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ACL Protective Footwear Design

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by

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1. Anterior Cruciate Ligament
2. Non-Contact
3. Athletic Shoe

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Abstract

The occurrence of non-contact ACL tears is extremely high in athletes. The reduction of such tears would keep more athletes on the field participating in their respective sports. The objective of this project is to design a load mitigation device that will reduce the occurrence of non-contact ACL injuries in athletes. This device will be integrated into the shoe. ACL injuries are very serious and prevalent in many different sports across a variety of skill levels. Research has already been conducted on the causes of ACL injuries. Using this data and further research into preventing ACL tears we created a system that mitigates the forces associated with non-contact ACL tears. The device is integrated into an athletic shoe that will reduce the occurrence of ACL injuries. Reducing the occurrence of ACL tears is accomplished by designing and prototyping a device integrated into an athletic shoe sole which mitigates the injurious loads in the knee associated with ACL tears during athletic activity and maintains normal performance of the athlete when loads are under injury threshold. This patent pending prototype design was realized using Axiomatic design principles. A mold for the prototype was modeled in SolidWorks then created using CNC machining. The prototype was tested using a force plate analyzed using Netforce software for data acquisition and Bioanalysis software for gait, balance and power; and with a uniaxial tensile test on an Instron machine. Through testing the prototype exhibited characteristics that would reduce the occurrence of ACL injuries.

1.0 Introduction

Anterior cruciate ligament (ACL) tears have kept athletes off of the field for months at a time, occasionally benching players permanently. Repairing a torn ACL requires surgery and extensive physical therapy to regain full range of motion in the knee. Even with these measures severe arthritis can still develop within the knee. Many of these injuries are caused from non-contact situations where direct contact to the knee never occurs. Approximately 250,000 ACL injuries occur per year and about 70% of these are non-contact situations (Dowling, 2010). The goal of this project is to determine how such injuries are occurring and prevent these injuries from happening. Once it was determined how non-contact ACL tears occur, a review of methods to prevent injury level forces from reaching the ACL was done. Through our research it was determined that ground reaction forces contribute highly in the tearing of the ACL in non-contact situations. The high ground reaction forces are found to focus in on specific areas of the foot associating with the non-contact ACL tears. Figure 1 demonstrates the location of these high forces in the shoe associated with an athletic cleat.

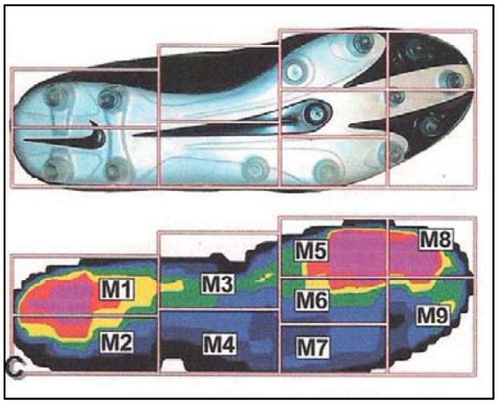


Figure 1: Force Concentrations in cleat when running (Burkhart, 2008)

A mechanical system was then developed based off of conducted research that focused on preventing dangerous ground reaction forces from reaching the knee, keeping the forces in the foot, never reaching the ACL. The project is divided into two different systems that can be applied to various ground reaction forces found in the foot that cause ACL tears. These two systems were realized through our research and the application of the Axiomatic Design Process.

1.1 Objective

The objective of the project is to reduce the occurrence of anterior cruciate ligament (ACL) tears in athletes participating in shoe (non-cleated) sports. The prevention or reduction of ACL tears will be accomplished by redesigning the sole of an athletic shoe. Redesigning the sole of the shoe was identified as a solution by determining that the ground reaction forces played a large role in non-contact ACL injuries. The sole redesign may also reduce the potential for other injuries to other portions of the body including the ankle. The application of the two mechanical systems in the shoe sole will mitigate injurious loads (ground reaction forces in the shoe), preventing them from affecting the ACL and preventing it from tearing. The prototype will be designed so it does not impede the athlete during normal playing conditions but allow the absorption of injurious loads when the injury threshold is reached. After loads are mitigated, the device will be able to restore itself to normal functions and be reused time and time again providing the same absorption functions.

1.2 Rationale

There is a high occurrence of ACL injuries in NCAA athletics as well as other athletic divisions. The NCAA Injury Surveillance System determined that there were approximately 5000 ACL injuries reported over a 16 year period; with football recording the highest number of ACL injuries. These numbers do not represent only non-contact situations; they also include a high percentage of ACL injuries which are non-contact related. This study also showed a high occurrence of lower limb injuries due to non-contact situations, more commonly occurring in practice situations (Hootman, 2007). Reviewing the variation between men and women and the occurrence of ACL tears it was determined that there is a much higher occurrence of tears among women ranging from 3-5 times greater risk (Nahr, 2005). Reviewing knee positions between men and women, showed that women have a much higher occurrence of positioning the knee in a valgus position. This position has been determined to cause non-contact ACL tears in athletes (Chaudhari, 2003). An example of valgus positioning can be viewed in Figure 2.

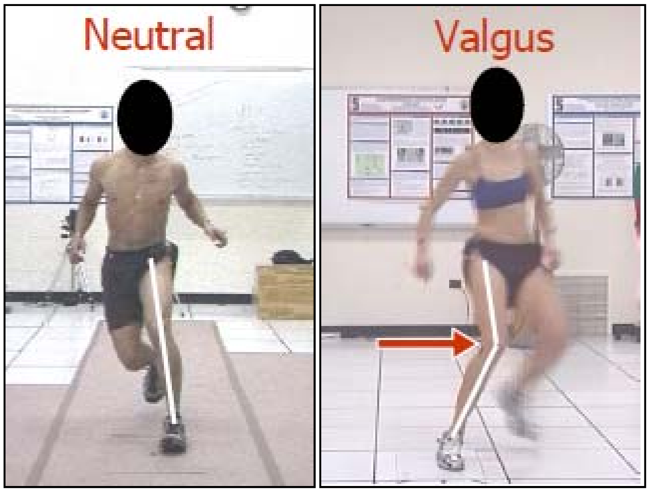


Figure 2: Demonstration of Valgus Position (Chaudhari, 2003)

It was also discovered that females have a smaller ACL, decreased ACL strength and a less-efficient ACL ultrastructure which can directly relate to why females experience a greater number of ACL tears (Hashemi, 2011). The highest incidence of ACL tears is found in younger adults playing sports classified as pivoting sports. These include football, basketball, and team handball as well as other sports (Nahr, 2005).

Reviewing the literature and the mechanisms behind a non-contact ACL tear, it was concluded that a review of ground reaction forces in the shoe is essential to decreasing the occurrence of injuries. The timing of the injury, measurement of forces and how they occur are essential components to the design solution. A review of foot position, landing and contact points was done to determine that ground reaction forces could in fact be absorbed in the shoe preventing the injurious loads from reaching the ACL. Shoe loading patterns were reviewed to determine the location of the forces and determine the location of the mechanical systems placed into the shoe (Burkhart, 2008).

1.3 State of the Art

There has already been substantial investigation into non-contact ACL tears to determine how to reduce the occurrence of non-contact tears in sports athletes. Reviewing injury prevention research it was determined that the project must be broken down into four components. First, establish the extent of the injury, next establish the mechanisms of injury, then Introduce a new preventative measure and lastly assess its effectiveness by reviewing step one. The majority of the project follows these terms beginning with researching the extent and severity of the injury, determining ways to prevent it, applying the solution directly and analysis to determine its effectiveness (Nahr, 2005). After research on the occurrence of ACL tears, it has been determined that there are several reasons why ACL tears occur and some current solutions to the problem. The following will review this research.

1.3.1 How is the ACL Injured

The Anterior Cruciate Ligament (ACL) is the major supporting ligament in the knee which stabilizes the knee, preventing abnormal movements of the knee, such as extreme rotations and hyperextensions of the knee. The ACL prevents forward translation of the tibia in relation of the knee which is seen as an abnormal motion (Olsen, 2004). ACL tears can occur in athletes although they have not made contact with another player. An example of tibia rotation can be viewed in Figure 3.

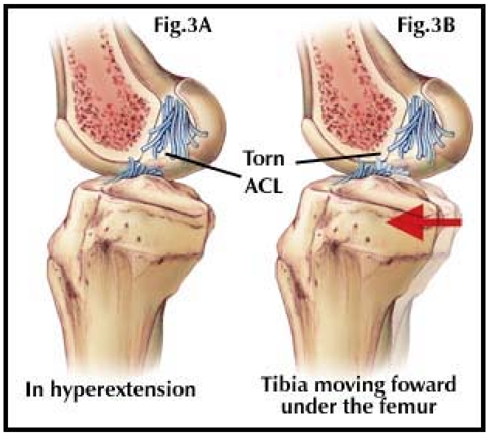


Figure 3: Example of motion of the Tibia that causes ACL Tears
http://prospektmarch.blogspot.com/2012/03/week-7.html

This happens because of a sudden deceleration of the player placing high forces on the knee. This sudden deceleration is usually followed with a change in direction of the athlete on the field. It is believed that the ACL tear occurs after the sudden deceleration but before the change of direction. Along with the sudden deceleration causing ACL tears it is also noted that during the motion of the body the knee appears to be at full extension with a valgus collapse of the knee (Dowling, 2010). Reviewing the main muscle groups involved in an ACL tear include the quadriceps muscle which when flexed causes a high force on the patellar tendon creating anterior tibial rotation of the knee, which when given high enough forces in the rotation can cause ACL injury. The free body diagram demonstrating the direction of forces in the knee can be viewed in Figure 4. Contraction of the quadriceps muscle applied a high strain to the ACL when the knee is located between 15-30 degrees of flexion with the highest strain readings associated with the 15 degree angle. Reviewing the ground reaction forces that cause the tear it is determined that the heel strike is directly associated with a high quadriceps contraction. It is believed that this heel strike and the valgus positioning of the knee is a direct cause to the non-contact tear (Olsen, 2004).

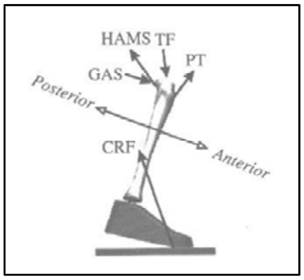


Figure 4: Free body diagram of ligaments, muscles and ground reaction forces (Kutz, 2009)

To prevent this from happening, the hamstring muscle must be developed with equal strength to balance the forces created by the quadriceps muscle (Podraza, 2010). With this being said, there is current research continuing to focus on the impact of ground reaction forces and their contribution to injuries to the ACL. The interaction of the muscles is a direct response to the ground reaction forces experienced at impact (Hashemi, 2011). As viewed in Figure 5, even with walking, a high force is experienced on the ACL when full contact is made with the ground. This is due to the ground reaction force and the occurrence of anterior tibial rotation of the knee.

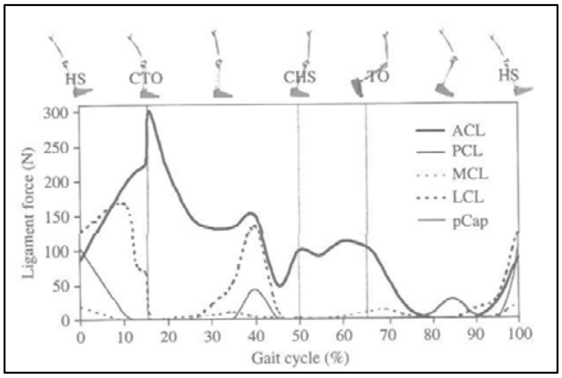


Figure 5: Ligament Force vs. Gait chart; demonstrates high ACL force with flat plantation of foot (Kutz, 2009)

Determining that the ground reaction forces are a high contributing factor to the tearing of an ACL in non-contact situations it is essential to model the interface between the foot, shoe and ground. It can be reviewed as a non-linear spring-damper system. The following equations are used to model the interfaces in the interfaces listed above (Chaudhari, 2006).

$$F = 0, y > 0$$

$$F = Ay^{b} + Cy^{d}v^{e}, y \leq 0$$

$$A = 1.0 * 10^{6}, b = 1.47, C = 2.0 * 10^{4}$$

$$d = 0.74, e = 1.0$$

Where y is the distance in meters between the foot and the ground in the global Y coordinate system and v is the velocity in m/s of the foot with respect to the ground in the global Y coordinate system. Further analysis of the model can be viewed in the paper “The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury” by A. Chaudhari and T. Andriacchi. The equations above and explanations are directly taken from this paper (Chaudhari, 2006). The analysis done determined that the peak value of forces on the leg equated to about 5.1 times body weight of the individual, with varying results with different hip stiffness and knee alignments (Chaudhari, 2006).

1.3.2 Non-Contact Injuries

Many ACL injuries have been associated with an increased coefficient of friction with the shoe surface. Surfaces such as astro-turf and high friction shoes have been known to lead to ACL tears. With this determined, a way of decreasing the coefficient of friction with the ground is considered and seen as a way of decreasing injuries (Dowling, 2010). Also contributing factors to non-contact ACL injuries include hard dirt surfaces, wooden floors and those that would create higher ground reaction forces in the shoe. It was also determined that a lower occurrence of tears occur when a frozen surface is present, as the coefficient of friction is greatly decreased reducing shoe surface traction (Burkhart, 2008).

Reviewing mechanisms of non-contact ACL injuries it is determined that there are a number of mechanisms that can cause an injury. They include the athletic motions named a fast break, zone defense, charging, cutting, setting up for a shot, defensive rebound, man-to-man defense, disturbance by an opponent, foul, sideways translation, rotation of the body around the fixed foot speed at impact, foot in front center of mass, valgus movement and pivot shift of the tibia relative to the femur. These moves are associated with the sport of basketball. Most of these moves include mechanisms where no outside contact is associated with the tear. These include the valgus movement, the pivot shift of the tibia relative to the femur, sideways translation, cutting, and fast breaking. These motions are of direct interest to the prevention of non-contact ACL tears in athletes (Nahr, 2005). These motions are commonly associated with the player receiving a ball, maneuvering a ball, passing the ball or defending the ball. The incorrect placement of the knee is associated with the player not paying direct attention to foot placement. The misplacement of the foot is associated with the non-contact injury but also associates the flat plantation of the foot creating a high ground reaction force (Boden, 2009). These motions are summarized and focused on two different motions that are associated with non-contact situations. These motions are the plant and cut mechanism (sideways translation) and one foot push offs. All situations are directly related to the phrase “sudden deceleration with a change in direction.” Some circumstances are associated with no change in direction but most athletic maneuvers contain both a sudden deceleration with a change in direction (Olsen, 2004).

Over 95% of injuries to the ACL are recorded on dry fields where ground reaction forces would be greater (Burkhart, 2008). Ground reaction forces are a leading cause of non-contact ACL injuries. Reviewing a single drop landing of an athlete, without injury, it was determined that there are two peak forces that are found; one measured 1.7 ± 0.1 body weight (BW) and occurred at 12 ± 0.3 ms from initial contact with the ground. The second peak occurred at 38 ± 1.6 ms and measured about 3.9 ± 0.4 BW. The first peak occurs with initial contact with the ground; while the second peak happens when the heel makes contact with the ground (Pflum, 2004). With this, a focus on ground reaction forces at the heel are analyzed; with a maximum ground reaction force associated with the timeframe of the ACL injury. This injury timeframe was determined to be 42 to 65 ms after initial contact with the ground with a maximum ground reaction force of 2.2 to 5.7 BW (Hashemi, 2011).

As ground reaction forces are revealed to be a high contributing factor in ACL tears it is also apparent that flat plantation of the foot (heel, midfoot, and forefoot) creates the highest ground reaction forces. These areas are concentrated in the medial heel, medial forefoot and the hallux. The injury itself occurred when the individual’s center of gravity is found to be behind the knee and when flat plantation of the foot occurred with heel and forefoot contacting the ground simultaneously (Burkhart, 2008). The easiest way to lower ground reaction forces in athletes is to land with a flexed knee, allowing the legs to work as a shock absorber, absorbing the kinetic energy at impact (Podraza, 2010). This is demonstrated in Figure 6 with a high patellar force at impact (heel and forefoot) and a decrease in forces as the knee bends.

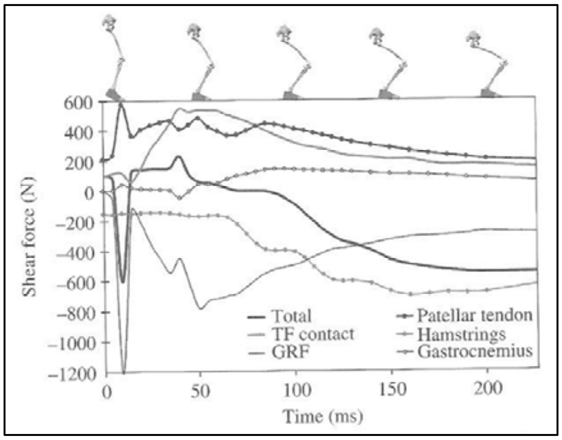


Figure 6: Shear Force vs. Time: Ligament, muscle and Ground Reaction force during drop landing (Kutz, 2009)

1.3.3 Current Solutions to Prevent ACL Tears in Athletes

Products currently on the market for preventing knee injury in athletes are external knee supports and rehabilitation exercises that can aid in preventing ACL tears. Many athletes, once they experience an ACL tear, are fitted with a custom knee brace that would prevent a second injury to the knee. These braces are usually very bulky and heavy, but prevent unwanted twisting and anterior tibial rotation of the knee. Maintaining an anatomically correct position in the knee is essential, as after surgery and rehabilitation, normal support muscles and tendons are weaker leading to an increase in repeat injuries. However, these braces are not meant for athletes who have not had a tear, and many knee braces are not marketed to prevent injury but to aid in supporting the knee after an injury.

Rehabilitation exercises and preventative strengthening motions aimed at stretching out the knee and balancing the strength between the hamstring and quadriceps muscle to prevent unwanted motion of the knee are recommended. This aids in preventing the valgus positioning of the knee, unwanted twisting and anterior tibial rotation. However, this is not a solution to the problem as positioning of the knee is not the sole reason for why the ACL tear occurs.

Through patent research we discovered a series of patents that review ways of preventing knee injuries in athletes. Many of the designs are fail systems which are designed to release the sole of the shoe when high longitudinal forces are applied to the shoe. This Decreases the friction associated with high ground reaction forces (Dennison, 2007). A torsion shoe is developed to allow a twisting motion to occur that is separate from the foot holder in the shoe. This allows for a decrease in friction associated with walking. The design was for users with diabetes who experience a loss of feeling in the bottom of their foot. The rotation decreases the friction on the bottom of the foot causing less irritation (Lehneis, 1999). An additional break away design was designed to break away the cleats when high forces are experienced in the lateral direction. The breakaway system is claimed to help in preventing lower limb injuries (Weiss, 1993). Another patent was a rotatable forefoot design that allows the foot to rotate at a greater angle preventing high torsional forces that are associated with lower limb injuries (Nedwick, 1972). A breakaway shoe is designed for safety purposes. The breakaway sole allows for the issue of high friction surfaces and high forces to be decreased with the separation of the sole from the shoe. A spring system is designed to control the activation of the system and the path of the system (York, 1972). Additional patents in the area of safety shoes include patent numbers 4670997, 4546556, 5456027, 3782011, 5155927, 7254905, 5255453, and 5867923.

1.4 Approach

Reviewing the literature we determined that it supported our claim that the occurrence of non-contact ACL tears can be reduced with a decrease in the maximum ground reaction force experienced in the shoe. Once this was confirmed we realized various systems that could solve the issue of absorbing ground reaction forces in the shoe. Through the application of injury prevention systems and the creation of a mechanical system in the shoe to absorb ground reaction forces, a graph was realized to explain how the system was designed based off of a predetermined Injury Threshold and High Injury Risk values. As seen in Figure 7, the curved line represents the absorption of forces in the shoe with an activation of the system at the injury threshold line; preventing the load in the system from never reaching the High Injury Risk Line. A standard shoe is represented with a linear line reaching the High Injury Risk Threshold.

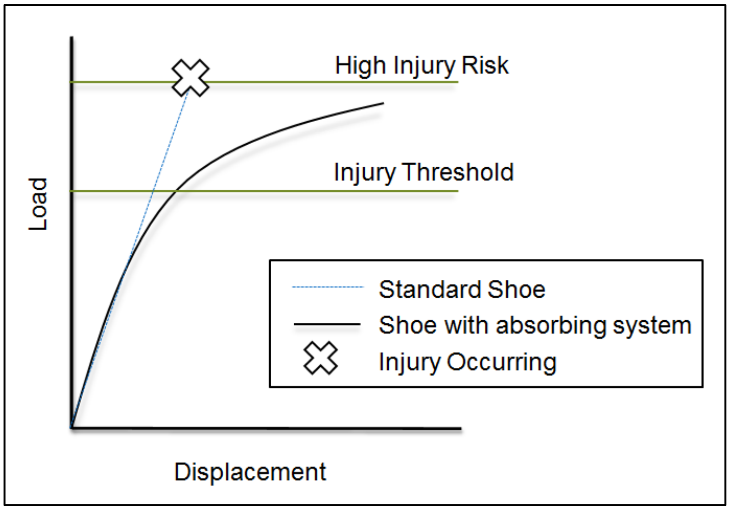


Figure 7: Graph Representing Activation of Force Mitigating System

Using Axiomatic Design principles and Acclaro Software, a design was visualized, prototyped and tested. Using the breakdown of functional requirements and design parameters the design was created following the two axioms of the Axiomatic Design Process. A prototype was then built and tested to determine if the design could be effective in mitigating injurious loads. Through testing, we believe the system is able to mitigate the ground reaction forces that are known to cause the non-contact tears to occur.

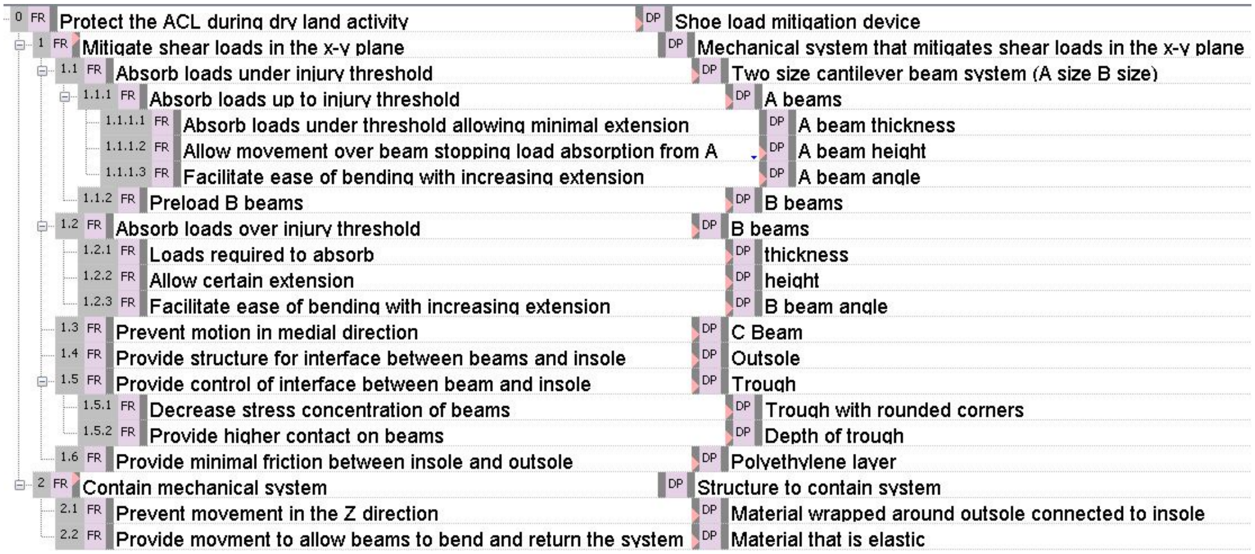
2.0 Design Decomposition and Constraints

Current technology provides an interface between an athlete and a playing surface. The interaction is a conduit for ground reaction force to reach the knee putting the ACL in danger or rupture. An axiomatic design process was used to develop a device that reduces the forces on the knee propagated from the ground reaction forces through the shoe.

Axiomatic design methods were used and implemented by Acclaro design software. Axiomatic design was used to streamline the design process by achieving a design that abides by the Axiomatic design rules, being collectively exhaustive, mutually exclusive with minimal information. Axiomatic design helps decouple the design making sure there is no interference of functions.

Functional Requirements (FR) are created through the customer needs and research. FR's are broken down by level with all of the children summing to the parent. They are broken down by complexity with each child describing in more detail until the function is completely exhausted. Each functional requirement is achieved through a Design Parameter (DP). DP's are part of the physical domain, they are how the function will look and act. The top level FR, classified as FR-0, is the goal of the project, to protect the ACL during dry land activity. FR-0 is accomplished with DP-0, a shoe load mitigation device.

Once the initial functional requirement and design parameter where established, constraints were defined, as to set a guideline for which the further decomposition would have to abide by. The first and main constraint of the design is that the final design must be able to be integrated into a shoe. Children of that constraint are components of the final product integrated into a shoe must act and appear as a normal shoe and not have any negative effects on the performance of the user. The second main constraint of the final design is that it must be self returnable within one step. All of the state of the art designs are fail systems. A fail system is a system that when the loads reach an excessive magnitude the shoe fully breaks apart with no way of being returned. The final design needs to be self returnable within a single step as to have little to no know affect on the user. Making the shoe self returnable will also lower the cost of the final product because there will be no need to purchase another one due to activation of the device. The final design must not exceed normal costs to the consumer. Once the initial level and constraints were complete the decomposition could be achieved. Figure 8 is the decomposition created in Acclaro.



0	FR	Protect the ACL during dry land activity	DP	Shoe load mitigation device
1	FR	Mitigate shear loads in the x-y plane	DP	Mechanical system that mitigates shear loads in the x-y plane
1.1	FR	Absorb loads under injury threshold	DP	Two size cantilever beam system (A size B size)
1.1.1	FR	Absorb loads up to injury threshold	DP	A beams
1.1.1.1	FR	Absorb loads under threshold allowing minimal extension	DP	A beam thickness
1.1.1.2	FR	Allow movement over beam stopping load absorption from A	DP	A beam height
1.1.1.3	FR	Facilitate ease of bending with increasing extension	DP	A beam angle
1.1.2	FR	Preload B beams	DP	B beams
1.2	FR	Absorb loads over injury threshold	DP	B beams
1.2.1	FR	Loads required to absorb	DP	thickness
1.2.2	FR	Allow certain extension	DP	height
1.2.3	FR	Facilitate ease of bending with increasing extension	DP	B beam angle
1.3	FR	Prevent motion in medial direction	DP	C Beam
1.4	FR	Provide structure for interface between beams and insole	DP	Outsole
1.5	FR	Provide control of interface between beam and insole	DP	Trough
1.5.1	FR	Decrease stress concentration of beams	DP	Trough with rounded corners
1.5.2	FR	Provide higher contact on beams	DP	Depth of trough
1.6	FR	Provide minimal friction between insole and outsole	DP	Polyethylene layer
2	FR	Contain mechanical system	DP	Structure to contain system
2.1	FR	Prevent movement in the Z direction	DP	Material wrapped around outsole connected to insole
2.2	FR	Provide movment to allow beams to bend and return the system	DP	Material that is elastic

Figure 8: Decomposition of Final Design

The theme for this decomposition is the direction of the forces as well as the components the design needs to have in order to achieve the goal while staying within the constraints. The first level of functional requirements are children of FR-0, protect the ACL during dry land activity. FR-0 is broken down into two children; mitigate the shear loads in the x-y plane and to contain the mechanical system. The coordinate system used in the decomposition can be seen below.

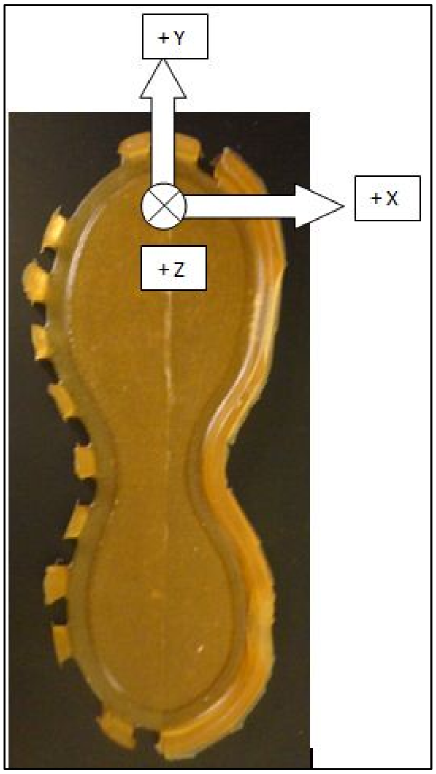


Figure 9: Coordinate system of Decomposition

FR-1 Mitigate the shear loads in the x-y plane

The first functional requirement has do deal with how to absorb the ground reaction forces preventing them from reaching the ACL. In the preliminary research it was found that shear loads produced by cutting motions with improper body positions are a major reason why ACL injuries occur.

DP-1 Mechanical system that mitigates shear loads in the x-y plane

The mitigation of the shear loads will be most easily integrated into the shoe using a mechanical system. There are regulations on having augmented footwear in which the augmented shoe enhance performance of the user. A mechanical system was the most feasible to stay within the constraints, mainly act and perform as a normal shoe. Other systems would add too much weight as well, making the shoe bulky and inhibit performance.

FR-1.1 Absorb loads under injury threshold

One of the main constraints of the design is it must not have any negative effects on the performance of the user. To achieve this, the shoe must perform the same as a normal shoe under the injury threshold. Not having predictable shoe response under the injury threshold would change the characteristics of the shoe and possibly make it dangerous.

DP-1.1 Two size cantilever beam system (A size B size)

From the injury threshold graph Figure 7, a system needed to have two separate parts. One part needed to absorb all the loads associated under the injury threshold load and the other needed to absorb the loads over the injury threshold. The first part needed to stop absorbing loads at the injury threshold load. As the load increase the absorption needed to increase, it needs to get softer as the load increases. As a force travels down the length of a cantilever beam the more the beam deflects. This theory exhibits the concept that is needed, as the load increase the load will travel down the beam deflecting more causing a “softer” system.

FR-1.1.1 Absorb loads up to injury threshold

To achieve normal shoe functions under the injury threshold a system of cantilever beams need to be implemented into the sole. This series of beams will maintain normal shoe functions letting the user be able to perform with no notice of a safety system built in.

DP-1.1.1 A beams

This series of beams need to be uniform and independent of the second system of beams. They need to be shorter than the other beam system to allow full extension transferring the load onto the other beams at the injury threshold.

FR-1.1.1.1 Absorb loads under threshold allowing minimal extension

The A beam system needs to be stiff with minimal extension. Excessive extension of the beams will lead to a greater displacement of the upper sole. Greater extension of the A beams will increase the risk of potential injury and decreased performance.

DP-1.1.1.1 A beam thickness

To decrease extension of the beams while absorbing loads the A beams have to have a certain thickness. This thickness will be determined by the size of the user. A thicker beam will have a smaller extension under the injury threshold.

FR-1.1.1.2 Allow movement over beams stopping load absorption

Once the load reaches the injury threshold load the A beams need to be fully deflected contributing no load absorption. This allows the B beams to take on all load absorption and to have a greater extension.

DP-1.1.1.2 A beam height

The height of the A beams will determine at what distance of displacement the A beams will fully deflected. The taller the A beams are the further the shoe upper will need to displace to have a change in load absorption.

FR-1.1.1.3 Facilitate ease of bending with increasing extension

The theory behind the system working is the cantilever beam theory. In this system it means that as the beams are pushed over the point of contact on the beam gradually rises. As the point of contact rises the force to bend the beam decreases causing more deflection and absorption.

DP-1.1.1.3

The cantilever beam theory is dependent of the base of the beam being thicker at the base then at the end. The ratio of the thicknesses describes the deflection of the beam. A thicker base with a thin end will have a large displacement per length.

FR-1.1.2 Preload B beams

When the A beams are fully extended and contributing no absorption the B beams are the only load absorption system. In order to have a smooth transition between systems the B beams need to be preloaded so there is no notice from the user.

DP-1.1.2 B Beam location

The first iteration of the decomposition had the B beams off set from the A beams. The thought behind this was that once the A beams were full extended the load would be transferred from the A to the B beams. It was decided that this would be noticeable to the user. To eliminate the load transfer the B beams were put in line with the A beams. As the load was applied in the shear direction both A and B beams would bend absorbing forces. The loads absorbed by the B beams are used to preload the beams.

FR-1.2 Absorb loads over injury threshold / DP 1.2 B beams

The same principles for FR-1.2 and its children are the same as in FR-1.1 and its subsequent children. Instead of under the injury threshold FR-1.2 is for loads over the injury threshold and are describing the B beams in the same manner.

FR-1.3 Prevent motion in medial direction

The system is designed to mitigate shear loads in the x-y plane. The excessive loads being absorbed by the system are in the positive x-y plane. The system does not need to absorb forces in the negative x-y plane as the forces have not been seen to contribute to ACL injuries.

DP-1.2 C beam

To prevent motion in the medial direction a solid beam is implemented on the sole along the inside of the foot. This beam will make the shoe act normally in the medial direction under all loads.

FR-1.4 Provide structure for interface between beams and insole

The beam system needs to have a structure to attach to as well as be an interface for the insole and the playing surface.

DP-1.4 Outsole

A rubber material that is used to make the beams is used to create a solid structure containing the beams. It provides a solid platform for the insole to come in contact with as well as an attachment for the beam system. A flexible rubber that is able to flex under the stride of the user.

FR-1.5 Provide control of interface between beam and insole

The contact point of the insole on the beams causes different beam characteristics. Control is needed for the point of contact on the beams. The interface between the two also leaves room for beam attachment design.

DP-1.5 Trough

To allow control of the beam contact point a trough can be made in the outsole between the base for the insole and the beams.

FR-1.5.1 Decrease stress concentration of beams

Having square edges on the beams build stress concentrations on the beams where stress builds up. Where the concentrations are the highest are points where failure could occur. This system is intended to be used as a normal shoe with normal life expectancy.

DP-1.5.1 Trough with rounded corners

The trough allows for the attachment point of the beams with the outsole to be rounded. Rounded attachment points decrease stress concentrations and increase the life of the system.

FR-1.5.2 Provide higher contact on beams

Having a higher contact point on the beam gives a “softer” feel but allows for a bigger beam. It also allows for a shorter displacement of the insole while having a taller beam.

DP-1.5.2 Depth of trough

The trough can have a varying depth depending on where the beam needs to be in contact with the insole.

FR-1.6 Provide minimal friction between insole and outsole

To insure the proper sliding mechanics of the shear system there needs to be a controlled coefficient of friction. The friction needs to be low for the system to slide above the injury threshold. This will ensure the beams are absorbing the entire load and are not affected by friction.

DP-1.6 Polyethylene layer

A layer of polyethylene between the outsole and the insole will reduce the friction.

<u>FR-2 Contain the mechanical system</u>

The original vision of the design had an independent shoe sole from the upper sole. This was to allow free motion of the upper sole above the injury threshold. This would allow high that any high forces can be absorbed and not directed through a channel not allowing absorption. In order for this to occur a system needs to contain the sole and the upper sole. This system needs to prevent movement in the z-direction but allow free motion in the x-y plane above the injury threshold.

<u>DP-2 Structure to contain system</u>

A structure that allows movement in the x-y plane under a certain load and allows no movement in the z-direction is needed.

FR-2.1 Prevent movement in the Z-direction

With two independent layers a system needs to be in place to contain them. Sliding in the x-y plane is desired but motion in the z direction is not. The shoe would not act normal if there was play in the z direction.

DP-2.1 Material wrapped around outsole connected to insole

A material that wraps around the outsole and connects to the insole contains the system and prevents motion in the z-direction.

FR-2.2 Provide movement to allow beams to bend and return the system

The material needs to be able to allow the beams to bend over above the injury threshold. The material also needs to aid in the return of the system.

DP-2.2 Material that is elastic

An elastic material will contain the system allowing movement of the beams above the injury threshold. An elastic material stretches with force as well act as a force to return the system after the loads are taken off.

3.0 Physical Integration

The integration of the mechanical systems into the shoe consists of a shear absorption system as well as a vertical absorption system. The system is placed into the shoe below the foot bed and above the tread system. This allows the shear absorption of the shoe to be close to the ground preventing ankle injuries but still allows the vertical absorption to have the required distance traveled needed to decrease the ground reaction forces. Figure 10 demonstrates the placement of the systems and how they integrate into the shoe.

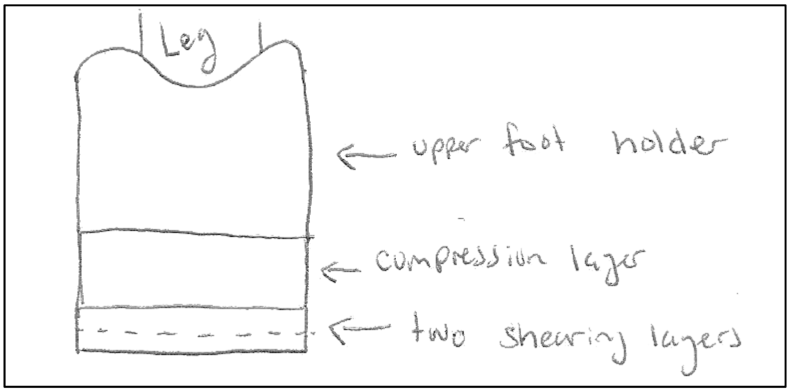


Figure 10: Diagram Locating the Shearing and Compression Layers of the Design

3.1 Vertical Absorption

Compression absorption in the heel of the shoe is essential to preventing non-contact ACL tears from jumping and landing. This injury can occur with the jump of one leg and landing on the same leg that left the ground last. The landing usually occurs with a flat plantation with the ball of the foot and the heel impact the ground simultaneously. This causes a high ground reaction force to occur, high flection of the quadriceps muscle causing anterior tibial rotation. The anterior tibial rotation in the knee creates high forces in the knee, specifically to the ACL. Decreasing the ground reaction forces in the shoe prevents the high forces from reaching the knee. Thus the design for vertical absorption is essential to preventing ACL tears in athletes.

The system designed is an air compression system. The main system is ball shaped and positioned under the heel where high ground reaction forces are determined to occur. This ball contains two valves in the system to contain the air and release when ground reaction forces begin to reach injury threshold level. The first valve is a one way valve, this valve contains the air into the round system, but allows air to enter during the recovery phase. Figure 11 outlines how the system works and the placement of the valves in the designed system

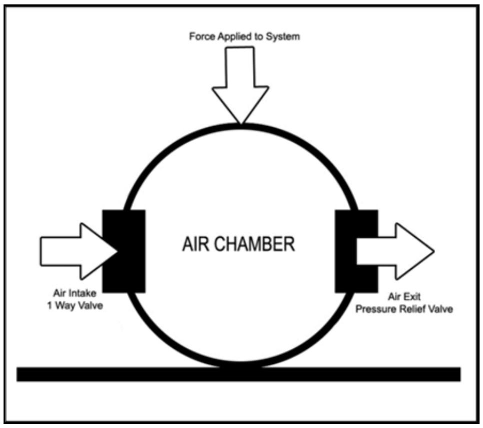


Figure 11: Diagram Demonstrating Theory of Compression System

The following calculations demonstrate how the system would be designed, how to select the proper valves, how to select the material and how to determine the size of the material based off of size constraints of the shoe, external forces and hoop stresses that occur in the system.

Calculations:

Average injury forces applied to system is equal to 4 to 5 times a person's body weight. Calculations are done based off of a 215 pound male.

To determine activation forces of pressure relief valve the following calculations need to be done.

Force acting on system

$$F = 215\ lbs * (4\ and\ 5) = 860\ to\ 1075\ lbs$$

With Volume and Temperature constant in the system the internal pressure of the system is equal to the external pressure applied to the system. Converting the force into the pressure applied to the valve is calculated using the following equation.

$$P_{valve} = \frac{F_{external}}{A_{valve}}$$

With the Force ranging from 860 to 1075 lbs and A equal to the surface area of the valve.

Determining the material to create the chamber from:

$$V_{system} = \frac{4}{3}\pi r^3$$

Radius used for calculation is 0.75 in

$$V = 1.77\ \mathrm{in}^3$$

Calculating hoop strain determines the strain on the material with the max pressure on the system to determine if the material can withstand the strains of the system

$$\sigma_h = \frac{P_{max} r}{2t}$$

Pmax of the system, r radius of system, t thickness of system

$$\sigma_h = \frac{1075\, psi * 0.75\, in}{2 * 0.25\, in} = 1612.5\, psi$$

Material choices for system:

Butyl Rubbers - 0.725 to 1.45 ksi

Styrene Butadiene – 2.32 to 3.77 ksi

** Natural Rubber – 3.19 to 4.64 ksi

Isoprene – 2.9 to 3.63 ksi

**Natural Rubber would be the best choice as it can withstand much higher strains then the calculated max hoop strain

3.2 Shear Absorption

Many non-contact injuries in athletes occur with the sudden deceleration of the athlete paired with a change in direction. These movements create circumstances in the knee that can cause ACL tears. These include the valgus position of the knee, which with excess forces cause the tear to occur. Preventing these tears from occurring requires a reposition of the knee, a decrease in ground reaction forces and a system that allows for greater travel in the foot when impact is made with the ground. Reviewing the requirements it was determined that we can design a system that both decreases ground reaction forces as well as allow for greater travel of the foot on impact. We have determined two different systems that can create the desired system.

3.2.1 Beam Design

The first shearing system consists of a series of beams that bend when shearing forces are applied to the shoe. The beam system is a double beam system with a series of shorter and longer beams. The shorter beams are much more difficult to bend over thus holding the system together until forces begin to reach injury level. When the forces are high enough the lower beams bend over, the forces are then applied just to the taller beams. With the forces just on the taller beams, a greater displacement occurs as well as the beams act as a force absorption taking some of the shock out of the sudden deceleration and change in direction. The pictures below show the bending of the beams and how the system works. Figure 12 demonstrates the shearing layers applying the force to the beam system.

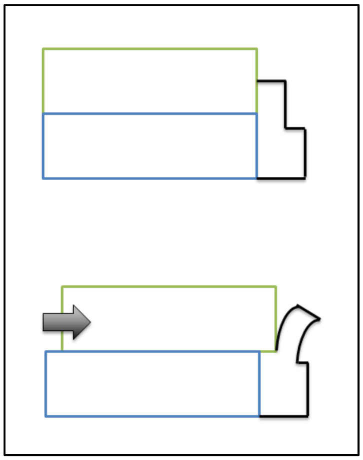


Figure 12: Theory of Shearing Layers and Beam System

The beam design was determined through various iterations of the design as well as a series of FEA analysis completed to determine high stress concentrations on the beam and redesign to avoid such concentrations. A fillet is added to the lower portion of the beam to lower the stress concentration in the lower half of the beam. The beam is also tapered to provide a more even bend in the beam and a delay in the shearing contact point. The taper also allows the shearing layer to bend over the beam activating the next beam in the system. Figure 13 is an example of the FEA analysis of the final beam design that will be discussed in section 3.3.

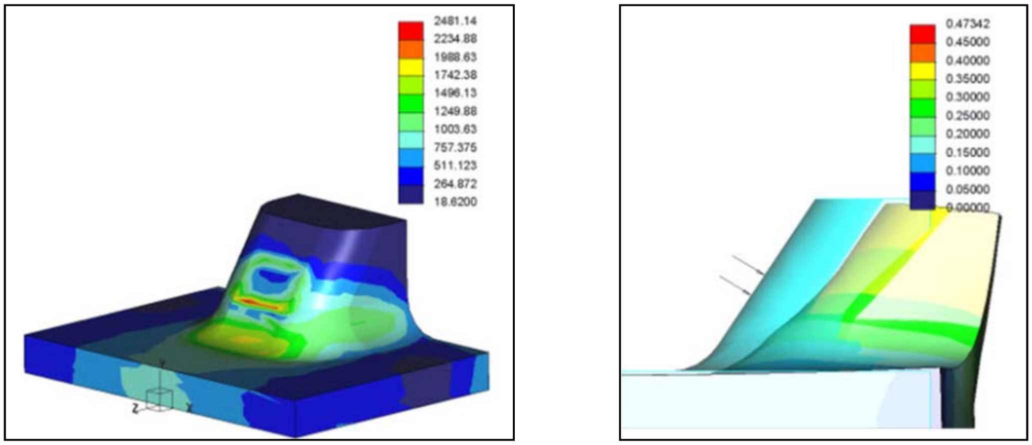


Figure 13: FEA Analysis of Beam

3.2.2 Tube Design

The second shearing system design incorporates an air compression system into the shearing layers. This system works similar to the beam system in that additional movement takes place when an increase in shear forces is experienced. Like the compression system a two valve system is established containing a one way valve and a pressure relief valve. Calculations to determine the required valves and material are very similar to the above calculations for the compression system. The major variation in the calculations is determining the stress in the system. The compression system is a spherical chamber which only uses the equation

$$\sigma_1 = \sigma_h = \frac{Pr}{2t}$$

You also need to calculate the longitudinal stress (σ_1) as well as the hoop stress (σ_h) of the system. This ensures that the stresses found in the system do not exceed the determined max stresses of the material chosen. The following equations would be used to determine such stresses in the system.

$$\sigma_1 = \frac{Pr}{2t}$$

$$\sigma_h = \frac{Pr}{t}$$

Average injury forces applied to system is equal to 4 to 5 times a person's body weight. Calculations are done based off of a 215 pound male.

To determine activation forces of pressure relief valve the following calculations need to be done.

Force acting on system

$$F = 215\ lbs * (4\ and\ 5) = 860\ to\ 1075\ lbs$$

With Volume and Temperature constant in the system the internal pressure of the system is equal to the external pressure applied to the system. Converting the force into the pressure applied to the valve is calculated using the following equation.

$$P_{valve} = \frac{F_{external}}{A_{valve}}$$

With the Force ranging from 860 to 1075 lbs and A equal to the surface area of the valve.

Determining the material to create the chamber from:

$$V_{system} = \frac{4}{3}\pi r^3 + \pi r^2 h$$

The volume calculates the volume of the cylinder with each end of the cylinder rounded to reduce the stresses of the system. Therefore the volume of the system is the volume of the cylinder plus the volume of the sphere.

The material choices for the system are going to be very similar to the compression system and are found below.

Material choices for system:

Butyl Rubbers - 0.725 to 1.45 ksi

Styrene Butadiene – 2.32 to 3.77 ksi

Natural Rubber – 3.19 to 4.64 ksi

Isoprene – 2.9 to 3.63 ksi

3.3 CAD Modeling

The solid model of the mold to be used to cast the prototype was created in Solidworks. The mold was created as a negative of the model of the prototype itself. The first step in creating the model was creating the base drawing which outlines the outer edge of the sole of the shoe that would be used in the final prototype. The drawing (Drawing 1) can be seen in Figure 14. All the dimensions were measured on the shoe at inch increments and then connected in the drawing using a spline.

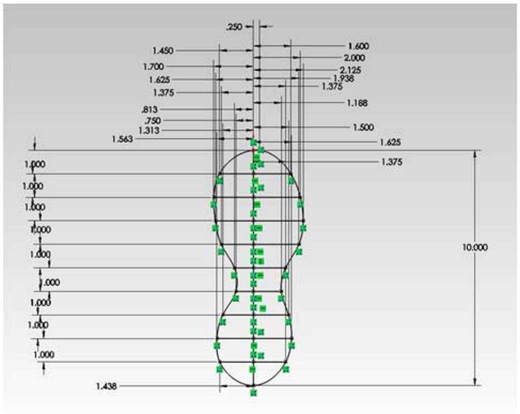


Figure 14: Drawing of CAD Model

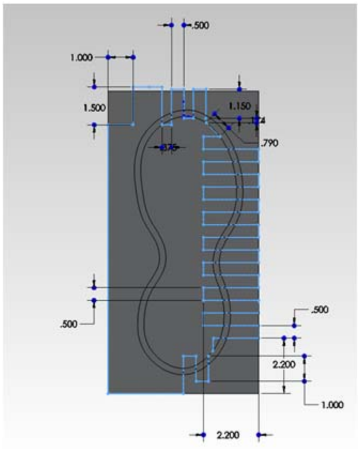


Figure 15: Dimensions of CAD Model

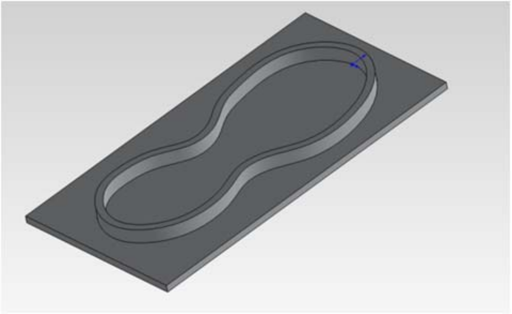


Figure 16: CAD Model, Placement of Beams

Next, the base of the mold was created. It is simply a rectangular extrusion. The beam structure was created afterwards. A thin extrusion was created, extending outward from the profile created by Drawing 1. The feature (Extrude-Thin3) can be seen in Figure 16. The second step of creating the beam structure was to cut out the area that the molding material would be filling in. This was done by creating a cut extending down from the top of Extrude-Thin3. The drawing for this cut can be seen in Figure 15. The length of this cut only extended down as far as the depth required for the A beams, as shown in Figure 17. The last step of creating the beam structure was to use another cut feature to remove the remaining material to allow space for the B beams and the wall on the inside of the shoe. These deeper cuts can be seen in figure 18.

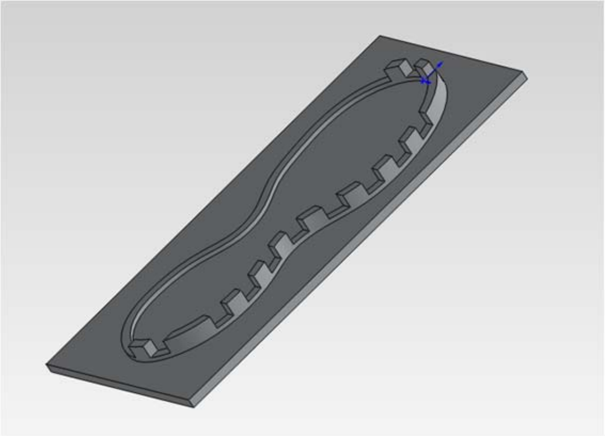


Figure 17: Beam Shapes Cut Out

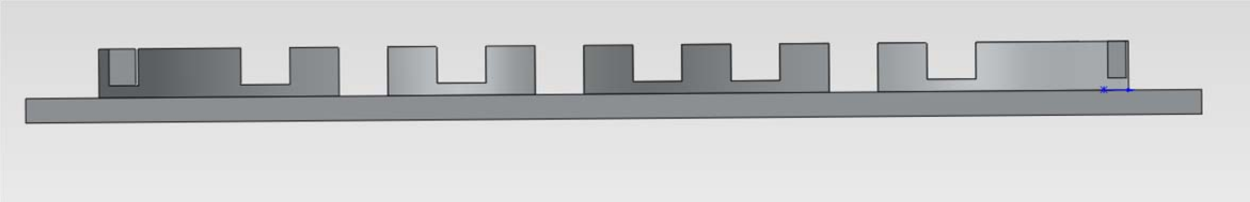


Figure 18: Beam Shape

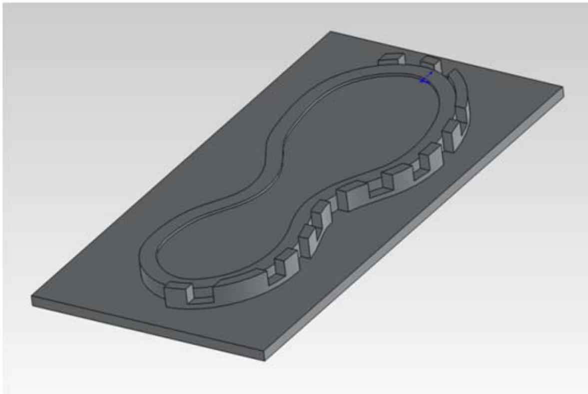


Figure 19: Beam Placement

With the beam structure completed, the next step was to create the structure underneath the sole of the shoe. First, the trough of the prototype was modeled. That was done by creating a thin feature (Extrude-Thin1) which extended inwards from the contour created by the Drawing 1. Next, the rest of the structure was filled in using a solid extrusion. The contour of Drawing 1 was used for this feature as well, since it did not extend up past Extrude-Thin1. Figure 19 shows both of these features added to the model.

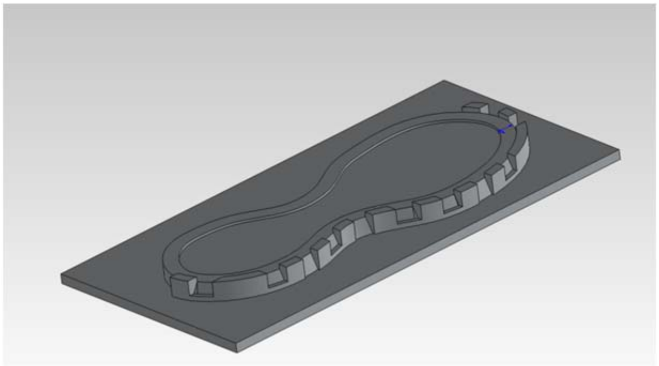


Figure 20: Detailed Beam Placement

The next three features (Sweep14, Sweep15, Sweep16) are all sweep features that create the angle on the beams. Three separate composite curves were created for these features so they would be able to negotiate the curves of the shoe without any gaps. The gaps between these curves are hidden inside the remaining material of Extrude-Thin3. Figure 20 shows these features added to the model.

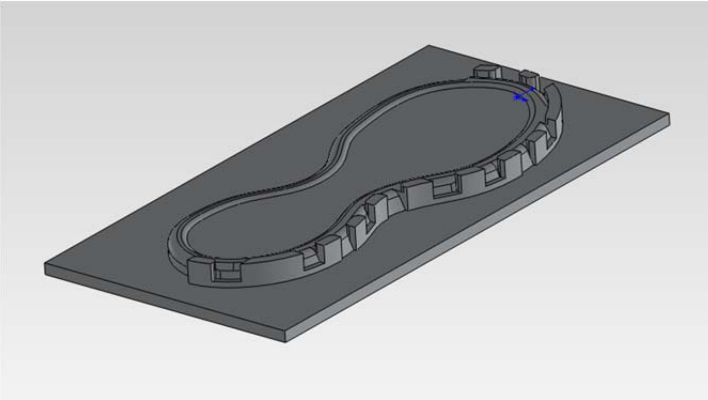


Figure 21: Filets Applied to Beams

The next step was creating the filets on the model. This was done using the FilletXpert function of Solidworks. Whatever fillets the program could not resolve were done manually by reducing the desired radius. The filetted model can be seen in Figure 21.

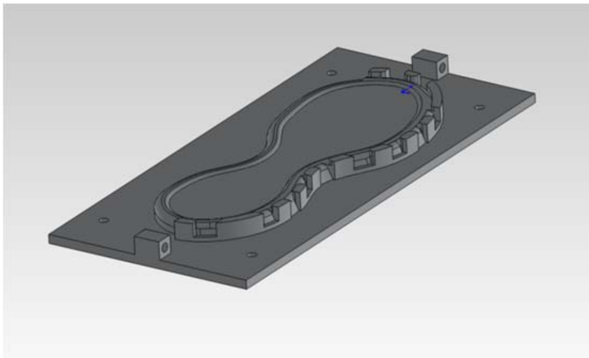


Figure 22: Features added to Mold Assembly

With the structure of the prototype fully modeled in the mold, focus was shifted to adding features to the base which would assist with mold assembly. These features include the extrusions on either end of the base, and the six holes. Figure 22 shows the completed mold model. When the mold was imported into the CAM software ESPRIT, it was necessary to divide the model, as demonstrated in Figure 23. That was done simply with an extruded cut feature. The model was cut to be even small when test molds were machined.

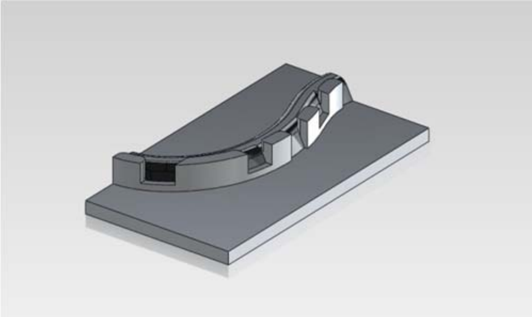


Figure 23: CAD Model of Test Mold

In addition to the model on the mold, it was necessary to create drawing to be used to cut the acrylic pieces to be used as the side pieces of the mold. These drawings can be seen in Figure 24. The drawings were created by importing the edges of the base around the central structure, and resizing them to fit around the structure correctly.

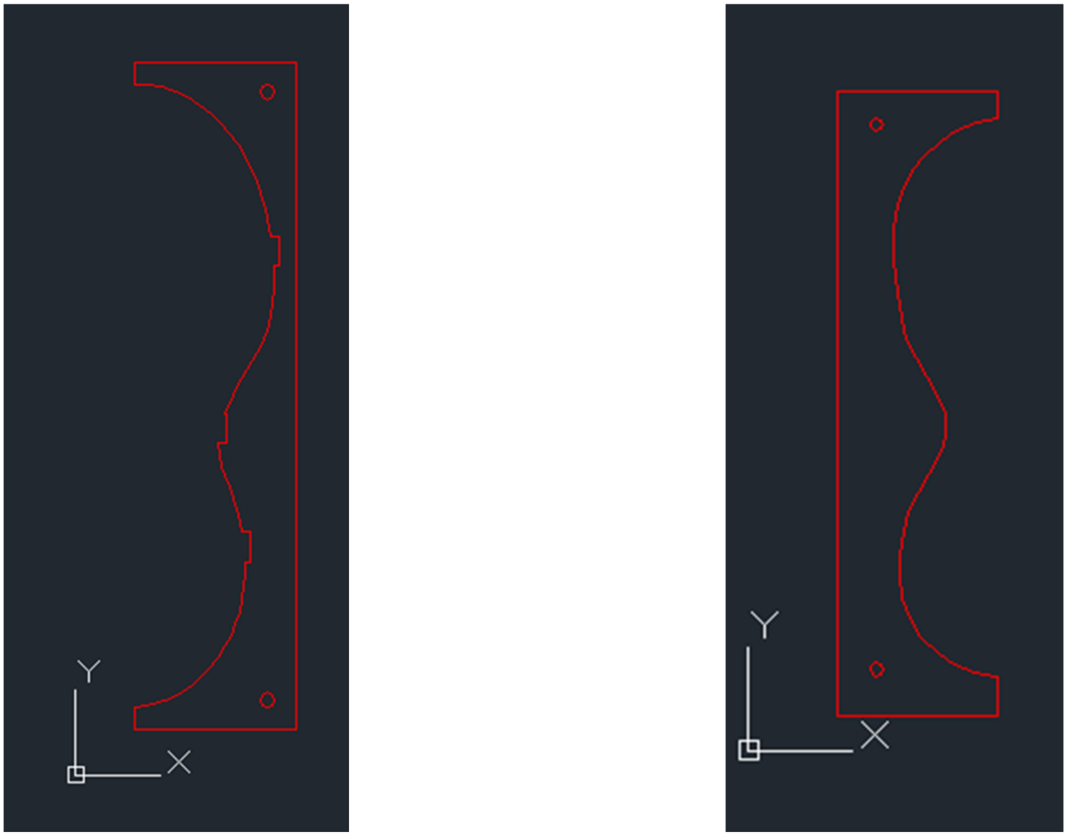


Figure 24: Drawings for Laser Cutter

3.3.1 FEA Beam Analysis (Creo Parametric)

A finite element analysis of the beam design was carried out using Creo Parametric. An example on one of the models used for the analysis can be seen in Figure 25. An 80 Newton force was applied perpendicularly to the angle face of the beam. The force was applied over an area which was designed to mimic the area that the actual testing apparatus would apply its load on. The model was constrained such that the bottom, front, right, and left faces of the base were fixed in place. The results of the analysis can be seen in Figure 26. With these results, the team was able to determine the ability of the material selected for the prototype to withstand testing. In addition, the deflection of each beam design could be compared.

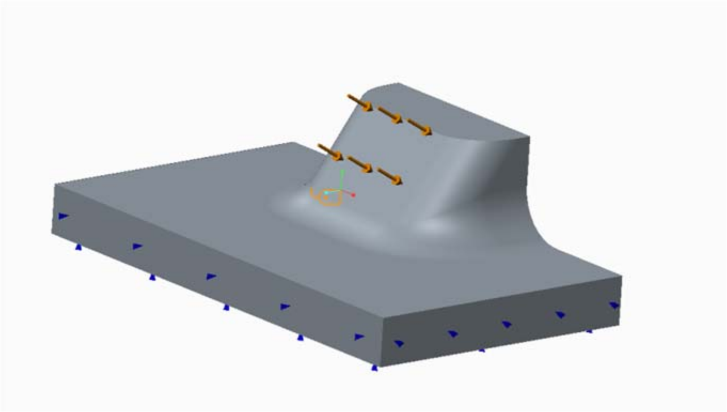


Figure 25: Force Placement on Beam

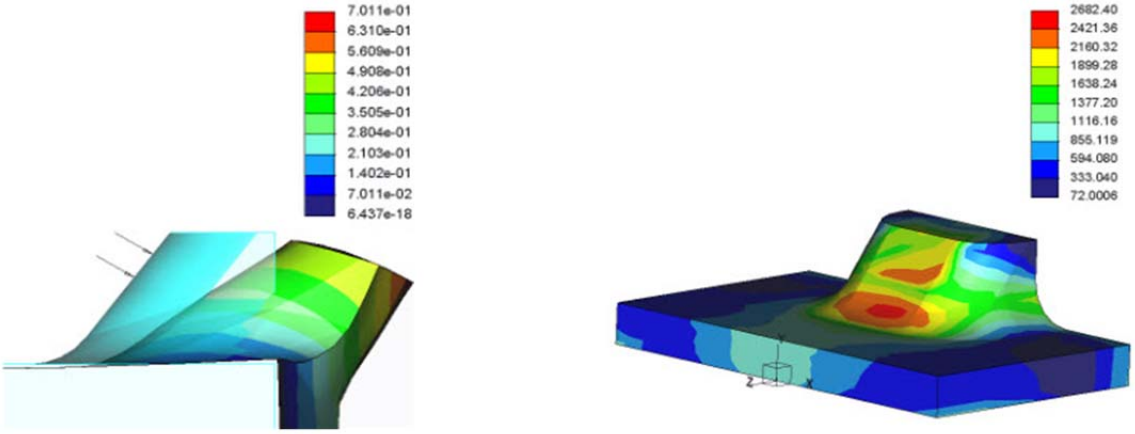


Figure 26: FEA Results

4.0 Prototype Production

Production of the prototype included deconstruction of the shoe, cutting of shearing layers, molding of beam system, mixing of materials and reconstruction of the final prototype. The following outlines this process.

4.1 Manufacturing of Parts

The major manufacturing that took place in the project was the creation of the mold for the beam system that is implemented into the shoe. Section 4.1 outlines how the final mold was created for the beam system.

4.1.1 Test molds

Before the full-scale mold was machined, test molds were created to test machining strategies, the molding process, and the small-scale behavior of the beam system. To do this, the solid model of the full mold was cut into about a quarter of its size, so that only half of the heel portion of the mold would be created (see Figure 27). This smaller model was then imported into the CAM software ESPRIT in order to create tool paths. A variety of path calculating functions are available in ESPRIT and many were used during the process of making the test molds. A comparison of these functions can be seen in Figure 28.

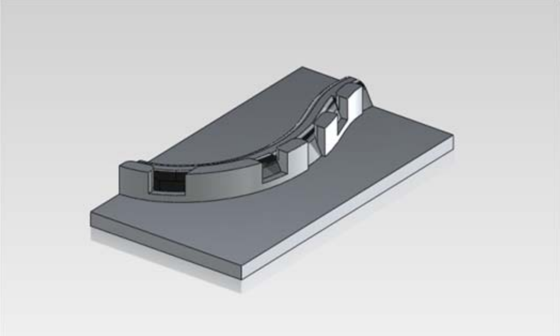


Figure 27: Image of Test Mold

Operation	Pros	Cons
Traditional Pocketing	Faster operation times, less data to send to machine	Can be difficult to define pocketing areas around complex geometry
Traditional Drilling	Straightforward way to drill a hole	
Mold Z-Level Roughing	Easy to define surface clearances, easily navigates complex geometry	Requires extra step of defining stock material, can be difficult to influence the actual strategy of the tool path
Mold Parallel Plane Finishing	Can be used to create complex surfaces	Operation is very time and data intensive
Mold Z-Level Finishing	Can be used to create complex surfaces	In this application, would cause too much scalloping
Mold Radial Finishing	Can be used to create complex surfaces	In this application, cannot be controlled enough to create all of the geometry required.

Figure 28: Comparison Table of CAM Operations

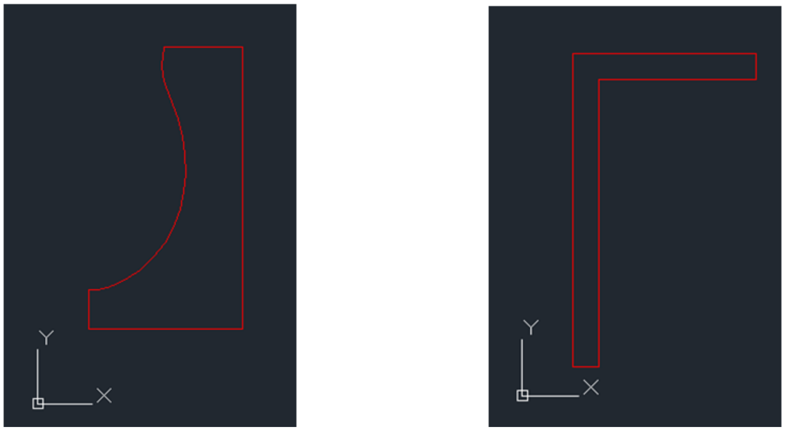
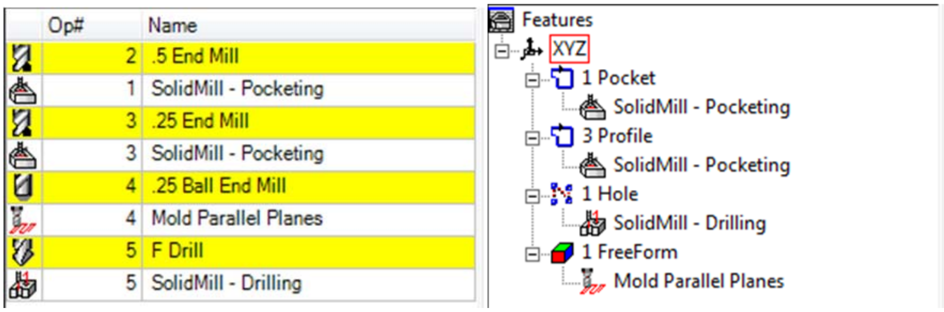


Figure 29: Laser Cutter Drawings for Test Mold

The test molds required smaller pieces of acrylic than the full scale mold, so the drawings were reworked for the new size. These drawings can be seen in Figure 29. These smaller acrylic pieces allowed for the group to determine the necessary settings on the laser cutter to cut the material cleanly. When all the components of the test mold were created, the acrylic pieces were clamped to the aluminum piece, and the urethane material was mixed and poured in. This process is described in greater detail in section 4.2.

4.1.2 Full-Scale Mold

Once the solid models for the mold designs were finalized, they were imported into esprit so that the tool paths could be created. The feature tree and operation order for the left mold can be seen in Figure 30. For the left mold, pocketing operations could be used to machine most of the part due to its relatively simple geometry. A parallel plane finishing operation was used to machine the rounded edge of the mold. The final operation is a drilling operation which machines the holes in the mold.

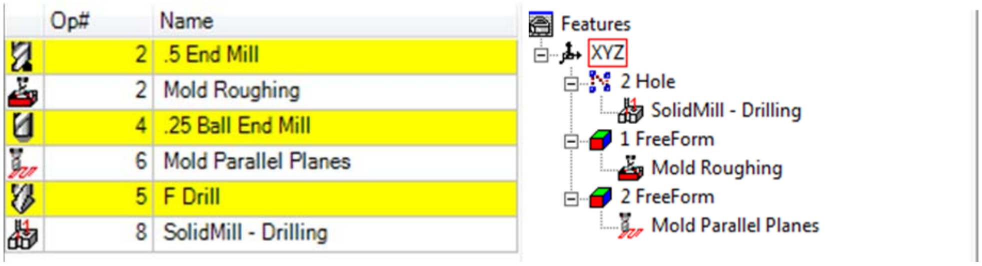


Op#	Name
2	.5 End Mill
1	SolidMill - Pocketing
3	.25 End Mill
3	SolidMill - Pocketing
4	.25 Ball End Mill
4	Mold Parallel Planes
5	F Drill
5	SolidMill - Drilling

- Features
  - XYZ
    - 1 Pocket
      - SolidMill - Pocketing
    - 3 Profile
      - SolidMill - Pocketing
    - 1 Hole
      - SolidMill - Drilling
    - 1 FreeForm
      - Mold Parallel Planes

Figure 30: Feature Tree and Operation Order

The feature tree and order of operation for the right mold can be seen in Figure 31. Unlike the left mold, a z-level roughing operation was used to rough the part, because of its more complex geometry. A parallel plane finishing operation was used to create to rounded surface of the mold, as well as to machine the beam structure. The final operation of this process was also to machine the holes through the mold.



Op#	Name
2	.5 End Mill
2	Mold Roughing
4	.25 Ball End Mill
6	Mold Parallel Planes
5	F Drill
8	SolidMill - Drilling

- Features
  - XYZ
    - 2 Hole
      - SolidMill - Drilling
    - 1 FreeForm
      - Mold Roughing
    - 2 FreeForm
      - Mold Parallel Planes

Figure 31: Feature Tree and Operation Order 2

The acrylic side pieces of the mold were created from the AutoCAD drawings detailed in Section 3.3, Figure 24. These drawings were imported into the laser cutter's software and then power and speed settings were specified.

The size of the workpieces being machined required that the larger VF4 Mill be used as opposed to the Minimills, which did not have enough travel to machine the workpieces. Two clamps were used to fix the workpiece in the machine. The clamps were straightened to within a tolerance of 5 thousandths of an inch. The tools used for the machining process were a .5 inch end mill, a .25 inch end mill, a .25 inch ball end mill, and an F size drill. The machining operations that these tools were used in can be seen in Figures 30 and 31. Before the parts were machined, the workpieces underwent a facing operation at one end to insure that they were the correct length. When the workpieces' size was finalized, they were re-probed and machined into the finished parts. The two holes used to connect the two halves of the mold were drilled afterwards with a drill press because the machine was not able to drill them, given they are at a 90 degree angle from the other features.

Before the entire mold was assembled it was necessary to seal the acrylic side piece to assure that a minimal amount of material would leak out of the bottom of the mold. This was done by adding duct tape to the inward side of the two acrylic pieces. After that, the two aluminum halves were bolted together and the acrylic pieces were bolted into the aluminum. The two parts of the urethane rubber material Shore 70A chosen for the prototype were then mixed together to prepare it for pouring. A coating of release agent is then sprayed on the mold, and the rubber is poured into it. Figure 32 shows the assembled mold.

Figure 32: Final Mold Assembly

4.2 Assembly Process

After the mold was finished the final prototype was assembled, in which Ray's Shoe Repair of Worcester was instrumental to the creation. A pair of shoes as seen in Figure 33, were used to create the prototype.

Figure 33 Shoe before assembly in final design

The left shoe was used as it was the one created in the mold. The first step taken was to acquire the rubber material used for wrapping. It is fitness rehabilitation bands cut into strips. The next step was to remove the rubber tread on the bottom of the shoe. Ray, of Ray's Shoe Repair, used a heat gun to heat the glue binding the tread to the shoe. He then slowly removed the tread of the shoe.

The rubber material and the polyethylene were cut to shape and size before final assembly. The polyethylene was cut to fit just on the base of the mold and not to exceed over the trough. The components in Figure 34 are final pieces before assembly.

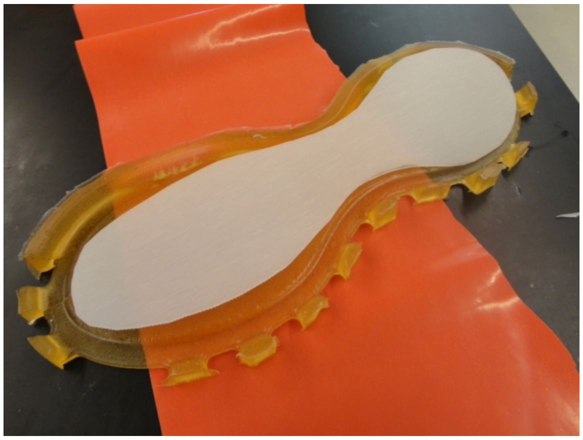


Figure 34 Components of final prototype, rubber material to contain parts, mold with beams and polyethylene layer

The shoe was then assembled by Ray using a sewing machine customized for shoe repair. He stretched the rubber while sewing to preload the rubber allowing for easy containment in the z direction under running conditions. The stitching can be seen in Figure 35 at the top of the rubber layer.

Figure 35 Final prototype assembled

The final assembled prototyped, seen in Figure 35, is a fully working prototype and is the one used in the force plate testing. The shoe did not fall apart nor did it need and repairs during the testing.

5.0 Testing of the Final Design

Testing was done to validate the behavior of the beams and to finalize the design of the beams before a final mold design was created. The initial Instron testing was completed to determine how we can control the forces needed to completely bend over the beams by changing the shape and dimensions of the beams as well as determine the forces and extension of the bending of the beams in the final design. Once a final beam design was realized, a final mold was created and the beam system was placed into a shoe for final testing of the beam behavior. Force Plates were used in this situation to get the ground reaction forces associated in the x, y, and z-axis. The testing was done with the shoe placed on the test subject and the test was run. This test was designed to get the behavior of the ground reaction forces when the beams were activated and how they would bend over. This test was videotaped to get a view of how the shoe layers separated and the activation taking place.

5.1 Instron Testing

The Instron testing conducted was a uniaxial test that pulled a plastic component over the beam system. Instron Testing was completed to determine the beam behavior and the loads that could be experienced by the beam design. A series of beams were designed in order to achieve the behavior wanted. A design of a custom holding apparatus was done to ensure the plastic component pulled over the beam system uniformly and straight without any unwanted lift over the beams. The images in the photo analysis section outline the setup procedures of the test.

The test was designed to see how the beams would behave with a constant force applied to the beam. Altering the shape and dimensions of the beam allowed us to control the results. Figures 36 and 37 are a representation of our final beam design and testing apparatus setup. The test was run at 1200 lbs/min.

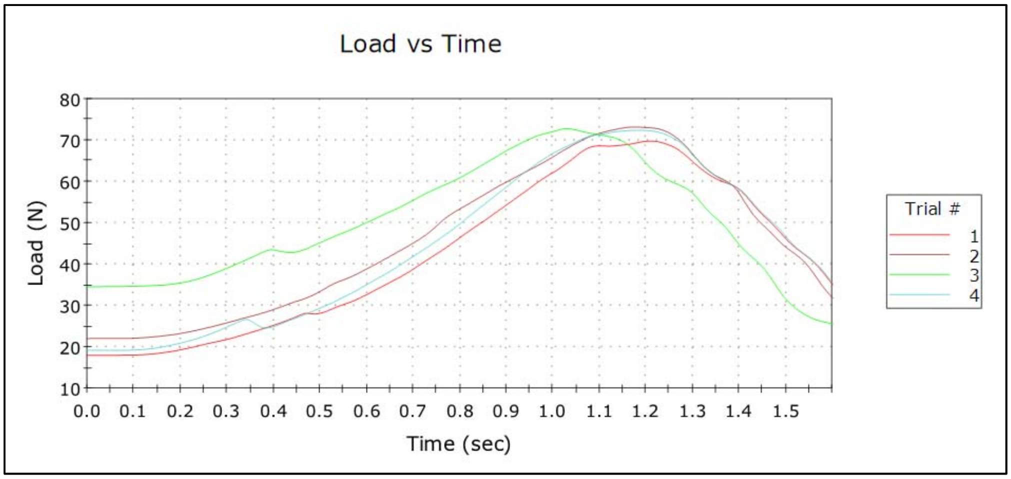


Figure 36: Load vs. Time Instron Test

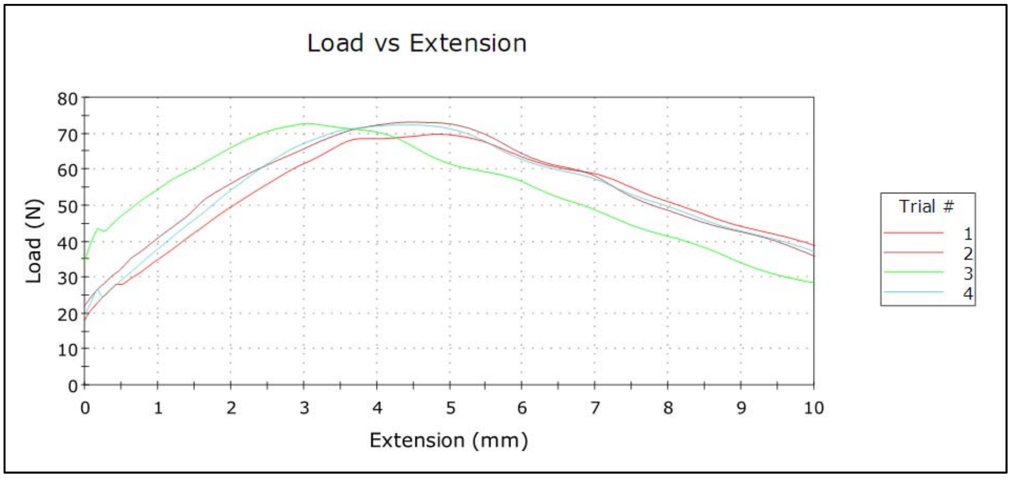


Figure 37: Load vs. Extension Instron Test

Reviewing the graphs above, the two graphs are the same test scale and trial numbers; just a change in the x-axis from Time to Extension. Looking at the extension graph you can see that initially all the beams are loaded and a full force is applied to the beams. As the Extension begins to increase, you can see a change in the slope of the graph roughly around the 3mm mark. This is where the first series of beams are fully bent over and forces are just applied to the second series of beams. The change in slope means that it was much easier for the Instron to apply the force and extension happened at a faster rate. Once the Graph peaked is when full bending off all the graphs is achieved. This provides us with the max force needed by the machine to bend over the beams as well as the needed extension to bend over the beams. The data is consistent to the extension values noted above except for trial 3 which has a higher initial load. Trials 1, 2 and 4 should be viewed for consistent results.

5.1.1 Test Setup and Procedure

Figure 38 shows the setup of the testing apparatus in the Instron machine. The apparatus is clamped directly into the Instron machine as demonstrated. The top clamp moves the entire system up while the bottom clamp is fixed. The white portion slides over the beams when the upper apparatus moves up.

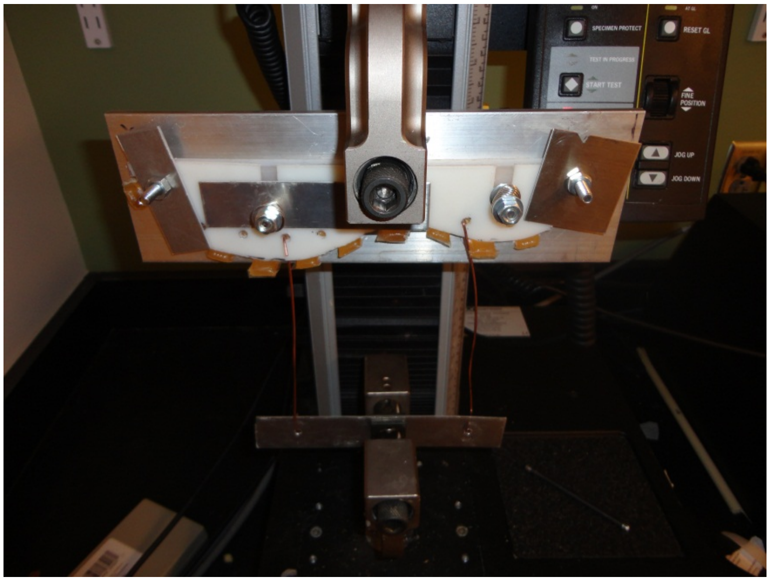


Figure 38: Setup of Instron Test

A spring system is used to keep the white plastic piece from sliding up and over the beams while also providing the necessary force to hold the system together. The flat metal components are also used to hold the device together. Figure 39 and 40 show a side view which shows the beam system in the testing apparatus, the spring system and the white plastic portion that applies the forces to the beams.

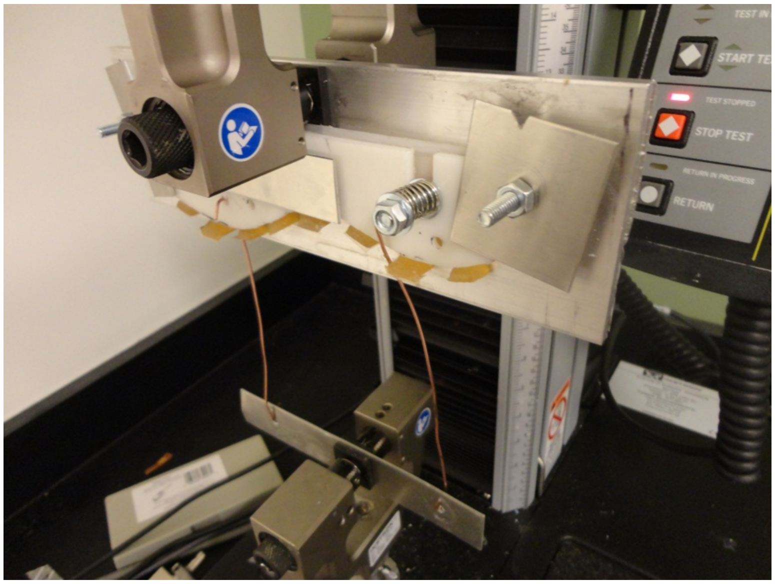


Figure 39: Angled View of Test Setup

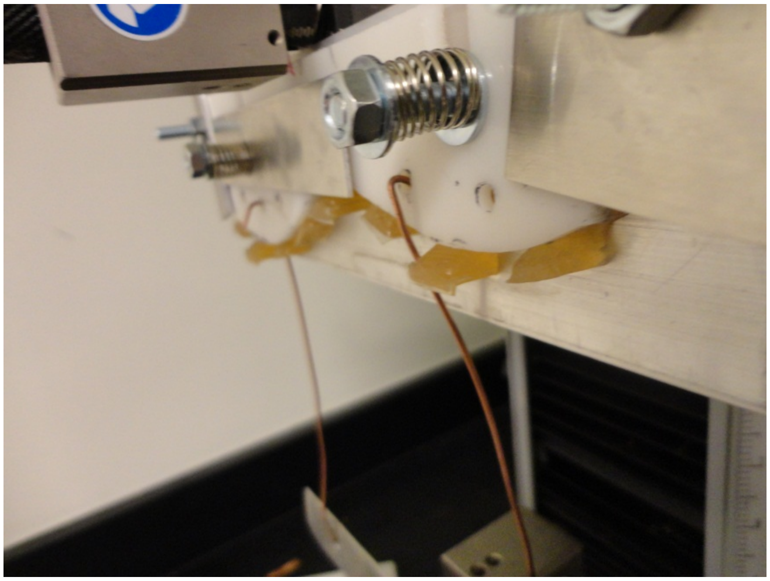


Figure 40: Close up of Spring Application

As the white plastic portion applies a force to the beams, the beams begin to bend over. Figure 41 represents the bending of the beams in the system. In the image you can see the smaller beam completely bent over, with the larger beam in the process of bending. The test was stopped in order for the image to be taken.

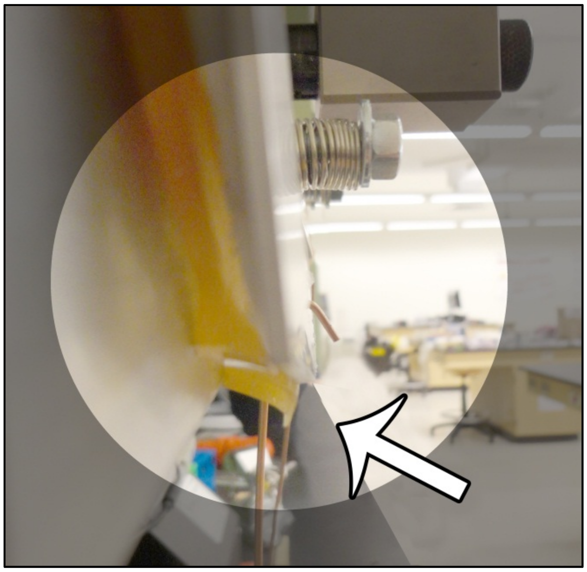


Figure 41: Image Showing Bending of Beams in Instron Test

The final results of the test can be reviewed in the above section, with an analysis of the graphs as well as previous test runs in Appendix B.

5.2 Force Plate Analysis

Finalizing the beam shape and dimensions was completed using the Instron Machine; final testing was completed once the beam system was integrated into the shoe. The test was completed with the subject first wearing the control shoe then wearing the prototype shoe. The control testing and the prototype testing was done with the left foot. Having the testing done on the same foot creates a more repeatable test using both the control and the prototype design. The test subject was not put through a blind test but was able to practice enough to repeat the same motion when wearing both the control and the prototype.

Figure 42 represents the data collected from the control test and the prototype test. The black line on the left represents the prototype data and the graph on the right is the control data collected on the left foot. As you can view from the chart, there is a drastic change in the x-direction ground reaction forces viewed from the force plate data. The initial peak in the data is the initial contact with the force plate. The downward slope represents the deceleration of the subject on the force plate.

The next increasing slope represents the push off, off of the force plate, associated with the change in direction of the test subject. At this point you can see a change in the data. The control shoe demonstrates a steep slope up with a long peak force that plateaus for an extended period of time. However, reviewing the prototype data the slope associated with the push off of the platform experiences two different slopes. The initial when the shearing forces are applied to both beams then there is a change in the slope when the first (A Beam) is bent over and all of the forces are applied to the second taller beams (B Beam). You can view a drop in the forces when the change of slopes takes place demonstrating that there is absorption of the ground reaction forces and a delay of when the peak forces occur does not change. It is also noted that the peak force does not plateau as long as the control data.

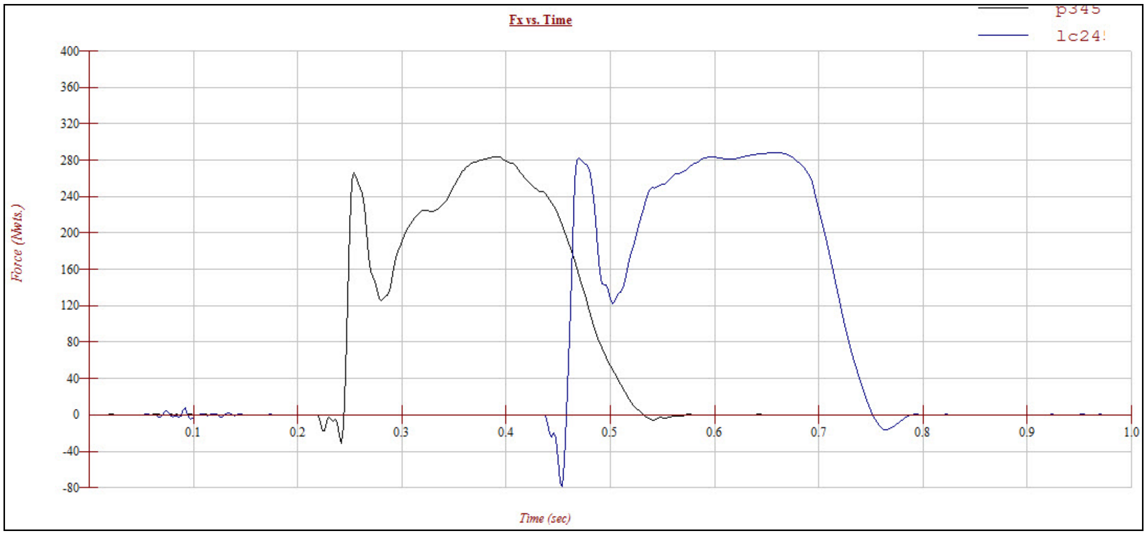


Figure 42: Comparison of Control vs. Prototype Force Plate Data

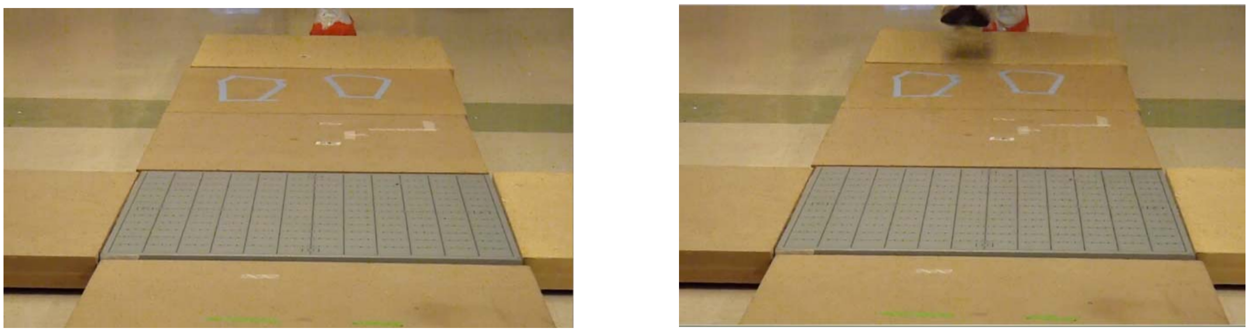
5.2.1 Video Analysis

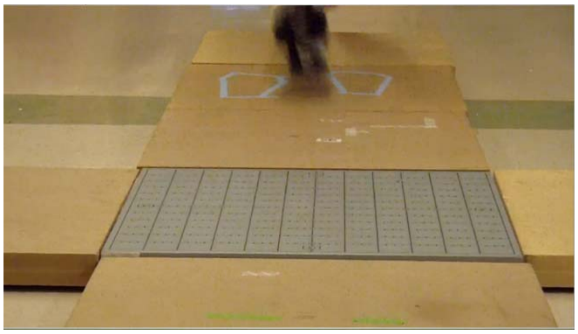
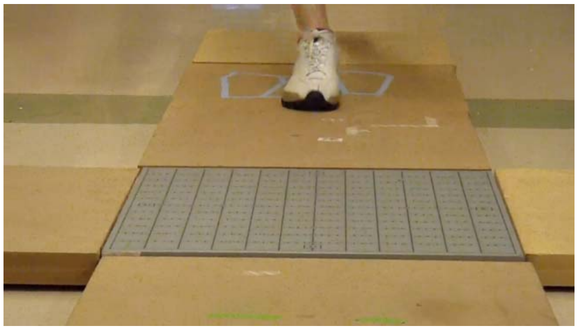
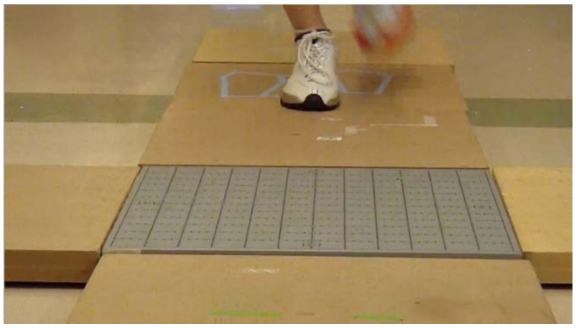
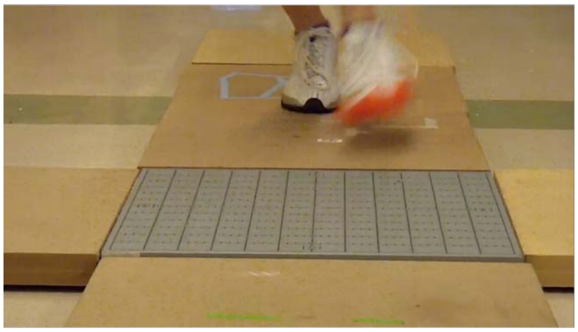
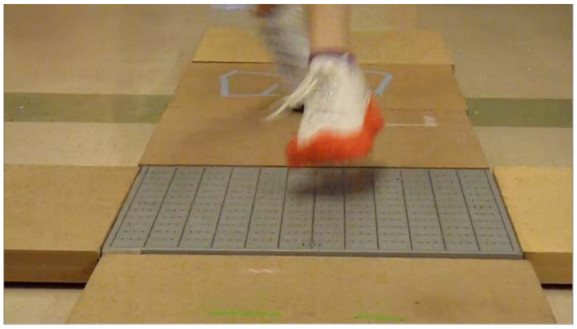
Video analysis was done on the force plate testing, and demonstrated that the beams are activated when the test is run. Figure 43 demonstrates one test that accurately demonstrated the shearing action of the shoe and the activation of the beam system as outlined in the graph above.

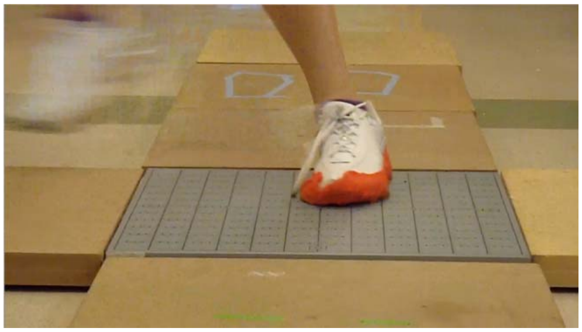
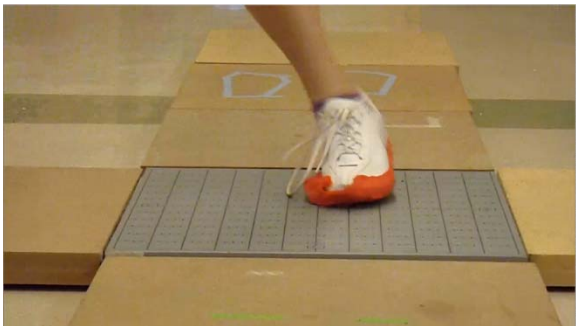
Figure 43: Frame Image of Force Plate Test

5.2.2 Instruction of Test

The subject ran directly at the force plate at a 50% speed stepping onto the force plate with the left foot. Once the foot is placed on the force plate, a sudden deceleration occurs and the subject changes directions and moves in the right direction running off of the force plate at about a 45 degree angle from original impact with the force plate. This motion simulates the cutting motion that causes high ground reaction forces and a valgus position of the knee that can cause non-contact ACL tears in athletes. The series of images below (Figure 44) outline the test done with the prototype on. The sequence begins in the upper left picture and continues to the right and down until the series of images ends. The wooden platforms are used to ensure that the subject does not need to step up onto the platform that the movement from the ground to the force plate is on an even surface. The force plate itself is the grey platform in the testing. Further testing data can be found in Appendix C.



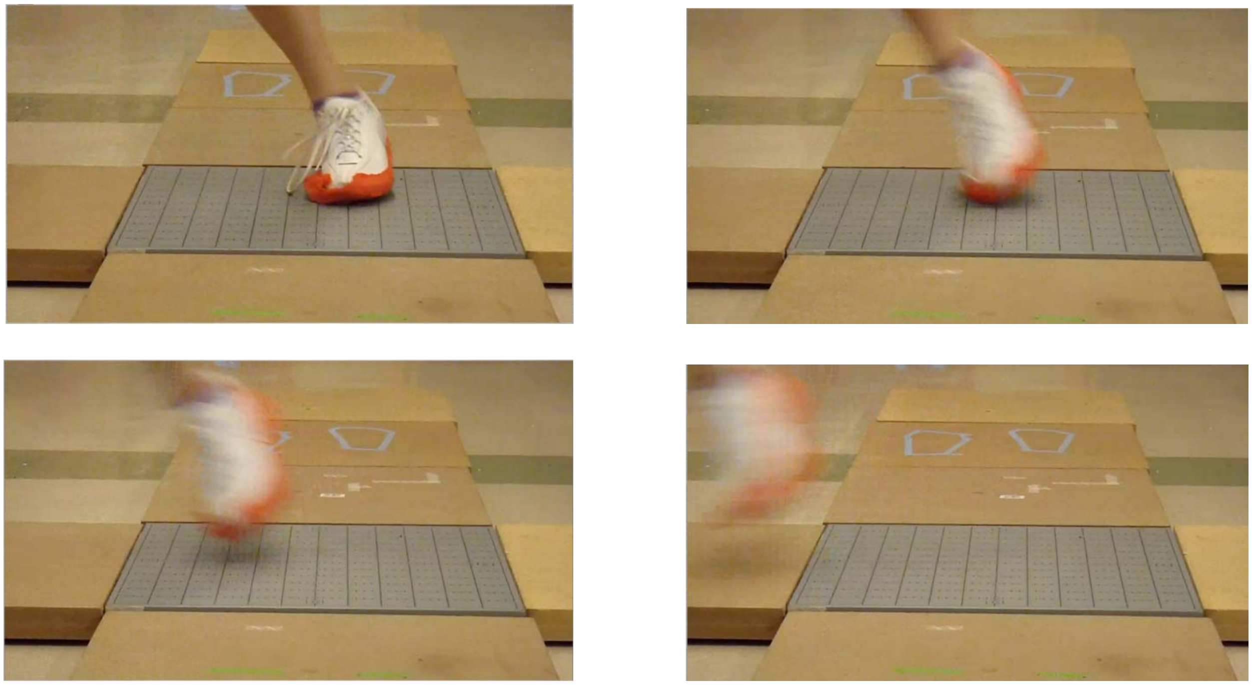


Figure 44: Video Frame of Entire Force Plate Test

6.0 Iterations of the Design

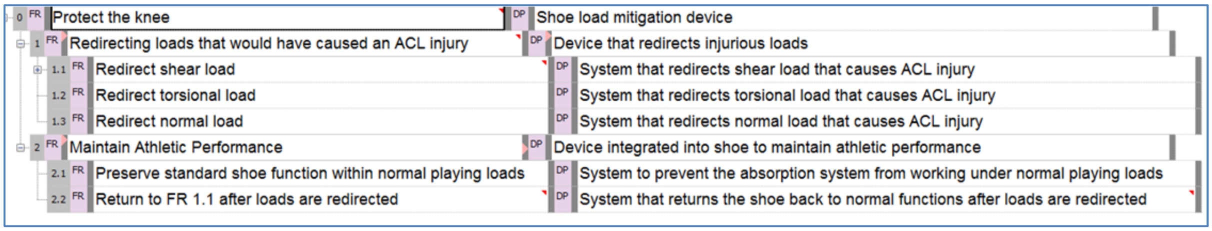
Iterations are made to the design throughout the entire design process. This section outlines the two major components of the design and the design modifications that are associated with them.

6.1 Beam Design

During the process of finalizing the prototype design, it was necessary to iterate the design. These iterations were done based on results from the tensile tests in the Instron machine. The first iterations were pertaining to the beam design. Given that the material on the test molds was easier to remove than to add to, the beams were made smaller in order to observe the effects of the design changes on the test results. Based on the results, it was determined that the B beams needed to be thickened in order to improve the performance of the prototype above the injury threshold. In addition, the center plane was raised to reduce the effect of the A beams in the system.

6.2 Decomposition Structure

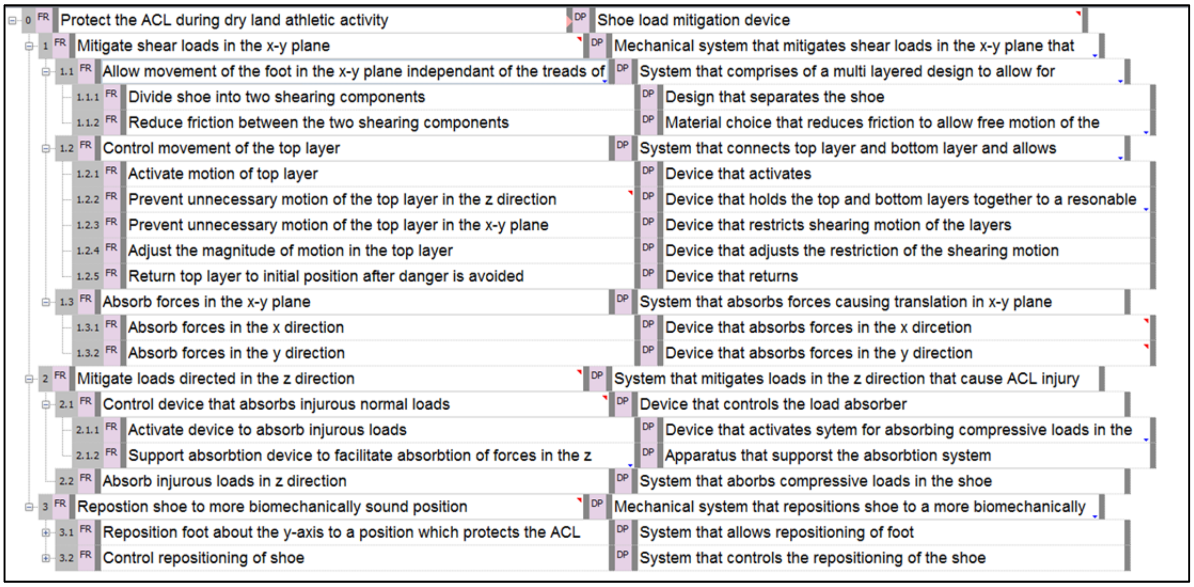
The initial decomposition structure focused on how the forces would be absorbed and the directions that the forces would need to be absorbed; with a second focus in maintaining athletic performance in the shoe. The term "redirect" was used because it was unsure whether or not the forces could be absorbed so a redirection was used. This was then changed to absorbing and mitigating injurious loads. Figure 45 is our first decomposition.



0	FR	Protect the knee	DP	Shoe load mitigation device
1	FR	Redirecting loads that would have caused an ACL injury	DP	Device that redirects injurious loads
1.1	FR	Redirect shear load	DP	System that redirects shear load that causes ACL injury
1.2	FR	Redirect torsional load	DP	System that redirects torsional load that causes ACL injury
1.3	FR	Redirect normal load	DP	System that redirects normal load that causes ACL injury
2	FR	Maintain Athletic Performance	DP	Device integrated into shoe to maintain athletic performance
2.1	FR	Preserve standard shoe function within normal playing loads	DP	System to prevent the absorption system from working under normal playing loads
2.2	FR	Return to FR 1.1 after loads are redirected	DP	System that returns the shoe back to normal functions after loads are redirected

Figure 45: Initial Decomposition

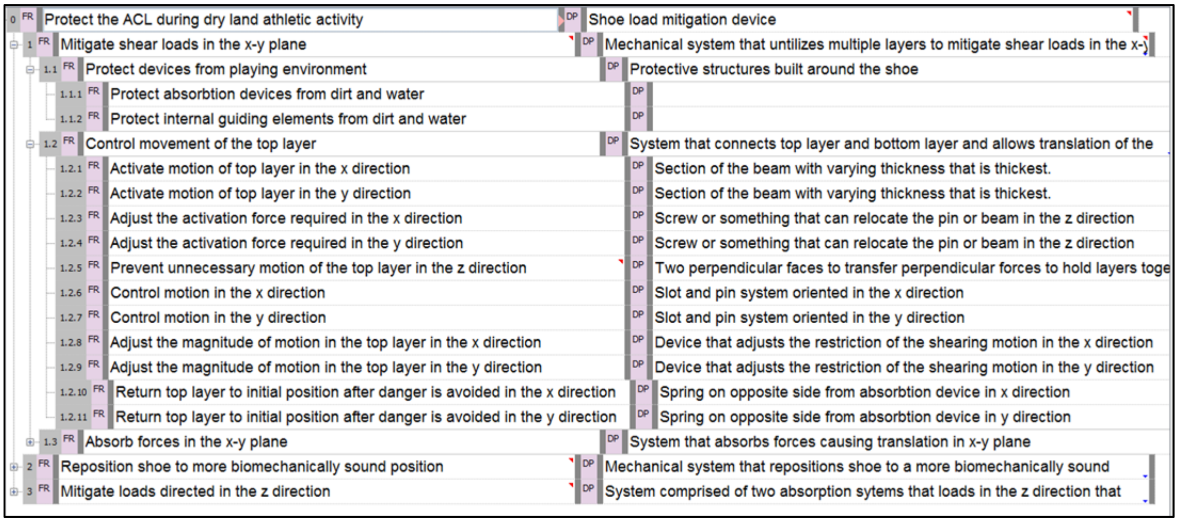
Once a better understanding of the direction of forces and how they are applied to the shoe, a much more detailed decomposition is created. Controlling the motion and absorbing the forces was a direct focus in that area. Also the concept of repositioning the foot to a more biomechanically sound position was discussed. This was determined to not be possible and still maintain a similar weight and shoe function, as well as induce other injuries in other areas of the lower body. Figure 46 outlines this decomposition.



0	FR	Protect the ACL during dry land athletic activity	DP	Shoe load mitigation device
1	FR	Mitigate shear loads in the x-y plane	DP	Mechanical system that mitigates shear loads in the x-y plane that
1.1	FR	Allow movement of the foot in the x-y plane independant of the treads of	DP	System that comprises of a multi layered design to allow for
1.1.1	FR	Divide shoe into two shearing components	DP	Design that separates the shoe
1.1.2	FR	Reduce friction between the two shearing components	DP	Material choice that reduces friction to allow free motion of the
1.2	FR	Control movement of the top layer	DP	System that connects top layer and bottom layer and allows
1.2.1	FR	Activate motion of top layer	DP	Device that activates
1.2.2	FR	Prevent unnecessary motion of the top layer in the z direction	DP	Device that holds the top and bottom layers together to a resonable
1.2.3	FR	Prevent unnecessary motion of the top layer in the x-y plane	DP	Device that restricts shearing motion of the layers
1.2.4	FR	Adjust the magnitude of motion in the top layer	DP	Device that adjusts the restriction of the shearing motion
1.2.5	FR	Return top layer to initial position after danger is avoided	DP	Device that returns
1.3	FR	Absorb forces in the x-y plane	DP	System that absorbs forces causing translation in x-y plane
1.3.1	FR	Absorb forces in the x direction	DP	Device that absorbs forces in the x dircetion
1.3.2	FR	Absorb forces in the y direction	DP	Device that absorbs forces in the y direction
2	FR	Mitigate loads directed in the z direction	DP	System that mitigates loads in the z direction that cause ACL injury
2.1	FR	Control device that absorbs injurous normal loads	DP	Device that controls the load absorber
2.1.1	FR	Activate device to absorb injurous loads	DP	Device that activates sytem for absorbing compressive loads in the
2.1.2	FR	Support absorbtion device to facilitate absorbtion of forces in the z	DP	Apparatus that supporst the absorbtion system
2.2	FR	Absorb injurous loads in z direction	DP	System that aborbs compressive loads in the shoe
3	FR	Repostion shoe to more biomechanically sound position	DP	Mechanical system that repositions shoe to a more biomechanically
3.1	FR	Reposition foot about the y-axis to a position which protects the ACL	DP	System that allows repositioning of foot
3.2	FR	Control repositioning of shoe	DP	System that controls the repositioning of the shoe

Figure 46: Second Decomposition Sample

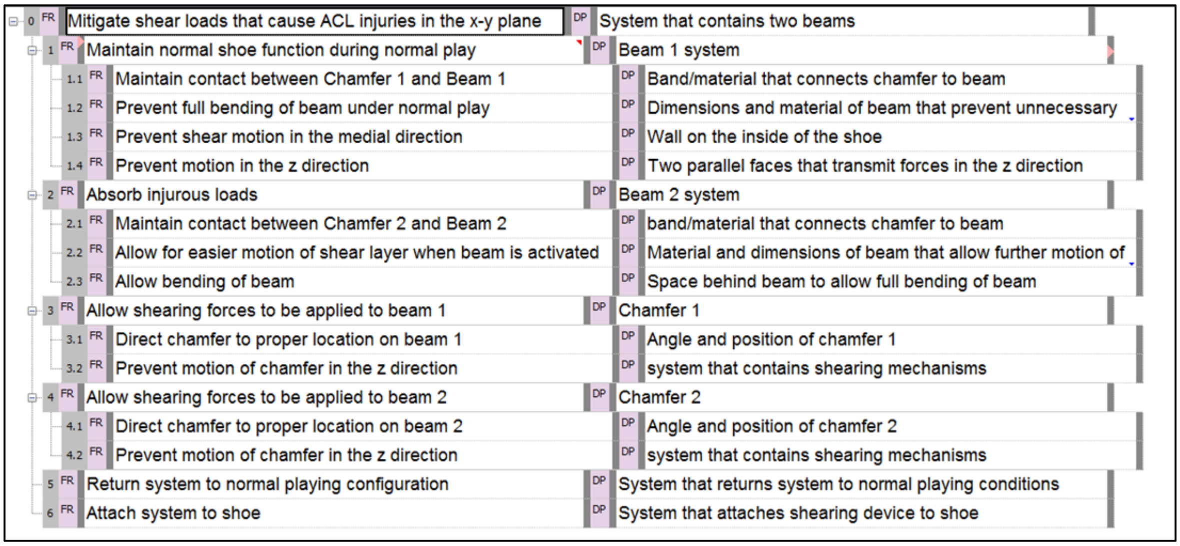
Further review into the directions was done to determine that we needed to maintain normal function of the shoe as well as a focus in the shearing direction and how to absorb the forces and controlling the motion. The review of creating an adjustable system was also added. It was also determined that we would need an activation force needed to provide the motion of the system. Figure 47 outlines our decomposition at this portion of the project.



0	FR	Protect the ACL during dry land athletic activity	DP	Shoe load mitigation device
1	FR	Mitigate shear loads in the x-y plane	DP	Mechanical system that untilizes multiple layers to mitigate shear loads in the x-
1.1	FR	Protect devices from playing environment	DP	Protective structures built around the shoe
1.1.1	FR	Protect absorbtion devices from dirt and water	DP	
1.1.2	FR	Protect internal guiding elements from dirt and water	DP	
1.2	FR	Control movement of the top layer	DP	System that connects top layer and bottom layer and allows translation of the
1.2.1	FR	Activate motion of top layer in the x direction	DP	Section of the beam with varying thickness that is thickest.
1.2.2	FR	Activate motion of top layer in the y direction	DP	Section of the beam with varying thickness that is thickest.
1.2.3	FR	Adjust the activation force required in the x direction	DP	Screw or something that can relocate the pin or beam in the z direction
1.2.4	FR	Adjust the activation force required in the y direction	DP	Screw or something that can relocate the pin or beam in the z direction
1.2.5	FR	Prevent unnecessary motion of the top layer in the z direction	DP	Two perpendicular faces to transfer perpendicular forces to hold layers toge
1.2.6	FR	Control motion in the x direction	DP	Slot and pin system oriented in the x direction
1.2.7	FR	Control motion in the y direction	DP	Slot and pin system oriented in the y direction
1.2.8	FR	Adjust the magnitude of motion in the top layer in the x direction	DP	Device that adjusts the restriction of the shearing motion in the x direction
1.2.9	FR	Adjust the magnitude of motion in the top layer in the y direction	DP	Device that adjusts the restriction of the shearing motion in the y direction
1.2.10	FR	Return top layer to initial position after danger is avoided in the x direction	DP	Spring on opposite side from absorbtion device in x direction
1.2.11	FR	Return top layer to initial position after danger is avoided in the y direction	DP	Spring on opposite side from absorbtion device in y direction
1.3	FR	Absorb forces in the x-y plane	DP	System that absorbs forces causing translation in x-y plane
2	FR	Reposition shoe to more biomechanically sound position	DP	Mechanical system that repositions shoe to a more biomechanically sound
3	FR	Mitigate loads directed in the z direction	DP	System comprised of two absorption sytems that loads in the z direction that

Figure 47: Third Sample of Decomposition Structure

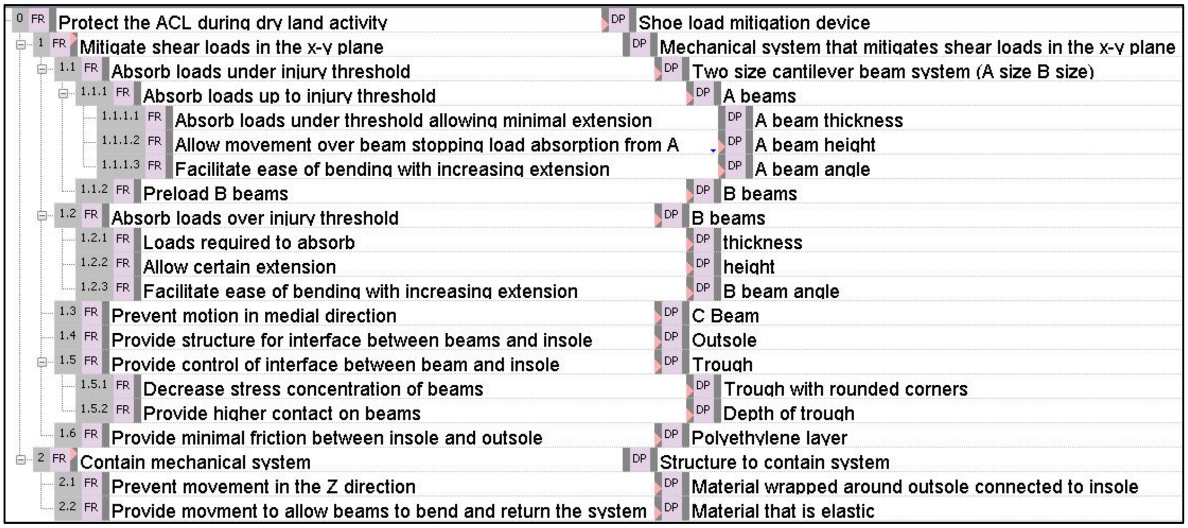
Getting to a more final decomposition it was finally determined that the repositioning of the shoe cannot take place. This was removed from the system. This decomposition applies the double beam system to the shearing components, demonstrating when they would bend and how they would bend. It also outlines the material selection and dimensions of the beams. The attachment to the shoe was also considered. This is the closest to our final decomposition as seen in Figure 48.



0	FR	Mitigate shear loads that cause ACL injuries in the x-y plane	DP	System that contains two beams
1	FR	Maintain normal shoe function during normal play	DP	Beam 1 system
1.1	FR	Maintain contact between Chamfer 1 and Beam 1	DP	Band/material that connects chamfer to beam
1.2	FR	Prevent full bending of beam under normal play	DP	Dimensions and material of beam that prevent unnecessary
1.3	FR	Prevent shear motion in the medial direction	DP	Wall on the inside of the shoe
1.4	FR	Prevent motion in the z direction	DP	Two parallel faces that transmit forces in the z direction
2	FR	Absorb injurous loads	DP	Beam 2 system
2.1	FR	Maintain contact between Chamfer 2 and Beam 2	DP	band/material that connects chamfer to beam
2.2	FR	Allow for easier motion of shear layer when beam is activated	DP	Material and dimensions of beam that allow further motion of
2.3	FR	Allow bending of beam	DP	Space behind beam to allow full bending of beam
3	FR	Allow shearing forces to be applied to beam 1	DP	Chamfer 1
3.1	FR	Direct chamfer to proper location on beam 1	DP	Angle and position of chamfer 1
3.2	FR	Prevent motion of chamfer in the z direction	DP	system that contains shearing mechanisms
4	FR	Allow shearing forces to be applied to beam 2	DP	Chamfer 2
4.1	FR	Direct chamfer to proper location on beam 2	DP	Angle and position of chamfer 2
4.2	FR	Prevent motion of chamfer in the z direction	DP	system that contains shearing mechanisms
5	FR	Return system to normal playing configuration	DP	System that returns system to normal playing conditions
6	FR	Attach system to shoe	DP	System that attaches shearing device to shoe

Figure 48: Fourth Decomposition Structure

Approaching our final decomposition, we were able to outline a more accurate creation of our final prototype. Concepts are more outlined with defined design parameters. The image below is the final decomposition for the shearing beam system. It outlines how we will be mitigating loads, preventing motion under the injury threshold, and containing the system. Our prototype was created based off of this decomposition as seen in Figure 49.



0	FR	Protect the ACL during dry land activity	DP	Shoe load mitigation device
1	FR	Mitigate shear loads in the x-y plane	DP	Mechanical system that mitigates shear loads in the x-y plane
1.1	FR	Absorb loads under injury threshold	DP	Two size cantilever beam system (A size B size)
1.1.1	FR	Absorb loads up to injury threshold	DP	A beams
1.1.1.1	FR	Absorb loads under threshold allowing minimal extension	DP	A beam thickness
1.1.1.2	FR	Allow movement over beam stopping load absorption from A	DP	A beam height
1.1.1.3	FR	Facilitate ease of bending with increasing extension	DP	A beam angle
1.1.2	FR	Preload B beams	DP	B beams
1.2	FR	Absorb loads over injury threshold	DP	B beams
1.2.1	FR	Loads required to absorb	DP	thickness
1.2.2	FR	Allow certain extension	DP	height
1.2.3	FR	Facilitate ease of bending with increasing extension	DP	B beam angle
1.3	FR	Prevent motion in medial direction	DP	C Beam
1.4	FR	Provide structure for interface between beams and insole	DP	Outsole
1.5	FR	Provide control of interface between beam and insole	DP	Trough
1.5.1	FR	Decrease stress concentration of beams	DP	Trough with rounded corners
1.5.2	FR	Provide higher contact on beams	DP	Depth of trough
1.6	FR	Provide minimal friction between insole and outsole	DP	Polyethylene layer
2	FR	Contain mechanical system	DP	Structure to contain system
2.1	FR	Prevent movement in the Z direction	DP	Material wrapped around outsole connected to insole
2.2	FR	Provide movment to allow beams to bend and return the system	DP	Material that is elastic

Figure 49: Final Decomposition of Project

7.0 Discussion

This section outlines the major areas of the project and discusses in detail portions of the project that were not previously discussed in the paper.

7.1 Beam vs. Air System

Comparing the beam vs. air system developed it is determined that the air system is more adjustable and has more potential for mass production once a final product is created. This is true because the pressure relief valve in the system can be designed to be adjusted. Having the adjustable system means that the design does not need to be custom designed for the individual using the shoe. The beam system would have to be altered to the individual using the system or based off of anatomical proportions comparing body weight and foot size. This becomes difficult in ensuring that the shoe will be successful in decreasing the potential for non-contact ACL tears. Having an adjustable valve allows the valve to be set for the range determined by the user’s foot size and their body weight. When comparing the two systems there is potential for the air system to replace the beam system in the shearing components. This would be done by replacing the beams with a long air cylinder that would absorb the shearing impact and release air at the determined injury threshold. Because the air system is adjustable, further look into creating a prototype of this concept would have to be done for a final design to be considered.

7.2 Design Alterations to Prototype

The final design of the beam system was conducted for testing purposes; the injury threshold line was dropped drastically for this reason. If the material and beam design was created to protect the ACL it would be extremely difficult to retrieve testing data. Therefore, the beam system was set to bend at a much lower force, protecting the test subject and allowing for much easier data collection. Further modifications would have to be done to determine the proper material, beam shape, and locations of the beams. The prototype was created as a proof of concept model to test the behavior of the beams and ensure that the design could be implemented into an athletic shoe. Further alterations to the beam design could include additional layers to allow a decrease in the friction associated with the interface between the shearing layers. As well as a decrease in the friction a better system would need to be developed to hold the layers together. The material would need to be more durable and the entire system would have to be enclosed as well as waterproof. Preventing external materials from entering the system and limiting any error in the shearing components and make the system more reliable over varying playing conditions in outdoor environments.

7.3 Importance of the Design

As reviewed in the rational of the project, the occurrence of non-contact ACL tears is extremely high in athletes, specifically women. Tearing of the ACL usually means the athlete can no longer participate in their respective sport until surgical repair of the ligament is done and rehabilitation is completed to strengthen the muscles and regain full range of motion of the knee. This process can take months, potentially years depending on the severity of the injury, extent of surgical repair needed and the athletes drive to return back to athletic competition. If there is a shoe that can be designed to reduce the occurrence of such injuries, money would be saved both in the medical field, and in rehabilitation equipment. The simple solution of this is to prevent the ground reaction forces from ever reaching the knee preventing injury from occurring. Our design takes this to heart and applies the absorption of the forces directly into the shoe, maintaining the athlete's performance on the field and adding very little weight to the shoe itself. The design itself is created to maintain athletic performance while still providing the injury preventative measures needed to save the knee. Our prototype, with further modifications to the beam design, showed that the system can be integrated into the shoe and the beam system bends at the appropriate times noted. With further changes to the beam design, to activate at the injury threshold as well as the application and creation of the prototype of the air system into the shoe, we believe that the final design can help in reducing non-contact ACL tears in athletes.

Further analysis of the air system and the final beam system would have to be conducted to determine the percentage reduction of ACL injuries in athletes.

8.0 Concluding Remarks

Literature Review

- Literature showed that Ground Reaction forces are determined to be a high contributing factor to the occurrence of non-contact ACL injuries in athletes.

Engineering Design

- Axiomatic Design principles were used to realize a solution to mitigating ground reaction forces that can cause non-contact ACL tears.
- Project was broken down into two major components.
    - Shearing absorption
    - Compression absorption (Fluid Design)
- Creo Parametric was used for a Finite Element Analysis to determine the final beam design of the shearing components.
- Solidworks was used to create a solid model of the prototype beam system for final production
- Solidworks model was imported into ESPRIT for tool path programming in CNC Machines.
- A final mold design was created and Polyurethane Shore 70A was poured into the mold creating the final beam system
- The final beam system was tested in an Instron Machine to demonstrate desired characteristics of the beam and to finalize beam dimensions and shape.
- Final Beam system was integrated into a shoe, courtesy of Ray’s Shoe Repair.
- Once integrated, Force plate testing was conducted, and data demonstrated the shearing of the layers and the activation of the beams.

Recommendations for Future Work

- Modification to the beam design to create a model that activates at higher loads where there is a risk for injury (new load designation for injury threshold).
- Additional testing of modified design, once the beam system is finalized, to determine the system’s effectiveness in activating the system at the proper injury threshold.

9.0 Acknowledgments

A special thanks to Lisa Wall for assistance in the lab, Patent Lawyer Christopher Lutz, Technology Transfer Director Todd Keiller, Ray’s Shoe Repair, Axiomatic Design Solutions Inc for the use of Acclaro; and Alex Segala and Mik Tan for help in the Machine Shop.

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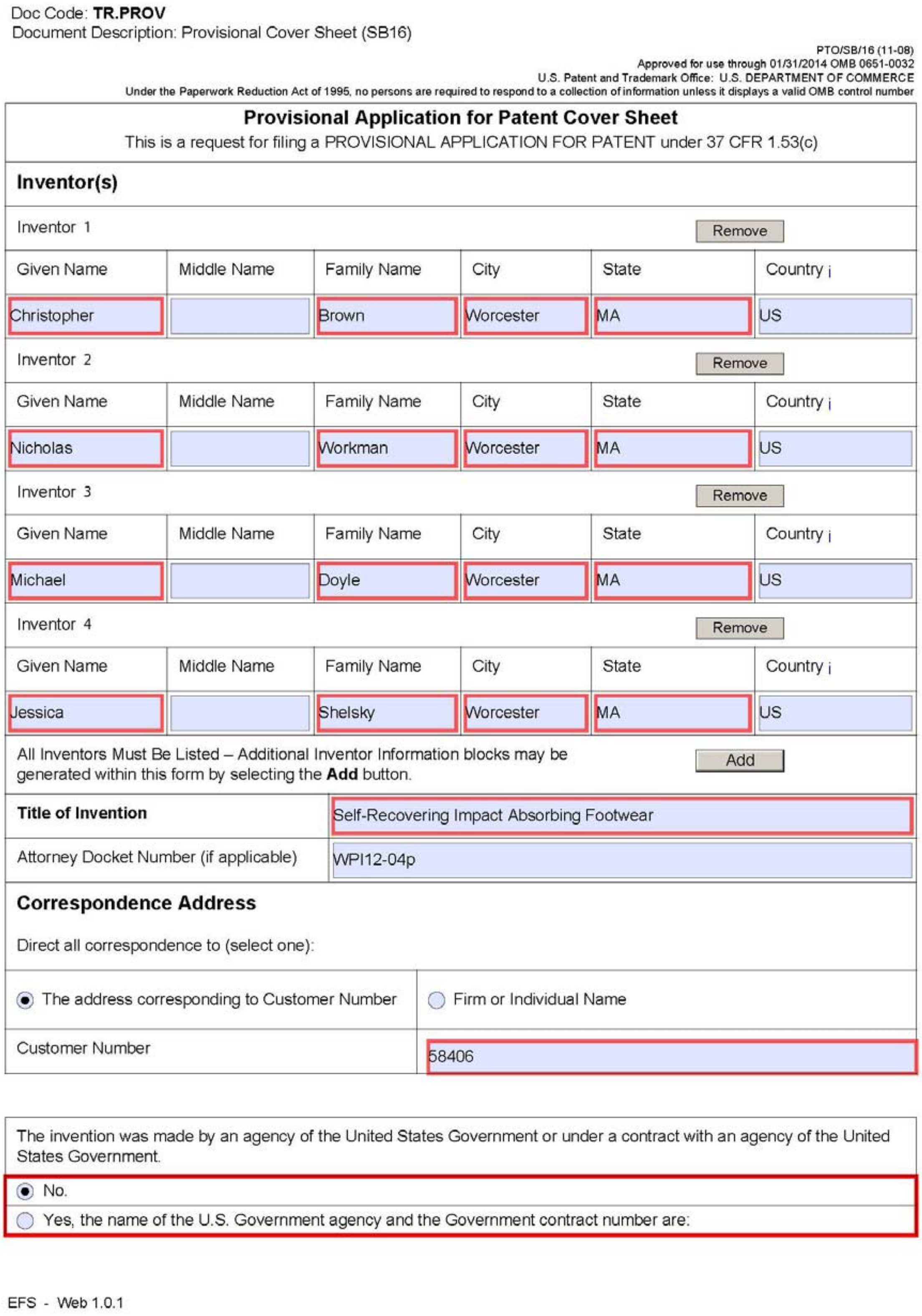
Appendix A: Provisional Patent Documentation



Doc Code: **TR.PROV**
Document Description: Provisional Cover Sheet (SB16)

PTO/SB/16 (11-08)
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Provisional Application for Patent Cover Sheet

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c)

Inventor(s)

Inventor 1

Given Name	Middle Name	Family Name	City	State	Country i
Christopher		Brown	Worcester	MA	US

Inventor 2

Given Name	Middle Name	Family Name	City	State	Country i
Nicholas		Workman	Worcester	MA	US

Inventor 3

Given Name	Middle Name	Family Name	City	State	Country i
Michael		Doyle	Worcester	MA	US

Inventor 4

Given Name	Middle Name	Family Name	City	State	Country i
Jessica		Shelsky	Worcester	MA	US

All Inventors Must Be Listed – Additional Inventor Information blocks may be generated within this form by selecting the **Add** button.

Title of Invention	Self-Recovering Impact Absorbing Footwear
Attorney Docket Number (if applicable)	WPI12-04p

Correspondence Address

Direct all correspondence to (select one):

● The address corresponding to Customer Number ○ Firm or Individual Name

Customer Number: 58406

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

● No.
○ Yes, the name of the U.S. Government agency and the Government contract number are:

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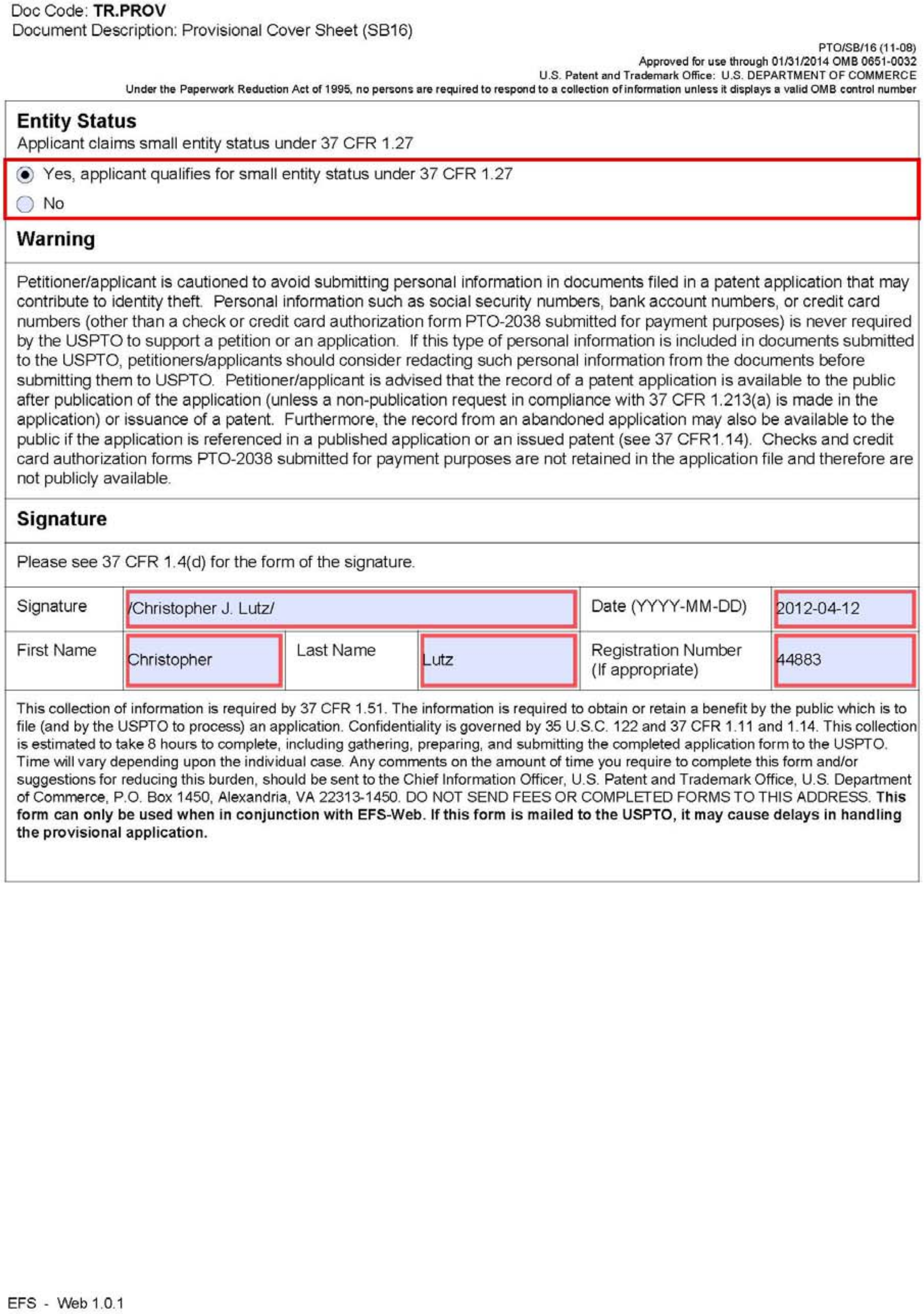

Doc Code: **TR.PROV**
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Entity Status

Applicant claims small entity status under 37 CFR 1.27

● Yes, applicant qualifies for small entity status under 37 CFR 1.27

○ No

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Signature

Please see 37 CFR 1.4(d) for the form of the signature.

Signature	/Christopher J. Lutz/			Date (YYYY-MM-DD)	2012-04-12
First Name	Christopher	Last Name	Lutz	Registration Number (If appropriate)	44883

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PATENT APPLICATION
BWC/CJL

Inventors: Christopher Brown, Nicholas Workman, Michael Doyle and Jessica Shelsky
Attorney Docket No.: WPI12-04p

SELF-RECOVERING IMPACT ABSORBING FOOTWEAR

BACKGROUND

Current applications of shoe redesign to prevent ACL tears consist of patents that contain fully releasable athletic shoes have been patented in recent years. US. Patent No. 7,254,905 (to Dennison) details a system that releases when a predetermined, longitudinally directed force is applied. The technique used to accomplish this is to have a fully detachable lower sole with a mechanical release mechanism that is designed to release when a predetermined force is applied. In this application the shoe has a longitudinal guiding element, allowing for release only do to longitudinal forces. The claims state the longitudinal direction of release prevents knee ligament injuries including ACL injuries. US Patent No. 3668792 titled Breakaway Athletic Safety Shoe issued to York in 1971 creates and discusses a breakaway system that removes the lower sole of the shoe leaving only an upper section of the sole still attached. The lower portion can include cleats or just a normal shoe tread. The system is spring loaded and completely releases with activation. Another type of releasable sole is detailed in US Patent No. 5,456,027, issued to Tecchio et al. This design utilizes an electronic breakaway system, which measures forces in the shoe with internal strain gauges. The electronic system must be pre-set before use, based on the athlete's body type and demands on the shoe during its use. If exceedingly high forces are experienced in the strain gauges, then the entire sole is automatically detached from the rest of the sole, avoiding injury. The sole could then be reattached to resume play. Other conventional approaches are disclosed in U.S. Patent Nos. 4670997, 4546556, 5456027, 3782011, 5155927, 7254905, 5255453, 5867923, 3668792, 3707047, 5255453, 5867923, 7254905.

SUMMARY

An impact absorbing footwear device employs opposed planar sole portions engaged by a selective resistance coupling that biases the opposed planar sole portions in a non-linear manner in response to forces exerted by the wearer against the sole portion in frictional contact with a floor surface. The selective resistance coupling includes a plurality of resilient deformation members that engage the planar sole portions in an opposed circumferentially aligned manner, selectively deform in response to pressure exerted by the wearer for preventing ACL and other impact related injuries, and recover to an undeformed rest position without breakaway to allow the wearer uninterrupted usage while dampening forces that surpass an injury threshold from the resilient deformation that allows the planar sole portions to temporarily misalign. The non-linear response of the selective resistance coupling provides a decreasing resistance once the wearer-exerted force exceeds an injury threshold, while an increased resistance response assures the wearer of responsive traction when the exerted force is below the injury threshold.

In addition to those cited above, there are also several patented designs that aim at reducing friction to allow rotation of the foot to avoid injury. US. Pat. No. 5,867,923 to Lehneis is an orthotic shoe with torsion sole. This shoe has an insole and an outsole that are placed together in the center on a pivot. The pivot allows relative rotation along the plane parallel to the shoe sole. This shoe is patented to be an orthotic to persons with diabetes but can be applied in our situation. US Patent No. 4670997 issued to Beekman titled Athletic Shoe Sole reviews the various tread patterns associated with injury of athletes. With this review they re-designed the tread to reduce friction on surfaces as well as allow more rotation at the ball of the foot in the shoe with decreased friction. The use of flexible fabric is used to provide greater rotation as well as a decrease in friction when the user pivots in the shoe. US Patent No. 4546556 titled Basketball Shoe Sole issued to Stubblefield designs the sole of an athletic shoe to be used on hard surfaces such as a basketball court. The design of the sole allows for the absorption of more forces in the shear direction as well as a sole pattern design that allows for easier pivot rotation of the foot. US Patent No. 3707047 titled Swivel Athletic Shoe by Nedwick claims that the shoe contains a pivot portion of the shoe located at the ball of the foot. This pivot point allows for easier rotation of foot on high friction surfaces, thus decreasing injury in athletes. Another method of shoe redesign to absorb large possible injurious loads is patent 5,255,453 to Weiss. In this shoe design the cleat has a means of breaking away with adhesive layer on the top portion of each cleat. The cleats and the adhesive layer have a predetermined failure shear force which causes the shoe to decompose and break apart absorbing the load and reducing the occurrence of injury.

Efforts have been made to create effective ACL injury reducing measures that do not involve redesigning the shoe. One of these measures is neuromuscular training interventions. The reasoning behind this training is that since non-contact injuries can be attributed to certain body positions and muscular reactions, then athletes can be trained to avoid these situations and therefore avoid injury (Silvers). Reduction in the occurrence of ACL injuries, when compared to control groups, are seen in the vast majority of training programs studied (Silvers). Some training techniques have demonstrated better results than others. High-intensity jumping plyometric exercises were successful in reducing injury by training the muscles and causing the athlete to focus on proper biomechanics. Having a trainer present to give immediate feedback and instruction on proper technique also improved results. The one type of training that was not effective was balance training. Alone, it is ineffective, but it can be beneficial when combined with the aforementioned training methods (Silvers, H.J. (2007). "Prevention of anterior cruciate ligament injury in the female athlete". British journal of sports medicine (0306-3674), (suppl 1), p.i52.)

DETAILED DESCRIPTION

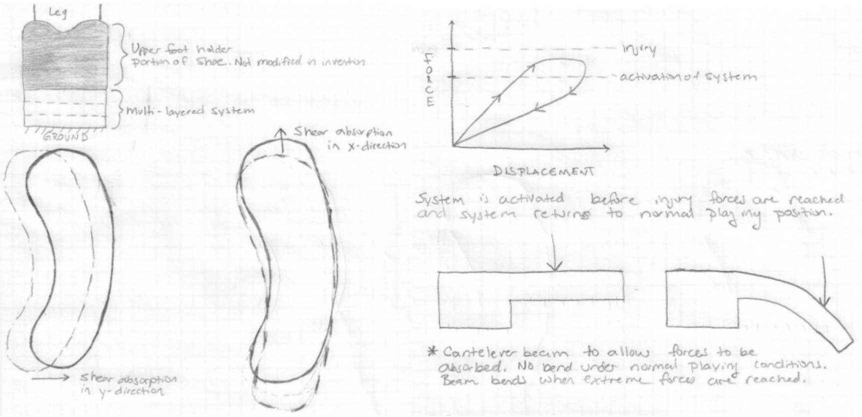
In a particular configuration, an injury preventative footwear apparatus includes a plurality of resilient members extending from a planar surface and an opposed planar surface engaging the plurality of resilient members, the opposed planar surfaces having a substantially similar shape and disposed in alignment at a rest position by the resilient members. The resilient members are adapted for deformation upon movement of the planar surface relative to the opposed planar surface, such that the resilient members bias the planar surfaces at a rest position and provide a selective resistance to the movement based on a predetermined threshold of force. A limiter coupling maintaining engagement of the opposed planar surfaces in response to forces exceeding the injury threshold such that the sole portions do not "breakaway" and separate completely but rather return to the undeformed rest position in a self-recovery manner, likely without the wearer being aware that an injury has been prevented. Thus, the limiter coupling is adapted to return the opposed planar surfaces to the rest position following deformation. In this configuration, therefore, the predetermined threshold is an injury threshold and the opposed planar surfaces are upper and lower sole portions of an athletic shoe prone to sudden forcefull movements of an athlete. The selective resistance of the resilient members increases with a force of the movement until an injury threshold of force, and then decreases for force exceeding the injury threshold.

Configurations disclosed herein overcome deficiencies of conventional approaches in that it incorporates multiple directions of force absorption including, but not limited to, shear and normal directions to the ground all absorbing ground reaction forces that contribute to ACL injuries in athletes. Patents provided offer single direction absorption or prevention of forces absorbed but do not include shear and normal ground reaction force absorption in one system. Additionally the invention will include a recoverable system that will recover quickly enough to be used in the next placement of the foot on the ground after the system has been activated. This is an improvement on patents including a fail system where components are detached when activated. The recovery system allows for the activation of the force absorbing mechanism without the athlete being able to detect that the system is active. The recovery allows for the player to continue playing without any change in gait of the athlete.

Particular configurations include the redesign of the sole of an athletic shoe with a mechanical system to prevent or reduce the occurrence of ACL injuries in athletes. We identified three directions of forces which cause ACL tears in athletes; normal to the ground, shear along the x-axis and shear along the y-axis with the x- and y-axis determined to be parallel to the ground. The shear force directions will be addressed with a multi-layered system in the sole of the shoe that allows additional motion in the shear directions described. A beam system will then absorb these forces when the system is activated. The system will only be activated when force levels begin to reach injury level. This beam system consists of a series of beams varying in height, allowing the layers to press against the beams absorbing the forces in this direction. Forces normal to the ground are absorbed with a mechanical system that allows additional motion in that direction when activated. This absorption is created with an air valve system. The activation of the system creates an airflow that removes air from the system allowing further compression of the shoe to take place. This increase in the distance traveled during injury level forces creates a system that can absorb additional forces; thereby limiting potential injury caused anterior tibia rotation in the lower leg. The system will only be activated when force levels exceed normal conditions. All systems described are completely recoverable, can be reused additional times, and experience an automatic recovery. Drawings attached describe the mechanical systems used and how they are incorporated into the shoe sole. The design of the fluid air system can also be applied to the shear directions in the x-y plane. Placing an air tube around the shoe in replace of the beam system can mimic the results the beam system can produce. In summary the fluid system can be applied to the shear and compression absorption and the beam system can only be applied to the shear absorption.

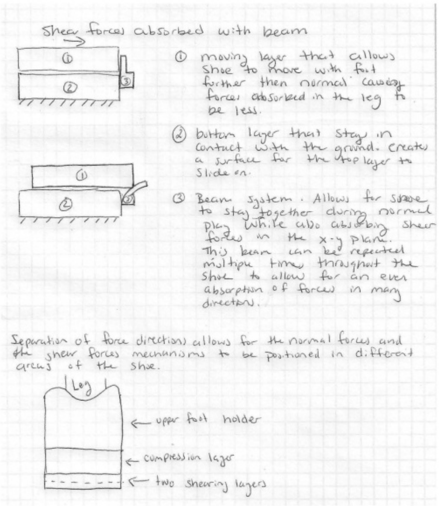
The multi beam system works by having a set of beams varying in height; some at a short length and some at a taller length. The beams hold the system in place during normal playing conditions. When the load on the beams approaches that which would be dangerous to the athlete, the shearing layer of the system will be forced over the shorter beams. At that point, the taller beams will be in control of the motion shearing layer, allowing more motion in the shear direction but a controlled motion that can mitigate the injurious forces. For adjustability, the shearing layer could be moved up and down relative to the beams, which would alter the forces required to force over the shorter set of beams.

The foregoing and other objects, features and advantages of the invention will be apparent from the following embodiments of the invention, as illustrated in the accompanying drawings. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.



System is activated before injury forces are reached and system returns to normal playing position.

* Canteleve beam to allow forces to be absorbed. No bend under normal playing conditions. Beam bends when extreme forces are reached.

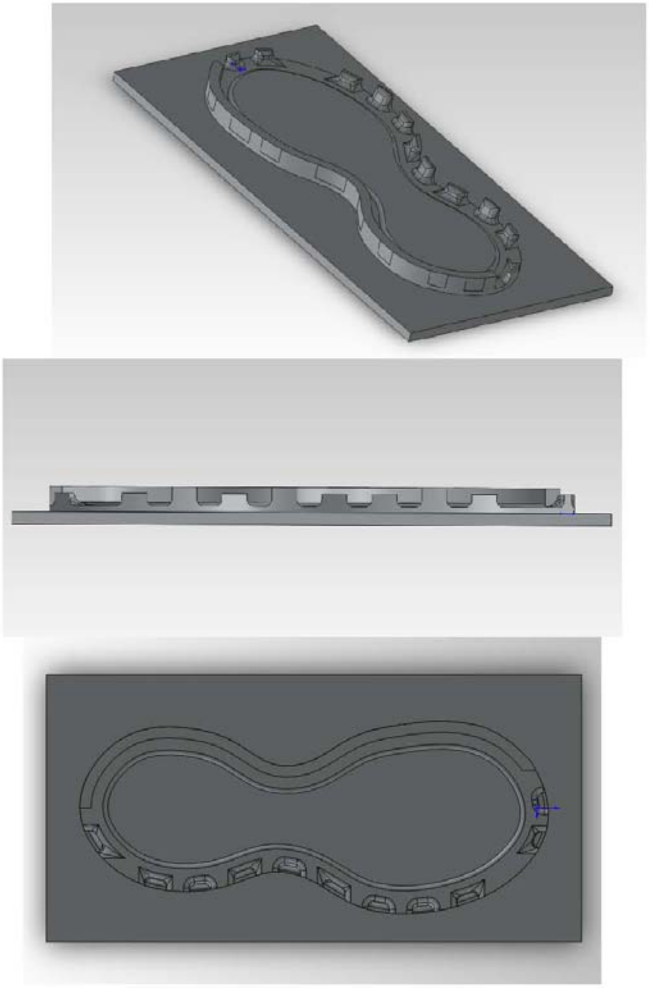


① moving layer that allows shoe to move with foot further then normal causing forces absorbed in the leg to be less.

② bottom layer that stays in contact with the ground. creates a surface for the top layer to slide on.

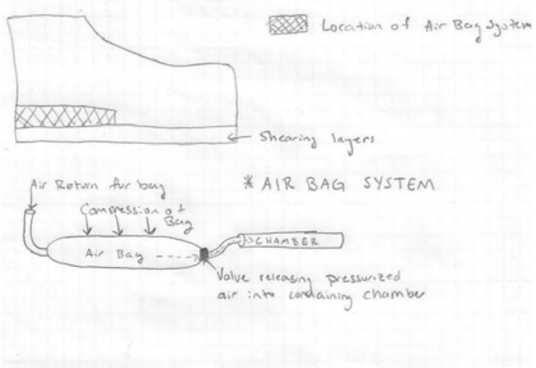
③ Beam system. Allows for shoe to stay together during normal play while also absorbing shear forces in the x-y plane. This beam can be repeated multiple times throughout the shoe to allow for an even absorption of forces in many directions.

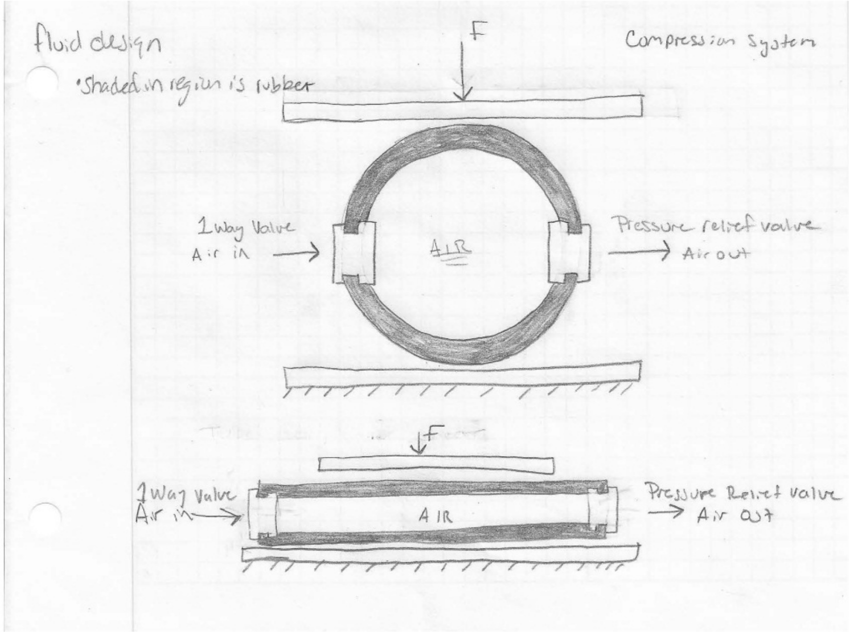
Separation of force directions allows for the normal forces and the shear forces mechanisms to be positioned in different areas of the shoe.



The compression mechanism allows for additional motion past the standard play forces. This allows for the initial impact forces to be absorbed in the shoe over a longer period of time. The graph associated with this absorption mechanism is also the graph found in the above drawings. As the forces increase an internal pressure in the rubber container is created. Once this force reaches a certain internal pressure, a pressure relief valve is opened releasing the air from the system. The release of air from the system allows additional motion perpendicular to the ground. This additional motion absorbs the forces over a greater distance and time preventing forces in the knee from becoming too high causing an ACL tear in the athlete. The use of a beam system can allow the motion only to be achieved when forces cause the beam to bend. The use of an airbag system allows the motion downward to be controlled with a pressure relief valve. The pressurized air in the system would only be released under specified conditions determined by the valve. Thus, allowing the design to control the output of the air in the bag. The air return must also contain a one way valve to keep air from escaping through the enclosed area but allow air to re-enter the system during the recovery phase.

Multiple mechanical systems can be designed to create the injury prevention system. One is the use of a beam system can allow the motion only to be achieved when forces cause the beam to bend. A spring system can also be used allowing the system to move in the downward position with the guidance of the springs located in the design. The use of an airbag system allows the motion downward to be controlled with a pressure sensitive valve. The overall compression system can be achieved with a spring system, beam system, airbag or air(gaseous) tube system or an additional mechanical system integrated into the sole of the shoe.





Configurations herein are amenable to multiple areas of commercial use including use by athletes, every day people and potentially military purposes. The invention itself would benefit all who are at any risk for ACL injury. Anyone participating in any physical motion that requires a sudden de-acceleration and change in direction are at risk for an ACL injury. Our major target audience for the product is athletes participating in sports that require a considerable amount of jumping and changing of directions. The invention can be applied to athlete's shoes allowing them to eliminate the worries of injuring the ACL associated with shear and compression forces.

While the system and methods defined herein have been particularly shown and described with references to embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

CLAIMS

What is claimed is:

1. An injury preventative footwear apparatus comprising:

a plurality of resilient members extending from a planar surface;

an opposed planar surface engaging the plurality of resilient members, the opposed planar surfaces having a substantially similar shape and disposed in alignment at a rest position by the resilient members,

the resilient members adapted for deformation upon movement of the planar surface relative to the opposed planar surface, the resilient members biasing the planar surfaces at a rest position, the resilient members providing a selective resistance to the movement based on a predetermined threshold of force; and

a limiter coupling maintaining engagement of the opposed planar surfaces in response to forces exceeding the injury threshold.

2. The apparatus of claim 1 wherein predetermined threshold is an injury threshold and the opposed planar surfaces are upper and lower sole portions of an athletic shoe prone to sudden forcefull movements of an athlete.

3. The apparatus of claim 2 wherein the selective resistance provided by the resilient members decreases following a predetermined threshold of force.

4. The apparatus of claim 1 wherein the limiter coupling is adapted to return the opposed planar surfaces to the rest position following deformation.

5. The apparatus of claim 2 wherein the selective resistance increases with a force of the movement until an injury threshold of force is attained, the selective resistance decreasing for force exceeding the injury threshold.

6. The apparatus of claim 5 wherein the resilient members are deformable beams biased to a rest position that engages the planar portions in substantially coplanar and circumferential alignment.

7. The apparatus of claim 5 wherein the resilient members are gaseous tubes biased to a rest position that engages the planar portions in substantially coplanar and circumferential alignment.

8. The apparatus of claim 5 wherein the resilient members include horizontally and vertically oriented members adapted for longitudinal and downward force dispersion, respectively.

Electronic Acknowledgement Receipt

EFS ID:	12530165
Application Number:	61623430
International Application Number:	
Confirmation Number:	3369
Title of Invention:	Self-Recovering Impact Absorbing Footwear
First Named Inventor/Applicant Name:	Christopher Brown
Customer Number:	58406
Filer:	Christopher J. Lutz/Pina L. Butler
Filer Authorized By:	Christopher J. Lutz
Attorney Docket Number:	WPI12-04p
Receipt Date:	12-APR-2012
Filing Date:	
Time Stamp:	18:05:28
Application Type:	Provisional

Payment information:

Submitted with Payment	yes
Payment Type	Credit Card
Payment was successfully received in RAM	$125
RAM confirmation Number	5169
Deposit Account	503735
Authorized User	LUTZ,CHRISTOPHER J

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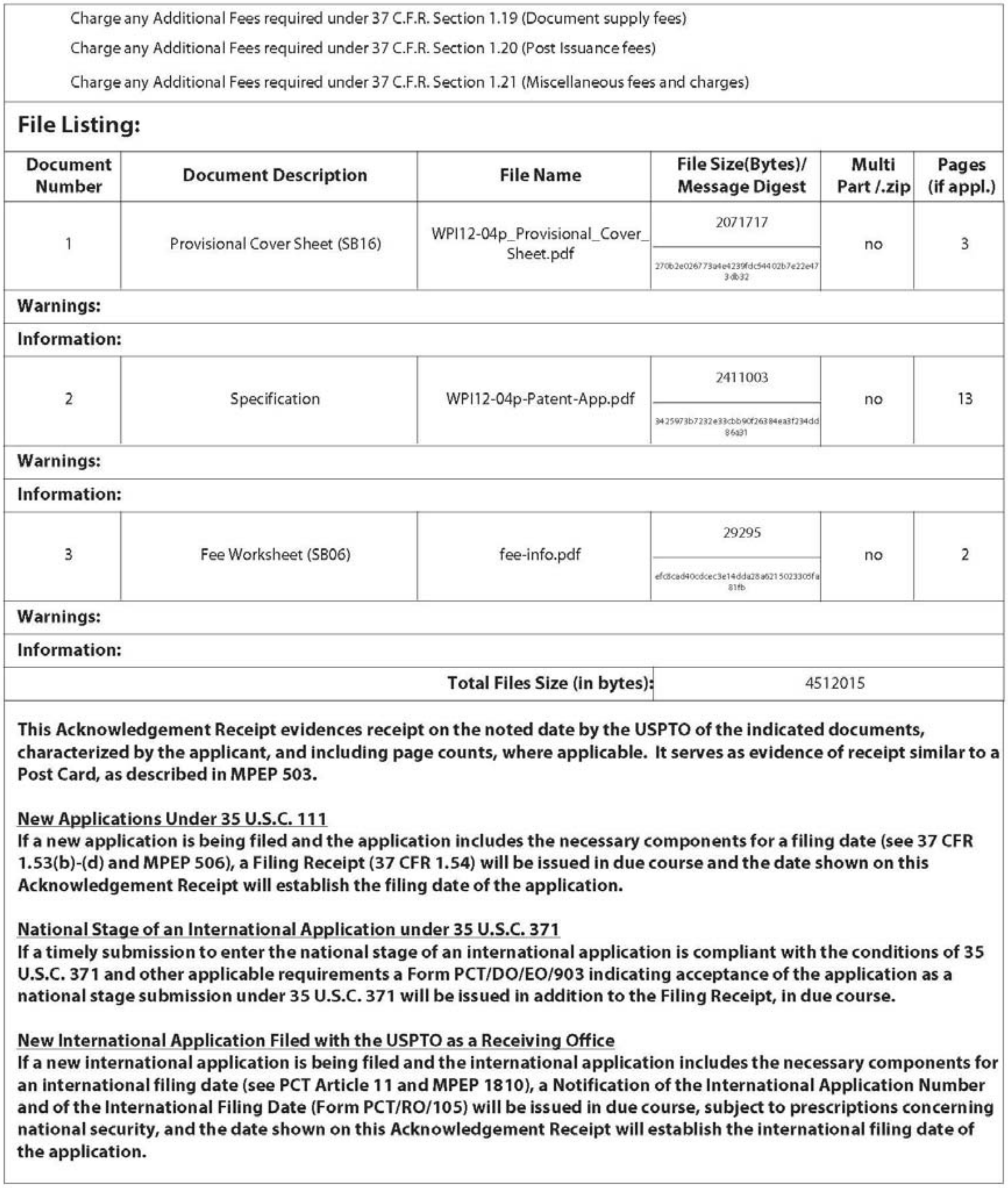

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New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

Appendix B: Instron Test Graphs

Additional testing was done using the Instron Machine that both allowed the final beam design to be created as well as a final holding apparatus to be designed. The series of graphs are paired with their corresponding time and extension graphs.

The first series of graphs outlines the full shoe beam size with no springs in the holding apparatus. Testing was very inconsistent and the apparatus needed adjusting. As well as modifications to the test set up in the Instron Machine Program.

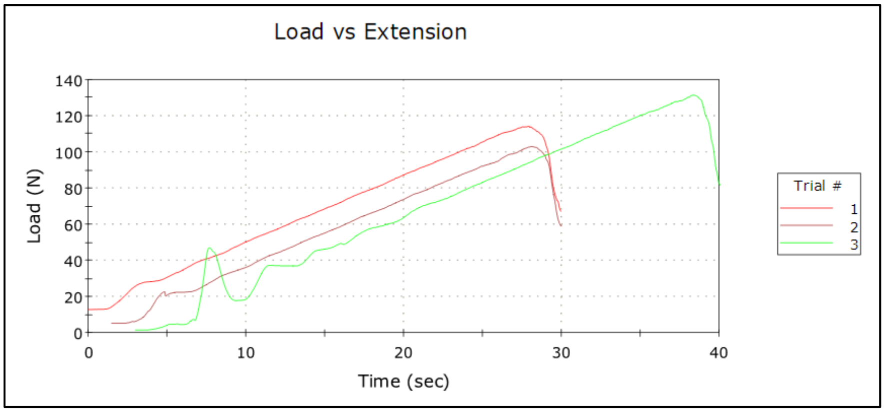

Figure 50: Full Shoe Beam Size Screwed Down No Spring Load vs. Time

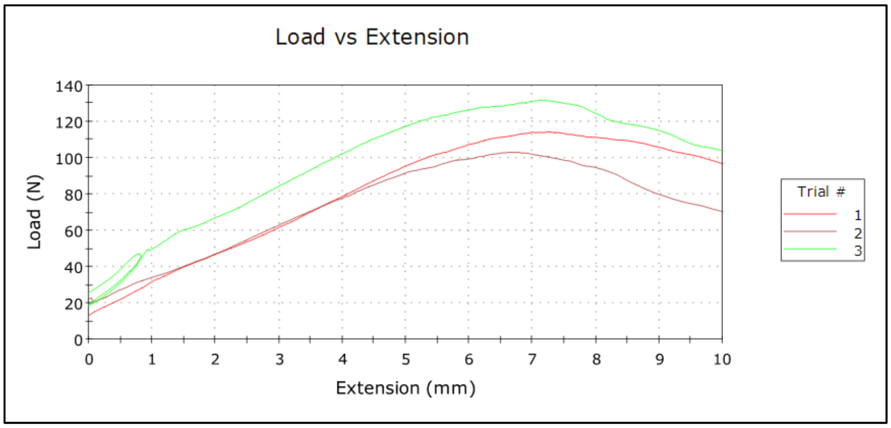

Figure 51: Full Shoe Beam Size Screwed Down No Spring Load vs. Extension

The next series of graphs show the cutting of the beams to allow the peak load to increase. This shows that the beam activation forces can be controlled by changing the dimensions of the beams. The testing apparatus was finalized at this point and data was much more accurate.

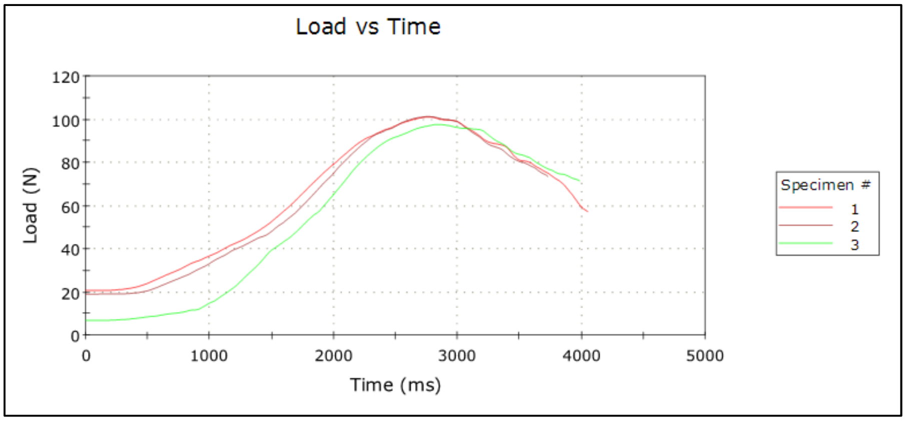

Figure 52: Full Shoe with beams cut smaller Load vs. Time

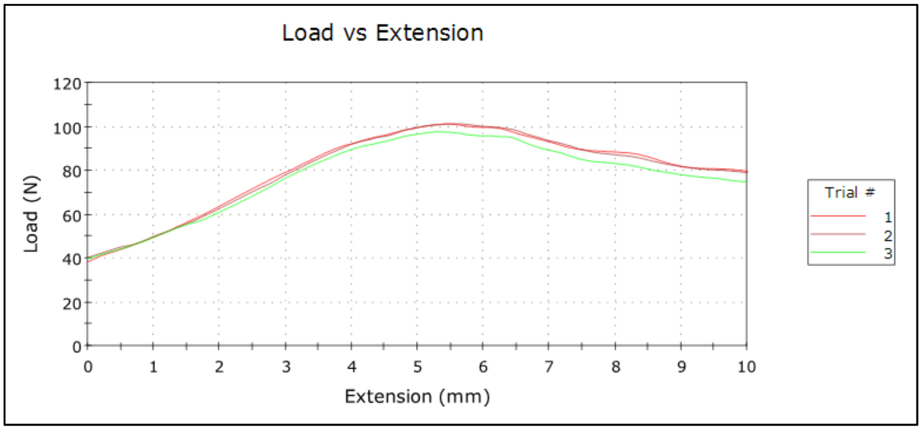

Figure 53: Full Shoe with beams cut smaller Load vs. Extension

The next series of data represents our testing of the beam design on a small scale. This portion of the beam design only incorporated the heel beam system. Testing was fairly consistent but the test setup was not finalized and the beam shape and design was not finalized. A series of these tests were conducted to determine the final beam design.

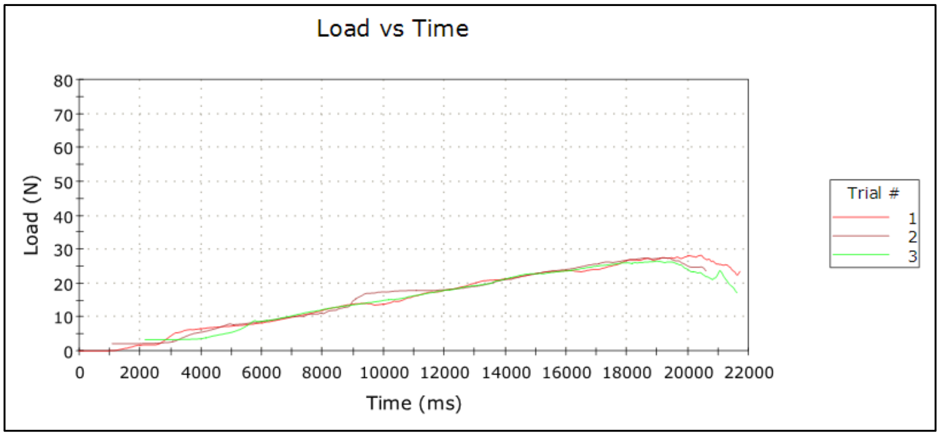

Figure 54: Original Beams Only heel Load vs. Time

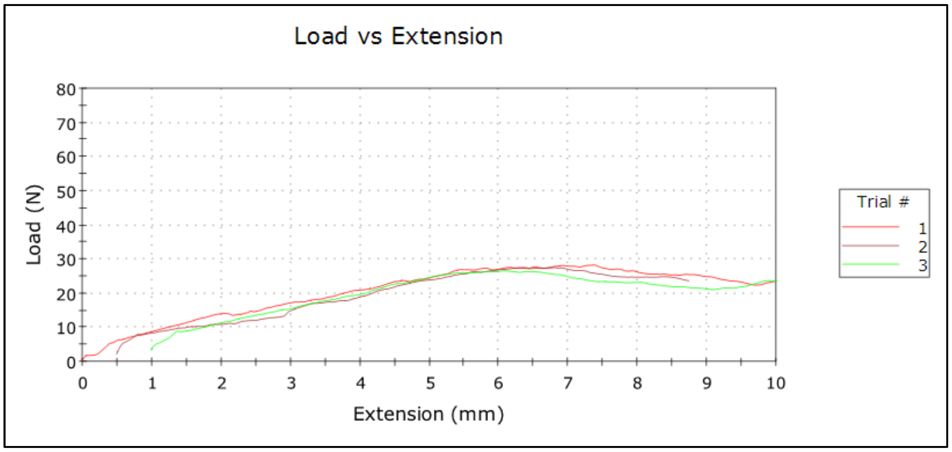

Figure 55: Original Beams Only heel Load vs. Extension

Appendix C: Force Plate Test

The following is all of our force plate data outlining the directions involved in the testing. For analysis only forces in the x-direction are considered. The first three graphs represent the control data while the last three graphs show the prototype data.

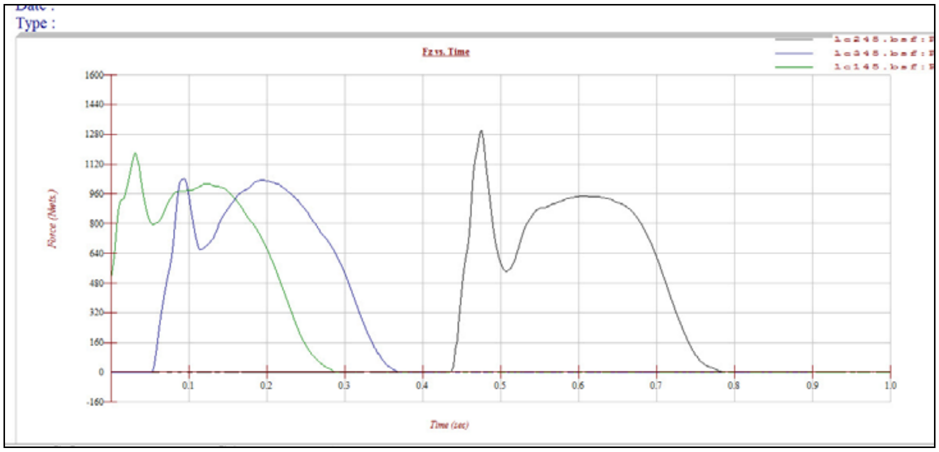

Figure 56: Force Plate Control z-direction

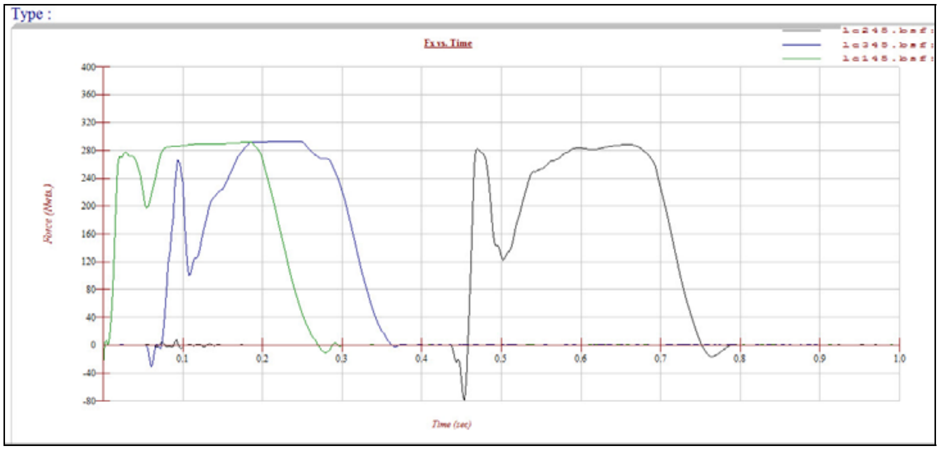

Figure 57: Force Plate Control x-direction

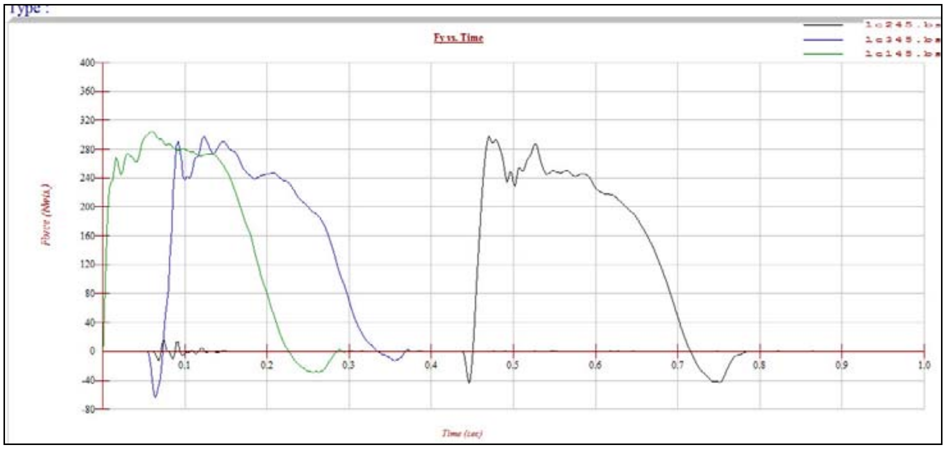

Figure 58: Force Place Control y-direction

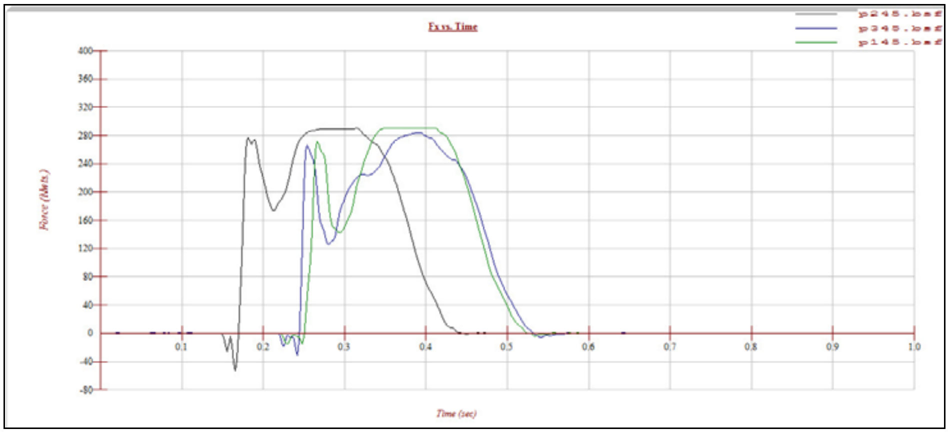

Figure 59: Force Plate Prototype x-direction

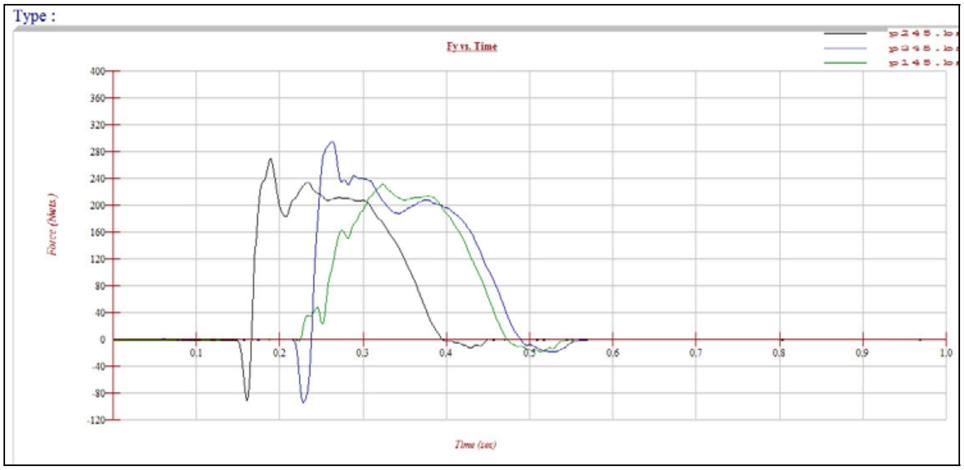

Figure 60: Force Plate Prototype y-direction

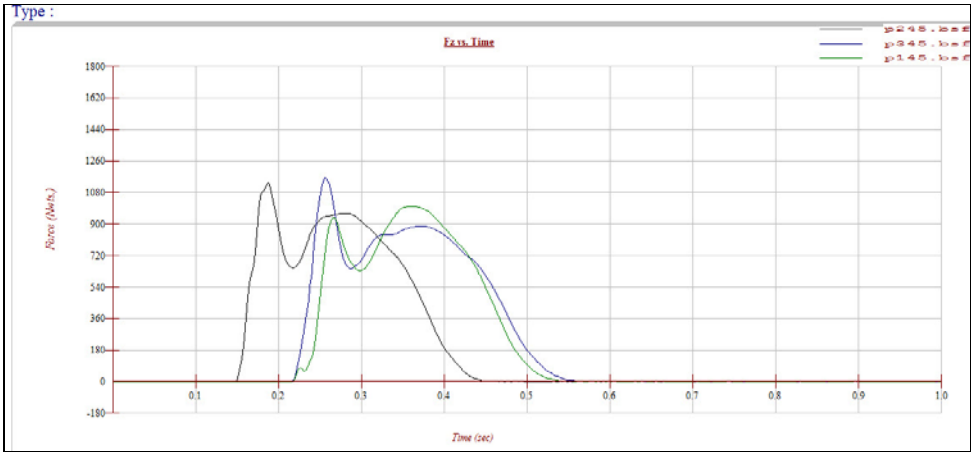

Figure 61: Force Plate Prototype z-direction