1.1	Rails must provide enough movement along x axis to satisfy all load situations	Rails of length 600mm
1.1.1.1.2	Coupler must be able to slide smoothly over rails without binding	Slider interfaces with roller bearings
1.1.1.1.3	Rails must deflect very little because they require very precise movements	Thick aluminum and steel construction
1.1.1.1.4	The "legs" must be attached to the slider mechanism	Large aluminum mounting plate with appropriate mounting holes
1.1.1.1.4.1	Must deflect very little because it must hold the rails straight	Thick aluminum construction (1/4" material)
1.1.1.1.4.2	Must be as lightweight as possible	Lightweight pocketing on inside of the plate
1.1.1.1.4.3	Mounting hardware must properly secure the plate without shearing	1/4-20 steel screws with lock nuts
1.1.1.2	Prevent Over Travel of the Slider	Plastic bump stops mounted on the ends of the rails
1.1.2	Allow Control input	Hand grip
1.1.2.1	Couple the movement of the hand grip with translation of the skis along the x axis	Mount the hand grip to the mounting plate
1.1.2.2	Must be shaped such that it is ergonomic and easy to grip	Hand grip based off of a ski pole
1.1.2.3	Hand grip must not break under the load of translating the skis along the x axis	Thick PLA construction
1.1.3	Positive return to neutral	Fore and Aft Extension Spring Assist
1.1.3.1	The spring assist must not impede the individual with reaching the full travel of the	Extension springs that have enough force to return to neutral, but not have so much force as to prevent the user from reaching
1.1.3.2	Springs must be mounted such that they do not interfere with the movment of the system	Mounted above and below the horizontal rail system
1.2	Enable independent control over lateral load on/from each ski to allow entire system to roll	System to vary the lateral load on/from each ski
1.2.1	Allow roll rotation of skis about x axis to enable control over edge angle	System to allow roll rotation about x axis
1.2.1.1	Allow one degree of freedom in roll	Pinned Joint Along the x axis with a metal shaft
1.2.1.2	Allow control input	Rolling movement of joystick
1.2.1.2.1	Allow lateral movement of lever to the left and right	Joystick Pinned Along the lateral Axis
1.2.1.2.2	The Lever Arm makes it easy for the user to alter the lean angle of the ski	Metal tabs create 2:1 mechanical advantage
1.2.1.2.3	Couple movement of the joystick with lean angle	Bowden Cables
1.2.1.2.4	Prevent over rotation of the ski to the left and right	Travel endstop on ski ankle
1.2.1.2.4	Prevent over rotation of the ski to the left and right	Travel endstop on ski ankle
1.2.1.2.5	Positive Return to Neutral	Skate Bushing
1.2.2	Allow movement of each "leg" along z axis to enable variable pressure on each ski, and to	System to allow displacement of each ski along z axis
1.2.2.1	Allow for the reduced acceleration of displacement along z axis to mitigate force on rider	Suspension System
1.2.2.1.1	Absorb the impacts of the terrain	Mountain bike shock
1.2.2.1.2	Allow translation of suspension system along the z axis	LM76 Rails
1.2.2.1.2.1	Rails must provide enough movement along z axis to satisfy the entire range of the shock	Rails of length 350mm
1.2.2.1.2.2	Coupler must be able to slide smoothly over rails without binding	Slider interfaces with roller bearings
1.2.2.1.2.3	Rails must deflect very little because they require very precise movements	Thick aluminum and steel construction
1.2.2.1.2.4	Prevent over travel of the sliding mechanism	Plastic bump stops mounted on the ends of the rails
1.2.2.2	Enable independent control over the vertical length of each "leg"	Electrical vertical length adjustment system
1.2.2.2.1	Allow control input	Vertical movement of joystick coupled with a compression/tension load cell
1.2.2.2.2	Assist Control Input	High torque motor connected to a ball screw
1.2.2.2.3	Allow translation of legs along the z axis	LM76 Slider Mechanism
1.2.2.2.3.1	Rails must provide enough movement along z axis to satisfy all situations	Rails of length 410mm
1.2.2.2.3.2	Coupler must be able to slide smoothly over rails without binding	Slider interfaces with roller bearings
1.2.2.2.3.3	Rails must deflect very little because they require very precise movements	Thick aluminum and steel construction
1.2.2.2.3.4	Prevent over travel of the sliding mechanism	Plastic bump stops mounted on the ends of the rails
1.3	Enable control over rotation of each ski about z axis to enable skidding, snow plows, and	System to yaw each ski
2	Support human over ski(s)	Human supporting system
3	Allow easy loading on/off chairlift	Chairlift loading method
4	Allow easy car transport	Car transport method
5	Allow multiple sized humans to operate	Size adjustment system