6-2018

Active Auxetic Heel Support for Achilles Tendon Therapy

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ENTITLED

ACTIVE AUXETIC HEEL SUPPORT FOR ACHILLES TENDON THERAPY

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
BIOENGINEERING

I. EMRE ARACI 6/8/18

Thesis Advisor(s) date

6/8/18

Department Chair(s) date

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By

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SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Bioengineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Bioengineering

Santa Clara, California

2018

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Abstract

The Achilles tendon, which stretches from the calf to the ankle, can be injured due to repeated daily activities or overstretching. In severe cases a tear in the tendon can prevent athletes from performing in games as well as individuals from completing their daily tasks. Achilles tendon injuries affect millions of people. The severe pain that occurs upon injury can take months to improve and for the Achilles tendon to heal. Our goal is to design an auxetic support to provide comfort, help heal the tendon, and allow the individual to continue to be active through the natural healing process. The auxetic will help protect from further injury when the individual is active because when force is applied longitudinally it results in expansion laterally leading to a shortening of the tendon, which promotes healing. This support is fabricated using elastomer molds that incorporate auxetic patterning, which was determined through testing, to make the device active while the individual is moving while wearing the support. The pieces are individually made, then pieced together to form the heel portion of the support, which is the crucial component for Achilles tendon healing. With compression testing we discovered that the Young's modulus of our auxetic structure is similar to that of the calcaneus tissue so it will be comfortable for the user. With shock absorption testing we were able to compare the energy absorption off our auxetic structure compared to bulk elastomers and foams. Overall, we believe the optimal auxetic heel support is comfortable and shock absorptive and heel supports should be made so they are capable of facilitating healing and protect from further injury of the Achilles tendon when an individual is active.

Acknowledgements

We would like to thank our Advisor, Dr. Emre Araci for his help and support throughout the year. With his guidance, insight, and expertise we were able to accomplish our project. We have learned so much from you and thank you for your patience along the way. We appreciate the time and effort you put into helping us with our project and allowing us to grow and succeed (and fail) along the way. Thank you for all that you have done for us.

We also want to thank the SCU Maker's Lab for allowing us to use their equipment and for their help throughout the year. In addition, we would like to thank Dr. Maryam Mobed-Miremadi for her help in our compression testing and analysis.

We want to thank all our family and friends for their continued support throughout the year. Thank you for always being there to listen about our projects and being there to support us throughout this endeavor.

Finally, we would like to thank the Santa Clara University School of Engineering for funding our project. This would not have been possible without your generosity.

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1.1) Background:

Many athletes and individuals take their ability to be physical active for granted, but, with injury, our lives can easily be changed. We walk, run, and play on our feet every day, but imagine if this was compromised. The Achilles tendon, which is also the largest tendon in the body, connects our calf muscles to our heel bone, making it a major component of our daily physical activity that involves the use of lower limbs. Achilles tendonitis is a condition that results from the overuse and abrupt tearing of the Achilles tendon that leads to its injury and inflammation. Achilles tendonitis begins with a mild pain and can lead to a severe rupture of the tendon which greatly affects the individual's mobility [1]. A study found that Achilles tendon injury accounts for 75% of injury in recreational athletes [2]. There are 10 out of 100,000 incidents of Achilles tendon rupture reported annually in the general population, with 24% occurring in competitive athletes. In addition, 40-50% of runners have an incidence of Achilles tendonitis in their lifetime [3]. As demonstrated, Achilles tendonitis is a major issue that impacts athletes as well as individuals participating in recreational activities. Our goal for this project was to design and create an active, stand-alone, auxetic orthotic that would allow individuals affected by this condition to return to their daily lives without sustaining further injury while allowing their injury to heal.

1.2) Review of Literature:

Given that Achilles tendonitis is a medical condition, we turned to existing literature and current marketed product reviews to determine what qualities in an orthotic Achilles tendonitis patients were looking for when recovering from injury to their tendon. We looked at published works detailing the biomechanics of the ankle, the Achilles tendon, and existing treatments to determine customer needs as well as the limitations of current treatment options.

1.2.1) Customer Needs:

Tendons, including the Achilles, are fibrous bundles of collagen filaments that are flexible, yet inelastic [4]. Their inelasticity is a defining property of the tendons that lead to conditions such as ankle sprains as well as Achilles tendinopathies. As such, we analyzed literature in which active patients with ankle injuries evaluated different types of braces for treatment effectiveness and overall satisfaction with the brace's design.

One published study compared the use of elastic support bandages to the patented Aircast ankle brace. During the study, researchers reiterated that continued, supported mobilization of the ankle in early stages of injury leads to quicker healing and less pain overall in patients [5]. From this, we concluded that we needed to produce an orthotic that would effectively allow patients with Achilles tendinopathies to remain active but prevent them from exacerbating their current injury.

The second piece of literature we consulted to better explore patient needs was a study conducted specifically on athletes. They surveyed runners, volleyball players, and soccer players who wore ankle braces during activity as an injury preventing measure [6]. In turn, the athletes ranked the compression, lace-up, and semi-grid braces in categories such as ease-of-use, quality, stability, and other related categories, as seen in Table 1.

Variable	Brace Type	Overall	Soccer	Volleyball	Running
Ease of use	Compression	4.1 (3.9, 4.3)	4.2 (3.9, 4.5)	3.9 (3.4, 4.4)	4.2 (3.9, 4.4)
	Lace-up	3.7 (3.5, 3.8)	3.5 (3.2, 3.9)	4.0 (3.6, 4.3)	3.5 (3.2, 3.8)
	Semirigid	3.9 (3.7, 4.1)	3.8 (3.4, 4.2)	3.9 (3.6, 4.4)	4.0 (3.7, 4.2)
Quality	Compression	4.1 (3.9, 4.3)	4.2 (4.0, 4.5)	3.9 (3.4, 4.4)	4.1 (3.7, 4.4)
	Lace-up	3.8 (3.6, 4.0)	3.8 (3.5, 4.0)	4.1 (3.7, 4.5)	3.6 (3.2, 4.0)
	Semirigid	3.6 (3.4, 3.8)	3.5 (3.2, 3.9)	3.7 (3.3, 4.1)	3.5 (3.2, 3.8)
Comfort	Compression	4.0 (3.8, 4.1)	4.0 (3.8, 4.3)	4.0 (3.6, 4.4)	3.9 (3.6, 4.2)
	Lace-up	3.7 (3.5, 3.8)	3.5 (3.2, 3.7)	3.9 (3.6, 4.2)	3.6 (3.3, 4.0)
	Semirigid	3.1 (2.9, 3.4)	2.8 (2.4, 3.3)	3.4 (3.0, 3.8)	3.2 (2.9, 3.5)
Stability	Compression	3.6 (3.4, 3.8)	3.8 (3.4, 4.1)	3.2 (2.7, 3.7)	3.7 (3.5, 4.0)
	Lace-up	4.0 (3.8, 4.2)	3.9 (3.7, 4.1)	4.3 (4.0, 4.5)	3.9 (3.5, 4.2)
	Semirigid	3.1 (2.9, 3.4)	2.9 (2.4, 3.5)	3.3 (2.8, 3.7)	3.2 (2.8, 3.6)
Hindrance	Compression	3.7 (3.5, 3.9)	3.7 (3.5, 4.0)	3.7 (3.3, 4.1)	3.6 (3.3, 3.9)
	Lace-up	2.9 (2.8, 3.1)	2.9 (2.6, 3.2)	3.2 (3.0, 3.4)	2.8 (2.4, 3.2)
	Semirigid	3.0 (2.7, 3.2)	2.8 (2.4, 3.2)	3.2 (2.7, 3.6)	2.9 (2.5, 3.3)
Satisfaction	Compression	3.4 (3.1, 3.6)	3.6 (3.2, 4.0)	3.0 (2.5, 3.5)	3.4 (3.0, 3.8)
	Lace-up	3.3 (3.0, 3.5)	3.0 (2.7, 3.4)	3.8 (3.5, 4.2)	3.0 (2.6, 3.5)
	Semirigid	2.7 (2.4, 2.9)	2.5 (2.0, 2.9)	3.0 (2.4, 3.5)	2.6 (2.2, 3.0)

[a] Scores represent the mean group value of each construct on a 1 to 5 scale.

Table 1: Comparison of braces Shows athletes ratings of three different brace types and the qualities they found important in wearing orthotic devices

Although many of the criteria used to compare brace models in this study were subjective and therefore difficult to quantify, we inferred some of the more basic aspects patients would be looking for in a support mechanism. We inferred that our orthotic needed to be comfortable, non-bulky so as not to hinder more active patients, and overall quality of the orthotic needed to be high to better satisfy the patient needs.

1.2.2) Current Supports:

There are currently hundreds of products in the market for ankle support, but only a select few genuinely alleviate pain, prevent further injury, and expedite healing in a manner similar to that desired for our proposed orthotic. As we continued our research, we wanted to discover what aspect of load bearing in the Achilles would put the most stress on the tendon in active, recovering tendinitis patients, and add components to alleviate this tensile stress. Through our literature search we found that light to moderate loads [7] eccentrically loaded onto the Achilles tendon and calf [8], were the most conducive to relieving pain and reducing inflammation in patients with Achilles tendinopathies. This helped us determine that our orthotic should provide intensive heel support to accommodate this phenomenon.

A few Achilles orthotics on the market featured some form of heel support (see examples in Figure 1), but, after reading customer reviews the primary complaints with these supports was that they are uncomfortable, lacked integrity, and offered only static support.

Figure 1: Current heel inserts Comparison of different heel inserts on the market. These popular inserts are commonly used for Achilles tendonitis pain management and are a variety of materials such as gel, silicon, and rubber

We decided to focus on these aspects in our proposed orthotic, providing force activation and durability with auxetic metamaterials.

1.2.3) Current Treatments:

The primary existing method of treatment is to simply rest the affected tendon for six to eight weeks until fully able to return to activity. However, in more severe forms of Achilles tendinopathy, such as Achilles tendon rupture, surgery may be required [9]. In less severe circumstances, physical therapy can be used to expedite the rehabilitation process. Physical therapy in the case of tendonitis can include ultrasound therapies [10] or shockwave therapies [11], but these can be expensive and time-intensive, stopping patients, especially athletes from maintaining an active lifestyle during recovery. We hope to limit patient expenses as well as allow recovering patients to remain active while staying relatively pain free with our auxetic orthotic. Additionally, our orthotic will hopefully retain similar results to physical therapy by reducing chance of reinjury during Achilles tendon recovery while limiting cost.

1.2.4) Proposed Technology:

The main technology being used to operate this device is an auxetic structure. This is created using an auxetic pattern. Auxetic materials become wider when stretched in one direction as opposed to becoming thinner because of the patterning made on the material. High energy impacts on auxetic materials have lower peak acceleration when a controlled force is applied to them [12]. This technology of auxetics, also known as metamaterials, allows a greater load to be applied on the object because compressing in one direction will lead to expansion in another [13].

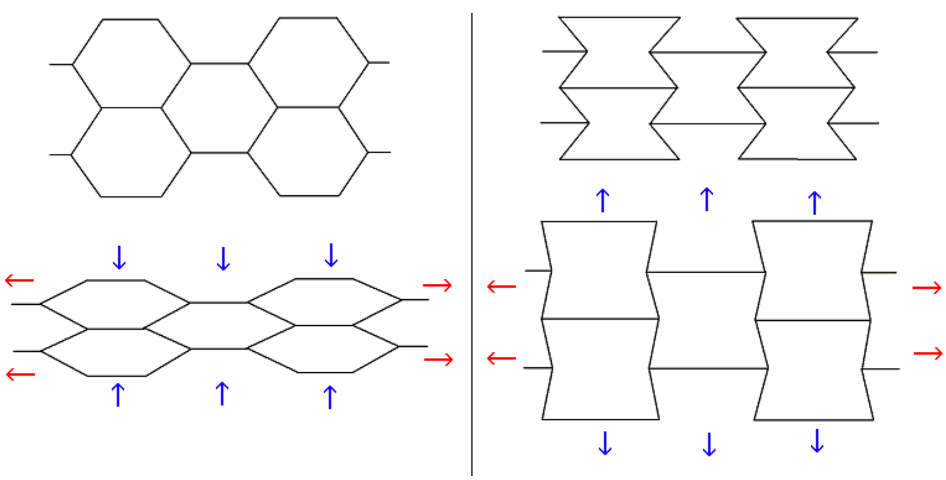

Figure 2: Auxetic structure Comparison of non-auxetic pattern on the left that does not expand when stretched lengthwise versus an auxetic pattern on the right that expands in the y-direction when stretched in the x-direction exhibiting auxetic behavior

Auxetic materials feature many proven benefits throughout sports medicine and footwear studies. For example, one study observing the use of auxetic patterning in sports safety helmets showed that auxetic materials were better than conventional materials when it came to reduce linear acceleration [14]. Additionally, another study concluded that auxetic materials were superior in resisting indentation when compared with the same material with traditional patterning [15].

Another study involving footwear and the use of high heels showed that auxetic pads were better at redistributing pressure in the foot than pads made of normal orthotic material [16].

For our design we are utilizing these properties of auxetics by creating the most suitable auxetic structure to allow expansion in the heel of our support. This is opposed to using foams which will de-compress over time and wear down. The auxetic structure will be placed in the heel portion of our insert to allow for comfort and expansion when it is most needed during active movement to protect the individual from further Achilles tendon injury.

1.3) Device Description:

The device we are proposing is a full shoe insert that provides protection for the Achilles tendon as well as encouraging healing in the long term. The heel portion will consist of a stacked auxetic structure engulfed in foam and with ankle aligners on the lateral sides. An auxetic material is one that exudes a negative Poisson's ratio. An auxetic is an example of a metamaterial, a material that derives its physical properties not from the material it's made of but from the shape of the structure. This will attach to the main portion of the shoe insert that extends from the base of the arch of the foot to the tip of the toe. This portion will be made of mostly soft compressive foam with a hard insert on the right middle part of the foot which will provide arch support. Encouraging arch support is linked with healing of the Achilles tendon due to reduced strain on both.

1.3.1) Project Goals and Objectives:

Over these next six months we have three main goals we want to achieve. The first, is to create the design for just the auxetic part of the heel support and subsequently 3D print the mold. This will be a defining moment as it will be the first instance of having a physical product and will be a great point of reference in moving the project forward. Our next step will be optimizing the auxetic until it shows the properties we desire (negative Poisson's ratio). This will be through stress and strain analysis using a tensile testing machine that we will design. We will then create the auxetic heel support and put it through compression and shock absorption testing since energy absorption and comfort are very important properties in our product. The basic outline of these goals is displayed on our timeline in section 1.5.2.

1.3.2) Technology of Device:

Our auxetic orthotic is going to look similar to any other shoe insert, but it will have an entirely new function and purpose. The base of the shoe insert will be created out of a comfortable material such as foam in the proper shape of the foot to ensure arch support and comfort. The main mechanics of this device will occur in the heel. In the heel we will create an auxetic pattern out of different elastomers because they will not wear as quickly as foams do. As the individual is active when they heel strike the foot becomes elongated in the x-direction and this will stretch the auxetic in this direction. As it is stretched along the bottom of their heel it will expand in the y-direction which will provide more protection when they are more prone to Achilles tendonitis injury. This expansion of the heel portion of the orthotic will help reduce injury and facilitate healing of the tendon. There will also be comfortable, flexible guides from the support along the sides of the ankle to ensure the proper gait pattern and movement of the foot when active to facilitate healing and comfort for the individual.

1.3.3) Expected Results:

From the strain testing on the auxetic portion of the orthotic we expect the metamaterial to have a negative Poisson's ratio. This is to mean that when it's extended lengthwise it also extends widthwise. This is essential for our design so creating and optimizing the auxetic will be our first task in winter quarter.

We expect that our stand-alone auxetic support will reduce pain and expedite healing in patients with Achilles tendon injury, reduce the chance of re-injury in active patients, and boast greater durability than currently marketed products. This can be accomplished if our support expands in height, leading to shortening of the tendon to promote healing. Also, the extra support under the tendon will reduce re-injury since the support is the optimal height to prevent Achilles tendon injury. By creating a product out of elastomers instead of foams we hope to achieve greater durability since foam cells easily wear down over time, whereas elastomers such as polyurethane which is commonly used in shoe support are more durable. If we cannot achieve all these results, we at least hope to make a low-costing auxetic heel support that provides healing and has greater longevity than current rehabilitative devices.

1.4) Significance:

The benefits of this project are that is helps individual's life an active life again. The orthotic will not only work to keep the individual comfortable but will provide adequate support to their Achilles tendon so there is no pain or discomfort. We think this project will be especially beneficial for athletes, both professional and recreational, because it relieves pain in the tendon as well as helping the tendon heal faster by shortening the tendon. This can impact many people because it will allow the tendon to heal and recover from injury while they are still active in their lives. The cost is less than physical therapy and the individual does not have to take time off work or their daily routine because they are not hindered by their injury. Overall, our stand alone, auxetic orthotic will provide individuals with a cost effective, comfortable support to allow them to continue an active lifestyle and help heal and prevent re-injury of the Achilles tendon.

1.5) Team Management and Operations:

The team consists of Anna Hinrichs, Kseniya Malukhina, Ishaan Sharma, and Micaela Vierra with Dr. Emre Araci as the advisor. We held weekly meetings with Dr. Araci to make sure we were on task and to keep the team updated with our progress. During the fall quarter Kseniya and Micaela focused on the market research and biomechanics of the Achilles tendon. Anna and Ishaan researched metamaterials and auxetic patterns to find the best structure for the orthotic. Most communication with the team was through informal text messages and emails. Also, the writing and literature sources were shared using Google Drive to make sure all team members had access to information and assignments.

1.5.1) Budget:

Item	Quantity	Cost
Gel Heel Cups Plantar Fasciitis Inserts	3	$60
Tuli's Heavy Duty Heel Cups	3	$60
Adjustable Orthopedic Heel Lift	3	$60
Ecoflex 00-50	1 Gallon	$200
Ecoflex 00-35	1 Gallon	$200

Mold Star 20T	1 Gallon	$200
PDMS (100 ml)	3	$600
Soft Foam (2”)	Full Sheet	$60
Lux HQ Foam (1.5’’)	Full Sheet	$60
Polyethylene Foam	Full Sheet	$60
Open Cell Poly Foam	Full Sheet	$50
Mann Ease Release	6 Cans	$100
Thi-Vex	1 Gallon	$130
Silc Pig (Pigment)	9 Pack	$30
Mixing Containers	Various Sizes	$60
Brushes and Additional Materials Needed		$70
Total		**$2000**

Table 2: Budget Outline of expenses for our senior design project, funded by Santa Clara University's Engineering Department

Challenges with our budget is the specificity of the products needed. Since there are many types of foams, elastomers, and orthotic supports we had to be really detailed and focused in our primary research for our budget to find the prices of the products that would be the best for our design.

1.5.2) Timeline:

See Appendix 4 for Gaant Chart

Fall Quarter	Winter Quarter	Spring Quarter
● Literature Review ● Calculations ● Overall Design ● Problem Statement ● Budget Proposal	● Build Design ● Test Design ● Test Current Products	● Finalize Design ● Final Testing ● Analyze Results

Table 3: Timeline Shows tasks for each quarter for the 2017-2018 school year

Chapter 2: Design Process:

2.1) Design Goals:

To begin our project, we first focused on finding the most ideal auxetic pattern that had the best negative Poisson ratio and highest maximum area expansion. This led to creating many iterations to optimize these qualities in our auxetic pattern. These designs were created in SolidWorks and then created into tangible objects through 3-D printing and laser cutting techniques to create molds which could then be filled with various materials such as foam, PDMS, and polyurethane and then tested to find the best auxetic pattern and material.

Our auxetic pattern has a few goals that it needs to follow. First, it must work properly and have auxetic properties, meaning that when stretched lengthwise it will expand widthwise. It also should be small enough to fit under an individual's heel and we also want it to be comfortable since it will have daily use. To achieve these goals, we based our auxetic pattern design on the research paper mentioned earlier and chose the designs with the highest negative Poisson ratio and maximum area expansion.

2.2) Customer Needs and System Requirements:

Our goal in this project is to create an orthotic device that will serve to help individuals with Achilles tendonitis. It will allow them to remain active, facilitate healing, and decrease chance of re-injury with its auxetic patterning in the heel. Therefore, the orthotic must be comfortable and the auxetic pattern must work properly so that as the individual is active, for example running, it will become thicker providing more protection when they are at higher risk of Achilles injury. Based on common heel supports and shoe inserts through research we can see that there is a need for a device like ours that will be comfortable for the individual and allow them to remain active whether is it in sports or in their daily activities. Using an auxetic pattern and comfortable materials such as foam and elastomers such as PDMS we can create a solid pattern that will serve its purpose and incorporate it into a comfortable, simple orthotic design that can be easily tailored for different individuals.

2.3) Auxetic Structure Overview:

The auxetic structure we are designing is based on a research paper that compares various auxetic patterns; finding their Poisson ratio, maximum area reduction, and Young's modulus [13]. Auxetic structures are certain patterns that when stretched instead of becoming thinner in one direction they become thicker. This means mathematically that they have a negative Poisson's ratio and a positive maximum area reduction (really an increase based on formula). We are using auxetic patterning to our advantage so that when the orthotic is compressed and stretched it will expands and get taller allowing more protection and support for the user.

2.3.1) Auxetic Patterns:

Based on the data from the research paper we previously found we decided to begin our testing by creating the pattern that had the highest negative Poisson ratio and the pattern with highest maximum area expansion. These were both Re-entrant Masters-Evans models that we re-created in SolidWorks.

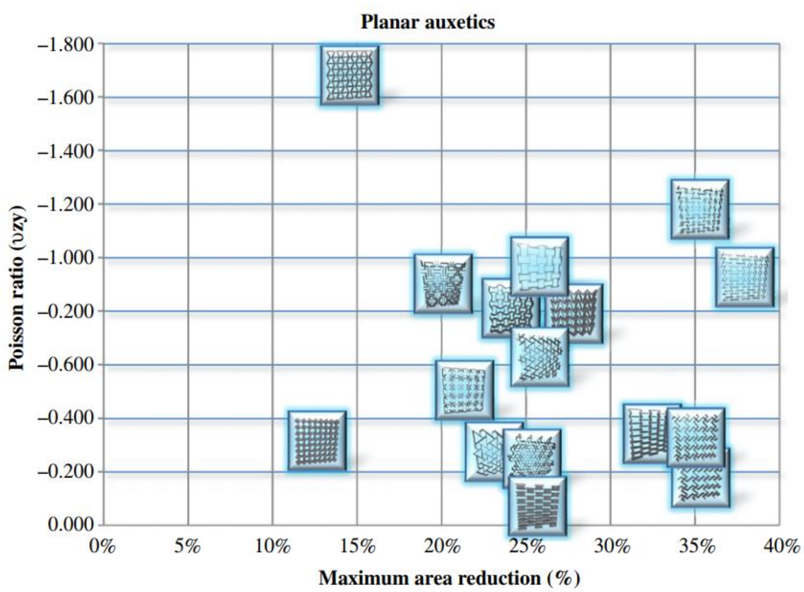

Figure 3: Graph of maximum area reduction and Poisson's ratio This shows that the auxetic pattern we want to design should have the most negative Poisson ratio and highest maximum area reduction

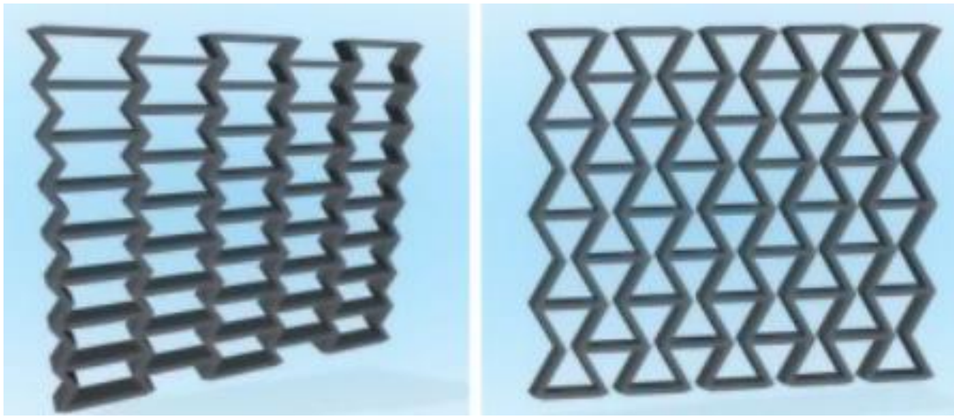

Figure 4: Re-entrant Masters-Evans models Based on the research paper these are the first two design we wanted to create for our auxetic patterns

2.4) Auxetic Pattern Prototypes:

2.4.1) Initial Mold Designs:

The initial mold design is 3-D because we wanted to 3-D print the auxetic structure and then be able to pour materials such as PDMS and liquid foams to get the auxetic patterning. This design is the Re-entrant Masters-Evans model that had the highest negative Poisson's ratio so that means that when it was stretched in their computer-aided study is expanded the most in the other direction compared to how far it was stretched. This design consists of the negative patterning and has a bottom piece and edges to allow different heights of PDMS to be poured. One edge piece is also removable so that after the PDMS has cured the piece can be removed and the PDMS can be easily peeled off the plastic. We also designed the other Re-entrant Masters-Evans model in a similar matter and this patterning presented a high maximum area expansion.

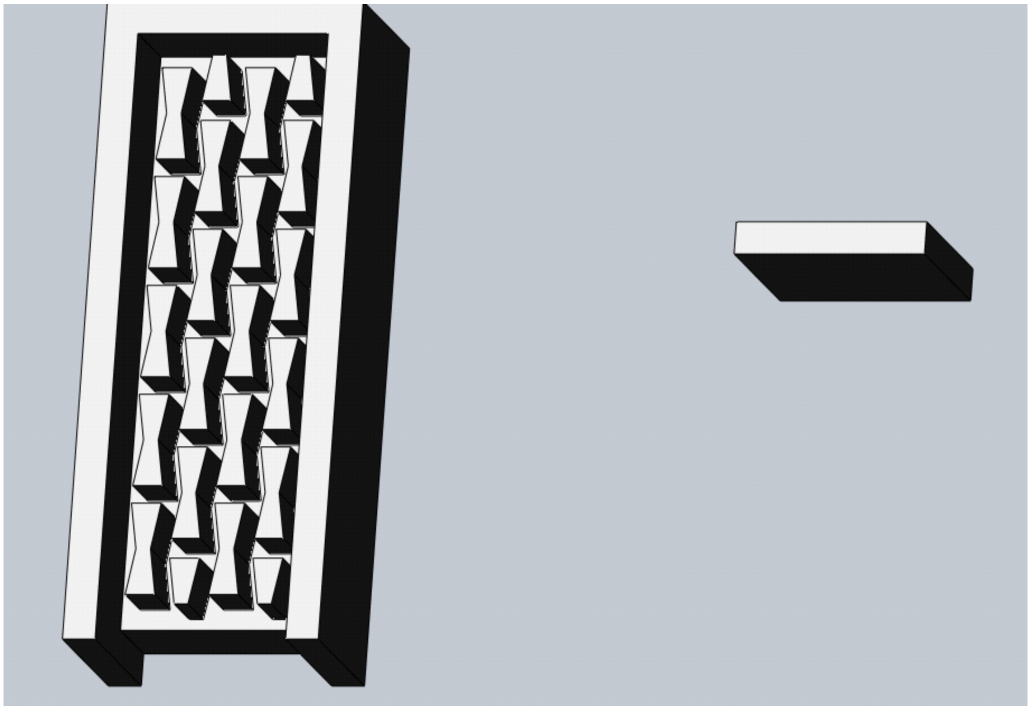

Figure 5: Re-entrant Masters-Evans model 1 This design was created in SolidWorks and has the most negative Poisson's ratio based on the computer-aided study of various auxetic patterns

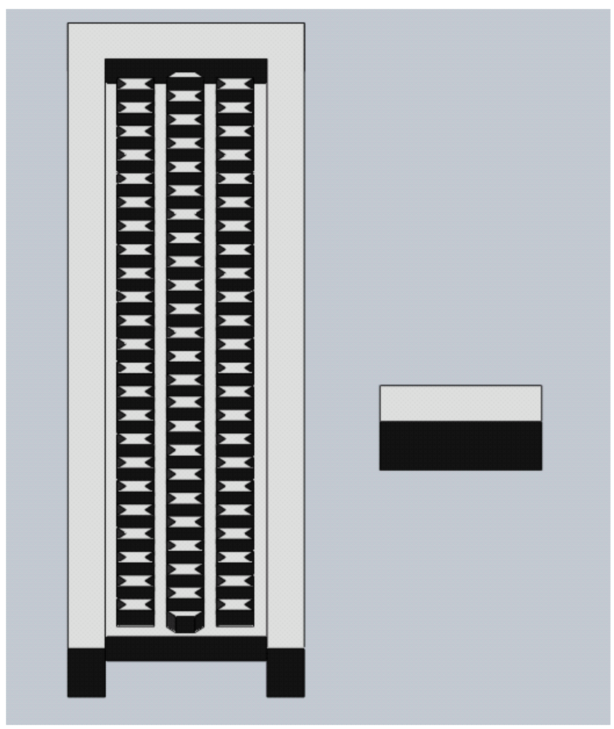

Figure 6: Re-entrant Masters-Evans model 2 This design was created in SolidWorks and has a high maximum area expansion when comparing various auxetic patterns

2.4.2) Second Mold Design:

Since 3-D printing the pieces was not successful we looked at other materials to use that would not stick to PDMS and our other materials. We decided to use acrylic. To design these molds, we laser cut the negative design from the pattern that we had previously 3-D printed. That way we can pour PDMS over the acrylic piece and it would create a mold that can then be used with various materials like PDMS and polyurethane that would not have bonding constraints. This piece of acrylic was also not as tall, so we will not have the same aspect ratio concern. This design was created in SolidWorks and saved as .dwg to be transferred to the laser cutter program. We designed both patterns again for testing.

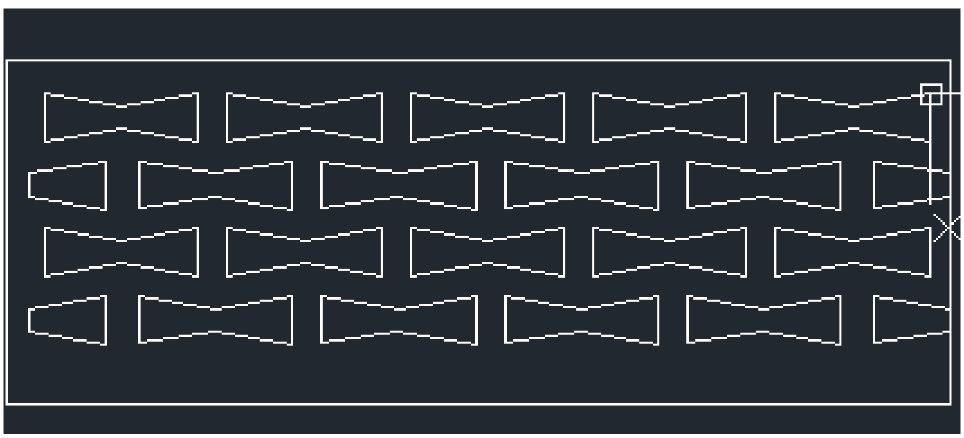

Figure 7: Re-entrant Masters-Evans model 1 drawing This design was created in SolidWorks and has the most negative Poisson's ratio based on the computer-aided study of various auxetic patterns

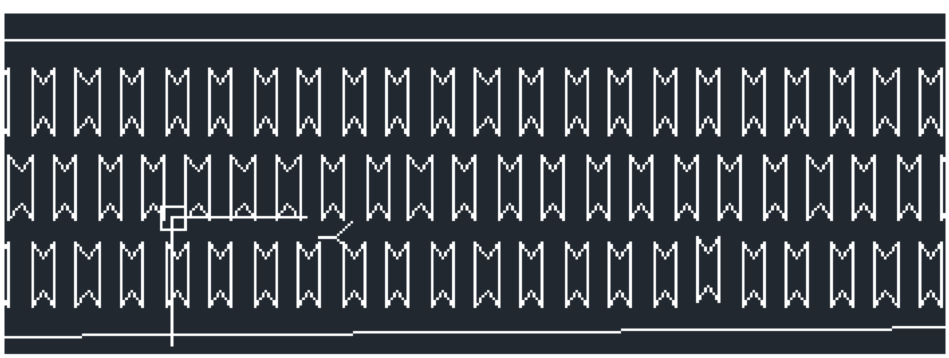

Figure 8: Re-entrant Masters-Evans model 2 drawing This design was created in SolidWorks and has a high maximum area expansion when comparing various auxetic patterns

2.4.2.1) Constraints:

There is some difficulty when making these pieces. For our initial testing of these designs we decided to change three specific conditions as listing in the table below. This will allow us to get accurate results and see which design and characteristics create the best structure.

	Model 1	**Model 1**	**Model 2**	**Model 2**
Small Size	PDMS	Polyurethane	PDMS	Polyurethane
Medium Size	PDMS	Polyurethane	PDMS	Polyurethane

Table 4: Models tested This shows the three variables we are changing in our testing resulting in a total of 6 different pieces to test their auxetic behavior and volume expansion (See Appendix 2 and Appendix 3 for PDMS/Polyurethane procedures and mold making procedure)

2.4.3) Final Auxetic Design:

After our testing, which will be explained in the results section, we concluded that the small size polyurethane, Model 1 was the best structure to use. This auxetic structure was ¼" thick, 0.827" tall, and 3.5" long. The height of this structure was determined through research because that is equal to about 21mm which the optimal height for Achilles tendon healing is. The length was determined from the average heel length of an individual. With testing this design proved to be the best design providing the highest negative Poisson's ratio when stretched. Once we decided to use this patterning, material, and size for our auxetic heel support we then altered it so that it would be more comfortable for the individual. As shown in Figure 10 below the design is like our original design, but there is a slope downward. This is for additional comfort between the heel and arch.

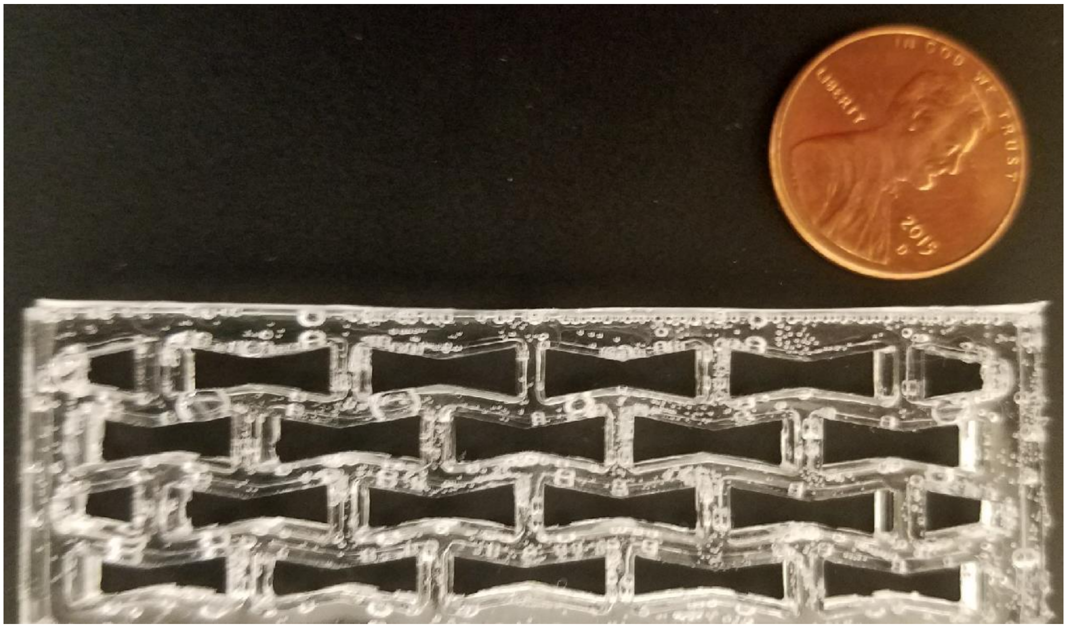

Figure 9: Small polyurethane model 1 This design is our final auxetic design we chose to use for our auxetic heel support because of the results in testing resulting in the most negative Poisson's ratio

Figure 10: Final auxetic heel support acrylic This is our final auxetic heel support structure created. It is the same dimensions as the rectangular piece above, but slopes downwards at the bottom for additional comfort. It is the model 1, small polyurethane structure

2.4.3.1) Constraints:

As seen in the figure 9 if the polyurethane was not de-gassed long enough it resulted in bubbles which led to errors in our testing since they added more air into the material. Also, when removing this structure from the mold we had to be careful that it did not tear by being patient and taking our time removing the piece. If there were tears in the piece, it could no longer be used because it is not at sturdy when pressure it applied.

2.5) Conclusion:

Throughout our testing we successfully determined the optimal auxetic pattern, material, and size to use for our heel support. Beginning our process with our literature search then determining the conditions previously mentioned that we wanted to alter to test for the best design was important in our design process. By changing these different conditions, we were able to determine the structure that resulted in the most negative Poisson's ratio which would lead to a greater increase in height when the support is stretched as the user is walking.

Chapter 3: Methods and Materials:

3.1) Methods:

3.1.1) Auxetic Mold Fabrication:

When creating our auxetic patterns we wanted to design a way that we could make multiple patterned structures out of different materials for testing. To accomplish this, we decided to design a mold that we could then pour different materials into to create different auxetic pieces for testing.

3.1.1.1) 3-D Printing Molds:

We first decided to utilize the Ultimaker, the 3-D printer available in Santa Clara University's Maker Lab, because it would serve as a cheap, fast way to print the molds. The molds were designed using the SolidWorks program because the SolidWorks software allowed these 3-D designs to be easily altered if necessary. Once these designs were created they were saved as an .stl file so that they were compatible with the Ultimaker. Each mold took about five hours to print and once they were printed we were ready to begin our testing.

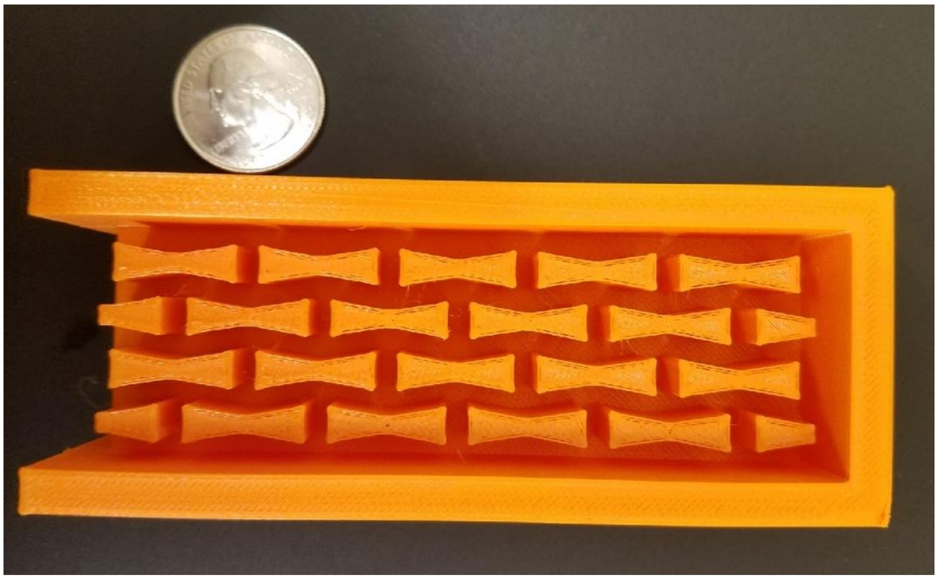

Figure 11: 3-D printed top view model 1 Top view of a 3D printed mold of the Re-entrant Masters-Evans model 1

Figure 12: 3-D printed side view model 1 Side view of a 3D printed mold of the Re-entrant Masters-Evans model 1

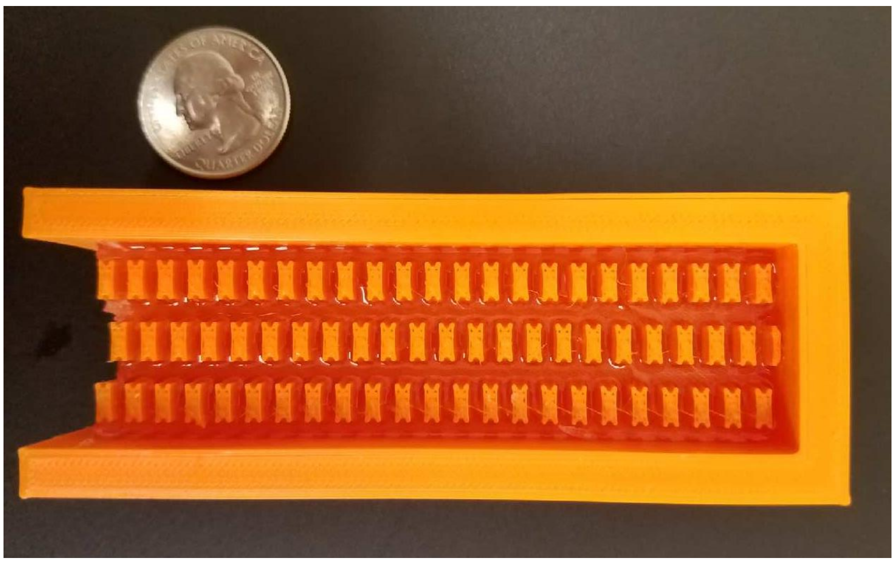

Figure 13: 3-D printed top view model 2 Top view of a 3D printed mold of the Re-entrant Masters-Evans model 2

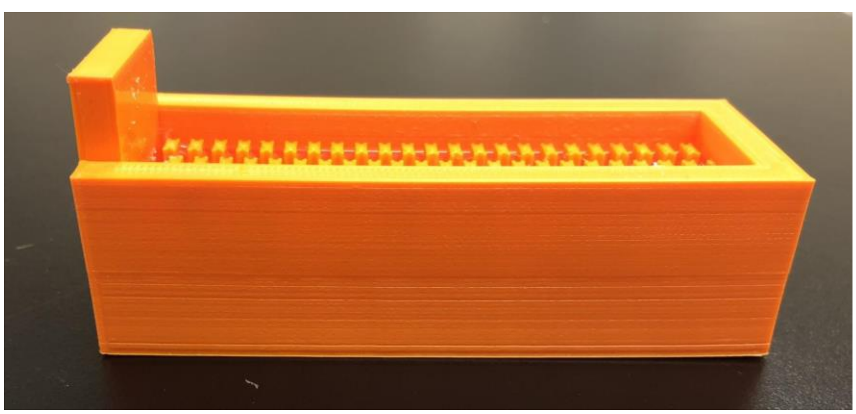

Figure 14: 3-D printed side view model 2 Side view of a 3D printed mold of the Re-entrant Masters-Evans model 2

3.1.1.1.1) Challenges:

Once these designs were 3-D printed we poured the PDMS in them to cure. We initially had problems because the heat was too high, and the 3-D printed piece became warped. We modified our procedure by letting the PDMS cure at a lower temperature for a longer amount of time. Even though the Ultimaker was an efficient, cheap way to create our molds it ended up not being our final mold design. The plastic material was not compatible with PDMS so that made it difficult and the patterned features were too tall and thin, so the material would not easily be removed from the mold. We then decided to coat the pieces with parylene c so that the PDMS would not stick to the plastic. Once this process was complete and the PDMS was fully cured, it did not stick to the plastic, but the aspect ratio was too high causing the thin and tall PDMS features to be torn when removing them from the mold. Therefore, we decided to try another way of creating molds for our auxetic patterns.

3.1.1.2) Laser Cutting Molds:

After 3-D printing the molds was unsuccessful we decided to use acrylic as our base material instead. Acrylic serves as a better material because it will not create strong bonds with PDMS or liquid foams and other material. We decided that using the Epilog laser cutter would work best. Once the 2-D designs were created in SolidWorks the file was saved as a .dwg so that it was compatible with the Curel program for the laser cutter. We used a thin piece of acrylic and set-up the laser cutter properly so that it would cut out the shapes fully instead of etching. This process was less time consuming than the 3-D printer and the molds turned out clean and the features were cut nicely. Once the features were cut out they had to be poked out with a little poking tool because they were still kind of stuck to the acrylic. This is done by poking lightly at the feature so that in the end of this process you have created an acrylic piece that will serve as a mold. We then want to fill this acrylic mold with PDMS to create a mold for the auxetic pattern. Since we cut out the opposite of our desired mold when it is filled with PDMS we will have a PDMS mold (See Appendix 2 for PDMS procedure). This PDMS mold will work well because we can easily remove foam, PDMS, and other materials off PDMS. Once this PDMS mold was made we then filled it with PDMS and Polyurethane (See Appendix 3 for procedure) and tested to find the ideal auxetic pattern, material, and size (See Appendix 3 for mold making procedure).

Figure 15: Re-entrant Masters-Evans model 1 acrylic Top view of a laser cut mold of the Re-entrant Masters-Evans model 1

Figure 16: Re-entrant Masters-Evans model 2 small acrylic Top view of a laser cut mold of the Re-entrant Masters-Evans model 2

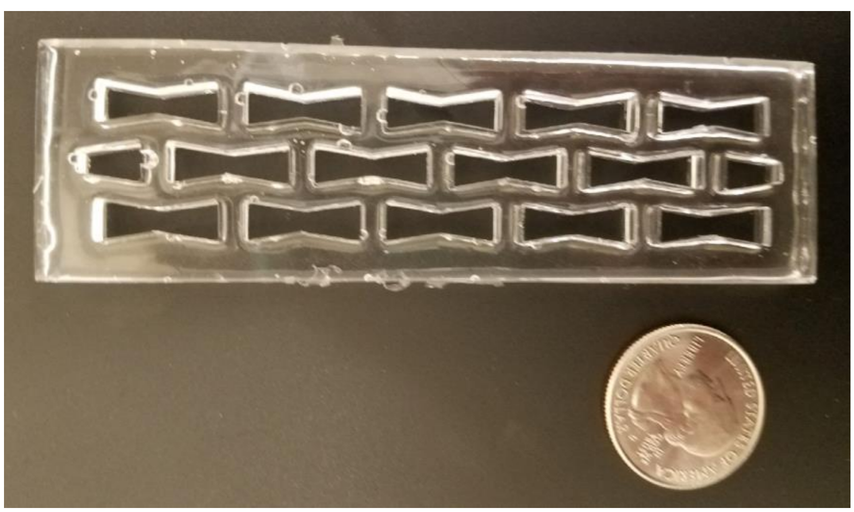

Figure 17: Re-entrant Masters-Evans model 1 medium This shows to scale the medium-size piece created from the PDMS mold that was used for testing

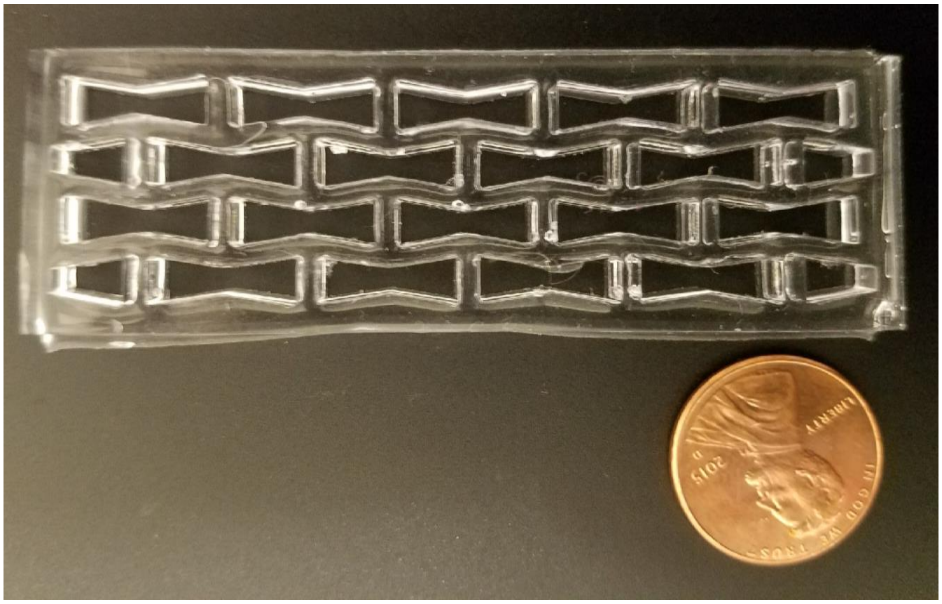

Figure 18: Re-entrant Masters-Evans model 1 small This shows to scale the small-size piece created from the PDMS mold that was used for testing

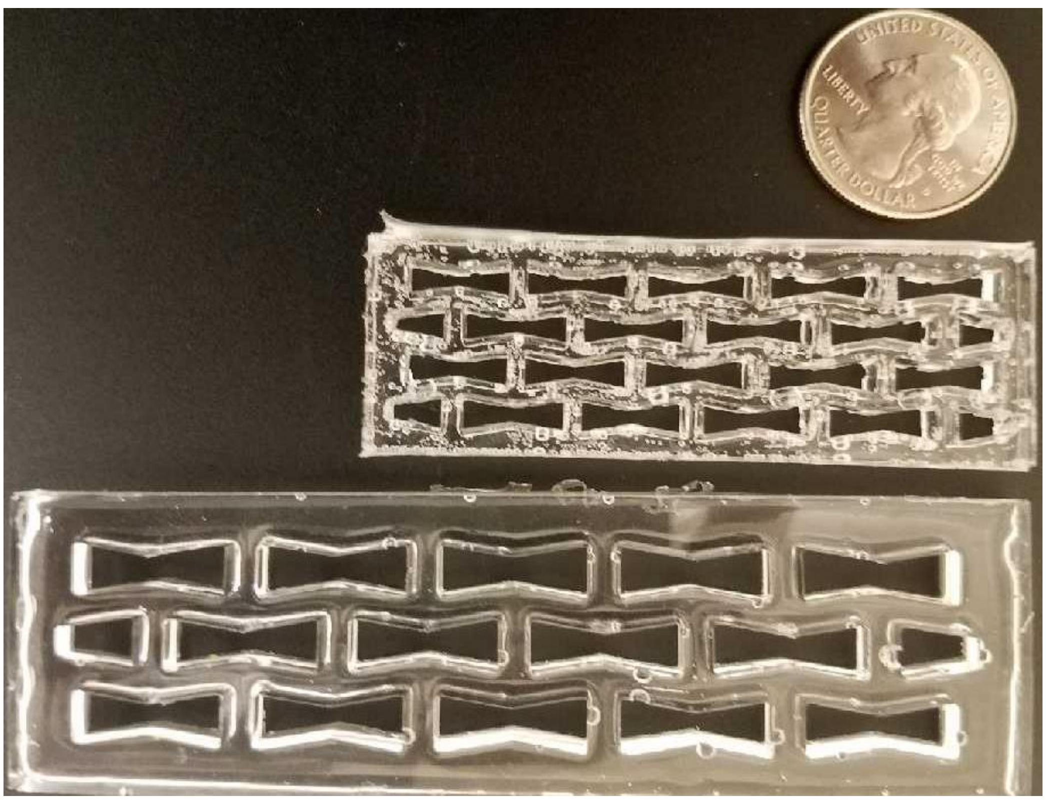

Figure 19: Re-entrant Masters-Evans model 1 small and medium This shows to scale the small-size piece compared to the medium-size piece created from the PDMS mold that was used for testing

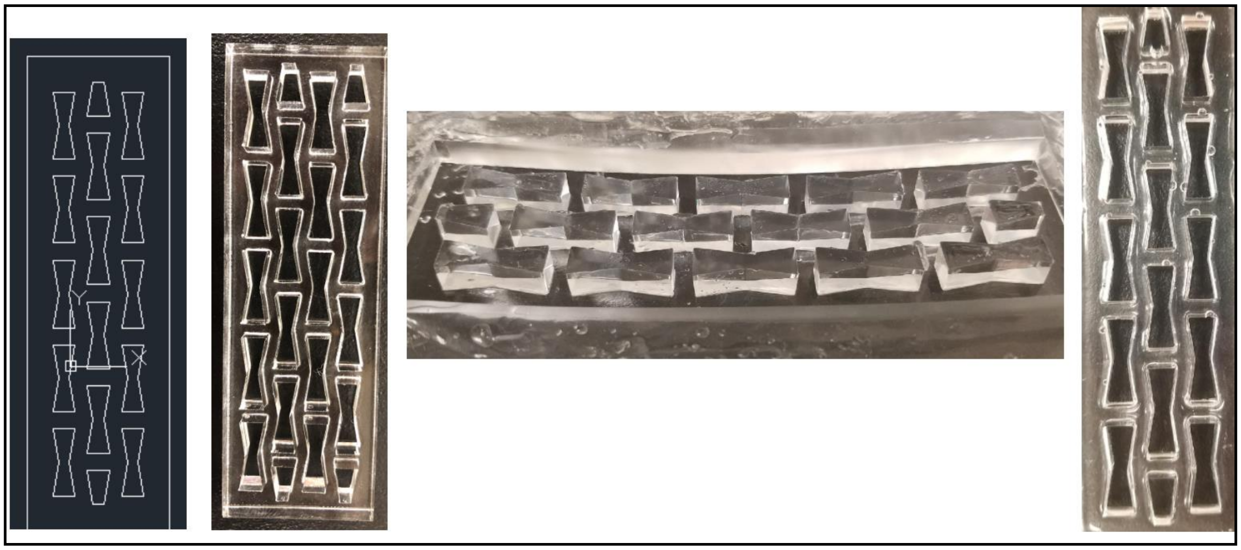

Figure 20: Mold making process on the left it shows the SolidWorks design we created, then the laser cut acrylic mold, next is the PDMS mold we created from the acrylic piece, then the Polyurethane/PDMS piece resulting from the PDMS mold

3.1.1.2.1) Challenges:

There were few challenges when cutting the acrylic pieces with the laser cutter. It was an efficient process that cut out the designs nice and cleanly. Issues were that while the laser cutter is in use you must be cautious and watch while it is cutting in case of a fire. Also, once the pieces were cut out since the features were so small they were still stuck to the main acrylic piece to had to be gently pushed out to get the final desired mold. Also, when creating the small design of model 2 we had issues removing the structures from the PDMS mold because they were so little, so we were just able to create the mold with larger structures. For the smaller structures in model two we ended up using ⅛" thick acrylic when laser cutting then it was easier to remove the materials when making the mold because of the lower aspect ratio.

3.1.1.3) Combining Auxetic Pieces:

Once the best auxetic pattern, size, and material was determined upon testing we combine the pieces together. We decided to create the heel portion of the support separate from the rest of the support that will contain the arch support and material for comfort. The heel portion is created in SolidWorks and resembles the structure of most heel supports with the auxetic pattern included at the correct position under the heel to provide extra support when active. This design is then cut out on the laser cutter and we performed the same process as before by making a mold of

PDMS out of the laser cut piece then filling it in with the chosen material. The result gives us ¼" pieces of the heel support. Then we combined these pieces together to get the desired width of the support. To combine the piece first make a few PDMS molds of the design. Then pour the polyurethane into the molds and let it cure in the oven for about two hours. After two hours the polyurethane pieces can be removed from the PDMS molds and then stuck together, making sure they are lined up evenly next to each other and placed in the oven to finish curing. This results in the final heel portion of the orthotic.

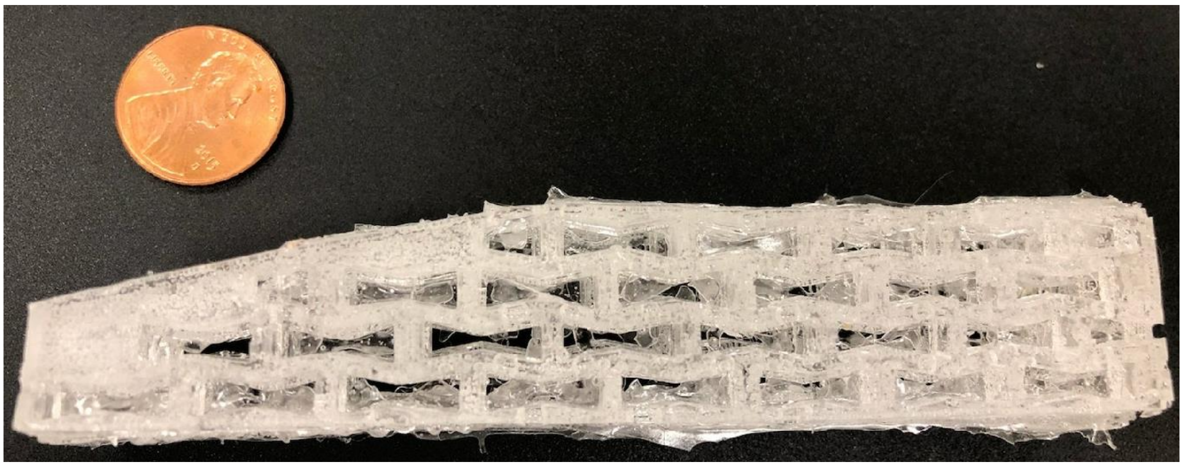

Figure 21: Heel portion of support This is the combined auxetic ¼" pieces that were stacked together and bonded to create a 1" wide piece of the heel support

3.1.2) Determining Best Auxetic Structure:

We created our own apparatus for testing the auxetic structures. We decided to create our own apparatus because the best machine we could use was the Mach1 which was not suitable for imaging and for the desired parameters we wanted to measure. In determining the best auxetic structure we want to look at the Poisson ratio as well as the maximum area expansion (See Appendix 1 for equations). These are determined mathematically once the material is stretched.

3.1.2.1) Clamp Set-up:

We wanted to make a setup that would be able to stretch the various auxetic patterns that we designed and have it to we would be able to take images and record the distance stretched of the material.

To do this we first wanted a base to attach it to, so we purchased a polyethylene strip. Once we went to set up this strip as a base for our clamp set-up in the lab, we quickly realized that the strip was too long. We then cut the strip down to table length with a hand saw and used sandpaper on the edges to ensure smoothness and evenness. We also 3-D printed holders for the clamps to immobilize them as best as possible in the hopes that this would reduce experimental error due to inconsistencies in our testing apparatus. To achieve this, we measured the standard clamps to be used in our apparatus and used the Ultimaker to 3-D printer to create a box that would fix the clamp in place. While this fixed the body of the clamp in place, the hinge was left free to better control the grip on the materials being tested.

We also decided to 3-D print a pair of blocks with grooves in them to act as guides and attached them to the edge of the apparatus so that string could be guided off the table evenly in both directions. This string was then attached to the clamps and fed through the guides at each end of the table. This string could then be attached to weights and hung off the end of the table. This apparatus will allow us to effectively test existing orthotics as well as our auxetic material.

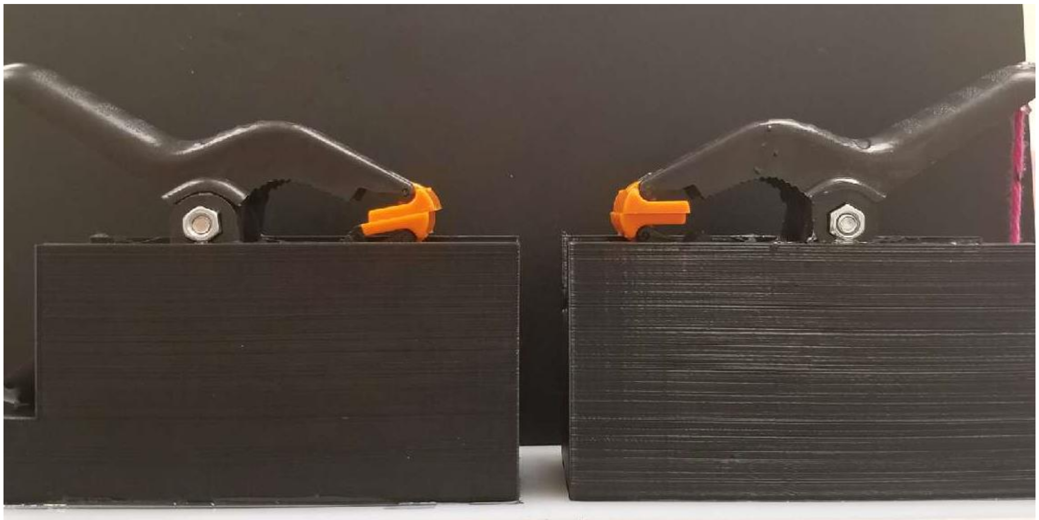

Figure 22: Clamp set-up This image shows the set-up we used for testing the heel support pieces, consisting of clamps help in place in the blocks and string on the right where weights are attached

Figure 23: Angled view of clamp set-up Shows clamp set-up for testing weights and the pink yarn being guided in the black block before going off the table where it is attached to the desired weights

3.1.2.1.1) Working Principle:

This experimental set-up is based on our need for an apparatus that could consistently apply a lateral stretching force on an object. This is needed to enforce the concept of our heel support as well as confirm it is auxetic. We will use this set-up to test three heel supports that are currently on the market as well as the structures we create to determine the most auxetic structure and quantify our results. This works because as the weight it applied to the materials it will stretch in the lateral direction. A normal, non-auxetic structure will compress in the axial direction when weight is applied, like the heel supports, but an auxetic structure will expand in the axial direction so it will therefore have a negative Poisson's ratio and the area will expand, which is the desired quality of our product.

3.1.2.1.2) Testing Procedure:

To have accurate testing we need to make sure the testing set-up device is precisely set-up and arranged so that we can record accurate, repeatable measurements for all the structures we are testing. Once it is set-up we will begin by testing the three on-the-market heel supports. This is to have objects to compare our results to. This is done by clamping the heel support into the contraption. Make sure the clamp is in firmly, so they do not slip; double check that the device is set-up correctly and begin recording. We filmed the entire process as well as took pictures whenever we added weight to get accurate results. Begin with no weight, then add 200 kg to the end of the string and record the data. Then we repeated this process recording the results at 400 kg and 800 kg. This was repeated with the additional two on-the-market heel supports. Finally, we began testing the auxetic structures we created in the same manner by clamping them in and then adding increments of weight. When recording this data, we were careful not to change anything except the weight to have accurate, consistent data.

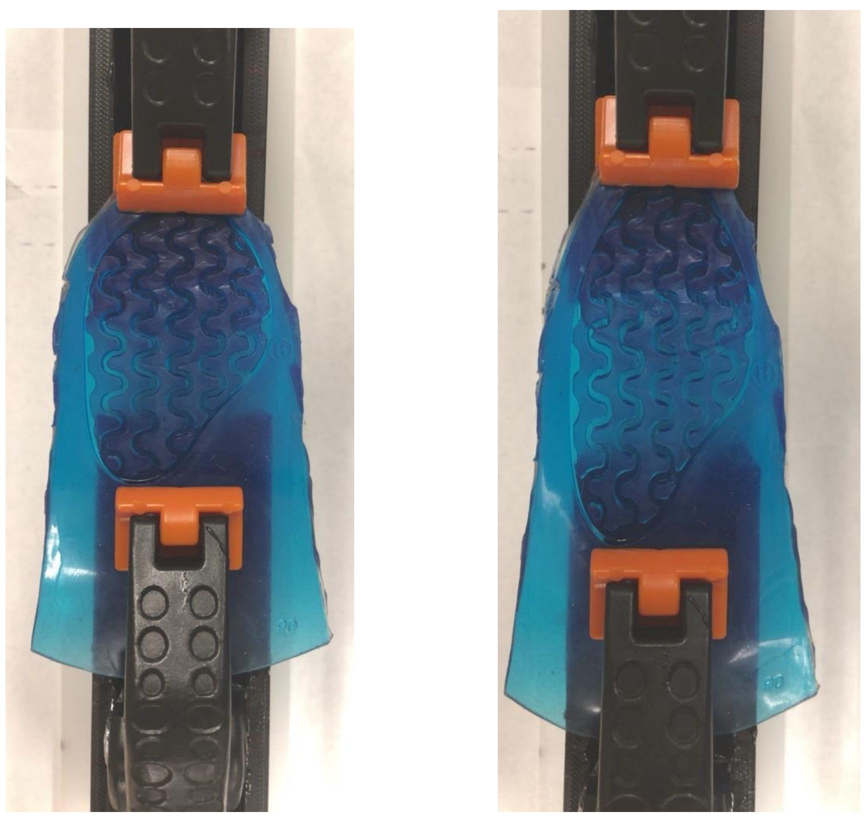

Figure 24: Example of testing Comparing the on-the-market heel support with the weight at 0 kg on the left and 800 kg applied on the right

3.1.2.1.3) Challenges with Clamp Set-up:

Challenges with the clamp set-up is that when measuring and collecting data we must make sure to be exact and concise and when we are going to take measurements it is best to do it all at once so that no aspect of our set-up is disturbed in between. There were some issues with the clamps slipping, but by making sure more material was clamped under that problem was prevented. Also, when clamping the pieces, we made sure it was taught so that there were no inaccurate measurements when the weight was applied.

3.2) Materials:

• Molds	• Hand Saw
• PDMS	• Clamps (2)
• Petri Dishes	• Polyethylene Strip
• ¼” Acrylic	• Sand Paper
• Epilog Laser Cutter	• Scotch Tape
• Punch Tool	• Phone (with camera)
• Aluminum Foil	• Ultimaker 3-D Printer
• String	• Phone Stand
• Weights	• Rulers
• ⅛” Acrylic	• Tweezers
• Polyurethane	• Sharpies
• Oven	• Scissors

Chapter 4: Results:

4.1) Poisson Ratio/Area Change Testing:

In our testing we decided to focus on the Poisson ratio and the change in area when the material is stretched laterally. As mentioned before we tested three current heel supports that are on-the-market to get a baseline and to be able to compare the results. After testing the three heel supports we began testing the small and medium sizes on our two auxetic patterns using both PDMS and Polyurethane.

4.2) Hypothesis and Initial Tests:

From common knowledge we believe that the three current heel supports will not expand in the axial direction when stretched. Therefore, we think they will have a reduction in area and a positive Poisson ratio meaning they are not ideal for our device. Since pattern 2 of our auxetic has a greater area expansion when stretched we believe it will be the ideal pattern for our experiment compared to pattern 1. Also, the smaller size should have more expansion than the larger size since the features are closer together. Overall, we believe that in testing the small pattern 2 auxetic structure will yield the best results, but we are not sure if PDMS or Polyurethane will be a better material to use, but polyurethane is a common material used in shoes inserts and could be a studier option.

4.3) Heel Supports:

Initially we started by testing the three heel supports. The first heel support did compress in the axial direction when stretched laterally which was expected (seen in Figure 24). The other two heel supports were very stiff, and we were not able to see any stretch when the weight was applied.

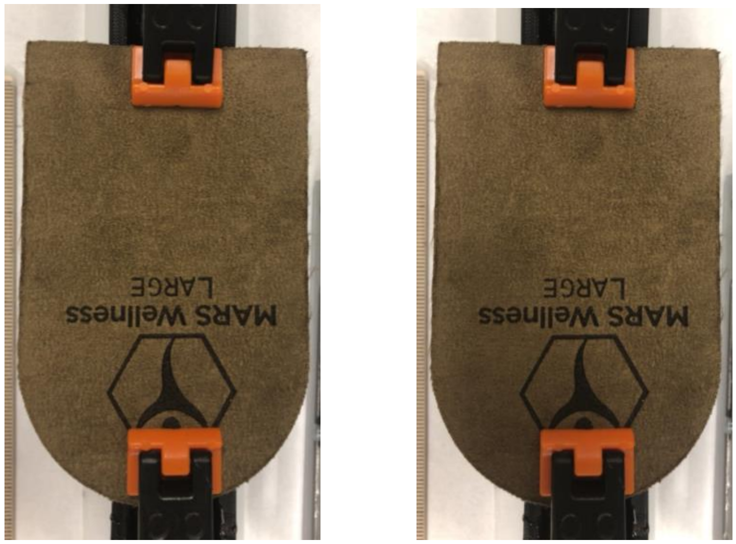

Figure 25: Heel support 2 clamp set-up the image on the left shows the support at 0 kg and the image on the right is with 800 kg applied and there is no stretching of the support

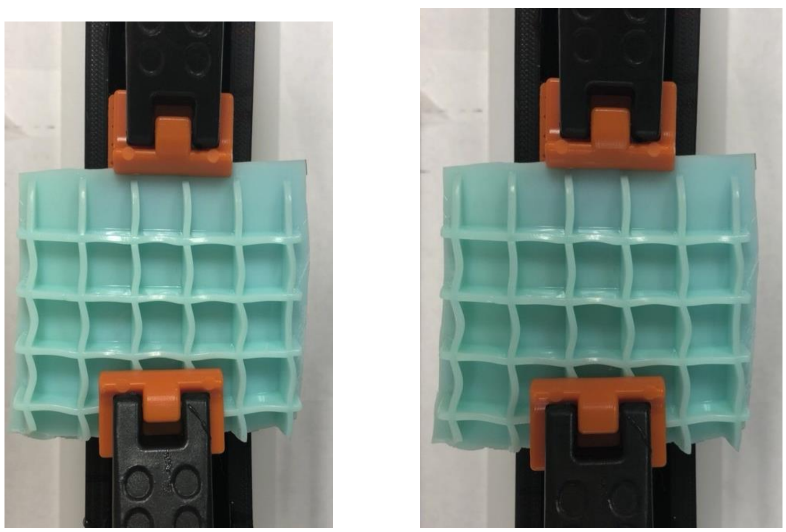

Figure 26: Heel support 3 clamp set-up the image on the left shows the support at 0 kg and the image on the right is with 800 kg applied and there is no stretching of the support and the clamp was slipping off

4.4) Auxetic Structures:

We began by testing the pattern 1 auxetic structure in Polyurethane. We tested the small and medium size pieces we had created and as seen in the images below they both expanded in the axial direction when stretched laterally which demonstrates a negative Poisson ratio and area expansion. Next, we tested the small PDMS structure which again showed similar results as the small Polyurethane structure. When increasing from 400 kg to 800 kg we can really see the difference in expansion of the features.

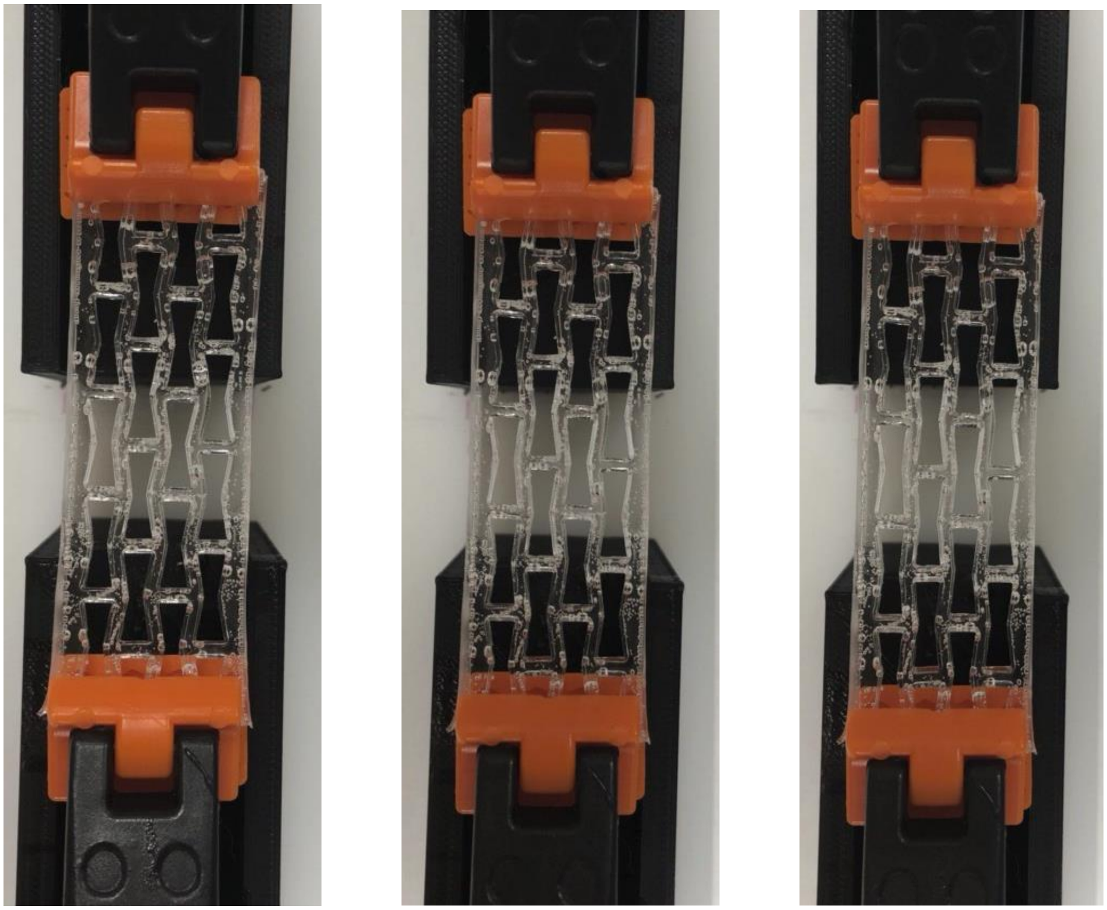

Figure 27: Small polyurethane model 1 clamp set-up the far left shows the small polyurethane of model 1 when 0 kg is applied, the middle shows the same structure with 400 kg applied, the far right shows the same structure with 800 kg applied and we can see the increase in features in the axial direction (the smaller PDMS of model 1 showed similar results)

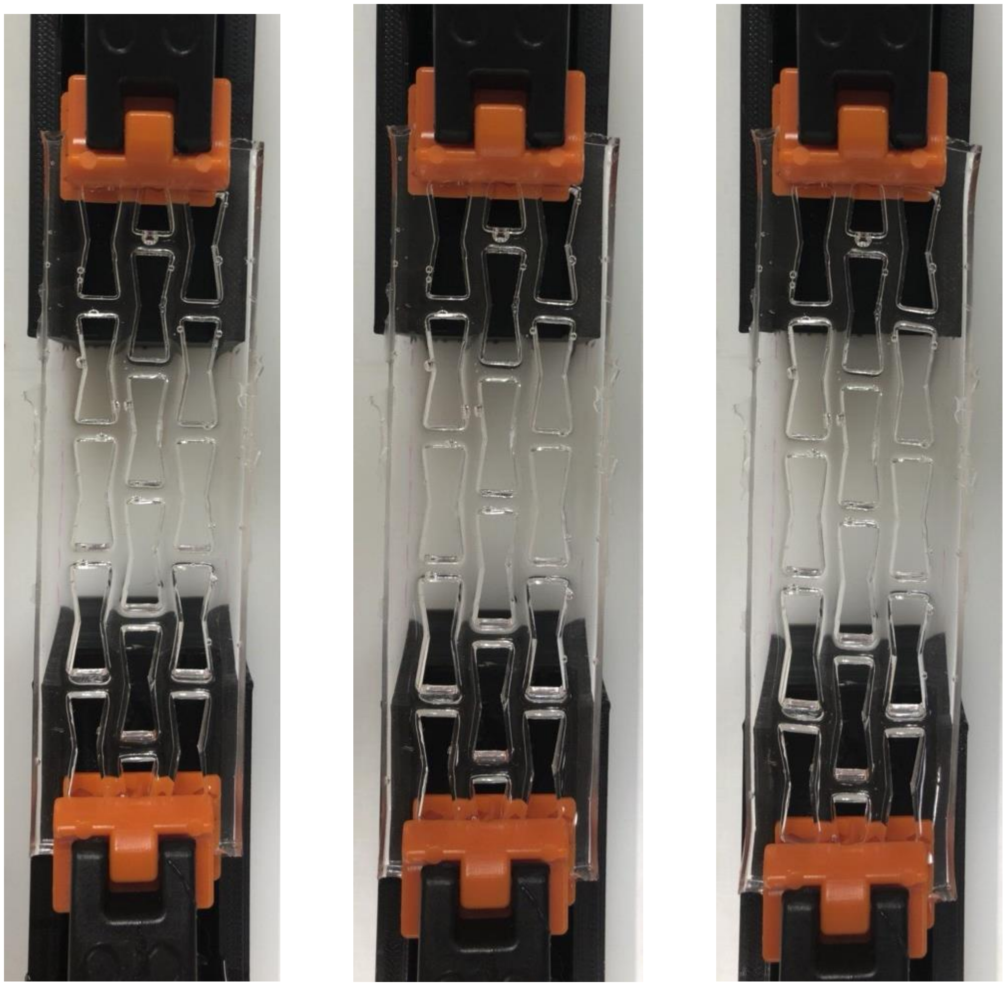

Figure 28: Medium polyurethane model 1 clamp set-up the far left shows the medium polyurethane of model 1 when 0 kg is applied, the middle shows the same structure with 400 kg applied, the far right shows the same structure with 800 kg applied and we can see the increase in features in the axial direction (the smaller PDMS of model 1 showed similar results)

4.5 Analysis of Results:

Analysis of our images was done using ImageJ software. ImageJ is a software that allows the user to convert pixel distance on an image into a distance measurement, such as centimeters or inches. To carry out this specific conversion, the software requires you to measure out and report an object of known scale from within the picture, so that a set reference for conversion of pixels to distance is present. For each of the orthotics and auxetic structures accounted for in the table below, we took pictures of them being stretched in our clamp setup at 0kg, 200kg, 400kg, and 800kg. Then, we measured a part of our clamp setup that would be consistent in each of the photos we took, the width of the black clamp holders, and used that as our base value for the distance to pixel base measurement.

Then, after using that value for the base conversion on each individual photo, we measured the distance between the smallest features on each of the orthotics or auxetics and recorded each of these values on a spreadsheet. After these distances were recorded in millimeters, thanks to the ImageJ conversion function, we plugged these values into the equation for the Poisson's ratio (found in the appendix). The final reported value in the table below is the average of six of the Poisson's ratios calculated for each material, with the reported error being the standard deviation from the mean for each of the seven structures.

Structure	**Poisson's Ratio**
Dr. Scholl's Heel Insert	0.94 ± 0.07
Tuli's Heel Cups	0.83 ± 0.1
Medium Polyurethane model 1	-1.85 ± 0.26
Small PDMS model 1	-1.55 ± 0.5
Small Polyurethane model 1	-1.87 ± 0.24
Small Polyurethane model 2	-0.08 ± 0.02

Table 5: Poisson's Ratio of structures tested Shows the 7 different structure we tested, and their corresponding Poisson's Ratio based on ImageJ analysis

4.6) Compression Testing:

Additional testing, we wanted to do to confirm that our auxetic was better than heel supports on the market was compression testing. For this we created a normal polyurethane piece to test against our auxetic polyurethane heel support. This piece was created by making rectangles ¼" thick the same dimensions as our individual auxetic pieces and bonding them together. The first test we wanted to do against our auxetic support and normal polyurethane test was compression testing. We used the Mach I machine to apply uniform, constant force on the pieces and measured the Young's Modulus. When the pieces were compressed 5 mm in depth the Young's Modulus of the auxetic structure was 92 kPa and the Young's Modulus of the non-auxetic polyurethane structure was 2000 kPa. The auxetic structure has a Young's Modulus very close to the Young's Modulus of the calcaneus bone, which is 175 kPa [17], so this demonstrates that our auxetic is softer, which could provide better comfort for the user compared to non-auxetic polyurethane.

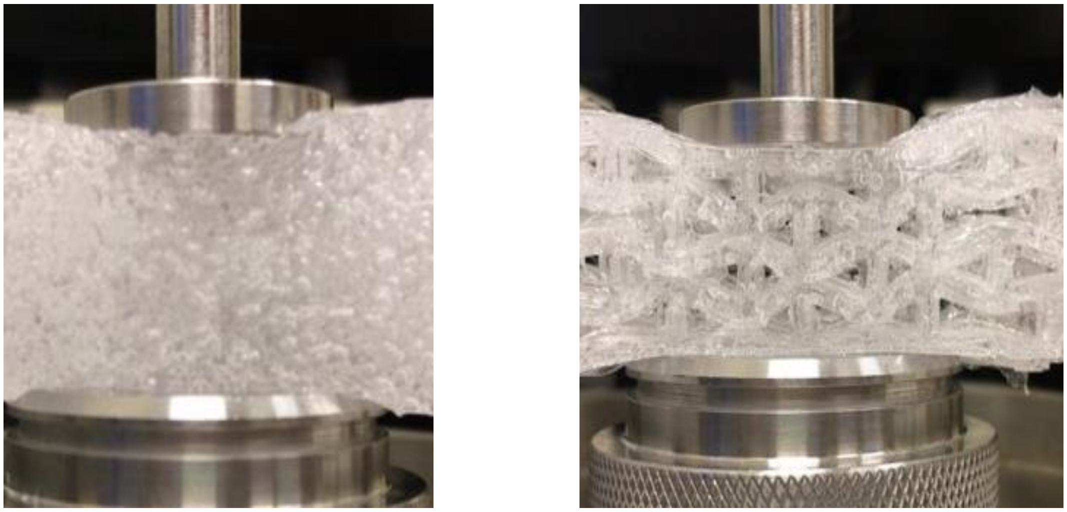

Figure 29: Compression testing Showing the compression at 5 mm of the non-auxetic polyurethane piece on the left and the auxetic polyurethane piece on the right

4.7) Shock Absorption Testing:

Additionally, besides performing compression testing we wanted to perform shock absorption tests. This was using the non-auxetic and auxetic polyurethane heel supports used for compression testing. To perform these tests, we created a testing set-up. This consisted of a ruler which was placed next to the support that was taped to the table so that it was stable. We had a steel ball which was dropped from a constant height and then recorded how high the ball jumped off the structure. From these two heights and the mass of the ball we were able to calculate the energy absorbed by the auxetic piece. The initial height that the ball was dropped was 9.5". The average final height of the ball drop with the non-auxetic polyurethane piece was 5.56" and whereas the average final height with the auxetic polyurethane piece was 4.88". To calculate the energy absorption, we use the formal $g*m*(h_f-h_i)$. Therefore, the auxetic piece had an energy of 0.148J and the non-auxetic piece had an energy of 0.126J. That means that there is 0.022J more energy absorbed by the auxetic structure than the non-auxetic in this experiment. Also, the percentage of energy absorbed in the auxetic piece is 48.63% and the percentage of energy absorbed in the non-auxetic piece is 41.47%. This demonstrates that 7.16% more energy is absorbed in the auxetic piece compared to the non-auxetic polyurethane piece. With this information we decided that we needed to complete more testing in order to see if the energy absorbed would be more substantial, so we tested foams. The three foams we tested were Soma Foama 15, Flex Foam IV, and Flex Foam X. The Soma Foama 15 had the lowest Young's modulus of about 26kPa and the Flex Foam X had the greatest Young's modulus. The results from this testing are included in the table below.

Type of Material	Energy Absorbed [J]	Energy Absorbed [%]
Auxetic Polyurethane	0.148	48.63
Non-auxetic Polyurethane	0.126	41.47
Soma Foama 15	0.172	56.58
Flex Foam IV	0.160	52.63
Flex Foam X	0.135	44.21

Table 6: Energy absorption of materials tested Shows the energy absorbed by each of the different foams and elastomers that we tested

From these results we can conclude that a material with a higher Young's modulus will result in less energy absorbed. The Soma Foama 15 and the Flex Foam IV demonstrate that more energy is absorbed during testing, but these foams are too soft and will compress over time. Also, if the material is too hard, like the Flex Foam X and non-auxetic polyurethane, this results in less energy absorption and the support is also uncomfortable to the user. This shows that overall the auxetic polyurethane piece gives the ideal energy absorption because it is sturdy while comfortable. These results can be further improved by stretching the auxetic piece while dropping the ball to determine if we get a higher energy absorption. Also, it can be improved by making smaller auxetic patterning inside the polyurethane piece to create a lower Young's modulus and would therefore have higher energy absorption.

Figure 30: Shock absorption testing on the left is the non-auxetic polyurethane structure that on average had a final height of 5.56” when dropped from 9.5” and on the right is the auxetic polyurethane structure that on average had a final height of 4.88” when dropped from the same height

4.8) Discussion:

Overall, through our testing we determined that the best auxetic structure was the small, polyurethane model 1. This gave us the most negative Poisson’s Ratio which means that when stretched laterally it resulted in the greatest increase in height. This will serve to provide more support when the individual is walking allowing for comfort, healing of the tendon, and shock absorption. The compression testing showed us that our created auxetic structure was comfortable when pressure was applied, and the shock absorption test showed us that our auxetic support provided more energy absorption than non-auxetic polyurethane so there is not as much force exerted on the Achilles tendon when the user is active.

Chapter 5: Professional Issues:

5.1) Cost Analysis:

When analyzing the projected cost for our prototype orthotic, the cost will be derived mostly from the materials that make up the final prototype. Factors such as cost to build our testing apparatus, mold release, and materials ordered but not utilized in our final design should not be included in the final price of our orthotic. These additional materials are intended to provide improved effectiveness and durability during testing. Also, even though we are utilizing different foams, elastomers, and devices such as the 3-D printer or laser cutter these are not included in the final cost of our product on the market because these materials are used in research. Overall, our orthotic should cost just as much or even a fraction more than other products on the market.

5.2) Engineering Standards and Constraints:

5.2.1) Ethical Considerations:

There are certainly a few ethical concerns to be considered in the context of our orthotic and its intended use. The first ethical concern is from a sustainability standpoint, as we will be using various foams, elastomers, and polyurethanes, as well as 3-D printed plastic molds to shape and design our auxetic pattern as well as our final prototype. Although the fabrication of our prototype will not leave a massive carbon footprint, it is important that we think about being sustainable and ecologically friendly when disposing of our auxetic pattern molds, early stage testing materials, and other waste products associated with our design process. Another ethical concern is from a general human health standpoint. Since our proposed orthotics intended purpose is to improve quality of life and daily activity for people recovering from Achilles injuries, our orthotic should be accessible to these people. Additionally, the orthotic should not sacrifice another aspect of the intended user's health or wellness while solving the problem of supporting the Achilles tendon (e.g.: transferring the force of impact when running to another part of the foot or body to divert it from the Achilles).

5.2.2) Social Considerations:

Orthotics are important devices for many individuals. They are used by professional athletes as well as everyday people for a variety of foot related injuries. Our device will help serve the general population because it will not only help with Achilles tendon therapy, but also provide comfort for the foot leading to help and support in issues with arch support, plantar fasciitis, or ankle injuries, especially with side ankle supports attached we are able to reach a large population of consumers. In our active, constantly moving society it is important for individuals to be able to move and function and if they suffer from foot/lower limb injuries it can greatly inhibit their daily lives and activities. Therefore, we constantly see a variety of supports ranging from shoe inserts to ankle supports to help individuals feel more comfortable and continue being active. We believe our device will add into this wide category of supports because it will allow consumers to continue their daily activities. They can still be physical and apply force on their injury because our support will compensate for that impact and provide them with a comfortable gait. Our device will also decrease or entirely limit trips to physical therapy or time off work because it allows the tendon to heal naturally and the user to remain active without decreased pain and be comfortable while maintaining a stable gait.

5.2.3) Economic Considerations:

The techniques we are using the create this orthotic makes it relative cheap. Economically this can have a great impact. Since we are using techniques like 3-D print and laser cutting through the school the expense is not that large. Also, a lot of the cost of materials like PDMS and Polyurethane is because of research and having to create several iterations of our design, however once we decide on the correct design that works the most effectively then it will be more cost effective. The design the device we will already have the acrylic pieces made and they can easily be re-used to make more molds, also once one PDMS mold is made from the acrylic that mold can easily be re-used to create several structures. Our design is also cost effective because when bonding the thin heel auxetic portions together the material easily bonds to itself, so we do not need expensive equipment to do this bonding. These considerations greatly help lower the cost of our device and when manufacturing large-scale with the correct, larger machinery it will greatly lower the cost and time spent on making the orthotic.

5.2.4) Health/Safety Considerations:

Health and safety is an important consideration in our design as well. This relates to the individuals creating the device as well as the consumer. First, when operating machinery such as the laser cutter one must be properly trained and be careful because it can be a dangerous machine. Also, when working with chemicals, such as PDMS there must also be proper training on how to use these chemicals and be safe while using them. The consumers health and safety are important as well because we need to design a device that does not do more harm than good to them. Our orthotic must be functional and provide support to their tendon in the correct position under their heel so that they are not further injured. We must also consider the material and if consumers can have allergic reactions and other safety concerns such as being less stable when walking or developing blisters if the device is uncomfortable.

5.2.5) Aesthetic Considerations:

When comparing our orthotic to similar products on the market, we would have to factor in aesthetics. This relates to the social aspect of our product. If this device does not work as it should and does not provide comfort and healing to the individual, then how is it better than existing orthotics? We need to be sure this device works accurately and will indeed help with Achilles tendon therapy by shortening the tendon and providing extra support during impact. Along with having a device that works correctly we also need a design that is attractive. If the orthotic is not attractive even if it is functional consumers may not want to buy it.

Chapter 6: Final Thoughts:

6.1) Summary:

Our lower limbs are an important aspect of our body and our feet are used daily whether participating in athletic events and sports, walking our dog, or moving around at the office. Achilles tendon injuries highly impact many athletes and non-athletic individuals and these injuries can easily occur with a misstep in the gait cycle. Achilles tendon injuries can result in individuals not being able to attend work, spending large amounts of money on physical therapy, and athletes not able to continue their athletic career. Our active auxetic support for Achilles tendon therapy will resolve these issues because our supports auxetic heel structure allow the Achilles tendon to be shortened when active to promote healing and it absorbs the impact when the user is active. This will save consumers money and time spent away from work and they can continue to participate in daily activities and their physical lifestyles. Our support was made using the laser cutter and then mold making techniques with elastomers to create the desired auxetic structure. We created several iterations of the auxetic structures and determined the best structure based on the Poisson's Ratio and area expansion or reduction of the piece on our clamp set-up. We then bonded the pieces together to create the heel portion of the orthotic and added the additional arch support for comfort and to enhance the stretching in the lateral direction. With added ankle supports this allow a stable gait when the individual is active and additional support and preventions of ankle injuries. Overall, our active support for Achilles tendon therapy provides users with a comfortable support that facilitates healing and allow them to continue to be active while wearing the support.

6.2) Future Work:

For our future work we want to confirm that our auxetic structure works well under compression and strain. To do this we would set-up a test combining Mach 1 and stretch the pieces longitudinally at the same time. This would simulate a person walking since the structure would stretch and compression almost at the same time. We also want to work on creating a full prototype of the entire support. This would include an additional pad around the heel with a lip for additional comfort and support, as well as an arch support for comfort and to increase the stretching longitudinally of the auxetic structure. Finally, we want to investigate other rehabilitative applications of auxetics and see where else they can be used to help heal, provide support, and additional comfort to parts of the body.

6.3) Lessons Learned:

Throughout this experienced we have learned and gained a lot of valuable information. We have had the opportunity to learn the process of developing a medical device, starting with research, design, testing, and more testing. We have discovered that it is not always a success and not as easy task. This project took a lot of hard work and time, but it is something we can always look back on as an incredible experience that we can use in interviews as well as techniques of testing and using equipment that will be helpful in our future careers. This experience has taught us a lot and brought us together. It has gone by so fast and even though at moments it may be stressful and frustrating when experiments didn’t work it was an experience we will always remember because we had the opportunity to design and create an idea of our own which will be valuable skills for our future.

Appendix 1: Equations Used to Find Best Auxetic Structure

Equation 1: **Poisson's Ratio**

Poisson's ratio, $\nu = -\varepsilon_{trans}/\varepsilon_{axial}$. ε_{trans} and ε_{axial} are the transverse and axial strains when the material is stretched or compressed in the axial direction. Strain refers to the change in length of the material being stretched divided by the material's initial length. Transverse strain refers to the strain of the material perpendicular to the direction of the stretching or compressive force. Axial strain refers to the strain of the material in the direction of the stretching or compressive force.

Equation 2: **Maximum Area Expansion**

Maximum area reduction: $MAR = -(A_0 - A_f)/A_0$. A_0 is the initial area of the 2D auxetic structure. A_f is the final area of the auxetic structure after the application of a uniaxial load.

Appendix 2: Making PDMS and Polyurethane

PDMS Procedure:

- Use PDMS Part A and Part B
- Mix Part A and Part B together (ratio of part A:part B should be 10:1)
- Pour Part A into plastic cup and weigh until desired amount (ex.-30g)
- Pour Part B into plastic cup and weigh until desired amount (ex.-3g)
- Mix part A and part B together in a separate plastic cup
- Place plastic cup with mixture into the hybrid mixer's cup holder and calibrate the weight scale in the mixer to the weight of the plastic cup with the PDMS mixture and cup holder (cup holder weighs 40g)
- Degas the PDMS mixture in a desiccator under vacuum for at least 10 minutes or until there are no more air bubbles in the mixture
- Pour the PDMS mixture into the mold
- Let cure for at least 2 hours in the oven at 80°C
- Carefully remove the cured PDMS from the mold

Polyurethane Procedure:

- Use Polyurethane Part A and Part B
- Mix Part A and Part B together (A:B should be 10:9.4)
- Pour Part A into plastic cup and weigh until desired amount (ex.-20g)
- Pour Part B into plastic cup and weigh until desired amount (ex.-18.8g)
- Mix Part A and Part B together in a separate plastic cup

- Place plastic cup with mixture into the hybrid mixer's cup holder and calibrate the weight scale in the mixer to the weight of the plastic cup with the polyurethane mixture and cup holder (cup holder weighs 40g)
- Degas the Polyurethane mixture in a desiccator under vacuum for at least 10 minutes or until there are no more air bubbles in the mixture
- Pour the Polyurethane mixture into the mold
- Let cure for at least 3 hours in the oven at 80°C
- Carefully remove the cured Polyurethane from the mold

Appendix 3: Mold Making Process

PDMS Mold Making Procedure:

- Place a thin sheet of aluminum foil on the bottom of a petri dish
- Smooth out the aluminum foil with a flat object to make sure the aluminum foil adheres tightly to the bottom of the petri dish
- Create a rectangular box out of the aluminum foil by turning up the edges of the aluminum foil to create the walls of the rectangular box (make sure the edges of the box are about a thumb width away from the edges of the acrylic mold that will be placed inside the box)
- Place two pieces of tape on the bottom of the acrylic mold to seal one face of the acrylic mold (this step is necessary to make sure the PDMS or polyurethane mixture does not leak out from the bottom of the acrylic mold when the mixture is poured on top of the mold)
- Place two more pieces of tape on the two edges of the acrylic mold with the width of the tape being greater than the height of the acrylic mold, making sure the sticky part of the tape is facing towards the face of the acrylic mold that has been sealed with tape
- Place the acrylic mold into the aluminum foil rectangular box with the edges of the acrylic mold taped down to the bottom of the rectangular box (this step is necessary to make sure that the acrylic mold adheres tightly to the bottom surface of the petri dish to prevent any PDMS mixture from flowing under the acrylic mold)
- Pour the 10:1 PDMS mixture into the aluminum foil rectangular box covering the whole surface of the acrylic mold and creating a 3-4 mm buffer layer above the acrylic mold to avoid tearing the cured PDMS mold when peeling the mold off of the acrylic mold
- Place the petri dish with the acrylic mold and PDMS mixture into the oven at 80 degrees Celsius for at least 2 hours

Appendix 4: Gaant Chart:

Tasks	**Owner**	October	November	December	January	February	March	April	May	June
Division of Tasks	All									
Research Current Technology	All									
Narrow Topic-Problem Statement	All									
Establish Budget	All									
SolidWorks Designs	Anna									
Fabrication Protocol	Kseniya									
Making Molds and Auxetic Pieces	Anna/ Kseniya									
Designing Test Set-up	Ishaan									
Testing Structures	Anna/ Ishaan									
Analyze Data	Micaela									
Optimize Auxetic Structure	All									
Design Final Orthotic	All									
Testing Final Orthotic	Ishaan/ Micaela									
Write Thesis	Anna/ Micaela									

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