Project Number: CAB 2102

ACL Injury Preventative Basketball Shoe

A Major Qualifying Project Report:
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science in
Biomedical Engineering & Mechanical Engineering

Date: May 6, 2021

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Introduction

Objective

The objective of this design project was to create a shoe that prevents anterior cruciate ligament (ACL) injuries. This design can be implemented in footwear for different physical activities, but this project focuses on basketball. The goal was to create a minimal, efficient shoe sole that adheres to industry standards. This project is a continuation of two Major Qualifying Projects “ACL Protective Footwear Design” (Doyle et al., 2012) and “Design of ACL Protection Shoe” (Quinn et al., 2017). The scope is limited to the sole of the shoe. The upper portion of the shoe and the outsole, such as material, laces, aesthetics, and tread are not within the scope of this design.

Rationale

Injury prevention is the focus of this design project. The prevalence of ACL injuries and their importance in today’s field of sports and athletics is increasing. Knee injuries make up about 91% of season-ending injuries. These occurrences are most common among female athletes, making them the population of interest. This design targets basketball since it has one of the highest incidence rates of ACL injuries. Knee injuries occur in 1 in 65 high school female basketball players annually (Ford, Myer, & Hewett 2003).

ACL reconstructions in the United States cost about $1 billion each year (Joseph, et al. 2013). Out of pocket costs are $800 to $3,000 for patients with health insurance and $20,000 to $50,000 for patients without (“ACL reconstruction cost”). Additional costs come with this type of injury. For example, any needed supportive post-operative medical equipment, physical therapy costs, pain medication, a second surgery, and potential costs of future issues from arthritis that is more likely to occur in these patients.

This design is taking the footwear-based approach as it has been shown in the past that stability footwear has the ability to mitigate harmful knee loading. This can be caused by the dynamic valgus motion seen in Figure 1 (Paterson et al., 2015). Females are shown to have an increased valgus motion compared to males, due to anatomical differences in hip-width, therefore, are more affected by this type of injury.

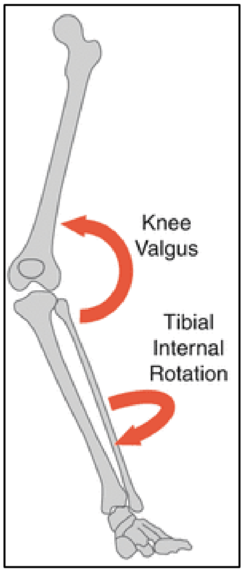


Figure 1. Dynamic valgus caused by inward pivoting motion

Stiff landings have shown to decrease peak knee flexion angle and increase vertical ground reaction force, which increases the risk of an ACL injury (Leppänen et al., 2016). ACL injuries can be prevented by modifying the knee flexion angle, external flexion moment, and vertical ground reaction force. In the sagittal plane, anterior tibial shear is shown to be the most direct loading mechanism (Padua & Distefano, 2009). The mechanics of the sagittal plane can be improved to decrease harmful impact loading while landing (Shimokochi et al., 2016).

Hamstring versus quadricep strength plays a role in ACL injury risk as well. Decreased hamstring strength was found to be linked to a greater risk of ACL injury among a study of women (Bennett et al., 2008). High forces of quadricep activation can cause the previously mentioned harmful anterior tibial shear force, which can lead to the rupture of an ACL. Increased hamstring activation and strength can offset this effect (Bennett et al., 2008). These injury loading mechanisms are all targets of the design.

State of the Art

The state of the art includes various ACL injury preventative designs implemented in footwear. Some designs have more narrow applications, such as rotating cleats meant to be used in football or soccer as they are sports that also have high ACL injury rates. An example of this is US Patent 5682689 A: Rotating Cleats for Athletic Shoes (Gooding and Walker, 1993). Some designs were broader to include a torque relief component (Reed, 2010) or self-recovering impact absorbing component (Brown et al., 2013). Another design is the US Patent 5692323A: Footwear with auto-returning turntable, which is a design utilizing a turntable in the shoe sole with a spring module to control the rotation (Goldberg, 1994). This is more commonly known as the design implemented in the Rota-Sole shoes as seen below in Figure 2. Other footwear-based approaches include the aforementioned MQP projects' designs like the "goat's head spring" (Brown et al., 2019), which is a force absorbing device. All of these designs have the common goal of mitigating ACL injury risk.

Figure 2. Rota-sole shoe incorporates a plate and spring rotation mechanism (Rotasole Women's Training Shoes Trainer 8 Rotating Sole SNEAKERS Black Tennis for Sale Online, n.d.)

Non-footwear-based methods for mitigating ACL injury risk include training and conditioning, practicing landing skills and direction changes, and working on muscle strength (*How to Prevent ACL Tears & Injuries* | UPMC, n.d.). Although these approaches are not based on physical product interventions, the team kept these in mind during the design process.

Approach

Based on the objective, rationale, and the state of the art, the team decided to approach the design with intentions of mitigating ACL injury risk from a biomechanical standpoint incorporated into a shoe sole. To mitigate potentially harmful forces and torsion, the team wanted to incorporate aspects of the design that would address the issues of excess dynamic valgus of the knees during pivoting, under-activation of the hamstring muscle groups, and high impact loads from landing. The team used Suh's axiomatic design process in the methods to develop these design ideas into a working, testable prototype (Suh, 1990).

Methods

Axiomatic Design

Axiomatic design (AD) is a design strategy that uses matrix methods to systematically analyze customer needs and translate them into functional requirements (FRs) and design parameters (DPs). This strategy uses two Axioms: the Independence Axiom, which maintains the independence between the FRs, and the Information Axiom, which minimizes the information content of the design (Suh, 1990). In the decomposition, the FRs are broken down into a "parent-child" format to determine the detailed requirements that the end design must incorporate. Using a collectively exhaustive and mutually exclusive (CEME) approach, AD ensures the end product meets as many customer needs as possible in the fewest FRs (Thompson, 2013).

The aforementioned objective is to mitigate ACL injuries associated with pivoting and landing in basketball. The customer needs were established which led to the selection criteria and constraints used to determine how the design would fulfill these needs. Selection criteria and constraints to the design include the consistency of material across the outsole, materials that can easily adhere, a maximum shoe weight of 700g, low maintenance, comfortable, and the ability to flex with natural foot movements. When designing the shoe, the team also adhered to traditional codes and standards of basketball shoes in that the sole height could not exceed 40mm (Köse, 2018.). These ensured that the design would not hinder or enhance performance. Concept-knowledge mapping was used to verify that the concepts from the decomposition were upheld by the appropriate amount of knowledge (Le Masson et al., 2017). Decision matrices were used for further analysis of the necessary criteria for specific components of the design. These matrices were used to choose the option that has the lowest information content (Appendix A).

Axiomatic Decomposition

In the initial attempt of the AD decomposition, the team determined that FR0 would be mitigating ACL injuries. FR1 would account for the absorption of high-risk impact loads. The children to address this were broken into horizontal and vertical directions. This would take into account the stopping and cutting loads in the x-y plane and the loads due to landing in the z direction. FR2 was determined to be the mitigation of harmful torsional movement at the knee, which led to the DP of a mechanical system. It was further decomposed into children that focused on torsion at the toe and heel of the foot. In this iteration the team continued to ensure that the design would not hinder any aspect of performance. The decomposition can be seen in Appendix B1.

One of the major changes from the initial attempt was the decision to focus FR1 on vertical load absorption only. Additionally, this attempt focused FR2 on horizontal load absorption. While the vertical direction accounted for the loads due to landing, the horizontal direction included the loads in the medial-lateral direction due to cutting. Both of these FRs led to the DP focusing on selection of a foam and viscoelastic material in the insole. This attempt also included the absorption of loads nonlinearly. FR3 was added to avoid the injury threshold, as seen in Figure 3, which established the mechanical system to be a rotating mechanism. FR3 also included mitigation of free spin of the rotating mechanism and prevention of movement interruptions. This FR included the mitigation of instability through activation of other muscle groups which led to the implementation of the toe lift. This attempt can be seen in Appendix B2.

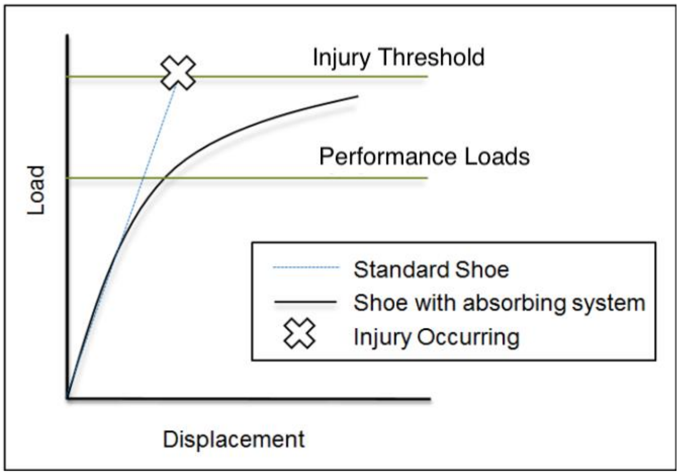
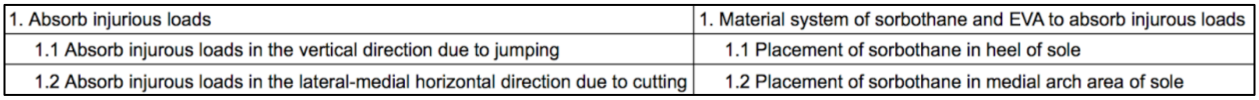


Figure 3. Injury threshold graph (Madura and Brown, 2014)

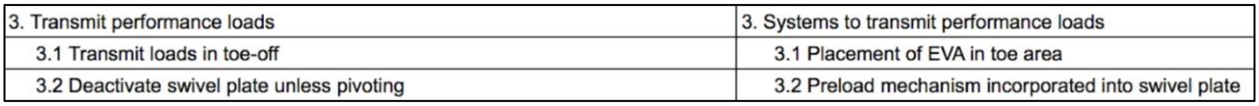
The next iteration of the decomposition re-focused each FR for a specific load transmission. FR1 combined horizontal loads in the medial-lateral direction due to cutting and vertical loads due to landing (Figure 4). FR2 was focused on the mitigation of harmful torsional loads from both internal and external rotation. Internal torsion was further decomposed to include tibial rotation during jump landings, and the activation of counteracting muscle groups. External torsion was decomposed to include torsion due to pivoting, rotation around the axis of the rotating mechanism, and tunability based on the weight of the athlete. This attempt no longer had a third FR as those elements were included within both the first and second FRs. To guide the critical thinking about this iteration and the changes from the last one, additional columns were added for constraints and justifications for the DPs. The full iteration can be seen in Appendix B3.



1. Absorb injurious loads	1. Material system of sorbothane and EVA to absorb injurous loads
1.1 Absorb injurous loads in the vertical direction due to jumping	1.1 Placement of sorbothane in heel of sole
1.2 Absorb injurous loads in the lateral-medial horizontal direction due to cutting	1.2 Placement of sorbothane in medial arch area of sole

Figure 4. Combination of horizontal and vertical loads in FR1

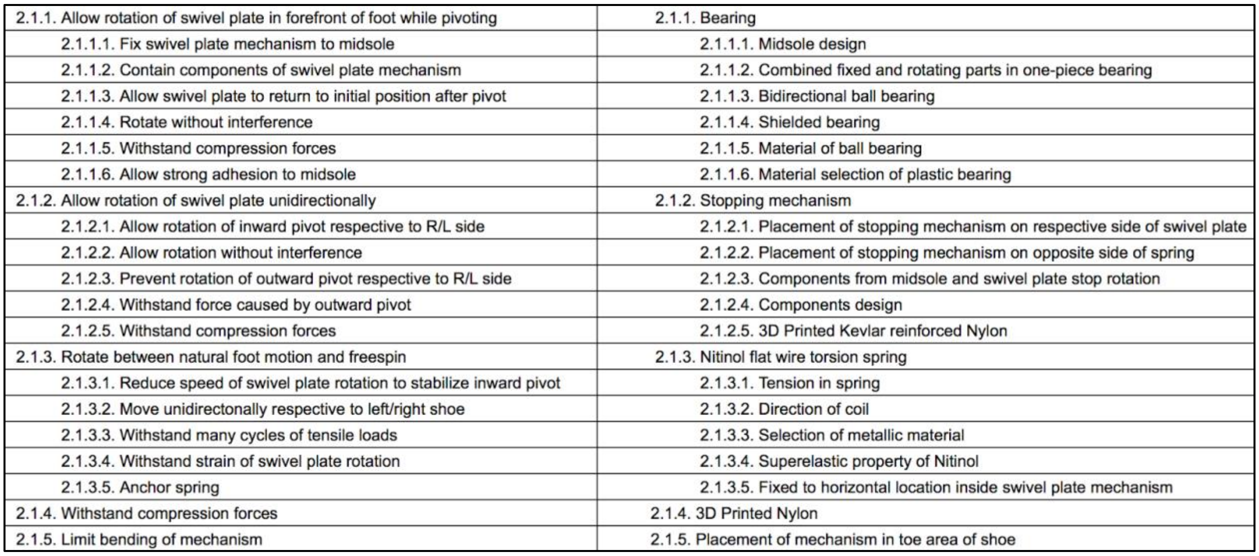
The changes from the previous iteration include the addition of FR3 that accounts for the transmission of performance loads (Figure 5), specifically during toe-off and the deactivation of the rotating mechanism. To transmit loads in the toe-off the team emphasized placement of foam that is flexible and soft in the toe region instead of the viscoelastic material that could hinder performance. To ensure the rotating mechanism would not free spin and interfere with natural playing loads, it would be preloaded. The full iteration can be seen in Appendix B4.



3. Transmit performance loads	3. Systems to transmit performance loads
3.1 Transmit loads in toe-off	3.1 Placement of EVA in toe area
3.2 Deactivate swivel plate unless pivoting	3.2 Preload mechanism incorporated into swivel plate

Figure 5. Addition of FR3 to the decomposition

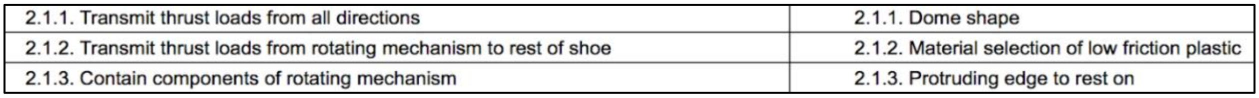
The next set of changes occurred specifically to FR2 by further decomposing the rotating mechanism. This introduced a ball bearing for the rotating mechanism, a torsional resistance component, and a stopping mechanism for unidirectional rotation in FRs 2.1.1. through 2.1.5 (Figure 6). The full decomposition can be found in Appendix B5.



2.1.1. Allow rotation of swivel plate in forefront of foot while pivoting	2.1.1. Bearing
2.1.1.1. Fix swivel plate mechanism to midsole	2.1.1.1. Midsole design
2.1.1.2. Contain components of swivel plate mechanism	2.1.1.2. Combined fixed and rotating parts in one-piece bearing
2.1.1.3. Allow swivel plate to return to initial position after pivot	2.1.1.3. Bidirectional ball bearing
2.1.1.4. Rotate without interference	2.1.1.4. Shielded bearing
2.1.1.5. Withstand compression forces	2.1.1.5. Material of ball bearing
2.1.1.6. Allow strong adhesion to midsole	2.1.1.6. Material selection of plastic bearing
2.1.2. Allow rotation of swivel plate unidirectionally	2.1.2. Stopping mechanism
2.1.2.1. Allow rotation of inward pivot respective to R/L side	2.1.2.1. Placement of stopping mechanism on respective side of swivel plate
2.1.2.2. Allow rotation without interference	2.1.2.2. Placement of stopping mechanism on opposite side of spring
2.1.2.3. Prevent rotation of outward pivot respective to R/L side	2.1.2.3. Components from midsole and swivel plate stop rotation
2.1.2.4. Withstand force caused by outward pivot	2.1.2.4. Components design
2.1.2.5. Withstand compression forces	2.1.2.5. 3D Printed Kevlar reinforced Nylon
2.1.3. Rotate between natural foot motion and freespin	2.1.3. Nitinol flat wire torsion spring
2.1.3.1. Reduce speed of swivel plate rotation to stabilize inward pivot	2.1.3.1. Tension in spring
2.1.3.2. Move unidirectonally respective to left/right shoe	2.1.3.2. Direction of coil
2.1.3.3. Withstand many cycles of tensile loads	2.1.3.3. Selection of metallic material
2.1.3.4. Withstand strain of swivel plate rotation	2.1.3.4. Superelastic property of Nitinol
2.1.3.5. Anchor spring	2.1.3.5. Fixed to horizontal location inside swivel plate mechanism
2.1.4. Withstand compression forces	2.1.4. 3D Printed Nylon
2.1.5. Limit bending of mechanism	2.1.5. Placement of mechanism in toe area of shoe

Figure 6. Further decomposition of rotating mechanism and its components

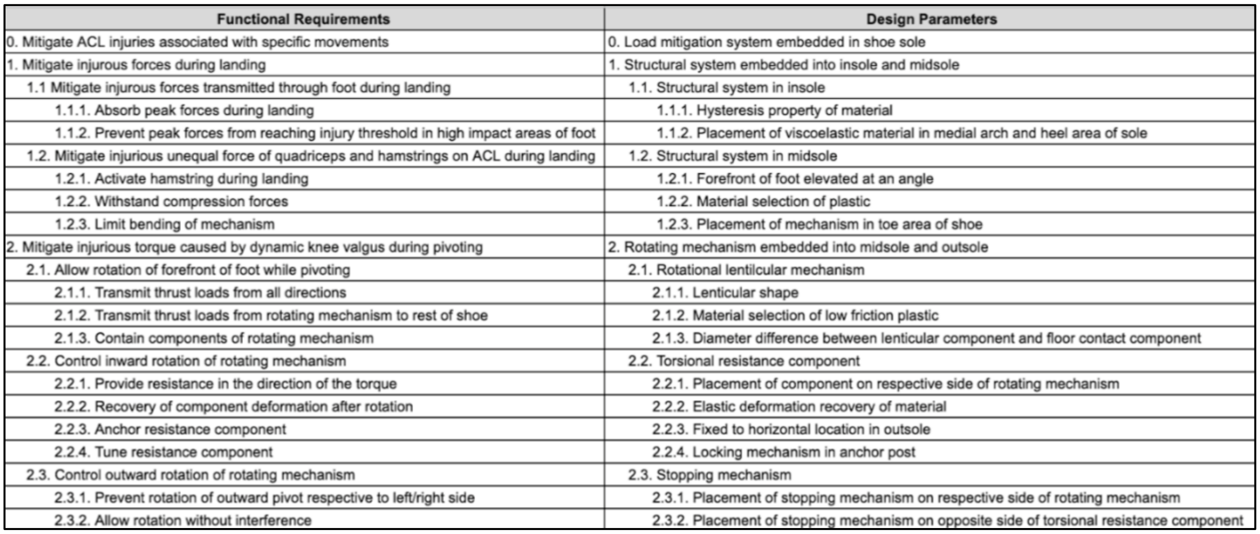
The rotating mechanism was re-designed such that a lenticular dome replaced the ball bearing component to transmit thrust loads through the solid midsole. This moved the transmission of loads to FR2 and removed FR3 as seen in Figure 7. Instead of preloading the spring to control directionality of the mechanism, a stopping mechanism was introduced. This allows the lenticular dome to swivel inward with the pivoting motion while resisting outward spinning during other movements of play. These changes allow for more stability to the user. This iteration can be found in Appendix B6.



2.1.1. Transmit thrust loads from all directions	2.1.1. Dome shape
2.1.2. Transmit thrust loads from rotating mechanism to rest of shoe	2.1.2. Material selection of low friction plastic
2.1.3. Contain components of rotating mechanism	2.1.3. Protruding edge to rest on

Figure 7. Transmission of loads under FR2

The final edits included condensing FR2, as well as broadening the language of the DPs. The final decomposition takes into account all previous discussions as shown in Figure 8 and Appendix B7.



Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Load mitigation system embedded in shoe sole
1. Mitigate injurous forces during landing	1. Structural system embedded into insole and midsole
1.1 Mitigate injurous forces transmitted through foot during landing	1.1. Structural system in insole
1.1.1. Absorb peak forces during landing	1.1.1. Hysteresis property of material
1.1.2. Prevent peak forces from reaching injury threshold in high impact areas of foot	1.1.2. Placement of viscoelastic material in medial arch and heel area of sole
1.2. Mitigate injurious unequal force of quadriceps and hamstrings on ACL during landing	1.2. Structural system in midsole
1.2.1. Activate hamstring during landing	1.2.1. Forefront of foot elevated at an angle
1.2.2. Withstand compression forces	1.2.2. Material selection of plastic
1.2.3. Limit bending of mechanism	1.2.3. Placement of mechanism in toe area of shoe
2. Mitigate injurious torque caused by dynamic knee valgus during pivoting	2. Rotating mechanism embedded into midsole and outsole
2.1. Allow rotation of forefront of foot while pivoting	2.1. Rotational lentilcular mechanism
2.1.1. Transmit thrust loads from all directions	2.1.1. Lenticular shape
2.1.2. Transmit thrust loads from rotating mechanism to rest of shoe	2.1.2. Material selection of low friction plastic
2.1.3. Contain components of rotating mechanism	2.1.3. Diameter difference between lenticular component and floor contact component
2.2. Control inward rotation of rotating mechanism	2.2. Torsional resistance component
2.2.1. Provide resistance in the direction of the torque	2.2.1. Placement of component on respective side of rotating mechanism
2.2.2. Recovery of component deformation after rotation	2.2.2. Elastic deformation recovery of material
2.2.3. Anchor resistance component	2.2.3. Fixed to horizontal location in outsole
2.2.4. Tune resistance component	2.2.4. Locking mechanism in anchor post
2.3. Control outward rotation of rotating mechanism	2.3. Stopping mechanism
2.3.1. Prevent rotation of outward pivot respective to left/right side	2.3.1. Placement of stopping mechanism on respective side of rotating mechanism
2.3.2. Allow rotation without interference	2.3.2. Placement of stopping mechanism on opposite side of torsional resistance component

Figure 8. Final Axiomatic Design Decomposition

Physical Integration

The insole incorporates Sorbothane, a synthetic viscoelastic urethane polymer, and ethylene-vinyl acetate (EVA), a flexible copolymer. Sorbothane absorbs peak forces during landing to avoid reaching the injury threshold in high-impact areas of the foot. Sorbothane's viscoelastic property allows for hysteresis behavior. The target high-impact areas of the foot, seen in Figure 9, were used to decide that Sorbothane was placed in the heel. Due to the increased pressure when a person rolls onto the medial border of their arch, Sorbothane was placed in this area in order to provide additional support. The ball of the foot is also a high-impact area, but Sorbothane was not placed here to satisfy the design criteria of avoiding performance hindrance. EVA was used across the first insole layer, besides the Sorbothane locations, since EVA is a typical foam used in shoe design. A second insole layer of EVA was placed over the EVA/Sorbothane layer to satisfy the comfortability criteria. This material system is the physical integration of FR/DP 1.1.

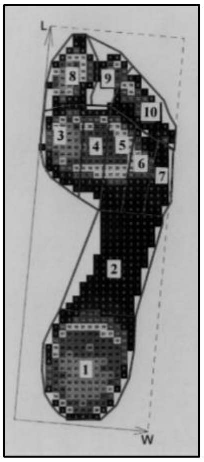


Figure 9. High impact areas of the foot (Pressure and Force Distribution Characteristics under the Normal Foot during the Push-Off phase in Gait | Elsevier Enhanced Reader, n.d.)

The toe lift aspect of the design is a four-degree slope integrated into the 3D printed midsole, sloping upwards from the heel to the forefront of the foot. Four degrees was calculated with trigonometric ratios of the shoe midsole and insole length. When the quadriceps have a greater activation than the hamstrings, this can induce injurious ACL loads by producing anterior tibial shear force (Bennett et al., 2008). This toe lift is aimed to activate the hamstrings to offset the imbalance, which satisfies the physical integration of FR/DP 1.2.1.

The design incorporates a lenticular shaped rotating mechanism in cohesion with a low friction plastic interface to allow rotation of the forefront of the foot while pivoting. Teflon and ultra-high molecular weight polyethylene (UHMWPE) were chosen for this interface based on FR/DP 2.1.2. This rotating mechanism is embedded into the midsole and outsole, which works to mitigate injurious torque caused by dynamic knee valgus during inward pivoting. The specific lenticular shape of the design satisfies the design criteria of preventing performance hindrance as well as FR/DP 2.1.1., the transmission of thrust loads necessary for performance. This aspect of the design also involves a stopping mechanism to control outward rotation of the rotating mechanism and increase stability as described in FR/DP 2.3.

To prevent free rotation, a torsional resistance component was incorporated into the design. Nitinol wire was chosen based on its superelasticity and shape memory properties, which satisfy FR/DP 2.2.2. To determine the diameter of the torsional resistance component, a study was performed to estimate the moment generated by a pivoting motion of the foot around the axis of the lenticular rotating mechanism. The protocol and report of this study can be found in Appendix C. These results were compared to the bending moment of different diameter wires caused by the lenticular rotating mechanism and a wire of 0.8mm was chosen.

Final Design

CAD Modeling

SolidWorks was used to design the midsole and lenticular rotating mechanism as well as model the assembly of the prototype. Figure 10 shows the exploded assembly of the design modeled in a right shoe. The outsole was included in the diagram for reference of how this design can be implemented into any athletic shoe with modification. Horizontal cuts were added to the midsole to allow bending around the ball of the foot to fulfill the comfortability criteria and avoid performance hindrance.

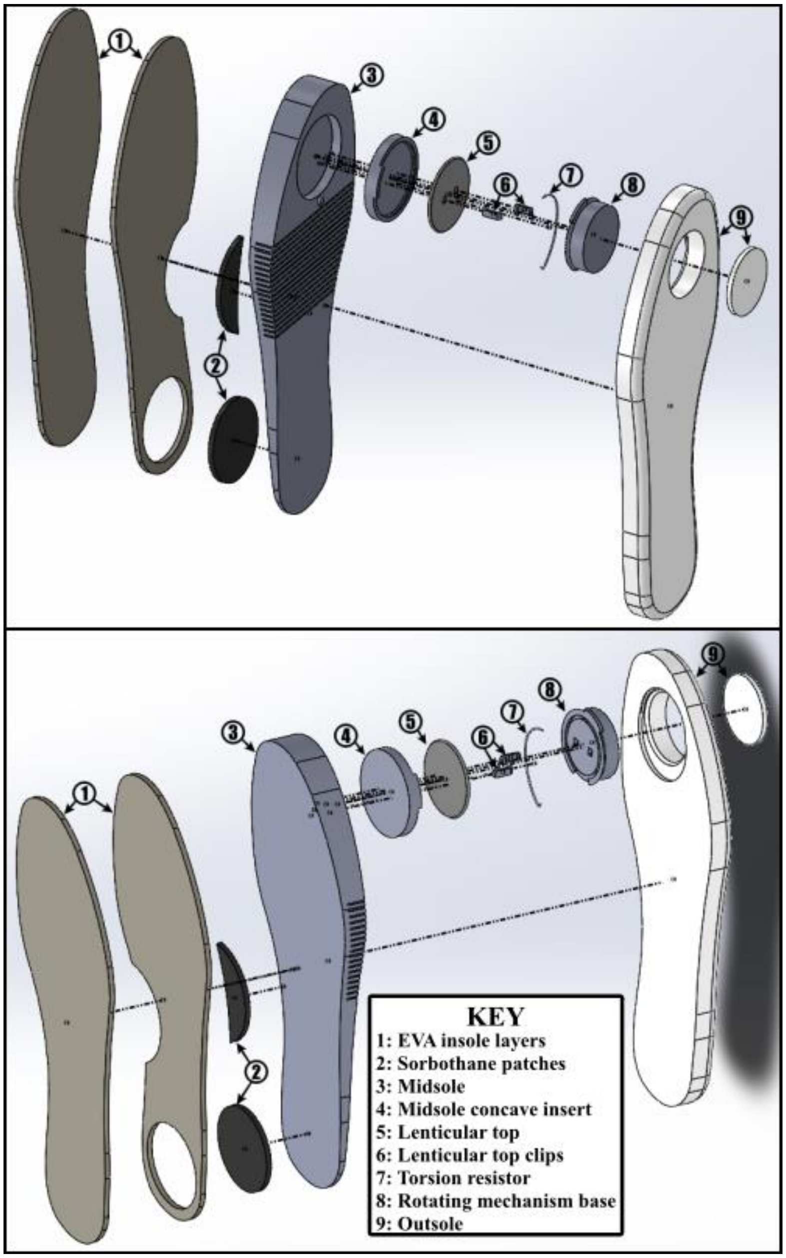


Figure 10. Exploded assembly of final design

3D Printing

The midsole was 3D printed with nylon on the Markforged Mark Two. The 3D printer and material were chosen due to the size of the midsole and the desired material properties outlined in the decomposition and criteria. The Markforged Mark Two prints with a layer thickness of 0.004in (approximately 0.102mm). However, the hole in the midsole measured 49.76mm in diameter when it was designed to be 50mm.

The lenticular rotating mechanism was printed on the Formlabs Form 2 using Durable. This mechanism includes the midsole concave insert, base, lenticular top, and two lenticular top clips. Since the rotating mechanism is small and requires smooth surface finishes on the midsole concave insert and lenticular top interface, Durable was chosen in place of a Teflon-Polyethylene interface based on availability and its low friction properties. The Formlabs Form 2 has a layer thickness of 0.001-0.004in (approximately 0.025-0.102mm) and prints support structures on the parts. The parts were oriented to avoid printing supports on the surfaces of the interface and the surfaces that had printed supports were sanded smooth. The parts were measured using calipers to compare to the CAD model. The diameter of the midsole insert ranged from 49.55mm to 50.09mm, so it was sanded down to fit into its 50mm corresponding hole in the midsole. The diameter of the mechanism base ranged from 39.72mm to 40mm. It was designed to be 40mm, so this part did not require sanding. The diameter of the lenticular top ranged from 43.95mm to 44.20mm; it was sanded along the edges to rotate smoothly within the midsole insert.

Assembly

The prototype was built using a right side women's size 8 Nike Precision iii basketball shoe. The 3D printed midsole was traced to construct the insole layers (component 1 in Figure 10). Measured areas of the heel and arch (component 2 in Figure 10) were removed from the bottom insole layer and replaced with Sorbothane patches. The heel patch was cut in a circle 5cm in diameter and the medial arch patch was cut in a semi-circle 6cm in diameter. The Sorbothane patches were attached to the bottom EVA layer using Shoe Goo adhesive. The insole layers were not adhered to each other nor to the midsole for testing purposes.

The midsole concave insert (component 4 in Figure 10) was adhered into its corresponding hole in the midsole (component 3 in Figure 10) using Gorilla Epoxy, lining up the right flat edge of the stopping mechanism with the bottom of the shoe. This placement is shown in Figure 11.

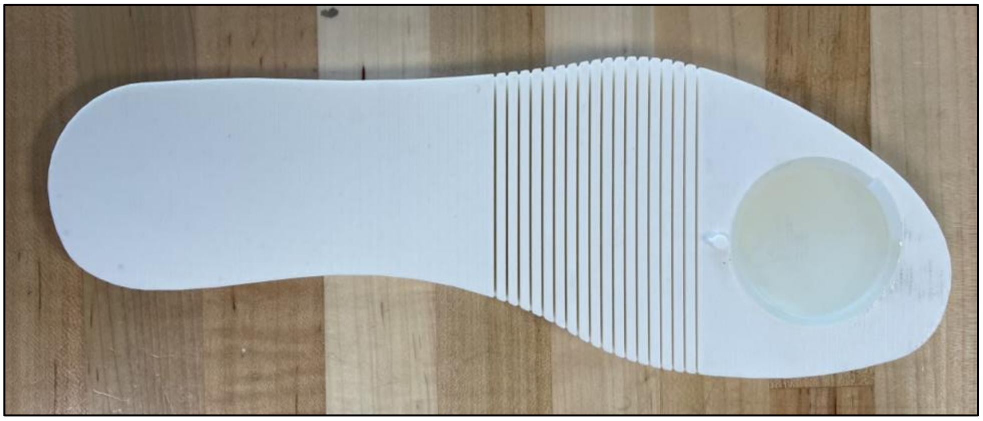


Figure 11. Midsole insert adhered to the midsole

The nitinol wire (component 7 in Figure 10) was bent at the top and secured with epoxy around the notch inside the rotating mechanism base (component 8 Figure 10). The lenticular top clips (component 6 in Figure 10) and their corresponding holes in the base had excess material. Since the holes were small (3mm x 4mm x 10mm in the CAD model), this material could not be sanded down. One clip was sanded and inserted into its hole to guide the placement of the lenticular top as it was secured with epoxy. This is shown in Figure 12.

Figure 12. Construction of rotating mechanism with epoxy

The opposite end of the nitinol wire was bent and anchored around a notch by soldering nylon around the wire and notch. Excess nitinol was removed with wire cutters. This anchoring can be seen in Figure 13.

Figure 13. Anchoring of nitinol to midsole

The outsole (component 9 of Figure 10) was then detached from the material top of the shoe. A hole measuring 40mm in diameter was drilled into the outsole where the rotating mechanism contacts the floor. This is shown in Figure 14. Both the hole and mechanism base were sanded to ensure smooth rotation. Material was removed from the outsole on the midsole-outsole interface to ensure it would not interfere with the nitinol wire.

Figure 14. Rotating mechanism hole in outsole

The midsole and rotating mechanism were clamped into the outsole and adhered with Shoe Goo overnight. The bottom layer of the removed outsole was adhered onto the base of the rotating mechanism to reconstruct the outsole and ensure it was flush. This can be seen in Figure 15.

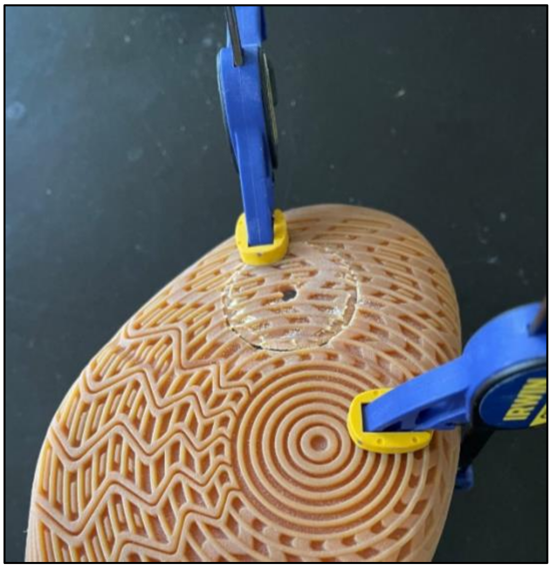


Figure 15. Adhering midsole to outsole

The shoe was reconstructed by sewing the material top of the shoe back onto the outsole and securing with Shoe Goo and pins. The insole layers were then placed on top of the midsole inside the shoe. The final prototype is shown in Figure 16.

Figure 16. Final prototype

Prototype Analysis

The prototype was inspected during and after assembly. Throughout assembly, it was noted that the model was designed assuming the outsole was flat. When the midsole and rotating mechanism were inserted into the outsole, the bottom of the rotating base was not level. The piece of outsole preserved to make the rotating mechanism continuous with the rest of the outsole could not be altered, so the base was sanded down. This possibly changed the angle of the thrust loads and how the lenticular top distributed the loads into the midsole and foot.

It was also noted that the rotating mechanism did not rotate with an applied torque. It was speculated that the nitinol was too stiff for its purpose in the design or that the epoxy used to adhere the outsole piece onto the base seeped out when clamped. Tests were still performed using the prototype, but these aspects were considered during data analysis.

Testing

Tests were created and performed to quantify the effectiveness of the design. The prototype shoe was compared to a control basketball shoe that was not modified in any way. Rota-sole shoes were used to test and compare the final design to the prior art. These Rota-sole shoes were only used in the dynamic valgus test.

Force Absorption

To test the effectiveness of the Sorbothane patches, the team created a testing protocol to measure and compare the force absorption of the insole layers using pressure sensing insoles. A setup and test protocol can be found in Appendix D. The test used NovaSol pressure sensing insoles to compare the force absorption between the insole layers with and without the use of Sorbothane. Statistical analysis, including hypothesis tests, were performed for better comparison.

The results showed the maximum force values during a vertical jump in three areas of the foot with the focus of this test on the "heel" portion. An example of one subject's force versus time graph can be seen below in Figure 17.

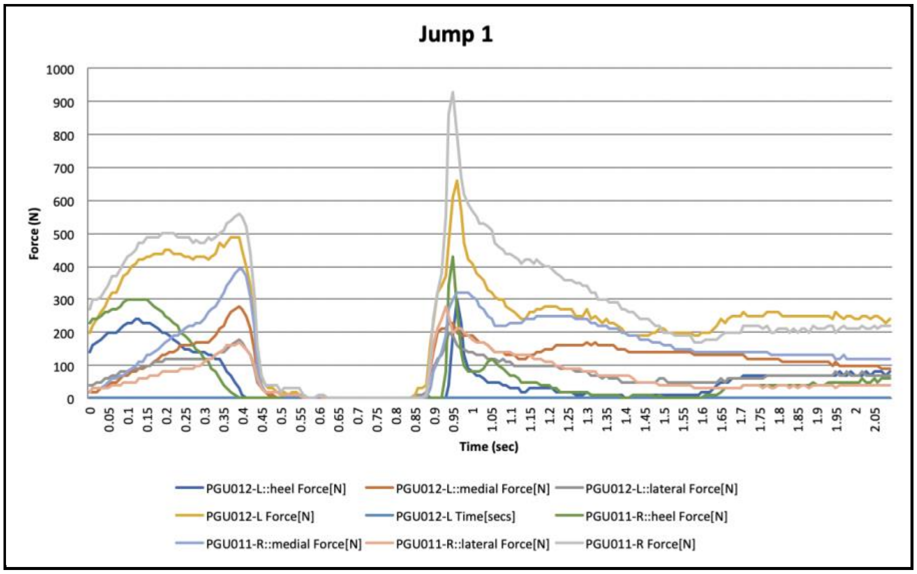


Figure 17. Example of force versus time graph for one jump

The maximum values of all five jumps from each test group (prototype with Sorbothane layer, prototype without Sorbothane layer, and control) were found and averaged. The mean maximum force values for the right heel portion of the foot for both subjects can be seen below in Figure 18. The mean maximum forces were compared between the groups through a two-tailed, equal variance t-test. There was no statistically significant difference between the three test groups when comparing the mean maximum force values in the right heel for both subjects. This shows the Sorbothane patches may need to be thicker or bigger in order to see their effects on reducing the peak forces.

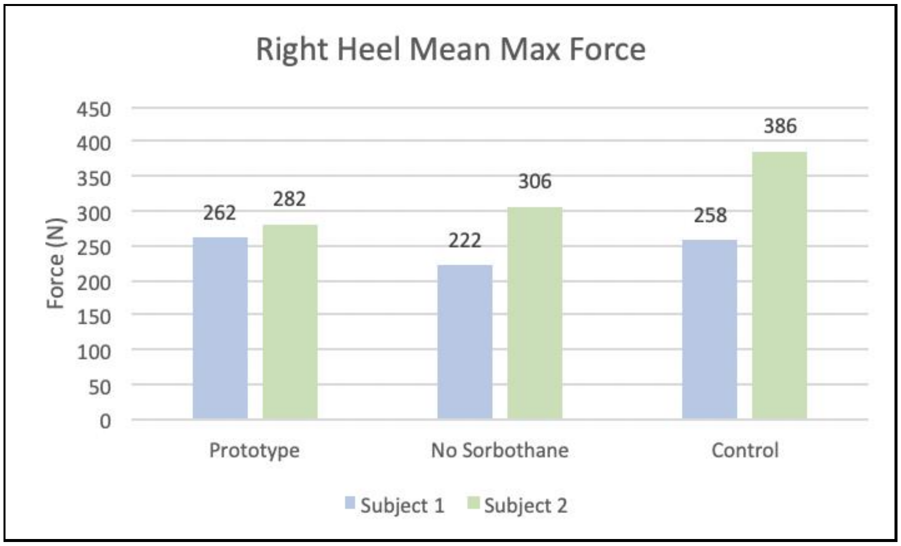


Figure 18. Right heel mean max force for both subjects

Muscle Activation

To test the "toe lift" aspect of the design, the team created a testing protocol to measure and compare the muscle activation of the quadricep and hamstring muscle groups. The setup required a Myoware sensor used in conjunction with an Arduino for electromyography. A setup and test method protocol can be found in Appendix E. The test compares the muscle activation with and without the prototype. Statistical analysis, including hypothesis tests, were to be performed to analyze the data.

The test did not yield accurate data. The protocol was followed, and the sensor output a signal to the Arduino serial plotter as expected, however, the signal was often lost or drifted when the subject did not move. It was determined that a more accurate sensor and electrode apparatus is necessary to complete this test.

Dynamic Valgus Angle

To test the lenticular rotating mechanism, the team created a testing protocol to measure and compare the dynamic valgus during the pivoting motion. The setup required a video recorder for two-dimensional motion analysis. A setup and testing protocol can be found in Appendix F. Two-tailed, equal variance t-tests were then run to compare the dynamic valgus angles using the prototype shoe, Rota-sole shoe, and control shoe.

This test gave the team the dynamic valgus angle measured from the front of the subject right before the pivoting motion as seen in Figure 19. Each subject performed five pivots in each shoe and the average angle was calculated and compared.

Figure 19. Dynamic valgus angle

It was found at the conclusion of the tests that there was no significant difference in the dynamic valgus angles while wearing each shoe, except in the case of Subject 2's control versus Rota-sole. It was observed that, on average, the prototype design did have a lower dynamic valgus angle than the Rota-sole. This can be seen in Figure 20 which illustrates each subject's average dynamic valgus angle.

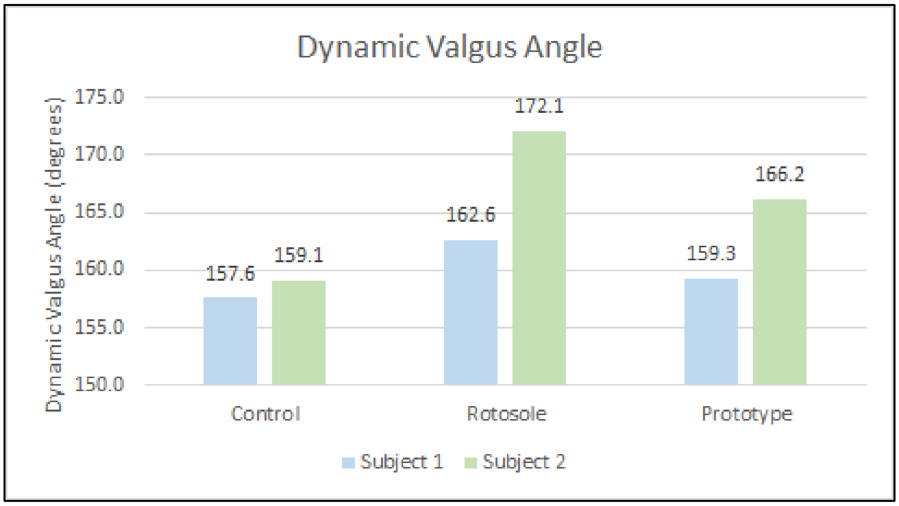


Figure 20. Average Dynamic Valgus Angles

Based on the results, the team recommends further testing for future prototypes. Changes to the testing may include, expanding the population and using three-dimensional analysis instead of two-dimensional analysis.

Discussion

Prototype

With the conclusion of prototyping, final design, testing, and analysis, the team made note of potential changes and recommendations. Since the upper portion of the shoe was not within the scope of the project, the addition of the insole material and toe-lift did not allow enough space for the participant's foot. Additionally, the midsole was unable to sufficiently flex with movement. This would be modified for future prototypes to improve comfortability.

Testing

The team attempted to test the effectiveness of the toe lift using a Myoware-Arduino sensor setup, but was unable to detect a stable signal for analysis. This could be accomplished in the future using a sensor with better accuracy. Additionally, the dynamic valgus testing was to be performed using 3D motion capture, but the sensors did not yield sufficient data. It is recommended to follow the test protocol in Appendix G.

Broader Impacts

This project was oriented around preventing ACL injuries in female basketball players specifically. The intention was to improve their lives and prevent the physical and economic harm that ACL injuries cause. The Mechanical Engineering Code of Ethics emphasizes the importance of the "safety, health, and welfare of the public," and this project aligns with these ideals (*Colorado Section | ASME Engineering Network*, n.d.).

The three components of the design were intended to ultimately prevent ACL injuries. While the design was implemented into women's basketball shoes, it could be incorporated into other shoes to benefit the public as well. Long-term testing would need to be performed to determine the impact of the design on the biomechanics of athletes. The shoe was made to reduce tibial torsion and balance hamstring-quadricep activation, but a possible unintended consequence includes a change in gait style that increases pressure in joints and muscles.

The average cost of a basketball shoe is around $100 with many variations given brand, style, and other features (Dunne, 2018). In the design and prototyping processes of this shoe cost was not a critical factor for material selection, but it was considered in the decision matrices as seen in Appendix A.

Given the high ACL injury rate and the costs associated with repair and rehabilitation, the proper implementation of an ACL injury mitigation aid could be profitable. This design is not the first to target ACL injuries as explained in state of the art. However, it is the first to incorporate a stopping mechanism within a rotating component. If the design is properly integrated into athletic shoes, it has the potential to reduce the numbers of ACL injuries, therefore reducing the associated costs and fees.

Concluding Remarks

Overall, the team was satisfied with the first prototype as they were able to gain the necessary experience and the knowledge to self-critique both their design as well as the materials and processes that were used. At the conclusion of this project, the team filed a provisional patent.

Acknowledgments

We would like to thank Professor Brown, Skylar Barthelmes, Erica Stults, Lisa Wall, Rob Kirch, Tristin Carlton & SEI, Professor Butler, Professor Troy, Foisie Makerspace Staff for all their help and insight.

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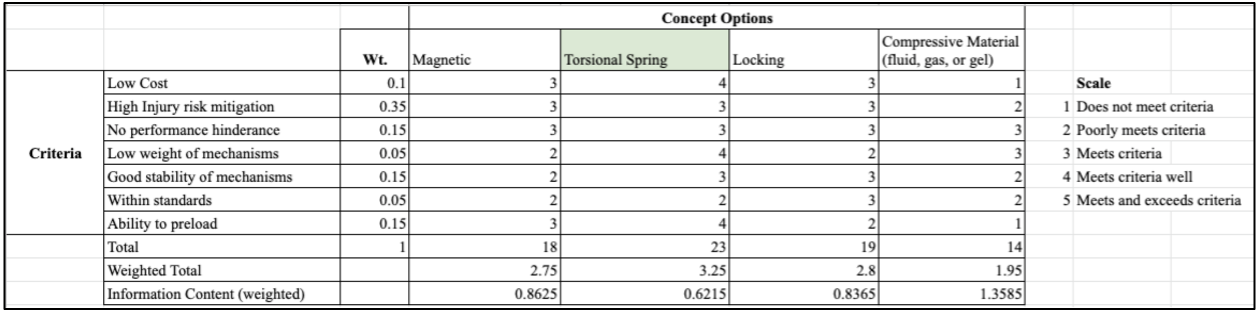
Appendix

Appendix A

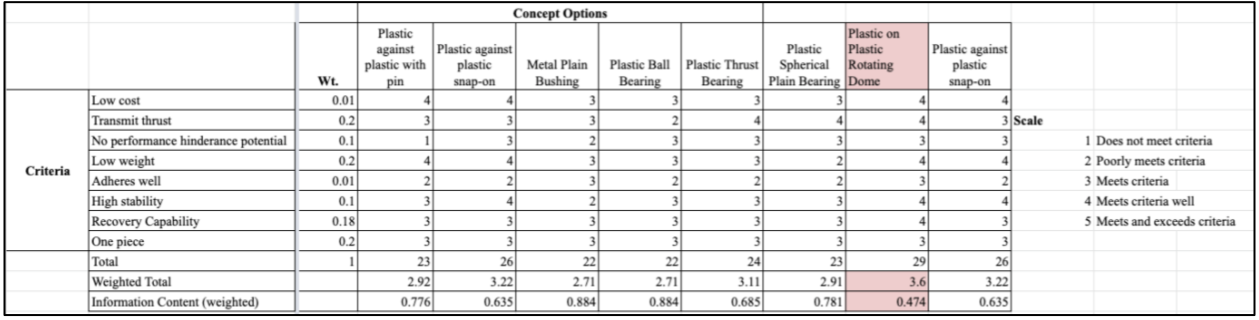
Decision Matrices

1: Torsion mitigation system



			Concept Options					
		Wt.	Magnetic	Torsional Spring	Locking	Compressive Material (fluid, gas, or gel)		
Criteria	Low Cost	0.1	3	4	3	1		**Scale**
	High Injury risk mitigation	0.35	3	3	3	2	1	Does not meet criteria
	No performance hinderance	0.15	3	3	3	3	2	Poorly meets criteria
	Low weight of mechanisms	0.05	2	4	2	3	3	Meets criteria
	Good stability of mechanisms	0.15	2	3	3	2	4	Meets criteria well
	Within standards	0.05	2	2	3	2	5	Meets and exceeds criteria
	Ability to preload	0.15	3	4	2	1		
	Total	1	18	23	19	14		
	Weighted Total		2.75	3.25	2.8	1.95		
	Information Content (weighted)		0.8625	0.6215	0.8365	1.3585		

2: Rotating mechanism

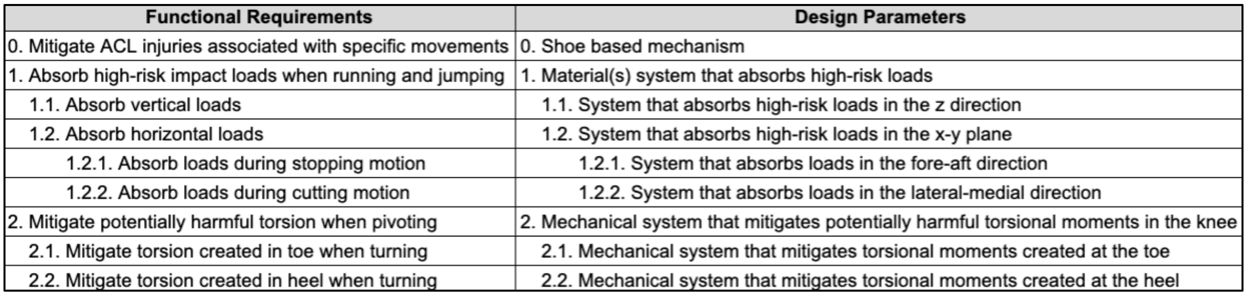


			Concept Options									
		Wt.	Plastic against plastic with pin	Plastic against plastic snap-on	Metal Plain Bushing	Plastic Ball Bearing	Plastic Thrust Bearing	Plastic Spherical Plain Bearing	Plastic on Plastic Rotating Dome	Plastic against plastic snap-on		
Criteria	Low cost	0.01	4	4	3	3	3	3	4	4		
	Transmit thrust	0.2	3	3	3	2	4	4	4	3	**Scale**	
	No performance hinderance potential	0.1	1	3	2	3	3	3	3	3	1	Does not meet criteria
	Low weight	0.2	4	4	3	3	3	2	4	4	2	Poorly meets criteria
	Adheres well	0.01	2	2	3	2	2	2	3	2	3	Meets criteria
	High stability	0.1	3	4	2	3	3	3	4	4	4	Meets criteria well
	Recovery Capability	0.18	3	3	3	3	3	3	4	3	5	Meets and exceeds criteria
	One piece	0.2	3	3	3	3	3	3	3	3		
	Total	1	23	26	22	22	24	23	29	26		
	Weighted Total		2.92	3.22	2.71	2.71	3.11	2.91	3.6	3.22		
	Information Content (weighted)		0.776	0.635	0.884	0.884	0.685	0.781	0.474	0.635		

Appendix B

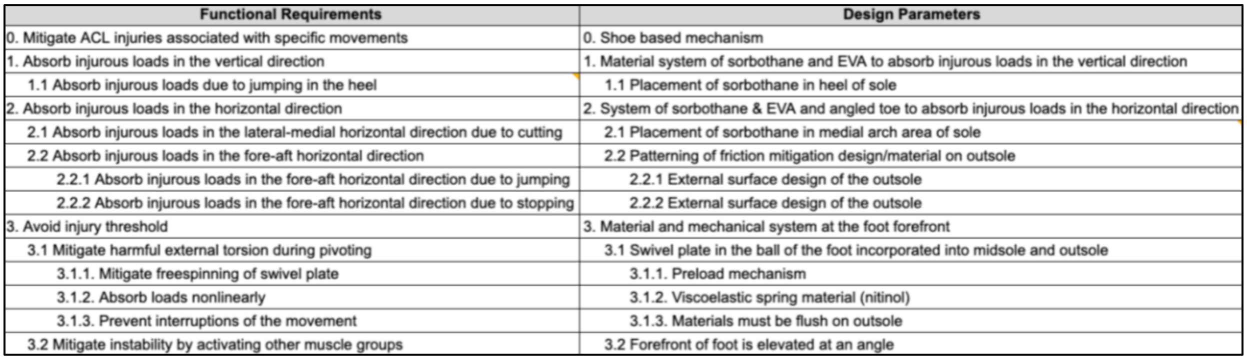
Decomposition

B1:



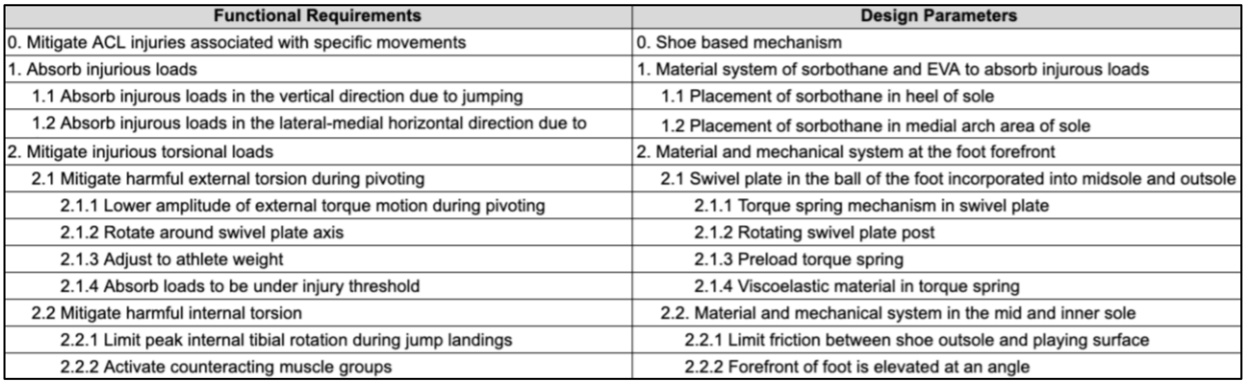
Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Shoe based mechanism
1. Absorb high-risk impact loads when running and jumping	1. Material(s) system that absorbs high-risk loads
1.1. Absorb vertical loads	1.1. System that absorbs high-risk loads in the z direction
1.2. Absorb horizontal loads	1.2. System that absorbs high-risk loads in the x-y plane
1.2.1. Absorb loads during stopping motion	1.2.1. System that absorbs loads in the fore-aft direction
1.2.2. Absorb loads during cutting motion	1.2.2. System that absorbs loads in the lateral-medial direction
2. Mitigate potentially harmful torsion when pivoting	2. Mechanical system that mitigates potentially harmful torsional moments in the knee
2.1. Mitigate torsion created in toe when turning	2.1. Mechanical system that mitigates torsional moments created at the toe
2.2. Mitigate torsion created in heel when turning	2.2. Mechanical system that mitigates torsional moments created at the heel

B2:



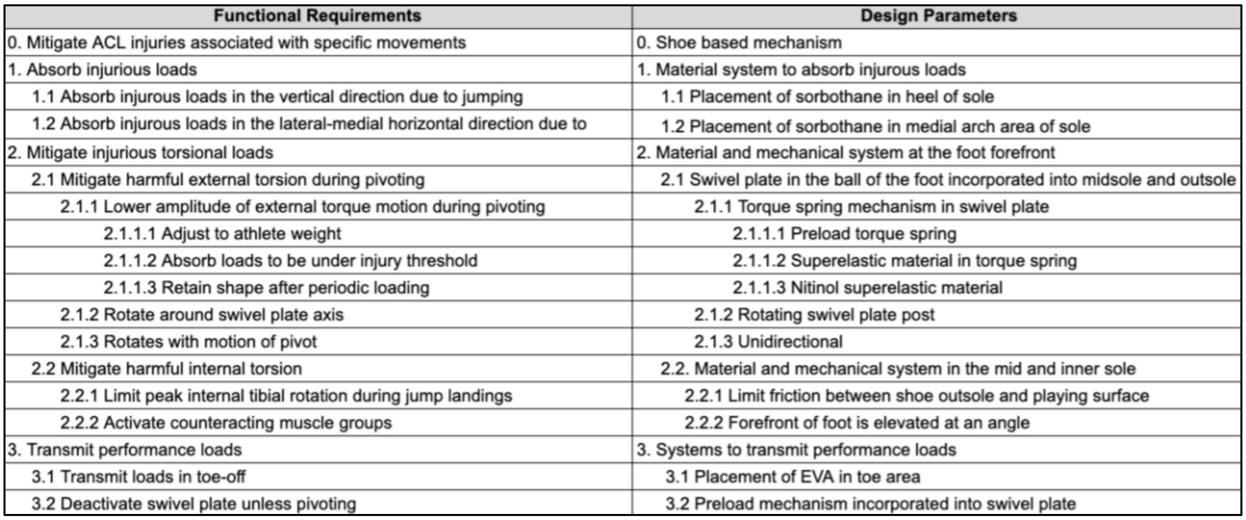
Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Shoe based mechanism
1. Absorb injurous loads in the vertical direction	1. Material system of sorbothane and EVA to absorb injurous loads in the vertical direction
1.1 Absorb injurous loads due to jumping in the heel	1.1 Placement of sorbothane in heel of sole
2. Absorb injurous loads in the horizontal direction	2. System of sorbothane & EVA and angled toe to absorb injurous loads in the horizontal direction
2.1 Absorb injurous loads in the lateral-medial horizontal direction due to cutting	2.1 Placement of sorbothane in medial arch area of sole
2.2 Absorb injurous loads in the fore-aft horizontal direction	2.2 Patterning of friction mitigation design/material on outsole
2.2.1 Absorb injurous loads in the fore-aft horizontal direction due to jumping	2.2.1 External surface design of the outsole
2.2.2 Absorb injurous loads in the fore-aft horizontal direction due to stopping	2.2.2 External surface design of the outsole
3. Avoid injury threshold	3. Material and mechanical system at the foot forefront
3.1 Mitigate harmful external torsion during pivoting	3.1 Swivel plate in the ball of the foot incorporated into midsole and outsole
3.1.1. Mitigate freespinning of swivel plate	3.1.1. Preload mechanism
3.1.2. Absorb loads nonlinearly	3.1.2. Viscoelastic spring material (nitinol)
3.1.3. Prevent interruptions of the movement	3.1.3. Materials must be flush on outsole
3.2 Mitigate instability by activating other muscle groups	3.2 Forefront of foot is elevated at an angle

B3:



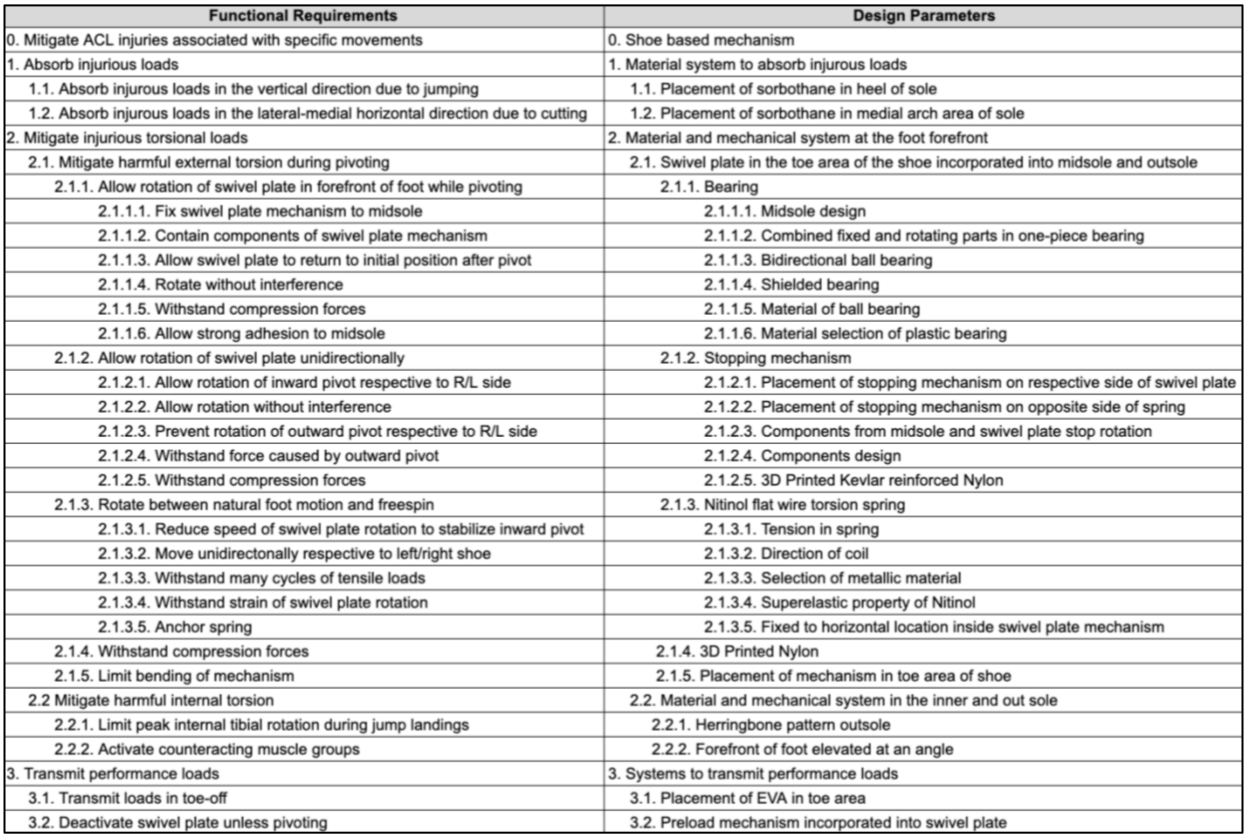
Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Shoe based mechanism
1. Absorb injurious loads	1. Material system of sorbothane and EVA to absorb injurous loads
1.1 Absorb injurous loads in the vertical direction due to jumping	1.1 Placement of sorbothane in heel of sole
1.2 Absorb injurous loads in the lateral-medial horizontal direction due to	1.2 Placement of sorbothane in medial arch area of sole
2. Mitigate injurious torsional loads	2. Material and mechanical system at the foot forefront
2.1 Mitigate harmful external torsion during pivoting	2.1 Swivel plate in the ball of the foot incorporated into midsole and outsole
2.1.1 Lower amplitude of external torque motion during pivoting	2.1.1 Torque spring mechanism in swivel plate
2.1.2 Rotate around swivel plate axis	2.1.2 Rotating swivel plate post
2.1.3 Adjust to athlete weight	2.1.3 Preload torque spring
2.1.4 Absorb loads to be under injury threshold	2.1.4 Viscoelastic material in torque spring
2.2 Mitigate harmful internal torsion	2.2. Material and mechanical system in the mid and inner sole
2.2.1 Limit peak internal tibial rotation during jump landings	2.2.1 Limit friction between shoe outsole and playing surface
2.2.2 Activate counteracting muscle groups	2.2.2 Forefront of foot is elevated at an angle

B4:



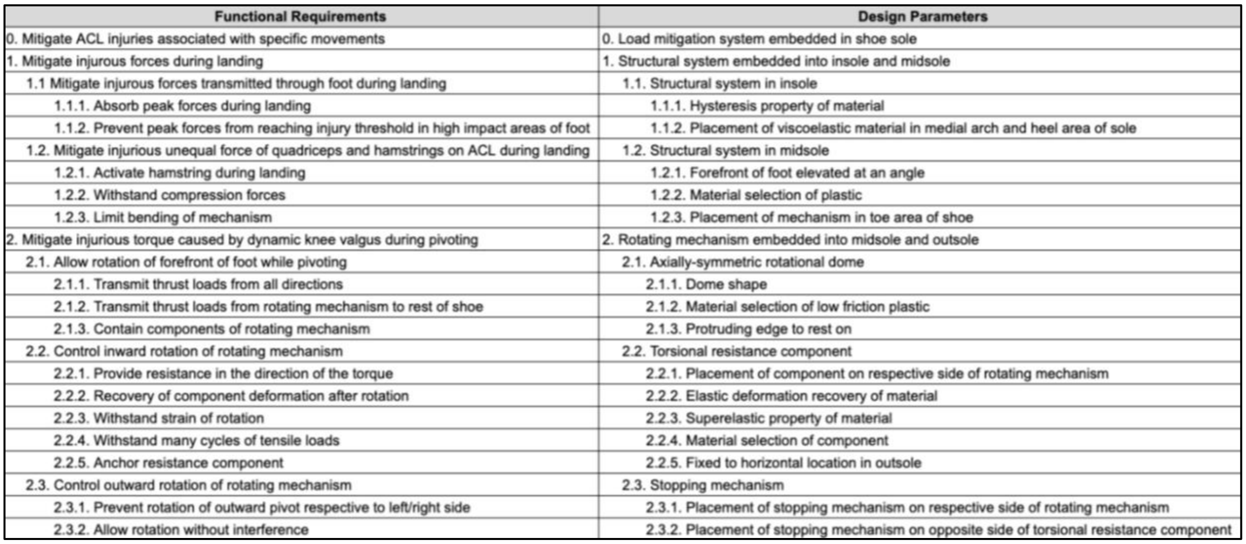
Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Shoe based mechanism
1. Absorb injurious loads	1. Material system to absorb injurous loads
1.1 Absorb injurous loads in the vertical direction due to jumping	1.1 Placement of sorbothane in heel of sole
1.2 Absorb injurous loads in the lateral-medial horizontal direction due to	1.2 Placement of sorbothane in medial arch area of sole
2. Mitigate injurious torsional loads	2. Material and mechanical system at the foot forefront
2.1 Mitigate harmful external torsion during pivoting	2.1 Swivel plate in the ball of the foot incorporated into midsole and outsole
2.1.1 Lower amplitude of external torque motion during pivoting	2.1.1 Torque spring mechanism in swivel plate
2.1.1.1 Adjust to athlete weight	2.1.1.1 Preload torque spring
2.1.1.2 Absorb loads to be under injury threshold	2.1.1.2 Superelastic material in torque spring
2.1.1.3 Retain shape after periodic loading	2.1.1.3 Nitinol superelastic material
2.1.2 Rotate around swivel plate axis	2.1.2 Rotating swivel plate post
2.1.3 Rotates with motion of pivot	2.1.3 Unidirectional
2.2 Mitigate harmful internal torsion	2.2. Material and mechanical system in the mid and inner sole
2.2.1 Limit peak internal tibial rotation during jump landings	2.2.1 Limit friction between shoe outsole and playing surface
2.2.2 Activate counteracting muscle groups	2.2.2 Forefront of foot is elevated at an angle
3. Transmit performance loads	3. Systems to transmit performance loads
3.1 Transmit loads in toe-off	3.1 Placement of EVA in toe area
3.2 Deactivate swivel plate unless pivoting	3.2 Preload mechanism incorporated into swivel plate

B5:



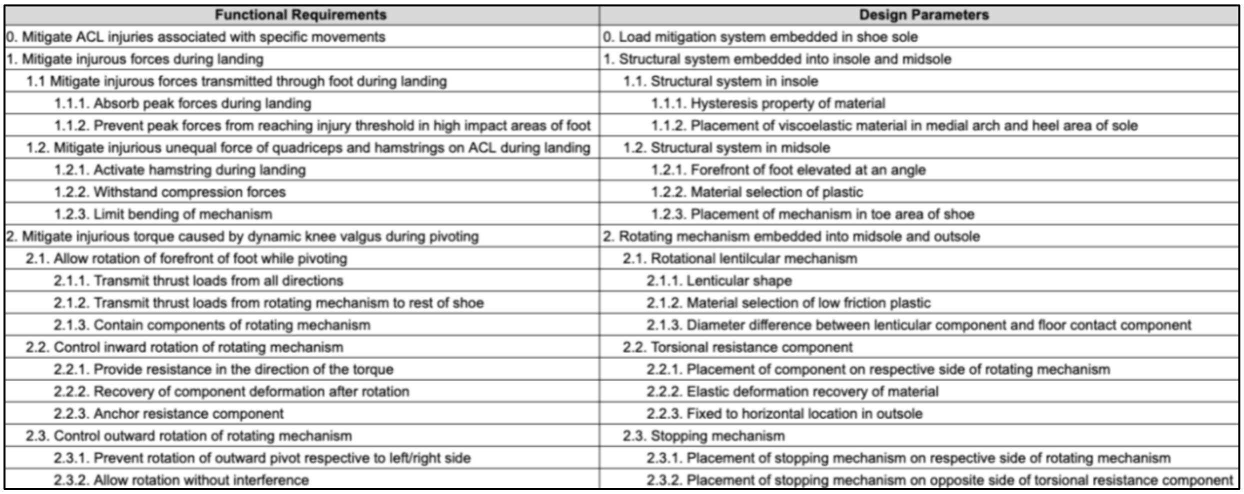
Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Shoe based mechanism
1. Absorb injurious loads	1. Material system to absorb injurous loads
1.1. Absorb injurous loads in the vertical direction due to jumping	1.1. Placement of sorbothane in heel of sole
1.2. Absorb injurous loads in the lateral-medial horizontal direction due to cutting	1.2. Placement of sorbothane in medial arch area of sole
2. Mitigate injurious torsional loads	2. Material and mechanical system at the foot forefront
2.1. Mitigate harmful external torsion during pivoting	2.1. Swivel plate in the toe area of the shoe incorporated into midsole and outsole
2.1.1. Allow rotation of swivel plate in forefront of foot while pivoting	2.1.1. Bearing
2.1.1.1. Fix swivel plate mechanism to midsole	2.1.1.1. Midsole design
2.1.1.2. Contain components of swivel plate mechanism	2.1.1.2. Combined fixed and rotating parts in one-piece bearing
2.1.1.3. Allow swivel plate to return to initial position after pivot	2.1.1.3. Bidirectional ball bearing
2.1.1.4. Rotate without interference	2.1.1.4. Shielded bearing
2.1.1.5. Withstand compression forces	2.1.1.5. Material of ball bearing
2.1.1.6. Allow strong adhesion to midsole	2.1.1.6. Material selection of plastic bearing
2.1.2. Allow rotation of swivel plate unidirectionally	2.1.2. Stopping mechanism
2.1.2.1. Allow rotation of inward pivot respective to R/L side	2.1.2.1. Placement of stopping mechanism on respective side of swivel plate
2.1.2.2. Allow rotation without interference	2.1.2.2. Placement of stopping mechanism on opposite side of spring
2.1.2.3. Prevent rotation of outward pivot respective to R/L side	2.1.2.3. Components from midsole and swivel plate stop rotation
2.1.2.4. Withstand force caused by outward pivot	2.1.2.4. Components design
2.1.2.5. Withstand compression forces	2.1.2.5. 3D Printed Kevlar reinforced Nylon
2.1.3. Rotate between natural foot motion and freespin	2.1.3. Nitinol flat wire torsion spring
2.1.3.1. Reduce speed of swivel plate rotation to stabilize inward pivot	2.1.3.1. Tension in spring
2.1.3.2. Move unidirectonally respective to left/right shoe	2.1.3.2. Direction of coil
2.1.3.3. Withstand many cycles of tensile loads	2.1.3.3. Selection of metallic material
2.1.3.4. Withstand strain of swivel plate rotation	2.1.3.4. Superelastic property of Nitinol
2.1.3.5. Anchor spring	2.1.3.5. Fixed to horizontal location inside swivel plate mechanism
2.1.4. Withstand compression forces	2.1.4. 3D Printed Nylon
2.1.5. Limit bending of mechanism	2.1.5. Placement of mechanism in toe area of shoe
2.2 Mitigate harmful internal torsion	2.2. Material and mechanical system in the inner and out sole
2.2.1. Limit peak internal tibial rotation during jump landings	2.2.1. Herringbone pattern outsole
2.2.2. Activate counteracting muscle groups	2.2.2. Forefront of foot elevated at an angle
3. Transmit performance loads	3. Systems to transmit performance loads
3.1. Transmit loads in toe-off	3.1. Placement of EVA in toe area
3.2. Deactivate swivel plate unless pivoting	3.2. Preload mechanism incorporated into swivel plate

B6:



Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Load mitigation system embedded in shoe sole
1. Mitigate injurous forces during landing	1. Structural system embedded into insole and midsole
1.1 Mitigate injurous forces transmitted through foot during landing	1.1. Structural system in insole
1.1.1. Absorb peak forces during landing	1.1.1. Hysteresis property of material
1.1.2. Prevent peak forces from reaching injury threshold in high impact areas of foot	1.1.2. Placement of viscoelastic material in medial arch and heel area of sole
1.2. Mitigate injurious unequal force of quadriceps and hamstrings on ACL during landing	1.2. Structural system in midsole
1.2.1. Activate hamstring during landing	1.2.1. Forefront of foot elevated at an angle
1.2.2. Withstand compression forces	1.2.2. Material selection of plastic
1.2.3. Limit bending of mechanism	1.2.3. Placement of mechanism in toe area of shoe
2. Mitigate injurious torque caused by dynamic knee valgus during pivoting	2. Rotating mechanism embedded into midsole and outsole
2.1. Allow rotation of forefront of foot while pivoting	2.1. Axially-symmetric rotational dome
2.1.1. Transmit thrust loads from all directions	2.1.1. Dome shape
2.1.2. Transmit thrust loads from rotating mechanism to rest of shoe	2.1.2. Material selection of low friction plastic
2.1.3. Contain components of rotating mechanism	2.1.3. Protruding edge to rest on
2.2. Control inward rotation of rotating mechanism	2.2. Torsional resistance component
2.2.1. Provide resistance in the direction of the torque	2.2.1. Placement of component on respective side of rotating mechanism
2.2.2. Recovery of component deformation after rotation	2.2.2. Elastic deformation recovery of material
2.2.3. Withstand strain of rotation	2.2.3. Superelastic property of material
2.2.4. Withstand many cycles of tensile loads	2.2.4. Material selection of component
2.2.5. Anchor resistance component	2.2.5. Fixed to horizontal location in outsole
2.3. Control outward rotation of rotating mechanism	2.3. Stopping mechanism
2.3.1. Prevent rotation of outward pivot respective to left/right side	2.3.1. Placement of stopping mechanism on respective side of rotating mechanism
2.3.2. Allow rotation without interference	2.3.2. Placement of stopping mechanism on opposite side of torsional resistance component

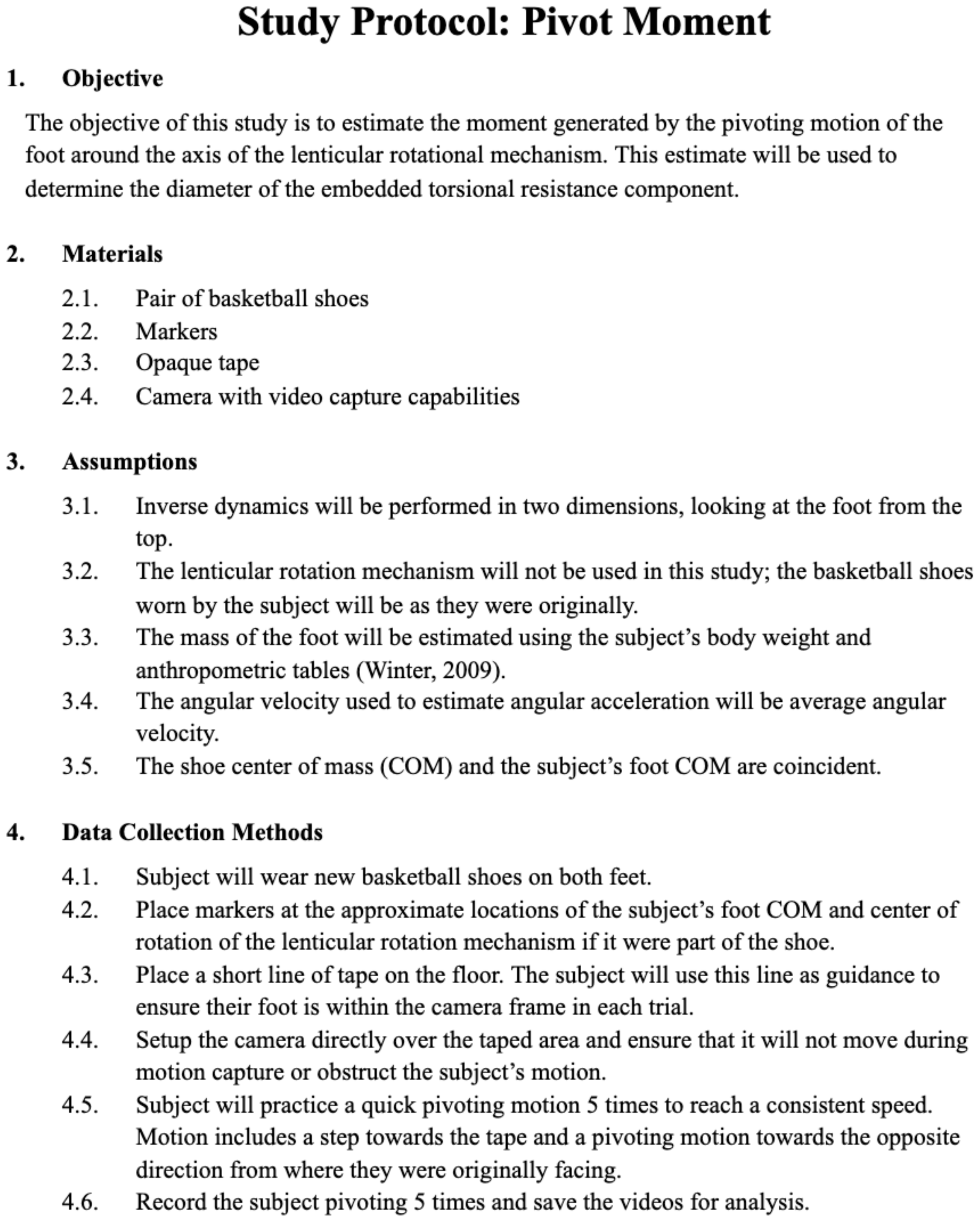
B7:



Functional Requirements	Design Parameters
0. Mitigate ACL injuries associated with specific movements	0. Load mitigation system embedded in shoe sole
1. Mitigate injurous forces during landing	1. Structural system embedded into insole and midsole
1.1 Mitigate injurous forces transmitted through foot during landing	1.1. Structural system in insole
1.1.1. Absorb peak forces during landing	1.1.1. Hysteresis property of material
1.1.2. Prevent peak forces from reaching injury threshold in high impact areas of foot	1.1.2. Placement of viscoelastic material in medial arch and heel area of sole
1.2. Mitigate injurious unequal force of quadriceps and hamstrings on ACL during landing	1.2. Structural system in midsole
1.2.1. Activate hamstring during landing	1.2.1. Forefront of foot elevated at an angle
1.2.2. Withstand compression forces	1.2.2. Material selection of plastic
1.2.3. Limit bending of mechanism	1.2.3. Placement of mechanism in toe area of shoe
2. Mitigate injurious torque caused by dynamic knee valgus during pivoting	2. Rotating mechanism embedded into midsole and outsole
2.1. Allow rotation of forefront of foot while pivoting	2.1. Rotational lentilcular mechanism
2.1.1. Transmit thrust loads from all directions	2.1.1. Lenticular shape
2.1.2. Transmit thrust loads from rotating mechanism to rest of shoe	2.1.2. Material selection of low friction plastic
2.1.3. Contain components of rotating mechanism	2.1.3. Diameter difference between lenticular component and floor contact component
2.2. Control inward rotation of rotating mechanism	2.2. Torsional resistance component
2.2.1. Provide resistance in the direction of the torque	2.2.1. Placement of component on respective side of rotating mechanism
2.2.2. Recovery of component deformation after rotation	2.2.2. Elastic deformation recovery of material
2.2.3. Anchor resistance component	2.2.3. Fixed to horizontal location in outsole
2.3. Control outward rotation of rotating mechanism	2.3. Stopping mechanism
2.3.1. Prevent rotation of outward pivot respective to left/right side	2.3.1. Placement of stopping mechanism on respective side of rotating mechanism
2.3.2. Allow rotation without interference	2.3.2. Placement of stopping mechanism on opposite side of torsional resistance component

Appendix C

C1: Pivot Moment Study Protocol



Study Protocol: Pivot Moment

1. Objective

The objective of this study is to estimate the moment generated by the pivoting motion of the foot around the axis of the lenticular rotational mechanism. This estimate will be used to determine the diameter of the embedded torsional resistance component.

2. Materials

- 2.1. Pair of basketball shoes
- 2.2. Markers
- 2.3. Opaque tape
- 2.4. Camera with video capture capabilities

3. Assumptions

- 3.1. Inverse dynamics will be performed in two dimensions, looking at the foot from the top.
- 3.2. The lenticular rotation mechanism will not be used in this study; the basketball shoes worn by the subject will be as they were originally.
- 3.3. The mass of the foot will be estimated using the subject's body weight and anthropometric tables (Winter, 2009).
- 3.4. The angular velocity used to estimate angular acceleration will be average angular velocity.
- 3.5. The shoe center of mass (COM) and the subject's foot COM are coincident.

4. Data Collection Methods

- 4.1. Subject will wear new basketball shoes on both feet.
- 4.2. Place markers at the approximate locations of the subject's foot COM and center of rotation of the lenticular rotation mechanism if it were part of the shoe.
- 4.3. Place a short line of tape on the floor. The subject will use this line as guidance to ensure their foot is within the camera frame in each trial.
- 4.4. Setup the camera directly over the taped area and ensure that it will not move during motion capture or obstruct the subject's motion.
- 4.5. Subject will practice a quick pivoting motion 5 times to reach a consistent speed. Motion includes a step towards the tape and a pivoting motion towards the opposite direction from where they were originally facing.
- 4.6. Record the subject pivoting 5 times and save the videos for analysis.

5. Data Analysis Methods

5.1. Use a video editing program to find a frame where the subject has fully stepped down, but has not yet started pivoting. Record the time of the frame and take a snapshot of the video. (NOTE: Make sure this is a snapshot and not a screen snip as this will not be comparable to the next frame.)

5.2. Find another frame just before the center of the COM marker can no longer be seen due to the pivot. Record the time of the frame and take a snapshot of the video.

5.3. Using a photo editing program, find and record the x and y coordinates (in pixels or other units) of the COM marker and rotation mechanism marker in each frame.

5.4. Calculate the difference in location of the rotation mechanism marker and subtract the difference from the second frame COM location to normalize the rotation.

5.5. Calculate the vectors from the rotation mechanism marker to the COM marker in each frame.

5.6. Use dot product to calculate angle of rotation.

5.7. Calculate average angular velocity and angular acceleration.

5.8. Repeat steps 5.1. - 5.7. for all trials.

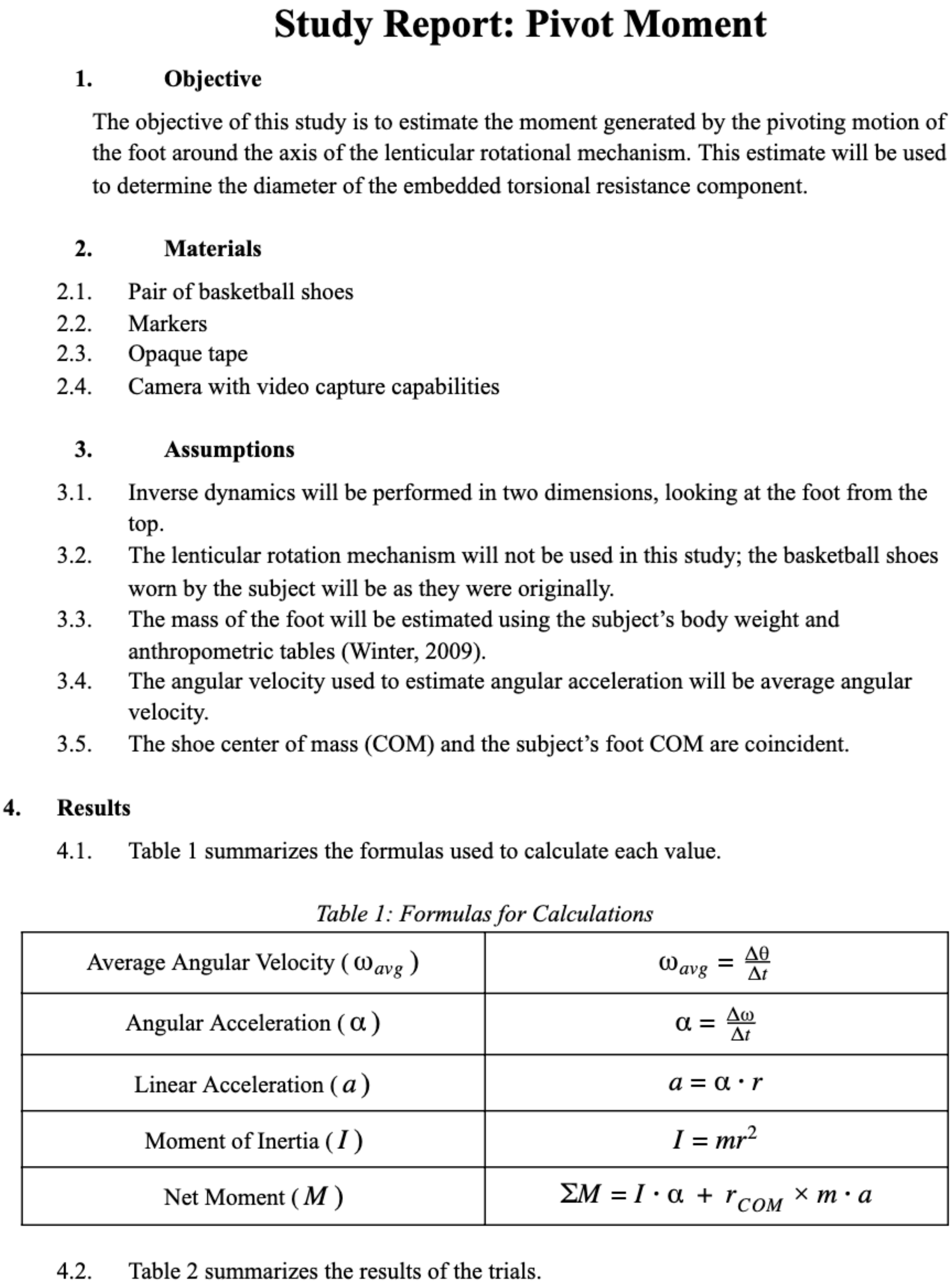
5.9. Find the average angular acceleration from each trial and the standard deviation.

5.10. Use the upper limit of the average to calculate linear acceleration at the COM.

5.11. Estimate moment of inertia.

5.12. Calculate the net moment around the rotation mechanism.

C2: Pivot Moment Study Report



Study Report: Pivot Moment

1. Objective

The objective of this study is to estimate the moment generated by the pivoting motion of the foot around the axis of the lenticular rotational mechanism. This estimate will be used to determine the diameter of the embedded torsional resistance component.

2. Materials

2.1. Pair of basketball shoes
2.2. Markers
2.3. Opaque tape
2.4. Camera with video capture capabilities

3. Assumptions

3.1. Inverse dynamics will be performed in two dimensions, looking at the foot from the top.
3.2. The lenticular rotation mechanism will not be used in this study; the basketball shoes worn by the subject will be as they were originally.
3.3. The mass of the foot will be estimated using the subject’s body weight and anthropometric tables (Winter, 2009).
3.4. The angular velocity used to estimate angular acceleration will be average angular velocity.
3.5. The shoe center of mass (COM) and the subject’s foot COM are coincident.

4. Results

4.1. Table 1 summarizes the formulas used to calculate each value.

Table 1: Formulas for Calculations

Average Angular Velocity (ω_{avg})	$\omega_{avg} = \frac{\Delta\theta}{\Delta t}$
Angular Acceleration (α)	$\alpha = \frac{\Delta\omega}{\Delta t}$
Linear Acceleration (a)	$a = \alpha \cdot r$
Moment of Inertia (I)	$I = mr^2$
Net Moment (M)	$\Sigma M = I \cdot \alpha + r_{COM} \times m \cdot a$

4.2. Table 2 summarizes the results of the trials.

Table 2: Results Summary

	Time (s)	Angle (rad)	Angular Velocity (rad/s)	Angular Acceleration (rad/s^2)
Trial 1	0.265	0.53	2.01	7.57
Trial 2	0.197	0.53	2.67	13.53
Trial 3	0.194	0.44	2.28	11.75
Trial 4	0.194	0.61	3.17	16.33
Trial 5	0.215	0.47	2.17	10.10
Avg.				11.86
Stdev				3.33

4.3. Table 3 summarizes the final calculations.

Table 3: Final Calculations

Maximum α (rad/s^2)	15.18
a (m/s^2)	1.52
I (kg*m^2)	0.108
M (N*m)	1.82
Force acting on torsional resistance component (N)	91.03

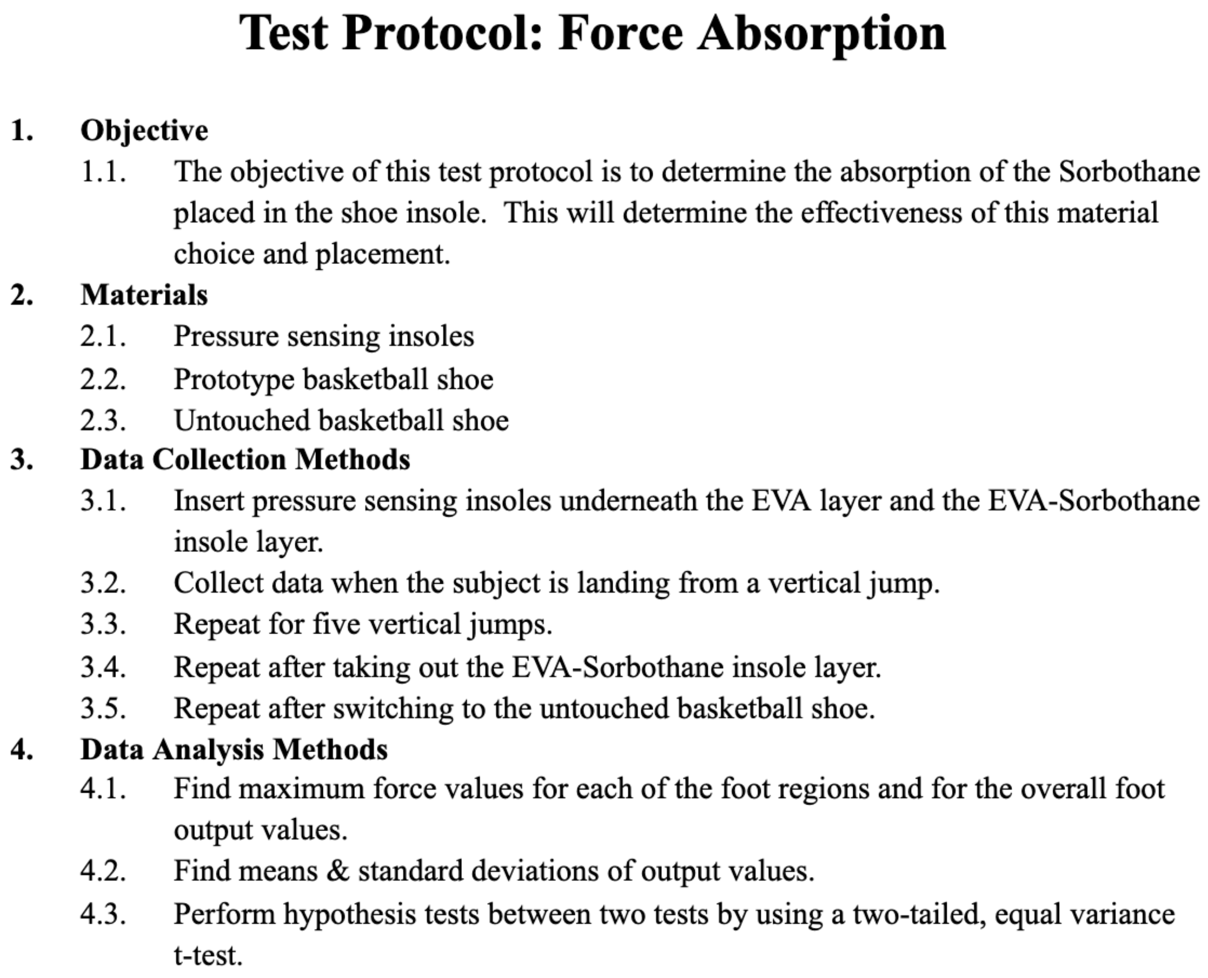
5. Discussion

5.1. The calculated moment about the rotation mechanism will be compared to the bending moment of the nitinol torsional resistance component to determine which diameter wire will best fulfill the functional requirements of the component.

5.2. It is important to note that this value is for comparison only as a foundation for design decisions. The actual value of the moment may be different for different basketball players.

Appendix D

Force Absorption Testing Protocol

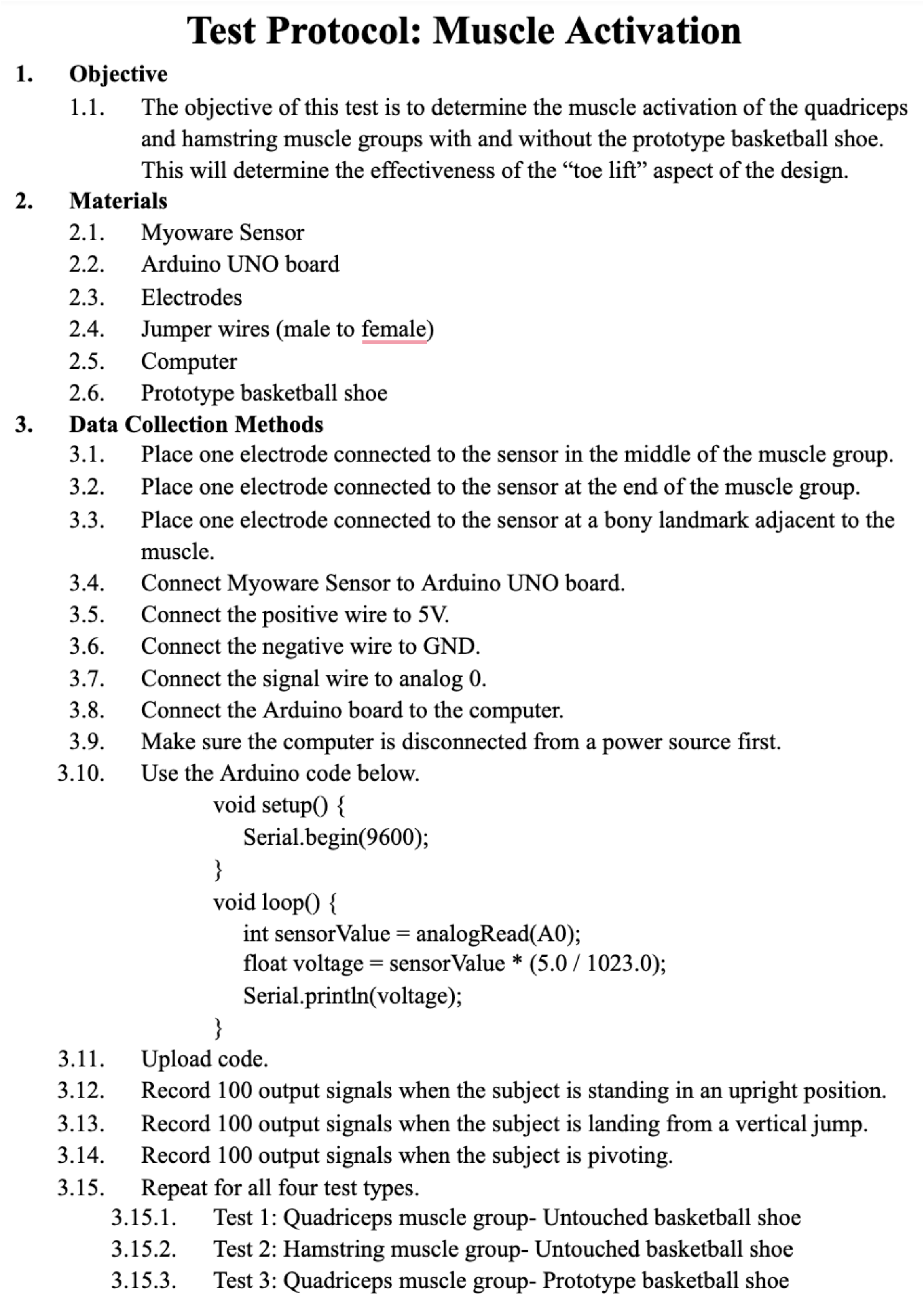


Test Protocol: Force Absorption

1. **Objective**
    1.1. The objective of this test protocol is to determine the absorption of the Sorbothane placed in the shoe insole. This will determine the effectiveness of this material choice and placement.
2. **Materials**
    2.1. Pressure sensing insoles
    2.2. Prototype basketball shoe
    2.3. Untouched basketball shoe
3. **Data Collection Methods**
    3.1. Insert pressure sensing insoles underneath the EVA layer and the EVA-Sorbothane insole layer.
    3.2. Collect data when the subject is landing from a vertical jump.
    3.3. Repeat for five vertical jumps.
    3.4. Repeat after taking out the EVA-Sorbothane insole layer.
    3.5. Repeat after switching to the untouched basketball shoe.
4. **Data Analysis Methods**
    4.1. Find maximum force values for each of the foot regions and for the overall foot output values.
    4.2. Find means & standard deviations of output values.
    4.3. Perform hypothesis tests between two tests by using a two-tailed, equal variance t-test.

Appendix E

Muscle Activation Testing Protocol



Test Protocol: Muscle Activation

1. **Objective**
    1.1. The objective of this test is to determine the muscle activation of the quadriceps and hamstring muscle groups with and without the prototype basketball shoe. This will determine the effectiveness of the "toe lift" aspect of the design.
2. **Materials**
    2.1. Myoware Sensor
    2.2. Arduino UNO board
    2.3. Electrodes
    2.4. Jumper wires (male to female)
    2.5. Computer
    2.6. Prototype basketball shoe
3. **Data Collection Methods**
    3.1. Place one electrode connected to the sensor in the middle of the muscle group.
    3.2. Place one electrode connected to the sensor at the end of the muscle group.
    3.3. Place one electrode connected to the sensor at a bony landmark adjacent to the muscle.
    3.4. Connect Myoware Sensor to Arduino UNO board.
    3.5. Connect the positive wire to 5V.
    3.6. Connect the negative wire to GND.
    3.7. Connect the signal wire to analog 0.
    3.8. Connect the Arduino board to the computer.
    3.9. Make sure the computer is disconnected from a power source first.
    3.10. Use the Arduino code below.

```
void setup() {
    Serial.begin(9600);
}
void loop() {
    int sensorValue = analogRead(A0);
    float voltage = sensorValue * (5.0 / 1023.0);
    Serial.println(voltage);
}
```

    3.11. Upload code.
    3.12. Record 100 output signals when the subject is standing in an upright position.
    3.13. Record 100 output signals when the subject is landing from a vertical jump.
    3.14. Record 100 output signals when the subject is pivoting.
    3.15. Repeat for all four test types.
        3.15.1. Test 1: Quadriceps muscle group- Untouched basketball shoe
        3.15.2. Test 2: Hamstring muscle group- Untouched basketball shoe
        3.15.3. Test 3: Quadriceps muscle group- Prototype basketball shoe

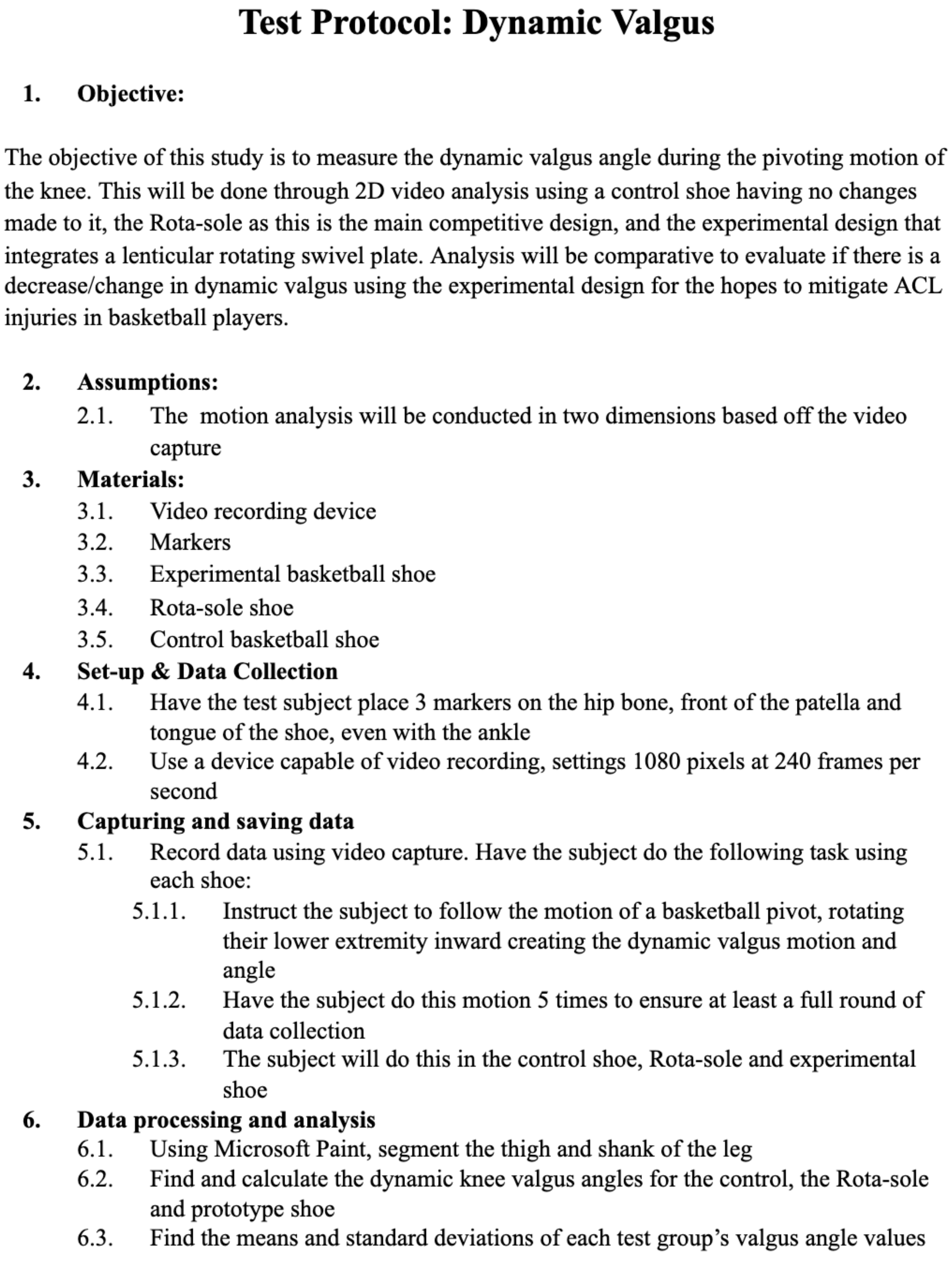
        - 3.15.4. Test 4: Hamstring muscle group- Prototype basketball shoe

4. Data Analysis Methods

- 4.1. Find mean & standard deviation of output signals.
- 4.2. Run hypothesis test between:
    - 4.2.1. Tests 1 and 3
    - 4.2.2. Tests 2 and 4

Appendix F

Dynamic Valgus Angle Testing Protocol



Test Protocol: Dynamic Valgus

1. **Objective:**

The objective of this study is to measure the dynamic valgus angle during the pivoting motion of the knee. This will be done through 2D video analysis using a control shoe having no changes made to it, the Rota-sole as this is the main competitive design, and the experimental design that integrates a lenticular rotating swivel plate. Analysis will be comparative to evaluate if there is a decrease/change in dynamic valgus using the experimental design for the hopes to mitigate ACL injuries in basketball players.

2. **Assumptions:**
   - 2.1. The motion analysis will be conducted in two dimensions based off the video capture
3. **Materials:**
   - 3.1. Video recording device
   - 3.2. Markers
   - 3.3. Experimental basketball shoe
   - 3.4. Rota-sole shoe
   - 3.5. Control basketball shoe
4. **Set-up & Data Collection**
   - 4.1. Have the test subject place 3 markers on the hip bone, front of the patella and tongue of the shoe, even with the ankle
   - 4.2. Use a device capable of video recording, settings 1080 pixels at 240 frames per second
5. **Capturing and saving data**
   - 5.1. Record data using video capture. Have the subject do the following task using each shoe:
     - 5.1.1. Instruct the subject to follow the motion of a basketball pivot, rotating their lower extremity inward creating the dynamic valgus motion and angle
     - 5.1.2. Have the subject do this motion 5 times to ensure at least a full round of data collection
     - 5.1.3. The subject will do this in the control shoe, Rota-sole and experimental shoe
6. **Data processing and analysis**
   - 6.1. Using Microsoft Paint, segment the thigh and shank of the leg
   - 6.2. Find and calculate the dynamic knee valgus angles for the control, the Rota-sole and prototype shoe
   - 6.3. Find the means and standard deviations of each test group’s valgus angle values

6.4. Run two-tailed, equal variance t-tests for comparative analysis, control vs. Rota-sole, control vs. prototype, Rota-sole vs. prototype

Appendix G

Pivot Moment Reduction Testing Protocol

Test Protocol: Pivot Moment Reduction

1. **Objective:**
   The objective of this study is to measure the dynamic valgus angle and pivot moment during the pivoting motion of the knee. This will be done using a control shoe having no changes made to it, the Rota-Sole, and the experimental design that integrates a lenticular rotating swivel plate. Analysis will be comparative to evaluate if there is a decrease in dynamic valgus and pivot moment while using the experimental design which will mitigate ACL injuries in basketball players.

2. **Set-up & Data Collection**
   - 2.1. Set up the Electromagnetic Tracking System:
   - 2.2. To Collect Data Using the G4 Sensors
   - 2.3. Setting up the source and sensors
     - 2.3.1. Set up the source and turn it on
     - 2.3.2. Plug in the RF dongle
     - 2.3.3. Use athletic tape to apply the sensors onto anatomic locations of interest. Make sure that you know where the center of each sensor is relative to specific anatomic landmarks, and that you have oriented the sensor precisely along the anatomic axis that you wish to measure. Avoid putting the sensors over soft tissue masses as much as possible. Bony landmarks will work best, as they will reduce motion artifacts. *Make sure that the sensor moves with the anatomy!*
     - 2.3.4. For this protocol, place the sensors on the subject's lateral ankle process, lateral patella, medial patella and lateral pelvis.
     - 2.3.5. Make sure your subject is standing on the +X side of the hub
     - 2.3.6. Turn on the hub
   - 2.4. Setting up the Computer
     - 2.4.1. Open up PiMgr
     - 2.4.2. Check to make sure the hub and sensors are connected (see User Manual)
     - 2.4.3. Hit the RUN arrow
     - 2.4.4. Data will display continuously and will collect at 120 Hz. Consult the User Manual for saving the data. Experiment with moving the segments with the sensors attached. The visual display should show the locations and orientations of each sensor.
   - 2.5. Setting up the force plate
     - 2.5.1. Set up the force plate to record at 200 Hz for a 6 second data collection
     - 2.5.2. Zero out the force plate before the person steps on it
     - 2.5.3. Have the subject center themselves on the force plate
     - 2.5.4. Start the data collection by clicking start on the computer
     - 2.5.5. Instruct the subject to pivot
     - 2.5.6. End the data collection

        - 2.5.7. Save data

3. Capturing and saving data

- 3.1. Record data from the EMT system. Have the subject do the following task using each shoe:
    - 3.1.1. Instruct the subject to follow the motion of a basketball pivot, rotating their lower extremity inward creating the dynamic valgus motion and angle
    - 3.1.2. Have the subject do this motion 5 times to ensure at least a full round of data collection
    - 3.1.3. The subject will do this in the control shoe, the Rota-sole, and the prototype shoe

4. Data processing and analysis

- 4.1. Find and calculate the dynamic knee valgus angles for the control, the Rota-sole and prototype shoe
- 4.2. Find the means and standard deviations of each test group's valgus angle values
- 4.3. Run two-tailed, equal variance t-tests for comparative analysis, control vs. Rota-sole, control vs. prototype, Rota-sole vs. prototype
- 4.4. Find maximum moment around the z-axis for each trial
- 4.5. Find the means and standard deviations of each test group's max moment values
- 4.6. Run two-tailed, equal variance t-tests for comparative analysis, control vs. Rota-sole, control vs. prototype, Rota-sole vs. prototype