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3D PRINTABLE ACCESSIBLE FOOTWEAR

MEC 825 - Design Project Report

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Abstract

Engineering at its fundamental core is geared towards helping human beings, oftentimes in small incremental steps that in hindsight looks like massive leaps. An idea that initially originated from a conversation between a nurse and software engineer at Sunnybrook Health Science Centre blossomed into a three month project that aims to take the small incremental steps necessary to facilitate the massive leaps. The first phase of the project begins with clearly defining the problem and a preliminary research stage to form a strategy to solve the problem at hand; the primary problem being a lack of customizable and accessible footwear for those that need it. By evaluating ways to improve accessibility and then integrating customizability, innovating existing accessibility solutions with 3D printing is possible to create a customizable accessible shoe. The design process consisted of first establishing a parametric design for the insole and midsole as these are arguably the most ergonomically impactful aspects of the shoe and also require the greatest amount of customizability. With the base established, the upper and accessibility mechanisms were designed and prototyped. The prototyping stage evaluated not only the viability of different designs but showed that the best way to assemble the shoe was to print it all in one go, rather than adhering different parts together. With the final design established after significant prototyping and concept refinement, a preliminary cost analysis shows that a pair of 3D printable shoes costs $68.33 to produce. Further work can be done by continuing to experiment with design choices like infill density and material choices as it can help address health conditions not immediately considered in this report. Ultimately, by broadening the scope beyond seniors, a larger audience can be reached to increase understanding of human comfort needs.

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1. Introduction

It is hypothesized that shoes have been around for more than 40,000 years [1]. While the design of shoes has progressed significantly over the years, becoming more ergonomic and biomechanically sound, there remains a glaring problem with them that still has not been fully explored and addressed. Many people instinctively bend down to put shoes on and tie the laces, not thinking twice about it. However, there is a subset of the population where that simple act is either impossible or more than a mere afterthought. Whether it be due to old age, arthritis, or partial paralysis, there are a vast number of people that lack the dexterity to wear conventional shoes. There is a growing category of shoes called 'hands-free shoes' that aims to address the needs of these individuals. Concepts ranging from a flexible heel to a shoe that bends into two have all been successfully made. However, another problem with shoes is their manufacturing time and process. Manufacturing a shoe requires a significant amount of human labor and coordination. It can easily take 60 to as many as 120 days for a shoe factory to fulfill a production order [2], a vast majority of which is attributed to organization and coordination; this includes getting the shoe materials and processing them. Furthermore, the current manufacturing process for shoes makes it difficult and expensive to make more custom shoes for individual buyers. However, 3D printing can remedy a lot of these problems and new startups have begun exploring 3D printing shoes. The aim is to bridge the gap between 3D printed footwear and hands-free footwear to create easily customizable hands-free shoes that can cater to each buyer's feet.

The need for custom-fit accessible footwear was first identified at Sunnybrook Health Sciences Centre when conversing with nurses responsible for taking care of the geriatrics and veteran ward. Those nurses described the struggle their patients encountered when using traditional footwear since many of them were unable to bend down to secure their shoes properly. This gave the opportunity for injury to arise and especially became a grave concern when one nurse saw their patient walking in the ward with one shoe haphazardly put on and the other foot in a sock exposed to the hospital floor. The idea for easily-accessible footwear has been mentioned in the hospital, but due to the complexity of finding properly fitting shoes for such a wide range of patients, slippers were made the de facto standard. However, nurses have also expressed concern that those shoes do not offer proper support for their patients. A proper solution would be shoes that could be on-demand manufactured for each patient quickly and cost-effectively.

Sunnybrook Health Sciences Centre is not the only institution to experience the pains of footwear that is difficult to put on; teachers at the Toronto District School Board responsible for taking care of kids with special needs have shared the same thoughts. Children with autism tend to lack the fine motor skills to complete things that the average person wouldn't think twice about, like cutting paper with scissors, zipping up a jacket, or tying shoelaces. The goal of these special education programs is to help children develop the skills necessary to become independent, and by giving these kids the ability to put on their own shoes, it helps reduce reliance on others around them. Putting accessible shoes into the hands of parents of children requiring special assistance will only help accelerate this independence.

The market contains products that already address many of these concerns using various solutions to make the shoes accessible. These products addressing special needs for accessibility include the Nike Go FlyEase and associated FlyEase series, Friendly Brand, Kizik, and Vans slip-on footwear. 3D printed shoes, although somewhat of a novelty, also exist in the market and are available from such vendors as Unis Footwear, SCRY, Adidas, and Parametriks. The literature review explores the existing hands-free and 3D printable footwear in greater detail along with diving deeper into the needs of the user groups.

2. Literature Review

Designing footwear is far from a novel concept; designs, use cases, and special considerations have been around for tens of thousands of years. The literature review is a compilation of key aspects of the initial research that goes into designing a shoe. First identifying the key user groups and their needs and limitations. Then highlighting and summarizing the existing products that will be taken into account throughout the design process. Accessibility is the driving force behind this project, so it is also pivotal that all possible options to improve accessibility are documented and researched. A lot goes into the design of shoes and small features and measurements can have drastic impacts on the rest of the body biomechanically. Research into the design of insoles and biomechanics is also crucial prior to any formal designing.

2.1 User Groups

It is important to first identify the user groups to design for and correctly characterize their abilities, limitations, and needs. The vast majority of those that would benefit from hands-free shoes are senior citizens. Due to the deterioration of their dexterity and mobility over time, they typically lack the ability to put on conventional shoes. Compounding this with conditions such as arthritis, Parkinson's disease, strokes, among others, senior citizens would be the primary beneficiary of hands-free shoes. However, limiting the scope to simply senior citizens when considering possible user groups would be insufficient. Among children, Down syndrome and autism can make conventional shoes suboptimal and many of these children and their parents would find value from hands-free shoes. Similarly, within the general population, a litany of chronic and acute conditions can make hands-free shoes useful. These disabilities can be but are not limited to [3]:

- Cerebral palsy
- Muscular dystrophy
- Multiple sclerosis
- Ataxia
- Fibromyalgia
- Degenerative disk disease

- Scoliosis
- Herniated disks

There are a few general things to emphasize when designing for the elderly. However, sometimes compromises need to be made. For example, prioritizing a non-slip sole can ensure stability and prevent falls, but at the same time, individuals that suffer from Parkinson's disease may want a smoother sole that accommodates a shuffling gait [3]. After formulating the requirements, the compromises allowed for this project can be effectively determined. For conventional shoes, it is recommended to have lace-free closures and a wider mouth. Integrating an accessibility mechanism to make the shoe hands-free will need to somehow implement those into the design. As anticipated, there is also a greater need for adequate padding for shoes designed for the elderly. Within the soles, the padding is to ensure adequate shock absorption and dispersion but padding within the upper is also integral, especially for those that tend to bump their feet against objects. A removable insole is also important, not only for the elderly but in general. A removable insole allows individuals to utilize custom orthotics if they want. To effectively stabilize the ankle, a high back with optimal padding is also important. Small changes in the different dimensions and anatomy of a shoe can have significant residual effects throughout the body. A raised wide but low heel can help take the strain off one's feet and legs, however, if the heel is higher than 1.5 inches, it distributes too much of the weight on the toes and balls of the foot [3].

In general, there are a few common foot problems within the elderly population that must be accounted for. Metatarsalgia is pain under the balls of the feet. Bunions are a result of one's big toe pushing against the second toe, this results in the expansion and protrusion of the big toe joint. Hammer toe is also fairly common, typically due to arthritis or from wearing tight-fitting shoes; it is a deformity where the toes curl or bend downwards [4].

As mentioned previously, it is important to consider beyond only the elderly population. Individuals with drop foot often need custom shoes that account for their ankle-foot and foot orthoses, such as insoles. Drop foot can result from various conditions, including some of the conditions mentioned already [5]:

- Multiple sclerosis
- Cerebrovascular accident or stroke
- Traumatic brain injury
- Poliomyelitis
- Cerebral palsy
- Sciatica
- Muscular dystrophy
- Neck or spinal cord injury
- Lower leg (peroneal) nerve injury
- Peripheral nerve trauma
- Diabetes
- Spinal stenosis

An example concept of these custom shoes is shown in the figure below. The design has to take into account the brace with the wide toe box along with the wide and extended shoe tongue.

Figure 2.1 [6]: Shoe for Drop Foot by Cascade Dafo

One of the primary drivers for this project is to allow increased customizability to hands-free shoes by making them 3-D printable. Therefore, whatever route taken to enable customizability should allow users to specify whether or not the design needs to account for a brace.

2.2 Existing products

The market does not currently have any manufacturers providing 3D printed accessible shoes, so research into existing products was conducted under two categories: existing accessible shoes and 3D printed shoe brands and concepts.

2.2.1 Accessible footwear

The footwear market has a variety of different shoes which aim to be easy to put on and easy to remove, thereby making them accessible shoes. Brands as big as Nike have footwear lines dedicated to making the task of putting on a shoe as simple as wearing slippers. There are also other smaller brands that focus solely on accessible footwear; each of these brands has a unique method of making shoes accessible. These methods will be gauged upon the desired requirement to create a shoe that needs no bending of the person or fine motor skills to put on.

2.2.1.1 Nike Go FlyEase

The Nike Go FlyEase shoe uses a unique design that incorporates a rubber band around the entirety of the outer shoe. This rubber band applies a force that allows the shoe to obtain a snug fit around the user’s foot. To remove the shoe, a user just has to apply a light force to the heel to relieve the elastic force of the rubber band. This requires no hands, no bending, and no fine motor skills to properly equip. Putting the shoe on just requires a foot to slide into the upper portion and step down to lock using the rubber band [7].

Figure 2.2: A user putting on the Nike Go FlyEase shoes [7].

The design of the Nike Go FlyEase is very akin to a slipper on the upper portion with a heel lock on the bottom. The midsole is cut along the heel to enable the opening action required for placement and removal. The heel portion incorporates a small bit of outer-sole to properly protect the shoe.

2.2.1.2 Nike FlyEase Brand

Similar to their novel derivative, the traditional easy slip-on brand of Nike FlyEase shoes has been available from Nike for those needing an easier method of putting on footwear. These shoes use a flexible back heel that bends down and out of the way to easily enable slipping feet into the shoe. The bending action is facilitated by cloth, rubber, foam, or a metal spring hinge depending on the model of the shoe, and uses spring or elasticity force to return to the secured position[8].

Figure 2.3: The array of Nike FlyEase shoes with their bendable back heels[8].

These shoes are likely to require slight adjustment when slipping them on, which may require bending. There are no fine motor skills required to put on the shoe, and removal is as simple as placing the alternate foot at the heel and pressing down.

2.2.1.3 Friendly Brand

Friendly Branded shoes are geared towards kids that require greater accessibility than the traditional style of shoes purchasable from the large shoe brands. They offer two options for easier access; zipper access on either the tongue or back heel[9]. This leaves plenty of clearance when removing or putting on the shoes, but does require bending down and fine motor skills.

Figure 2.4: Friendly Branded shoes that use a tongue zipper mechanism[9].

2.2.1.4 Kizik

Kizik is a lesser-known brand, however, their patented design of incorporating accessibility into shoes has risen to fame thanks to the Nike FlyEase series of shoes[10]. The mechanism used consists of a metal spring hinge incorporated into the neck border allowing for a smooth lower and easy rise for the back portion of the heel[11]. This is a patented design that Nike has agreed to use under licensing terms[10].

Figure 2.5: Kizik watermelon-colored Men's Athens shoes [12].

The patent, titled Rapid-Entry Shoe, showcases a simple spring hinge mechanism on a plain sole of a shoe and demonstrates the ease of access that comes with the design. It was awarded to Ogio International Inc in November of 2009. The patent is quite broad, stating that it covers "moveable elements [that] may include flexible elements, elements [that have been] constructed to have a memory of a native position, magnetic elements, and/or elastic elements" [11]. Many diagrams are used in the patent and cover a wide range of designs, but the most common are metal spring hinge assist assemblies [11].

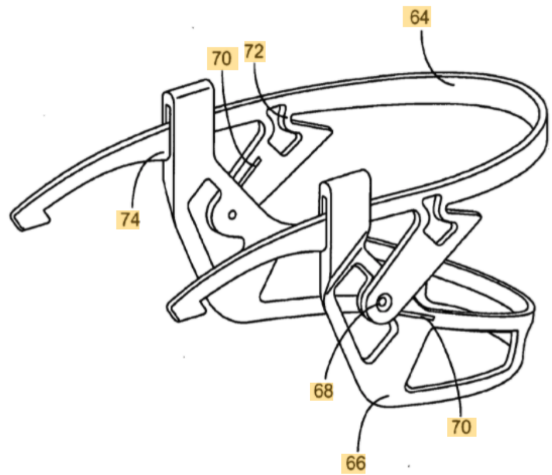


Figure 2.6: A patented spring-assisted mechanism design [11].

2.2.1.5 Vans Slip-On

Vans, the casual footwear brand best known for their flat skateboarding shoes, also has a pair of highly-rated slip-on shoes that require no bending down or fine motor skills to secure [13]. Vans accomplished this by increasing the size of the hole that a user places their foot into, making it more oval-shaped than its rounded counterpart. This does make the shoe slightly less secure than a traditional style shoe, but they are good enough for casual use.

Figure 2.7: Vans classic slip-on shoes [11].

The above designs all feature unique methods that make the shoe accessible, however, none of these shoes have 3D printed components to them. The next section goes into detail about existing 3D printed shoes.

2.2.2 3D Printed

The market for 3D printed shoes is still fresh and brand new. The scale of 3D printed shoes is limited by the slow print time of 3D printers. Due to this, shoe manufacturers will typically have a separate line with a smaller production run dedicated for shoes with 3D printed midsoles. There are also concept designs with shoes that are entirely 3D printed, but supply is limited by the speed of the printing process.

2.2.2.1 Unis Footwear

Unis Footwear is the first major result that comes up when searching for 3D printed footwear; it is for a good reason, they are on the cutting edge of 3D printing technologies, which even extends into 3D knitting. The shoe soles are foamless and entirely 3D printed using thermoplastic polyurethane, or TPU for short [14]. The top portion of the shoe is 3D knitted and is entirely made from recycled plastic [14]. The only portion of the shoe that is made without the use of a 3D printer or derivative is the outer sole, which they injection mold and attach after the fact. This is likely done to increase protection for the midsole since that outer sole will be making contact with the ground continuously.

Figure 2.8: The main showcased Unis Footwear design[14].

2.2.2.2. SCRY Shuttle Shadow

SCRY is a brand that is revolutionizing the use of 3D printers in the footwear industry by targeting high fashion. Their shoe designs are complex, interesting to look at, and use many techniques only manufacturable by 3D printers.

Figure 2.9: The unique and complex design of the SCRY Shuttle Shadow” [15].

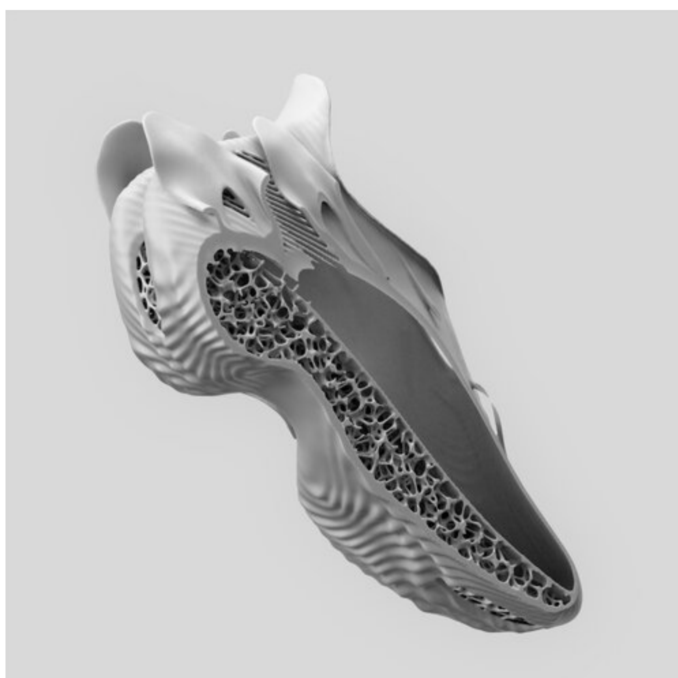


Figure 2.10: A lattice structure only manufacturable by 3D printers [15].

Their printing process is different from the traditional cartesian plane style of 3D printing; they use a model foot, called a last, and print around that foot [15]. A single, fully recyclable material is used to manufacture the entire shoe top to bottom [15]. There is a lattice structure in the midsole to aid in comfort and to make it softer during use [15].

Figure 2.11: The shoe’s special manufacturing process[15].

2.2.2.3 Adidas 4D Shoes

The Adidas 4DFWD running shoe’s midsole is 3D printed, the upper is textile, and the outsole is rubber. Carbon brand’s Digital Light Synthesis (DLS) 3D printing technology was employed for the midsole, and the substance used was Carbon's high-performance resin [16]. The midsole's lattice structure is very functional, and it is recognized to improve form and running economy. This thin and distributed lattice structure, on the other hand, will be impossible to construct with an FDM 3D printer utilizing TPU but serves as proof-of-concept for midsoles with a lattice structure [17].

Figure 2.12: Adidas 4DFWD [17]

2.2.2.4 Parametriks Print 001

Parametriks Print 001 is a concept design influenced by Crocs. Crocs are injection molded, whereas this is 3D printed using Static Light Scattering (SLS) technology, allowing for a sophisticated lattice structure utilizing TPU for flexibility. This shoe is merely a prototype intended to demonstrate the capabilities and applications of 3D printing and parametric design. The shoe is breathable and flexible, however, it has a lot of gaps that expose the foot, which might be undesirable for outdoor conditions such as rain and snow [18].

Figure 2.13: Parametriks Print 001 [18]

Parametriks Print 001 is a slip-on shoe that has no laces, velco, or any form of fastener. Slip-on shoes are the simplest form of accessible footwear possible, but do not provide as much ankle support as a regular shoe would. The next section discusses specific accessibility mechanisms that work to help maintain ankle support while keeping the shoe easy-to-wear.

2.3 Accessibility Mechanisms

There are multiple existing products on the market, as expressed earlier, that allow easy placement and removal of footwear. In addition to these existing products, additional methods were explored as potential mechanisms to satisfy the accessibility requirement. These are investigated in depth in the following subsections.

2.3.1 Tension Band (Go FlyEase)

In early 2021, Nike released their Go FlyEase, which was touched on in the existing products section. The Go FlyEase is split into two parts; a front and a back. Nike uses a tensioner in the form of an elastic band to merge the two parts to form a shoe. The tensioner adheres to the front of the midsole and the back of the heel. The tensioner is not adhered in the middle of the shoe, allowing for tension to be relieved by the user, which separates the two portions of the shoe, allowing the user to slip their foot in. The elastic band experiences tension again once the user applies force on the heel, merging the two parts of the shoe again.

This ingenious design creates a 100% hands-free shoe and serves as a source of inspiration for this project. The two portions are not entirely separate. Instead, they are joined together with the use of a small, hinge-like mechanism, seen on the next page circled in blue, in both the open and closed position.

Figure 2.14: Nike Go FlyEase hinge mechanism

The function of this mechanism is to ensure that the two parts of the shoe don't entirely separate and come loose. If the two parts were held together using only the band, then the shoe could come apart, and while it could be "reassembled" by the user, it defeats the entire purpose of being hands-free. Therefore, if the Go FlyEase were redesigned for 3D printing, it is possible to print both parts of the shoe in one go. The CAD model of the shoe would have a small gap between the parts so that the printer doesn't adhere both parts together. The main difficulty in terms of redesigning the Go FlyEase for 3D printing would be the tensioner. Determining the infill, material, and layer height would likely be a trial-and-error process since the tensioner undergoes cyclical loading with every step. Early fatigue of the tensioner is a possibility if flexible filament is used.

2.3.2 Compliant Mechanism

Complaint mechanisms were explored as an option to facilitate a two-state mechanism in an easily 3D printable design. Compliant mechanisms are systems that were designed to bend, replacing the need for linkages and reducing the number of parts required to create N-bar mechanisms [19]. These designs have been widely used in precision systems for their fine control of movements, smoothness, and high reliability [19]. Applications of this design methodology have been used in space satellites, medical equipment, nano-technology, and nuclear launch sites [20]. A two-state rigid design was chosen for experimentation to facilitate a motion similar to that of the Nike Go FlyEase shoe. These two state, rigid designs are referred to as bistable mechanisms and have been widely studied and researched to offer alternatives to parts such as switches [21]. Many bistable mechanisms are available as 3D models on the website Thingiverse.com, an open-sourced distribution network of 3D printable models, from Brigham Young University (BYU) [22]. Other variations of bistable mechanisms, such as a bistable 4-bar mechanism, are available on the same website.

Introducing a complaint mechanism into the design of the shoe would require additional assembly, but could offer a strong mounting point for the array of parts that may have to be individually printed and connected later. The intention would be to integrate this mechanism into the midsole, which would be the center focal point of the design, and allow for required cushioning around harder components of the mechanism.

Material fatigue overtime on the bends was a concern of the team, so a simple prototype was downloaded and printed from Thingiverse.com. The goal was to record the amount of bending cycles the bending joints could experience before breaking. The part chosen was a simple bistable switch offered by BYU and printed using PLA, as suggested by the Thingiverse.com listing [22].

Figure 2.15: The printed bistable compliant mechanism.

Once the print was complete, usage cycles were manually added and recorded. Unfortunately, the compliant mechanism experienced material fatigue very quickly and lasted only 33 cycles before breaking. It is unlikely that this was due to layer adhesion or the nature of FDM 3D printing since the cyclical load was applied against the printed material in one of the two strongest directions. Additional experimentation could be completed to test the material fatigue using materials like TPU or TPE, but the mechanism was quickly ruled out as a viable option for the shoe that would be experiencing tens of thousands of cycles over its lifetime.

Figure 2.16: The compliant mechanism broke after only 33 cycles.

2.3.3 Slide, Lock & Latch mechanism

Many portable electric gadgets that require external batteries, such as TV remotes, radios, and mobile phones, employ latching mechanisms. After the batteries have been plugged in, this device is utilized to secure them. There is a battery housing bay with two grooves at the corners of the base of the bay, and a separate component that slides in with the assistance of guide rails on either side of the housing bay. This separate component, also known as the cover, has two extruded sections that fit into the housing bay's grooves, as well as two rails that match the housing bay's guiding rails for simple alignment. The grooves are meant to keep the cover piece in place after it is slipped in, requiring a greater amount of force to remove it.

Using this approach to create an accessible shoe with a cover component that mimics the cover piece and a housing bay that resembles the remaining section of the shoe. This design is similar to the Nike Go FlyEase, which features a separated insole from the heel of the shoe that allows the user to slip their foot in. With an extruded component on the rear of the insole, the front tip of the insole may be pivotally coupled to the front of the shoe. On the inside of the heel, there is a guiding rail that the rear of the insole slides into and locks at the bottom of the heel.

To remove the shoe, the user must first put their foot forward to free the insole, then draw their foot back to slide the insole out of the shoe, latching the extruded component at the back of the insole to the top end of the heel.

2.3.4 Flexible/Collapsible Heel

A flexible or collapsible heel is similar to what is utilized in Kizik shoes, explained above in section 2.2.1. The primary concept behind the flexible or collapsible heel is it easily compresses when force is applied, allowing for easy slip-on. And once that force is removed, it quickly returns to its original state, providing a rigid but comfortable heel just as a regular shoe would.

Kizik refers to its shoe's features as foot-activated shoe technology (F.A.S.T.). This technology is owned by Kizik's parent company, HandsFree Labs. As mentioned, the patent that their shoe's use is simultaneously specific but ambiguous. It encompasses a lot of different approaches to accomplishing a collapsible or flexible heel. Figure 17 showcases what HandsFree Labs refers to as its Deformable Element design. It utilizes aerospace grade titanium to make an arc that can bend when force is applied to the heel and quickly spring back when that force is released. This mechanism is what's most commonly used within Kizik shoes, however, they've also released shoes with a mechanism that HandsFree Labs refers to as Cage.

Figure 2.17 [23]: HandsFree Labs Deformable Element

The figure below shows the Kizik Women's Athens shoe that utilizes the Cage mechanism. Unlike the Deformable Element, the Cage is present on the exterior of the shoe. HandsFree Lab and Kizik does not expand upon the design and mechanism much, but from users and critics key points of the mechanism can be deduced. The 'Cage' is made up of a deformable plastic material such as TPU that can maintain and spring back to a certain shape after deformation.

Figure 2.18 [24]: Cage Mechanism on Kizik's Women's Athens

Hands-Free Labs company website also highlights two other mechanisms called Arc and Squeeze It that are coming soon. Both appear to be conceptually similar to the Cage and Deformable Element, just implemented differently.

2.4 In-Sole Measurements

A team of researchers have put together a scientific paper titled "Analysis of 1.2 million foot scans from North America, Europe and Asia", and it is composed of data points and discussion around the 3D scanning of feet ranging from sex, age, and nationality across those three continents. The information was gathered via a Volumental 3D foot scanner placed in retail shoe stores and used by volunteers that were willing to have their measurements taken in exchange for the best suggestion of footwear to purchase in the store. While monetary interest for the retail stores was present, the researchers and purpose of the study were not financially motivated.

The measured aspects of the participant's feet were the foot length, heel width, ball width, and instep height. These measurements were recorded and used to develop foot outlines on a cartesian plane with average maximum width areas highlighted to better represent the data. The average maximum width of the heel was at approximately 15% of the foot length, the utmost lateral point of the foot between 50-80% of the foot length, and the utmost medial point of the foot was between 65-80% of the foot length [25]. The instep is measured at approximately 55% of the foot length [25]. These areas are represented in the figure below.

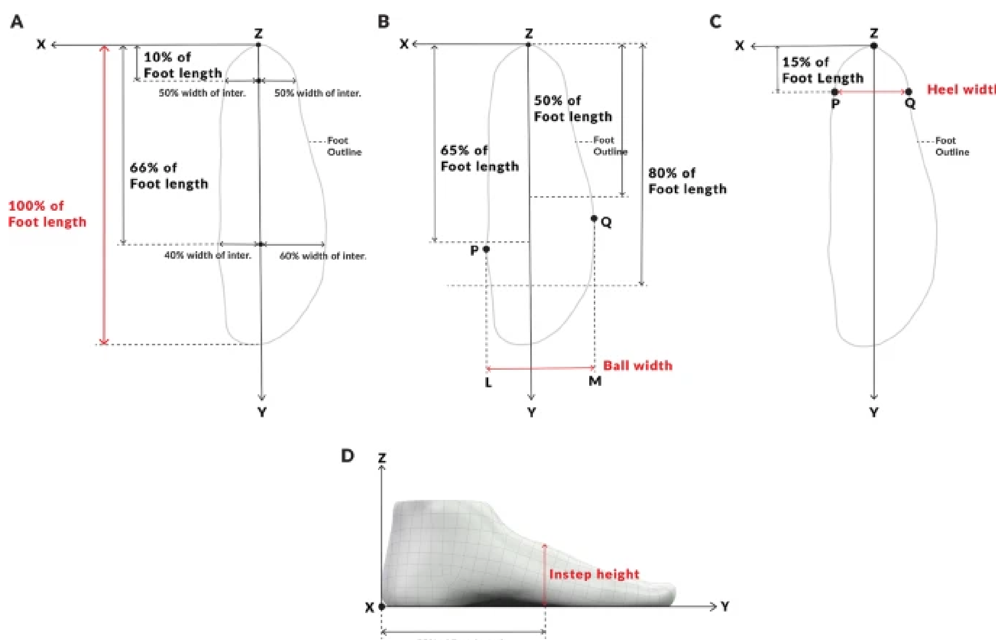


Figure 2.19: Foot outlines placed on a cartesian plane; P and Q in diagram B are the utmost medial and lateral points, respectively [25].

In addition to these revelations, the study suggested that to provide a proper fit for 90% of the population, 3 different shoe widths were required [25]. This is invaluable data for shoe manufacturers since it clearly defines three mass-manufacturable width targets that can be designed for. Additionally, North Americans and Europeans had very similar feet, whereas Asian feet tended to be smaller in both males and females [25]. This is likely due to colonization from Europe to the Americas.

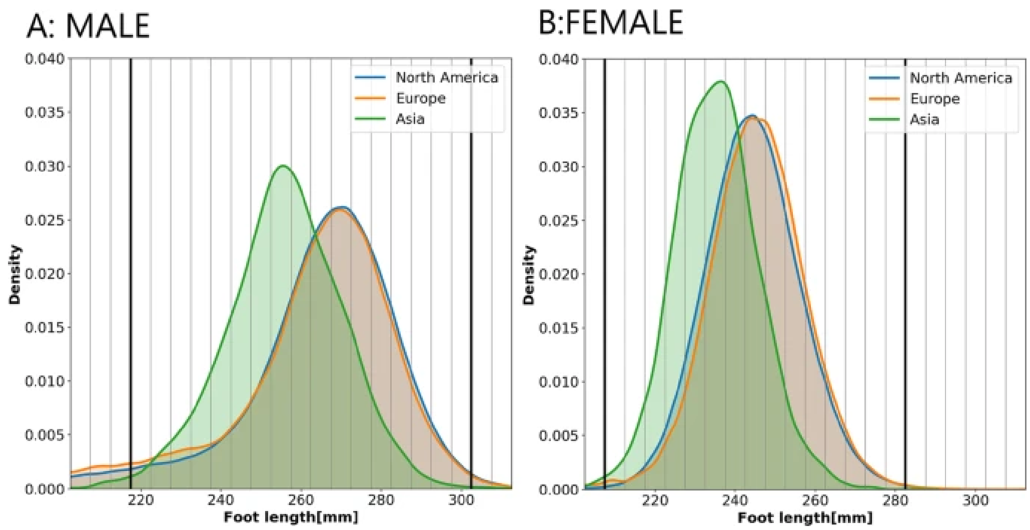


Figure 2.20: Comparison between foot sizes of North America, Europe, and Asia [25].

The data published by this study offers great insight into the formulation of parametric equations that can be used to create general CAD sketches that can then be easily modeled into custom-fit shoe designs for users. According to the findings of the paper, individual parametric equations must be created for specific target demographics like continental heritages, sex, and age. This can be compensated for with the creation of general equation sets for the demographic being targeted and using those to create the general CAD sketches for said demographic. For the purposes of this project, the focus will be on North American males and females.

An additional research paper was published by the Department of Industrial Engineering and Engineering Management at National Tsing-Hua University in Taiwan. This paper created a database of 3D foot scans from 135 participants across both sexes, five statues, and three bodyweight categories, with the purpose of comparing the previously generally accepted *Du Bois and Du Bois* method for finding body, and more specifically, foot surface area [26].

Stature Height (cm) Group		N	Body Weight Group (BMI)												Sub-total		
			Slim BMI <18.5				Medium 18.5 < BMI < 27				Fat BMI > 27						
Size	Definition		Range	Mean	S.D.	N	Range	Mean	S.D.	N	Range	Mean	S.D.	N	Range	Mean	S.D.
(a) Male (N = 135)																	
XL	>175.8	3	177.0–185.5	181.8	4.4	4	177.0–191.5	182.8	6.4	3	177.0–181.5	179.2	2.3	10	177.0–191.5	181.4	4.7
L	169.9–175.8	10	170.0–175.0	172.3	2.0	12	170.0–175.5	172.3	1.9	10	170.0–175.5	171.9	1.8	32	170.0–175.5	172.2	1.8
M	164.0–169.9	15	165.0–169.5	167.3	1.4	21	164.0–169.5	166.7	1.7	15	164.5–169.5	167.4	1.8	51	164.0–169.5	167.1	1.7
S	158.1–164.0	10	160.0–163.0	161.6	0.9	12	159.0–163.5	161.3	1.8	10	159.5–163.0	161.4	1.2	32	159.0–163.5	161.4	1.5
XS	<158.1	3	149.0–157.5	153.5	4.3	4	155.0–158.0	156.4	1.3	3	156.0–157.5	156.8	0.8	10	149.0–158.0	155.7	2.6
Sub-total		41	149.0–185.5	167.2	7.3	53	155.0–191.5	167.2	6.0	41	156.0–181.5	167.1	5.8	135	149.0–191.5	**167.2**	**6.2**
(b) Female (N = 135)																	
XL	>162.8	3	163.5–167.0	165.2	1.8	4	163.0–176.0	169.5	5.5	3	163.0–167.0	165.3	2.1	10	163.0–176.0	167.0	4.0
L	157.9–162.8	10	158.0–161.5	159.9	1.3	12	158.0–162.0	160.6	1.1	10	158.0–162.0	159.0	1.3	32	158.0–162.0	159.9	1.3
M	152.9–157.9	15	154.0–157.0	155.4	0.9	21	153.0–157.0	155.2	1.4	15	153.0–157.0	154.8	1.4	51	153.0–157.0	155.1	1.3
S	147.9–152.9	10	148.0–152.0	150.3	1.4	12	148.5–152.5	151.0	1.5	10	148.0–152.5	150.9	1.3	32	148.0–152.5	150.7	1.4
XS	<147.9	3	144.0–146.0	145.0	1.0	4	143.0–147.5	145.8	1.9	3	141.8–146.5	144.4	2.4	10	141.8–147.5	145.1	1.8
Sub-total		41	144.0–167.0	155.2	5.8	53	143.0–176.0	155.8	5.8	41	141.8–167.0	154.9	5.2	135	141.8–176.0	**155.4**	**5.6**
(c) Total (N = 270)																	
		N	Height (cm)				Weight (BMI)										
			Range	Mean	S.D.		Range	Mean	S.D.								
Total		270	141.8–191.5	161.3	8.4		34.0–105.6	61.3	15.2								

Figure 2.21: The anthropometric distribution of the database [26].

These data points were taken from participants in Taiwan, which represent a different size demographic than the feet of North Americans and Europeans, as stated by the previous study [25]. Similar measurement sites were used to obtain the heel and ball width, as well as the overall length of the foot [26]. These were used to correlate the findings of this study to that of the previous.

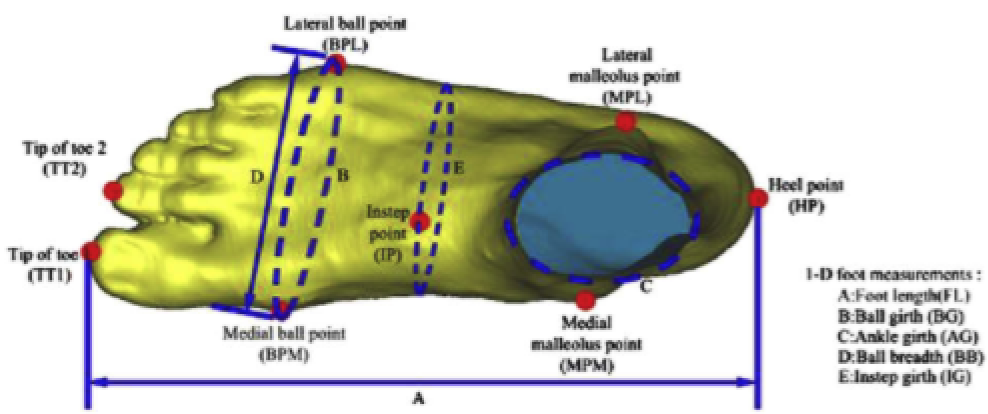


Figure 2.22: A 2D diagram of a scanned foot showcasing similar measurement sites to the previous paper [26].

This data was then used to establish formulas to estimate the foot surface area, which was then also subsequently added to the database. These formulas can be used in conjunction with the previous study's data to confirm the methodology used to conduct the experiment, which was valid. FL and BG refer to Foot Length and Ball Girth, respectively.

Gender	Regression model	*t*-value	*p*-value
Total	$FSA_{Total} = 1.0\,43 \times FL \times BG$		
Male	$FSA_{Male} = 1.0\,46 \times FL \times BG$	−0.496	0.311
Female	$FSA_{Female} = 1.0\,40 \times FL \times BG$	0.558	0.289

Figure 2.23: The general formulas found to calculate the foot surface area[26].

The study found that the generally accepted Du Bois and Du Bois method for finding foot surface area was underestimating the foot surface area due to the definition of surface area each study used[26]. Du Bois conducted his study using wrapping material around a sock that did not account for the surface area of toes, whereas this study took toes into account[26]. Other studies published by the National Institute of Health suggest that Du Bois lacked statistical reasoning for his derivation technique, and thus the equations are not suggested for use in practice[27]. For this reason, the study conducted by the National Tsing-Hua University team will be used to validate designs when required.

$$BSA = 0.007184 * Height^{0.725} * Weight^{0.425}$$

The Du Bois and Du Bois method formula[28].

Foot surface area formulas are also useful for the design of different soles based on weight class, since heavier set individuals apply more pressure to their feet the width increases slightly [26]. This is evident in the following figure which showcases the areas associated with each demographic.

Stature Height Group	Body Weight Group						Sub-total	
	Slim BMI < 18.5		Medium 18.5 < BMI < 27		Fa t BMI > 27			
	Range	Mean (S.D.)	Range	Mean (S.D.)	Range	Mean (S.D.)	Range	Mean (S.D.)
(a) Male ($N = 135$); unit: cm^2								
XL	685.32–724.33	702.33 (19.98)	662.25–771.04	723.29 (47.82)	667.38–742.42	705.56 (37.54)	662.25–771.04	711.68 (35.57)
L	618.34–680.7	647.9 (31.3)	614.65–759.11	683.9 (37.67)	692.95–766.74	728.24 (34.82)	614.65–766.74	686.51 (43.22)
M	591.44–617.21	600.18 (14.75)	613.13–720	664.53 (36.19)	667.36–737.63	698.09 (35.95)	591.44–737.63	655.47 (45.3)
S	562.77–620.67	597.93 (30.88)	556.9–595.14	574.57 (15.89)	632.56–669.45	649.2 (18.71)	556.9–669.45	605.19 (38.11)
XS	561.85–614.71	585.9 (26.75)	511.93–607.57	575.18 (43.55)	629.7–649.07	638.67 (9.76)	511.93–649.07	597.45 (40.54)
Sub-total	561.85–724.33	617.7 (49.73)	511.93–771.04	646.24 (61.27)	629.7–766.74	689.72 (44.9)	**511.93–771.04**	**650.78 (58.37)**
(b) Female ($N = 135$); unit: cm^2								
XL	507.04–576.11	545.3 (35.13)	558.2–684.43	608.92 (56.59)	640.2–672.51	659.91 (17.29)	507.04–684.43	605.13 (60.07)
L	475.53–546.88	519.46 (23.75)	474.06–582.92	548.5 (28.19)	584.76–620.95	601.25 (18.31)	474.06–620.95	555.91 (34.39)
M	427.1–547.66	484.5 (43.46)	473.57–570.58	518.23 (30.12)	543.58–596.76	566.69 (27.26)	427.1–596.76	522.56 (42.57)
S	478.63–543.77	504.83 (34.39)	464.59–528.94	494.08 (25.61)	517.96–594.75	549.79 (40.04)	464.59–594.75	514.85 (36.64)
XS	408.02–476.39	446.29 (34.91)	461.12–495.15	480.99 (14.45)	499.89–520.23	512.36 (10.92)	408.02–520.23	479.99 (33.09)
Sub-total	408.02–576.11	499.64 (41.34)	461.12–684.43	523.65 (45.71)	499.89–672.51	573.84 (55.84)	**408.02–684.43**	**531.60 (52.27)**
(c) Total ($N = 270$); unit: cm^2								
Measurement	Range	Mean (S.D.)						
FSA	408.02–771.04	591.19 (83.41)						

Figure 2.24: The tabulated foot surface areas based on the aforementioned demographics[26].

The measurements that contributed to the creation of the formulas and calculations for the figure above are available in Appendix A.

A smaller-scale study was also conducted internally amongst the team which rendered a table of known shoe-sole sizes from large-scale manufacturers like Adidas, Nike, Asics, and others. These data points act as boundaries to indicate general sizing that should be expected once the parametric equations are used in the CAD software to generate custom designs. This data is included in Appendix B.

2.5 Biomechanics

Shoes are arguably one of the most carefully designed products consistently used in day-to-day lives. Small variations in the design can have significant implications throughout the rest of the bodies; from ankle pain to back pain and even headaches. Many factors are taken into consideration in the design of shoes, some primary ones being shock absorption, flexibility, fit, traction, breathability, and weight among others. When designing a shoe the primary factors that are tested are [29]:

- Shock absorption
- Heel counter stiffness

- Flexibility
- Rearfoot stability
- Overall rearfoot control
- Sole wear
- Traction
- Permeability to water

Nearly every feature of a shoe is carefully chosen to perform a certain function, whether it be to increase breathability and comfort or help with support, control and stability. A few of these features and their corresponding functions are detailed in the figure below.

Feature	Function
Kinetic Outsoles	Shock Absorption and Traction
Dual-Density Midsoles	Shock Absorption and Control
Flared Heel	Control and Stability
Heel Counters	Control and Stability
Contoured Support Systems	Control, Stability, and Shock Absorption
Arch Support	Pronation Control
Toe Pitch	Smoother Push Off
Tubular (Moccasin) Construction	Flexibility
Soft Nylon	Lightness and Comfort
Mesh Nylon	Lightness, Comfort, and Breathability
Width Fittings	Fit, Comfort, and Support
Different Last Design (Women's)	Fit, Comfort, and Support
Orthotics and Correction Wedge or Inserts	Support, Control, and Stability
Solid Carbon or Blown Rubber Outsoles	Durability, Traction, and Lightness
Padded Tongue, ATP Collar	Comfort
Perforated Porometric Uppers	Lightness and Breathability
Soft Seamless Linings	Comfort
Tractions Soles	Durability and Grip
Reinforcements	Support and Durability

Figure 2.25 [29]: Shoe features and their functions

Research into what's considered in designing a shoe resulted in identifying six key measurements that are pivotal [29]:

- Ball Girth
- Waist Girth
- Instep Girth

- Long Heel Girth
- Short Heel Girth
- Stick Length (Overall heel-toe measurement on the last)

These measurements are illustrated in the figure below.

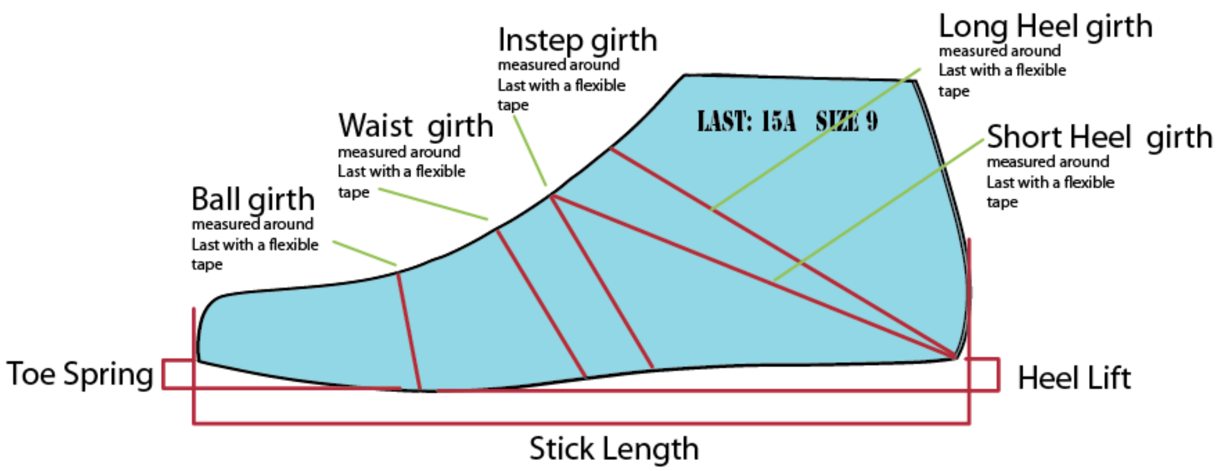


Figure 2.26 [30]: Key measurements for designing shoes

Running shoes usually take biomechanics into greater consideration than casual shoes because with the increased impact forces, the implications of biomechanics increase. While most of the individuals within the target demographic will likely not be running to the extent of a marathon runner, studying the ergonomics of a running shoe and everything that goes into designing it can be fruitful. Research showed an emphasis on a well-designed midsole with a carefully chosen material. Superficially it may seem that a midsole that is soft and squishy would offer the best shock absorption and maximize comfort; however, research indicates that a very soft midsole is detrimental compared to hard midsoles. This is primarily attributed to a bottoming out effect. Essentially if the midsole is too soft it compresses too fast and too much and fails to provide the benefits of a cushioned shoe. Therefore, it is advised to opt for a relatively hard midsole material. Even a dual-density midsole arrangement is a worthwhile option to explore in some cases [31].

2.6 Summary

Key aspects that must be considered during the problem analysis and design portions of the project were discussed at length above. Seniors, children, and everyday users are the selected groups that are being kept in mind during the design process, with each their own subset of requirements. Customization for medical apparati such as braces or even additional supports for arches must be considered. While many products exist to address the individual portions of the project, accessibility and 3D printed, few address both. Both Kizik and Nike FlyEase use mechanically simple and easy to design methods of increasing accessibility by offering flexible heel portions. The Parametricks Print 001 shoe showcases the intricate designs that are only manufacturable using 3D printers, and present the power of parametric design into shoes.

These parametric designs can be based on formulas derived from massive research studies conducted on over 1.2 million 3D volumetric foot scans, as thoroughly explained above. Using general positional ranges of notable foot features, parametric design sketches can be created for each of the mass target groups, which is based on continental heritages, sex, and age. Once the parametric formulas are defined, custom fit shoes that address the most important biomechanical and ergonomic features can be created. The most important features to address are arch support, mouth width, non-slip soles, contoured support systems, and removable insoles. These are addressed by taking specific measurements of the feet, which ties back into the parametric formulas that are created for ease of customization. These reviewed concepts will be addressed when analyzing the problem in the following section.

3. Problem Analysis

The goal of problem analysis is understanding and anticipating inconsistencies that a user can encounter when using the product, as well as establishing a set of requirements that aid in the improvement of the design. It keeps the team on the same page and ensures everyone understands the objectives of the design, and by having a prioritized compilation of requirements, the team can quickly make design decisions and have a focused approach to the design. The flow of the requirements is as follows:

1. Product Characteristics - specify what a product must be
    a. Functional Requirement -specify what a product must do;
        i. Constraint - specify what are the product limitations

1. Functionality
    a. Support and stabilize the feet effectively
        i. Support and stability protect the ankles from rolling and better align the feet for walking/running efficiency.
    b. Minimize permeability to water
        i. Water-resistant shoes help keep the feet dry and comfortable, preventing the risk of blisters.
    c. Optimize flexibility
        i. Flexible shoes provide comfort on uneven surfaces and rough terrain.
    d. Comfortable to wear
        i. The user must be able to wear the shoe for extended periods without sustaining any blisters.
    e. Provide traction
        i. Traction to prevent slipping in wet weather conditions and for a smoother slip on/off.
    f. Allow adequate airflow and breathability
        i. Better ventilation can allow heat to travel from within the shoe to the outside, preventing infections and sweat accumulation.
2. Usability
    a. Allows slip-on and off without the use of hands

            i. Easy slip on and off features make it more accessible and does not require the user to bend.
    b. Weigh less than 350 grams
        i. Lighter shoes require less muscle straining while walking, and 3D printing shoes allow them to be very lightweight.
    c. Made of biocompatible materials
        i. To avoid infections and harmful reactions, the shoe must be composed of skin-friendly materials.
    d. Aesthetically pleasing
        i. The shoe must be fashionable to all age-groups.
3. Producibility
    a. Minimize assembly time and steps
        i. Minimalizing time spent on assembly reduces overall cost and the chance for human error in assembly.
    b. Minimize the number of parts and complexity of parts
        i. The chance for printing errors is reduced with fewer parts and part complexity.
    c. Minimize production costs
        i. Minimized production costs increases the product scalability and allows for increased reinvestment into production supplies.
4. Maintainability
    a. Made of materials that are easily maintainable
        i. The shoe must be able to be maintained with substances readily available, like water.
5. Durability
    a. Made of durable materials
        i. The shoe must be able to withstand harsh terrain for extended periods without sustaining damage.
    b. Designed for longevity
        i. An average everyday shoe is usable for at least one year [32].
6. Sustainability
    a. Made of easily recyclable and biodegradable materials
        i. Material must be eco-friendly.
    b. Optimize print time
        i. Print time is adjusted to minimize the operation time, hence reducing power consumption.

4. Anatomy of a Shoe

Designing footwear requires a thorough understanding of the individual components that form the average shoe. Since the nature of this project is to design a 3D printed shoe, many of the up to 30 anatomical components are not required for the final design that will be constructed [33]. The most important external components will be the outsole, midsole, insole, and feather edge which come together to create the sole of the shoe [33]. Outsoles tend to be a harder material that can withstand the constant friction and rubbing on the environments a shoe may be subjected to. The outsole is also the area in which the grip pattern is found, making it incredibly important to the experience of wearing a shoe. The midsole is the slightly more cushioned internal portion of the sole which usually houses infill patterns or gels to cushion the foot from external extremities such as rocks underneath the shoe. This effectively acts as the suspension for a shoe [33]. The insole is the softest portion of the shoe and is found within the upper shoe; it is the portion of the shoe that makes direct contact with the user's foot. Finally, the feather edge is where the sole meets the upper shoe and is where the two subsystems come together. This tends to be where glue or staples are found in commercial shoes.

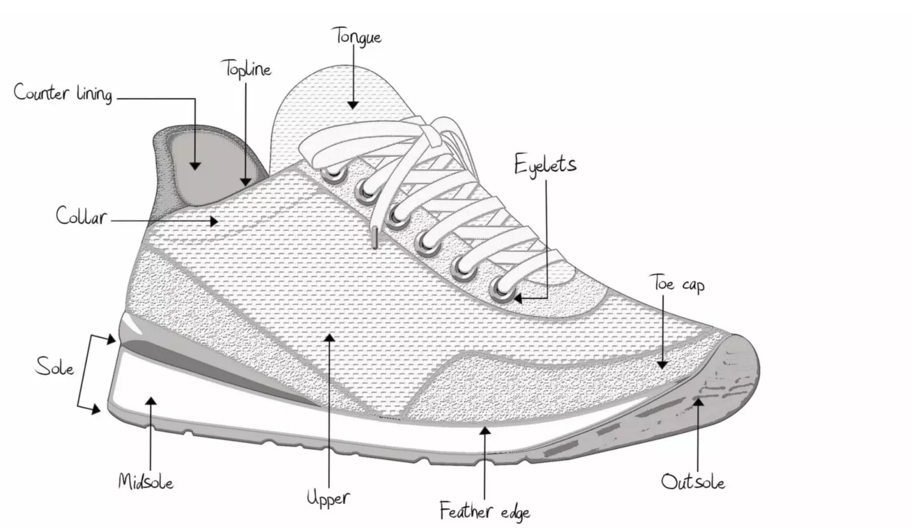


Figure 4.1: A shoe labeled to show the most important features [33].

The upper shoe contains the housing for the foot, which is at the instep height, the toe cap, tongue, collar, and counter. The toe cap is the front portion of the shoe which gives space to the user's toes and maintains the rigidity of the upper shoe at the front. The tongue acts as a pad between the potentially stiff laces and allows for some flexibility on instep fit since it offers space for the instep height to be slightly taller than that of the upper shoe. The collar is the portion of the shoe that creates the entrance for the foot and maintains the shape to make an easy wearing experience. Finally, the counter is the stiffer back of the shoe, over by the heel, which guides the foot into the collar and upper shoe while maintaining the structural integrity of the entire shoe [33].

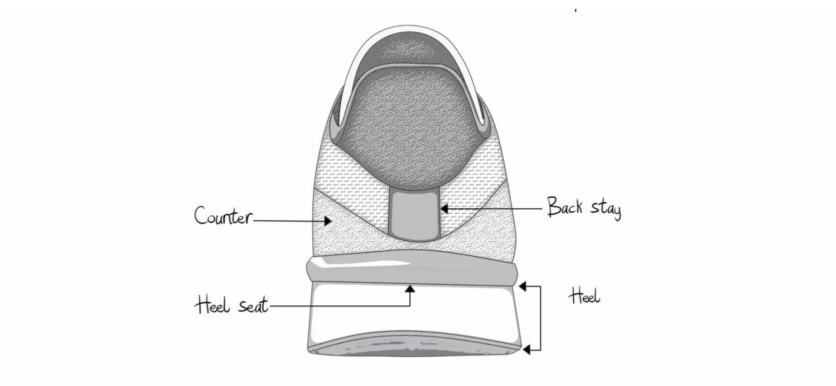


Figure 4.2: The back portion of a shoe showing additional components of importance [33].

Each aspect of the shoe requires specific material selection to be conducted to ensure that the component is as comfortable and/or as rigid as required to properly account for the expected use cases, as well as the biomechanical and ergonomic requirements. For this, various materials were considered for their printability, cost-effectiveness, comfort, and rigidity in the following section.

5. Material Selection

The outsole, midsole, insole, and upper are the four basic sections of a shoe. Each section serves a unique function of the shoe, and they are each made of different hardness levels to fulfill their specific functions in regards to foot health, safety, comfort, and aesthetics. After research and consultation, the following materials were shortlisted to be suitable for at least one of the sections or functions.

5.1 PLA

The most popular filament for FDM printing is polylactic acid (PLA). PLA is a biodegradable synthetic polymer that degrades into lactic acid components, although this shortens its life cycle as it degrades over time.[34] PLA has a low melting point and can adhere to almost any bed surface. PLA does not need to be printed on a warm surface; therefore, the object does not deform on the printing bed.[35] On the other hand, it has a glass transition temperature of 60 degrees Celsius, which means it will deform if exposed to higher temperatures for an extended period.[36] PLA is not ideal for functional prototypes since it cannot tolerate repetitive stress as it lacks strength, flexibility and can deform by heat caused by friction between moving parts.[34] PLA is recommended for beginners since it is simple to work with and just requires the most basic 3D printing equipment.

PLA+, as the name implies, is PLA with additives to improve overall material quality. PLA+ has increased strength and flexibility, allowing it to be used in functional components.[37] It also has greater thermal resistance than PLA, making it feasible for outdoor applications. However, while PLA+ is of higher quality, it is also more costly.[38]

5.2 Nylon

Another substance that is very popular even beyond the 3D printing space is nylon. Clothing, toothbrushes, tents, and parachutes are just a few of the many essential items made of nylon that require consistency.[34] Nylon is a polyamide-based synthetic copolymer; it is abrasion-resistant, chemically stable, and has a very low friction coefficient. With suitable printing conditions, larger nylon parts may be manufactured to absorb shock, while thinner nylon parts can be manufactured for flexibility.[39] In FDM printing, nylon is known to be one of the most thermally stable filaments. Nylon prints at high temperatures, therefore it is only practical for large-scale 3D printers that are utilized at an industrial level.[40]

5.3 TPE

Thermoplastic elastomer (TPE) is a rubber-like substance that is incredibly flexible, soft to the touch, and strong at the same time.[41] TPEs are noted for their abrasion, impact, chemical, and tear resistance, as well as their thermal stability and zero harmful emissions during printing. TPE has a rubber-like texture and is used to print phone covers, chair grips, and shock absorbers, among other items that must be long-lasting, durable, and consistent.[42] TPE filaments' major disadvantage is that they are difficult to print due to their flexible qualities, which increases print time.[43]

5.4 TPU

TPU is a form of thermoplastic polyurethane (TPU) with a smoother surface finish. TPU is known to have higher rigidity and has improved resistance qualities.[44] TPUs feature a wider spectrum of hardness and flexibility, allowing for more filament possibilities. TPU is used in footwear, helmet padding, rubber boats, and other similar applications.[45] When compared to TPEs, TPUs are denser and shrink less. TPUs are relatively easier to print since they are slightly stiffer, but difficult, nonetheless.[44]

TPU and TPE come in a variety of hardness and flexibility levels, ranging from 00 to 100 and Shore A to D, respectively. The shore hardness may be determined by using a durometer to measure the capacity to withstand needle penetration under high force. The number denotes the hardness, with 0 being the least hardness and 100 representing the most hardness. The letter A stands for high flexibility, whereas D stands for low flexibility or rigidity.[46]

TPU and TPE's of varying hardness or infill will be used in different layers of the shoe depending on their functionality. To be suitable for a variety of terrains, the outsole must be strong but at the same time flexible. The outsole's hardness levels should be between 87 and 95

Shore A. The midsole's hardness should be between 85 and 87 Shore A for great shock absorption while providing maximum comfort.

TPEs have a standard hardness of 85 Shore A in most cases. For comfort, the insole should be highly flexible and soft, with plenty of traction to avoid slipping within the shoe. After many uses, TPE insoles can take on the contour of the pressure points applied by the food. For ideal softness and fit, the top will be made of the same material as the insole, but with relatively less infill.

Table 5.1: List of TPU/TPE with different hardness.

Brand/Model	Material	Hardness	Layer of shoe
NinjaTek/NinjaFlex	TPU	85A	Midsole
NinjaTek/Chinchilla	Combination TPE resins	75A	Insole/Upper
NinjaTek/Cheetah	TPU	95A	Outsole
RECREUS/Filaflex 60A Pro	TPE	60A	Insole/Upper
RECREUS/Filaflex UltraSoft 70A	TPE	70A	Insole/Upper
Treed Filaments/Recycled tire TPE	TPE	80A	Insole/Upper
eSun/eLastic	TPE	85A	Insole/Upper
eSun/eTPU	TPU	95A	Outsole
Fillamentum/Flexfill TPU	TPU	92A	Outsole/Midsole
RECREUS/Filaflex 82A	TPU	82A	Midsole
RECREUS/Filaflex 95A	TPU	95A	Outsole

With the materials selected, suitable 3D printers need to be selected to ensure that they can be used for prototyping and final builds. Many factors need to be considered when selecting a printer, and these will be explored in-depth in the following section.

6. 3D Printer Selection

There are two major factors that impact the type of printer that could be selected to print the prototype and final designs; they are the print bed size and extruder. The print bed must be able to accommodate the maximum sized model the team wishes to print, which will be a size 13 and around 32 - 35 cm at its maximum point. Finding a print bed at this size proved to be a challenge, but Creality, a very popular hobbyist 3D printer provider, has some options for large format printers. A suggestion would be to make use of the Ender V5+ model printer for its large bed size at 35cm in both length and width [47]. This would be able to accommodate the shoe size without any need to divide the print into multiple parts.

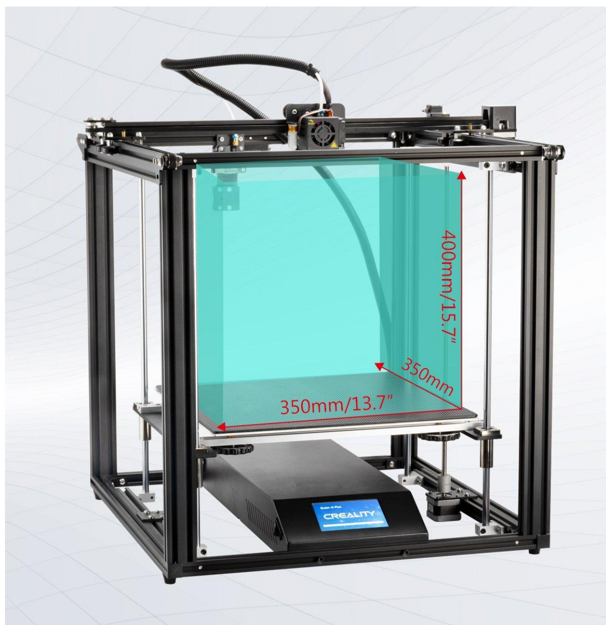


Figure 6.1: The printable area of the Ender V5+ printer [47].

The next factor to consider is if the extruder for the printer is capable of printing soft and flexible materials like TPU and TPE. The most common style of extruder used in 3D printers is called the Bowden extruder, which uses a method of pushing filament to feed the hot print head [48]. This style of extrusion is fine for harder materials like PLA and ABS plastics, but when it comes to materials that can flex, the long travel distance and push configuration causes material to get stuck at points within the tube. For this reason, a direct drive extrusion technique is suggested when printing TPU and TPE, as well as whenever a high print resolution is desired [48]. Direct drive extruders are still technically in a push configuration, however, they only push the filament about 2-3 inches, greatly reducing the risk of the material getting stuck. This 2-3 inch push is also conducted down a straight tube which removes the probability of bends adding extra inhibitors to the clean extrusion of material. These direct drive extruders are widely available upgrades that can be placed on many printers, including Creality's Ender series [48].

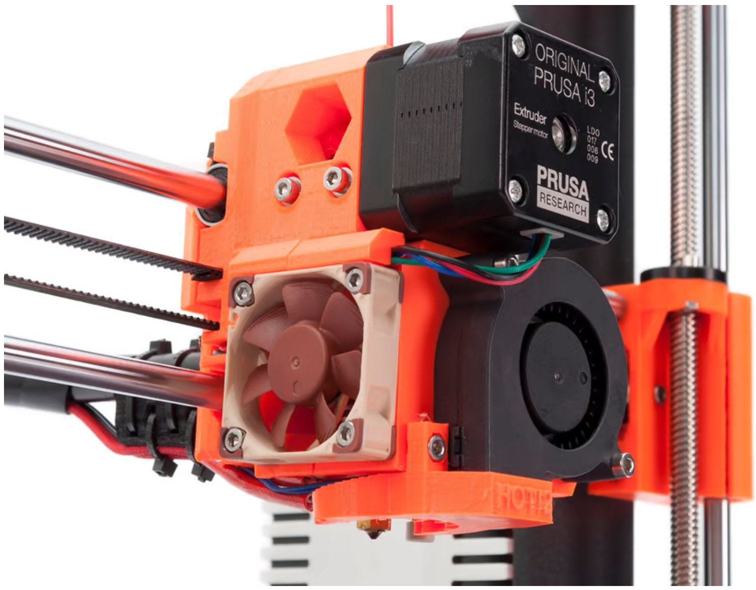


Figure 6.2: A direct drive extruder on a Prusa i3 printer [49].

For this project, prototyping speed is considered to be much more important than very wide print beds and high-resolution prints. These would be factors to consider when producing commercially available footwear, but quick rapid prototyping needs to be conducted in the design stages. For this reason, an Ender v6 printer was selected and upgraded with a BondTech Direct Drive eXtruder v3 (DDX v3). This is used for all prints requiring TPU or TPE filaments. For all other prints that can be created with PLA, an AnyCubic Mega i3 printer is used. Both of these selected printers are of the Fused Deposition Modeling (FDM) variety, as opposed to Stereolithography (SLA) for their reduced cost and a far wider range of printable materials [50].

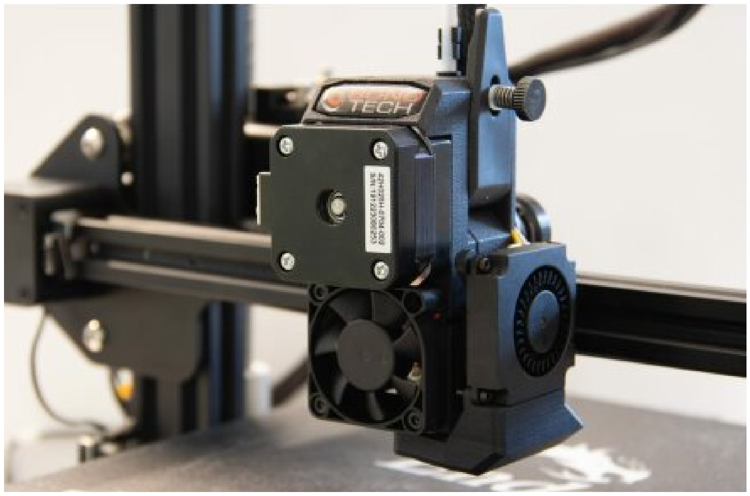


Figure 6.3: The Ender v6 printer with a DDX v3 extruder [51].

Figure 6.4: The AnyCubic Mega i3 printer [52].

No matter the resolution, drive type, bed, or print speed, a 3D printer is only as good as the sliced model created in software like Creality 3D's Cura. Print optimizations, component densities, in-fill patterns, cooling patterns, and much more finely controlled aspects of the print are directly controlled by the g-code that is output from Cura, or similar software. Appropriate modeling for FDM printers, such as the above being used for this project, is crucial for the repeatable and reliable manufacturing process. These considerations are incorporated into the following design methodology section.

7. Design Methodology

Using the information preceding this section, the design constraints, biomechanics, materials, and printer selection is used to create an effective design methodology that is incorporated into every step of the process. The following subsections showcase the design process that went into the selection of modeling software, formula creation, and accessibility mechanisms.

7.1 Biomechanical design

Anyone that has worn a pair of shoes that is poorly fitting or poorly designed will attest to the fact that it can have residual negative effects throughout the rest of the body. Within the literature review, the key biomechanical and ergonomic factors and features of a shoe are compiled. This section goes deeper into which features are going to be prioritized for the design and why they were chosen.

Arch support is already important in conventional shoes. However, its importance is amplified for the elderly and individuals that the shoe is being designed for. With increased age, feet tend to get flatter and wider. Tendons also begin losing elasticity, attributable to the increased width and sagging of the arches [53]. This usually results in increased needs for support. For those that are older, it is recommended that they have a more solid and thicker sole with stiffer arch support that doesn't easily bend [53].

As mentioned in the literature review, a wide mouth is also important for accessibility. Whether it be a static or dynamic mouth. Dynamic mouth refers to a mouth that can become wider when necessary such as the ones documented in the existing products.

A non-slip sole is already important for stability. However, its importance is magnified for many of the hands-free shoe concepts documented in existing designs. The shoe must stay in place as the individual slips their feet in and out.

Integrating a contoured support system is important for multiple functions, including but not limited to control, stability, and shock absorption. A 2019 study comparing the effects of contoured foot orthoses to a flat insole found evidence to validate the superiority of contoured orthoses for biomechanics and ergonomics [54]. Contoured orthoses redistribute the shock and force more biomechanically.

Removable insoles are consistently present in shoes for the elderly and those with disabilities. Even though the plan is to have custom insoles as a part of the shoes, it is important to still allow individuals the opportunity to remove insoles and use their own if they want to. A rigid and padded wide heel that's slightly raised can help relieve strain off one's feet and legs.

A thorough anatomical understanding of shoes and the individual components that make up the footwear is required to understand where to place these biomechanical and ergonomic optimizations. The next section explores the important components that will be highlighted in the proceeding sections on material selection, design, and prototyping.

7.2 Modeling Software

The premise of 3D printable shoes relies on the use of CAD modeling software which is used to create a 3D model of the shoe and insole. Many options are available for 3D modeling shoes and footwear, including general CAD and modeling software such as Rhinoceros 3D, Maya, Blender, Modo, Fusion 360, and more. More niche footwear modeling software also exists as well, such as iCAD3D+, Shoemaster, Romans CAD, and more. Each software has its own advantages and disadvantages in terms of modeling footwear. While dedicated footwear modeling software makes the job simple, it also removes a lot of creativity by giving cookie-cutter options, which limits design choices.

A key requirement of the modeling software is the ability to create parametric models, meaning that the model can be controlled using a system of parameters or equations. This is especially useful when it comes to creating custom shoes since it reduces the time required for customization. It also reduces the amount of work required to make different size shoes since it becomes possible to simply change a few parameters and have the software calculate the new shoe size and shape.

Furthermore, the amount of online support available for each software plays an important role in choosing the primary modeling software. While applications like Maya and Modo are both capable of creating parametric models, online support for this project is scarce, and their software packages are full of unnecessary functions for this project, making it bulky. Fusion 360, Blender, and Rhinoceros 3D (Rhino for short) are effective CAD tools at a low cost, or free in the case of Blender. For this project, both Fusion 360 and Rhino were experimented to see which one should be the primary software.

7.1.1 Fusion 360

Fusion 360 by Autodesk is a multifunctional cloud-based platform capable of CAD, CAM, simulation, analysis, rendering, and more. It was picked as the first choice of CAD software for its user-friendly interface and similarity to Solidworks. Fusion 360 comes equipped with many surface modeling tools and supports the use of T-Splines, which allows free-form organic shapes to be created very simply by manipulating faces, edges, and vertices of a surface. However, this design is all free-form, meaning it is not dimension-driven. So while sketches and models can be parametric, T-spline creations cannot be parametric. This means that the upper of the shoe cannot be parametrically designed, removing the ability to quickly make custom footwear. After this was discovered, Rhino was tested to see if it had the same problem.

7.1.2 Rhinoceros 3D

Rhinoceros 3D, or Rhino for short, is a CAD software first designed as a plugin for AutoCAD back in the 1980s. It is known for being a versatile surface modeler with many, many sketch, mesh, and surface tools at its disposal. Being an AutoCAD offspring, it comes with a command-line interface which makes searching for tools easy and quick. While Rhino is not as popular as other CAD tools like Solidworks and Catia, it sees heavy use in the jewelry and architecture industries. This is because when it comes to parametric surface modeling, Rhino comes out on top because of Grasshopper. Grasshopper is a visual scripting language that comes preinstalled with Rhino as a plugin and gives users the ability to create a near-infinite amount of complex parametric structures. Grasshopper is used in the footwear industry when lattice structures or other complex, parametric designs are desired. An example would be the Parametriks Print 001, which was made entirely in Grasshopper. The plugin also has an open SDK (software development kit), meaning users can create and publish plugins. These plugins include last makers, lattice generators, and even neural networks. It is for the reasons described above that Rhino was chosen as the primary CAD software for this project.

7.2 Formula Creation

To make a product that could be commercially viable, the amount of time spent tweaking design for custom-fitted shoes should be near zero since engineering and design teams are expensive to pay. With this in mind, formulas were created and derived to enable the parametric design of insoles and shoes. The objective of this was to lay the foundation for a programmatic approach to creating the 3D models once user measurements are entered, potentially creating an entire manufacturing process that requires no human intervention.

Using the research studies mentioned in the literature review, the team began prototyping formulas and in-sole designs based on their findings. Fusion 360 was the first CAD modeling software used for prototyping. After it was discovered that Fusion 360 was not ideal for this project, Rhino and Grasshopper were used for prototyping and design.

7.2.1 Fusion 360

The first insole CAD sketch was designed from scratch using the following metrics, as outlined in the research study that analyzed 1.2 million 3D scans of feet:

Heel Width:

$$HW_y = (0.15)FL \qquad (7.1)$$

Where,

HW_y is the heel width y placement along the foot length from the heel,

FL is the foot length

Ball Width:

$$BW_y = (0.65)FL \qquad (7.2)$$

Where,

BW_y is the ball width placement along the foot length from the heel,

FL is the foot length

Arch Placement:

$$AP_y = (0.5)FL \qquad (7.3)$$

Where,

AP_y is the arch placement along the foot length from the heel,

FL is the foot length

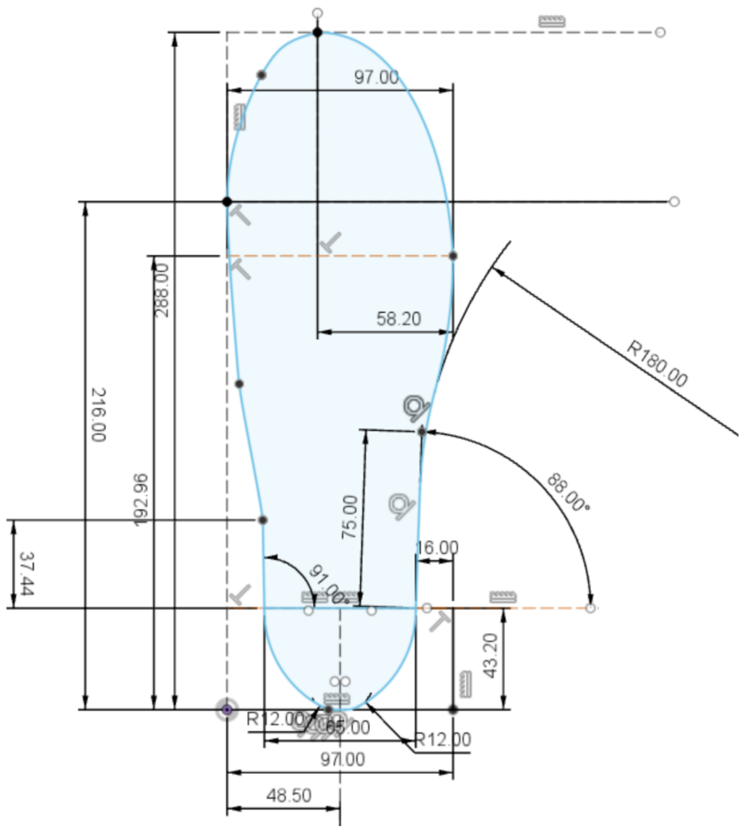


Figure 7.1: First draft Fusion 360 sketch

The sketch used multiple points to help define the shape of the sole and was not parametric yet. A mixture of straight lines, 3-point arcs, and splines was used to form the shape. The shape was then extruded. The arch was created by taking T-Splines in Fusion 360 and creating a mesh that contoured upwards. The height of the arch was set at 15mm tall for experimentation with no scientific basis, it was purely for trial and error testing. The first formula prototype print was a thin, flat extrusion designed for fit testing and determining the location of the arch support.

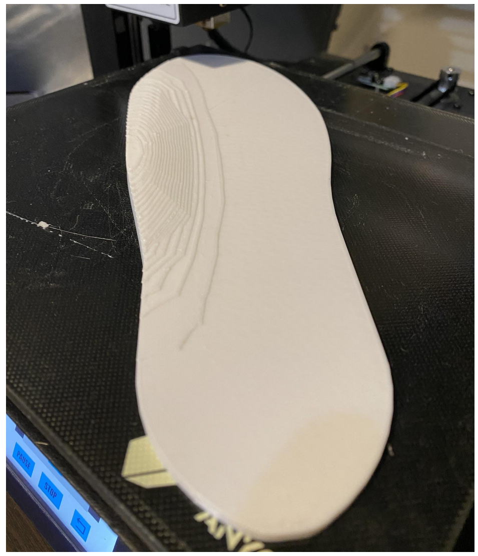


Figure 7.2: The first prototype print designed for fit testing.

The prototype insole was found to have a good fit, just requiring some further tweaks to the arch. The arch was also found to be too high on the foot and too short in height. The arch was moved down, closer to the heel, by 30mm, and was raised vertically by another 10mm. With the above changes, another design was created that also introduced internal contours to the in-sole. This was printed with PLA again for its prototyping speed. This design was found to have a perfect fit for the team member's foot and the contours were quite comfortable despite the hard plastic nature of PLA. The arch height was found to be suitable, but it still needed to be moved back by another 15mm.

Figure 7.3: The second prototype placed on the foot it was designed for.

Since the team was satisfied with this design, the process to make a parametric insole was started. A new sketch was created by tracing over an image of an insole. This new sketch was created entirely with splines and initially was designed to match the shape of the image of the insole. Once the team was satisfied with the shape, the dimensions of the points and splines were made parametric such that only three dimensions are needed to define the shape of the sole; sole length, heel width, and ball width. The image below shows the resulting sketch, which automatically changed size depending on the foot length, heel width, and ball width parameters. The highlighted values represent the parameters all equations/splines are based on.

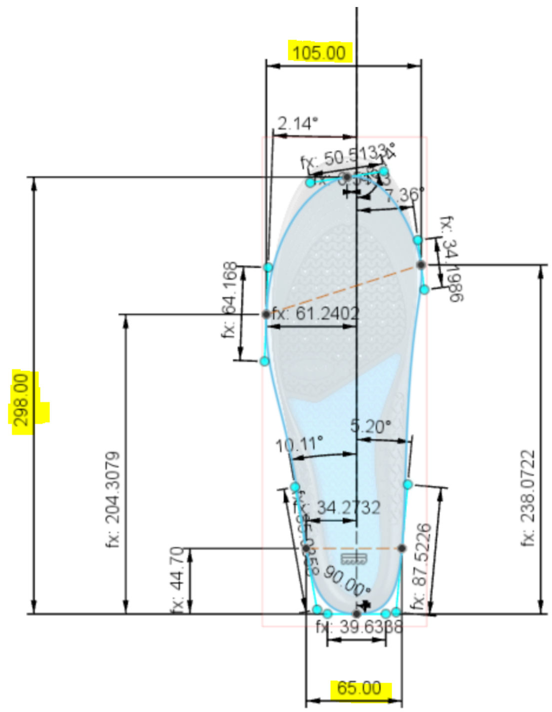


Figure 7.4: Second draft Fusion 360 sketch

It was after attempting to create parametric contours for the insole that the team found that Fusion 360 does not support parametric free-form modeling, meaning that future midsole and upper designs couldn't support custom footwear design. Due to this, the team transitioned to Rhino 3D.

7.2.2 Rhino 3D

The insole CAD sketch was created using the same technique as used in the Fusion 360 model. A top view of an existing insole was imported into Rhino. Then a set of six points were created to match the shape of the insole; the starting point at the bottom of the heel, two points for the heel midpoint, two points for the ball of the foot, and a point at the tip of the sole. Figure 36 shows the resulting image.

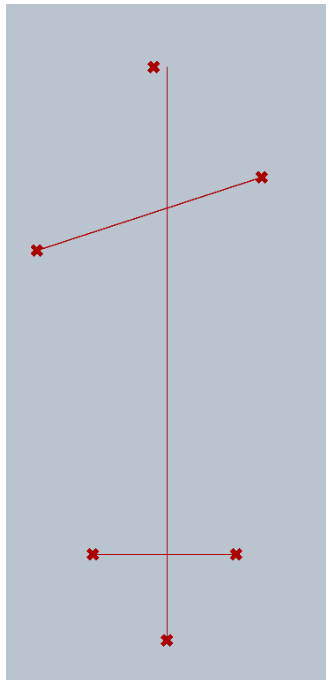


Figure 7.5: Basic outline of the insole 2D sketch

After the initial points are created, the dimensions are changed to be a percentage of the sole length in the y-direction, and a percentage of the heel or ball width in the x-direction. By doing this, the points that define the shoe are now parametric. The results are shown below in Table 2.

Table 7.1: Insole 2D sketch point locations

Point	% length of sole length	% length of heel/ball width
Heel Tip Point	-	-
Toe Tip Point	100%	6% ball width
Medial Heel Point	15%	48%
Lateral Heel Point	15%	52%
Medial Ball Point	81%	42%
Lateral Ball Point	68%	58%

From these 6 points defining the sole shape, an additional 12 points were created to better define the shape of the sole, with an additional point for the arch. These 12 points are made parametric by defining their dimensions to be a function of the original six points. Once the points have been created, a curve is constructed from the control points. The final shape for the 2D insole shape is shown below in Figure 37, with the new points highlighted in green, and the original points in red. The algorithm to construct the shape-defining points can be found in Appendix C.

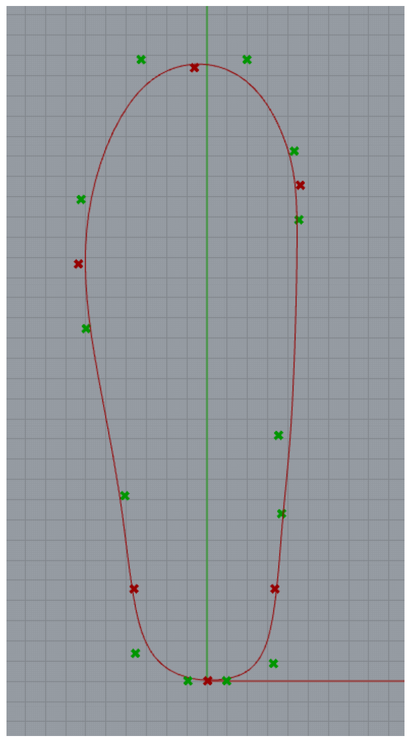


Figure 7.6: Finalize insole 2D sketch

7.3 Accessibility Mechanism

The Nike FlyEase heel mechanism was used as inspiration to create a new design utilizing the spring force in TPU to create the accessibility mechanism. To not infringe on the patent held by Kizik, there is no metal spring hinge within the design. While this may limit the overall action distance of the heel mechanism, it will not affect the security that the mechanism offers once properly used. Small slits are carved into the heel design, either in a tensile or compressive manner, to allow the needed bending and movement to widen the neck enough to easily slide a foot into the shoe. Diagrams of both the tensile and compressive systems are included below.

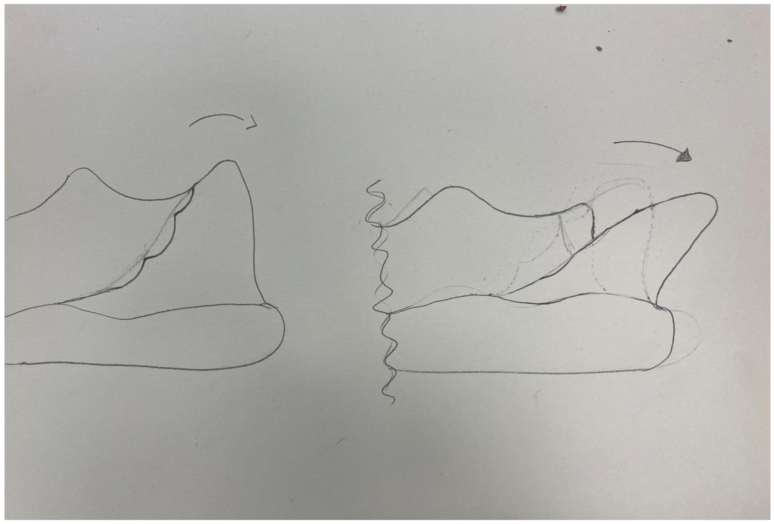


Figure 7.7: A diagram showcasing the tensile heel mechanism.

In the tensile configuration, a user places their toes into the neck of the shoe and uses their body weight to bend the heel back into a sliding position. The foot can then be comfortably slid horizontally into the shoe, and as such a movement takes place, the heel will flex back into its natural position locking the foot within the shoe. Once the user is prepared to remove the shoe, they place their alternative foot on the back heel and pull their locked foot horizontally and up out of the shoe. This will open the neck wide enough to allow the foot to easily exit while letting the heel return to its natural position and maintaining the form of the shoe.

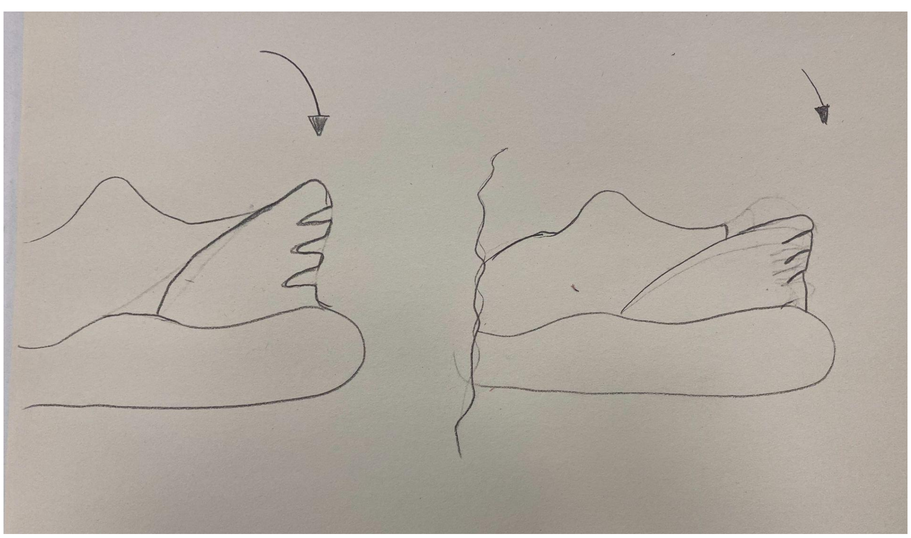


Figure 7.8: A diagram showcasing the compressive heel mechanism.

In the compressive configuration, the user places their toes within the shoe and uses their body weight to push the heel down, widening the hole. This is similar to the tensile configuration and offers equal accessibility to the user and shoe. Once the weight is lifted off of the compressive area of the shoe, the heel returns to its natural state and locks the foot within the shoe, as expected. Pulling their foot out of the shoe requires a small amount of force to be applied to the back of the heel using the other foot, and simply sliding out of the shoe. This action requires a bit more effort to remove fully since the action of the heel is downwards and the user is likely to pull their foot out horizontally and upwards. This heel may be better suited to children and those that can apply a bit more force to the shoe without worrying about balance.

Both of these designs are incorporated into various designs to facilitate different actions to place and remove the shoe from a user's foot. Furthermore, with biomechanical design finalized, modeling software chosen, and the insole formula created, the work on designing the insole and midsole can now begin. The next section covers this topic, as well as the design of the outsole.

8. Sole Design

The design of both the 3D insole and midsole model depend on the 2D insole sketch, which lays the groundwork for the shape of the shoe. The 2D insole sketch was first created by constructing six points that defined the sole length, heel width, ball width, and arch location. From these six points, an additional 12 are created; two for every point. These twelve points are entirely equation-driven and help to better define the shape of the insole. With the sole shape and size perfected, work can begin on the insole and midsole shape.

8.1 Insole Design

After the 2D sketch on Rhino was completed, the points were given a Z component to add depth to the sketch. A surface was created between the points using the patch tool. A copy of the original 2D sketch was created and offset to make it smaller than the top sketch. The patch tool was used on the smaller sketch to make a new surface.

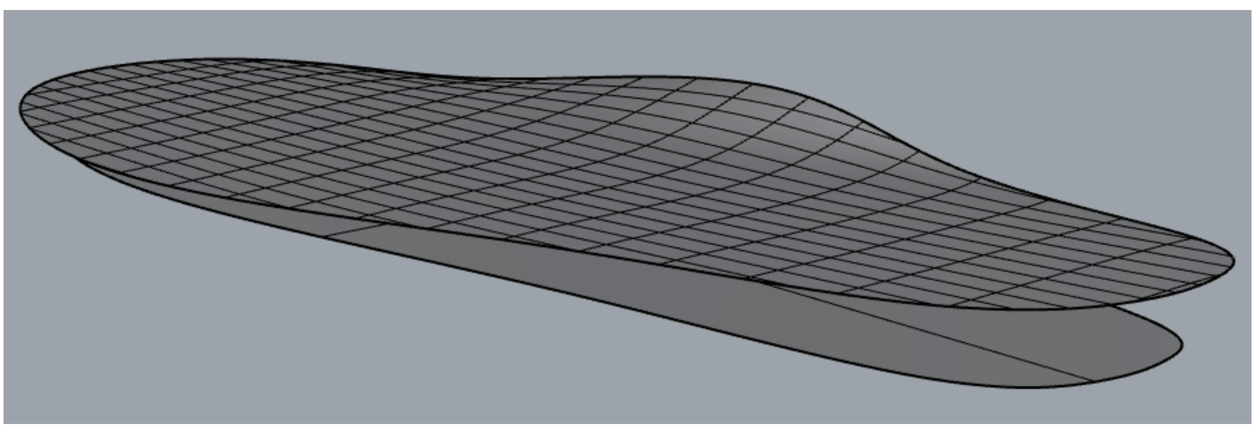


Figure 8.1: Unconnected upper and lower surface of the insole.

A third curve was created between the two existing surfaces. The patch tool was used on this middle curve to create a middle surface. The upper and middle surfaces were joined together using curved lines, with the lines being joined together with the loft tool. The same process was repeated for the upper and lower surface. These two separate surfaces were then merged together to create the final design of the insole. The Grasshopper script for this process can be found in

Appendix E. The design can still easily be adjusted based on how it feels after it has been printed with flexible material. The figures below show a rendering of the final design.

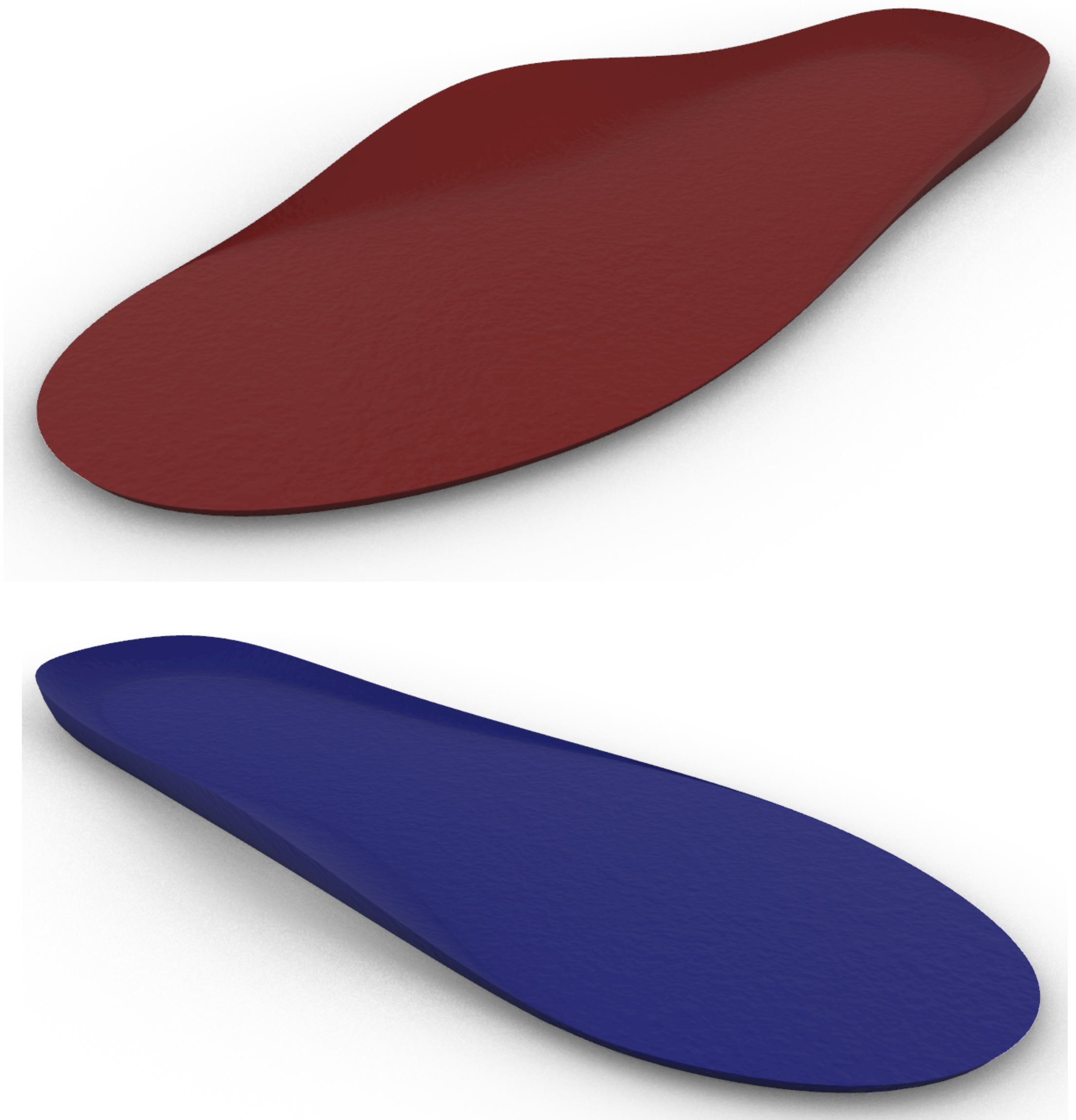


Figure 8.2: Insole design concept renderings.

This finalized insole design features contours around the heel for additional support, a high arch to provide ample arch support, and a higher thickness at the heel. The heel gently slopes down to the balls of the foot while keeping the bottom surface of the insole flat. The height of the contours, thickness of the material, exact location of the arch support, and even slope to the balls of the foot are all fully customizable just by simply changing a few parameters. This makes adjustments after testing the insole very easy to do. The arch shape of the insole is important when designing the midsole and upper since those components of the shoe must also support the arch.

8.2 Midsole Design

The design of the midsole is dependent on the shape of the insole. It is crucial that the midsole stays slightly bigger than the insole but still matches the general shape of the insole. For the purposes of rapid prototyping, a very basic design was chosen as the initial midsole. To create a basic midsole, the insole curve is taken and projected onto a flat surface such that the resulting curve is a flat curve in the shape of the insole - this curve is offset to be slightly larger than the midsole. Then the curve is extruded to make the bulk of the midsole.

To create the toe arch and to carve out the final midsole shape from the basic midsole block, a side profile is created. The side profile is created by making a block with the length of the insole, a width larger than the insole, and a height of the desired midsole thickness. At the end of this block, a curve is constructed in the shape of the desired toe curve. This side profile block and the above midsole block are created on top of each other, as seen below in figure 8.3.

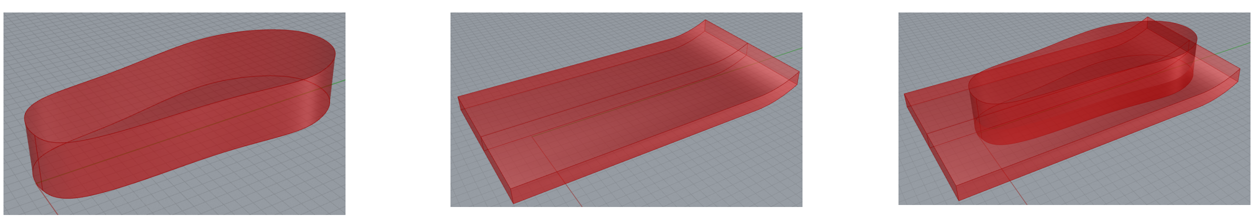


Figure 8.3: Midsole construction process.

From the overlapping shapes, the boolean intersection component is used to join together the two overlapping shapes and throw away the rest. The result is the final midsole block, as shown below in figure 8.4. This midsole block serves as a canvas and allows for future design ideas or requirements to be easily added to it.

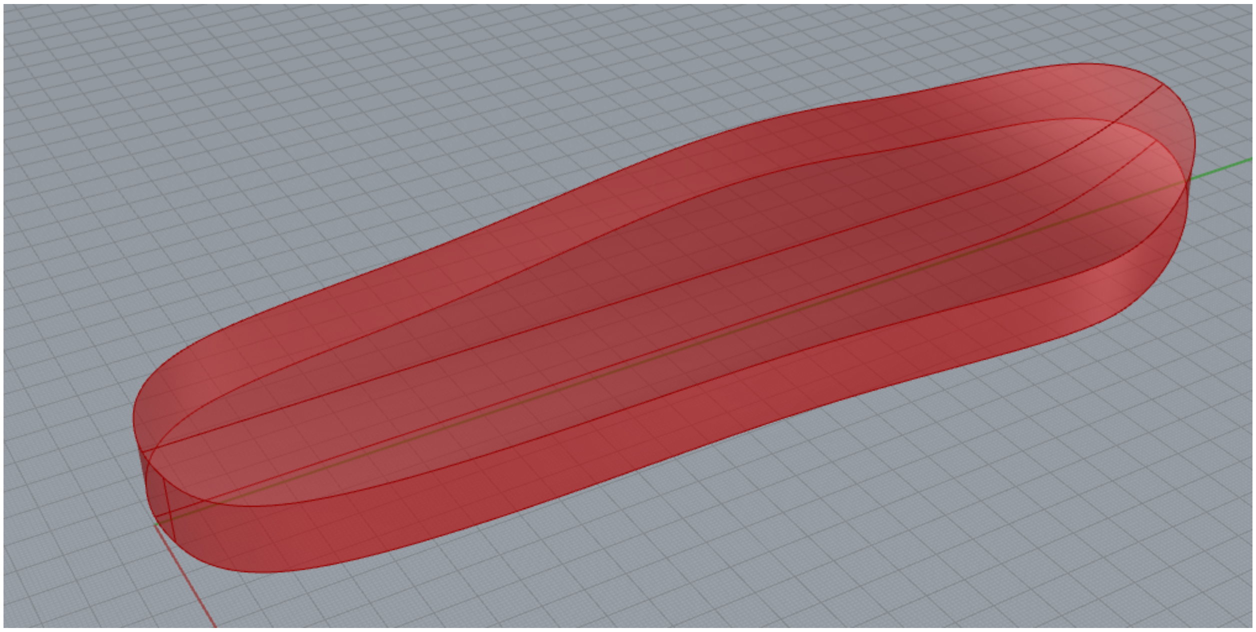


Figure 8.4: Basic midsole design.

While the length is dependent on the insole length, the thickness of the midsole and exact dimensions of the toe curve can be easily changed. The toe shape is created using a parabola curve. This midsole serves as the basis for the concept designs. If the concept designs require a midsole with a varying height on the top surface (instead of the flat top surface shown above), then the same method can be used for creating a midsole. The only thing that would change is that instead of projecting the insole curve to a flat surface, a new curve would need to be constructed in the shape of the desired midsole shape, which would then be extruded so that a new midsole block is created.

8.3 Outsole Design

The goal of the outsole is to provide traction to the shoe as well as protecting the users' foot from debris on the ground. Traction is typically provided by the material of the outsole and the shape. However, having a single-head extruder means only one material can be extruded at a time, meaning the outsole must be made out of the same material as the midsole. To get a firmer outsole, the number of bottom layers can be increased when preparing the model for printing to get a thicker outsole. The outsole shape can be created by creating a shape on the bottom surface of the midsole and using a form of extrude cut to cut into the midsole. However, unlike

Solidworks and many other CAD softwares, Grasshopper does not have an extrude cut tool. Therefore, the desired outsole shape must be created under the bottom of the midsole surface, then projected onto the midsole bottom surface (such that the desired outsole shape matches the midsole toe curve), then extruded into the midsole. Finally, a boolean intersection component is required to create the resulting shape. While this design may not provide the best traction, it serves as a proof-of-concept for the outsole, and can easily be improved or changed later on.

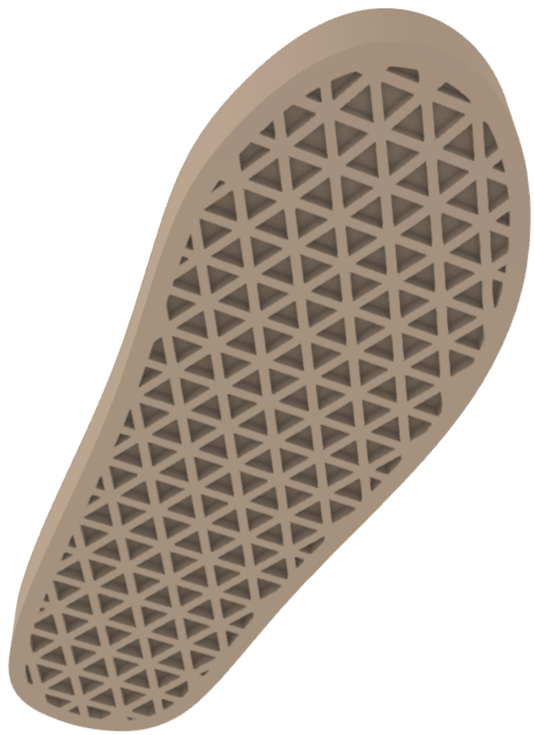


Figure 8.5. Outsole concept design.

8.4 Sole Design Conclusions

Rhino and Grasshopper were used to create and generate insole, midsole, and outsole designs. The root of all three designs start with three base dimensions, those that are assigned parametrically by user input, and are expanded by various equations to define and form the desired shapes. These designs were created with the intent of being easy to modify if and when design changes had to be made.

9. Upper Design

The upper of a shoe consists of everything above the midsole. On a typical shoe this includes the parts that cover the foot, the shoe tongue, and the shoe laces. Uppers are normally stitched onto the midsole on a typical shoe. However, the principle behind slip-on shoes is that no laces or fasteners are required. Therefore the upper is just material which surrounds the user's foot, and will require no stitches for assembly. There are two ways to accomplish stitchless assembly. The first is to print the upper and midsole at the same time, so that the upper directly adheres to the midsole during the printing process. This method provides the best adhesion between the upper and the midsole, but comes at the cost of a very long print time. The second option is to glue the two parts of the shoe together. This allows for a shorter printing time between parts, but the adhesion will not be as good when compared to the first method. Therefore the upper was designed with both options in mind. This was accomplished by creating a ridge between the top midsole surface and the lower upper surface. This ridge allows for easy gluing while also keeping the option of printing both upper and midsole together.

Creating the upper starts with two curves; the top opening curve (where the foot goes in) and the bottom curve, which is built off the top of the midsole surface. Then a series of lines are drawn between the two curves to connect them together. This includes lines on the right and left side of the top curve for the sides of the heel, a back line for the heel, a line in the middle to dictate instep height of the shoe, and two other pairs of lines to better define the upper. Once all the lines have been drawn, the *network surface* component is used to create a surface bounded by the defining curves. Figure 9.1 below illustrates the process of creating the upper.

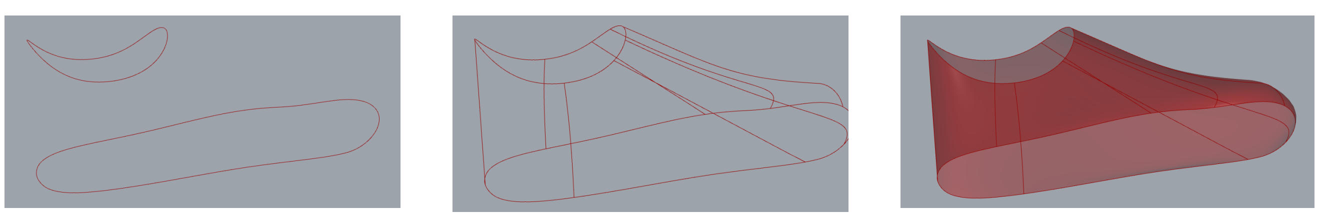


Figure 9.1: Upper surface construction process.

The result of the process produces a surface in the shape of the upper. However this surface is infinitely thin. To add depth to the upper, a second, slightly smaller upper surface is created. Then the two uppers are joined together to produce the final upper.

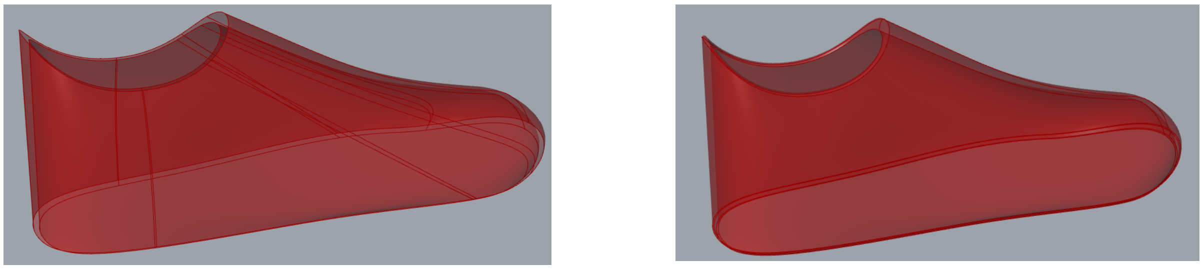


Figure 9.2: Final upper construction process.

The ridges, mentioned earlier, are created by first creating the ridges on the midsole top surface. Then the upper takes these curves and simply uses them as the bottom defining curve. This ensures that the upper and midsole are a perfect fit, whether it's for gluing or printing together.

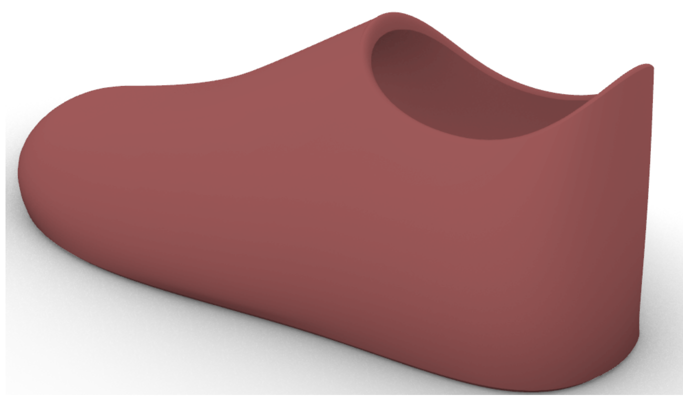


Figure 9.3: Rendering of the final upper design.

9.1 Upper Design Conclusion

The completion of the upper design combined with the completion of the midsole and insole design marks the completion of creating a 3D printable shoe, minus the accessible portion. By using Grasshopper, an entire shoe, including midsole, was created and made parametric by having a series of user inputs to define the foot shape. With the upper completed, work on heel can begin by using the same concepts used to create the upper.

10. Heel Design

The design of the heel in a traditional shoe is inconsequential to the overall design process, and besides accounting for baseline functionality within the scope of biomechanics, it is mostly overlooked. In stark contrast with tradition, the heel is one of the integral parts of this shoe design since it houses the entirety of the accessibility mechanism that thrusts the goal of accessible footwear into reality. To begin the design process, the tensive accessibility mechanism envisioned in 7.3 was selected to be integrated into the heel and designed in Grasshopper.

Making the heel in Grasshopper starts off with making an upper in the same fashion as described in section 9. After the upper is created, a straight line is generated and used to split the upper into two parts; one being the upper with no heel, and one being the heel. Figure 10.1 shows the before and after of splitting the upper into two parts.

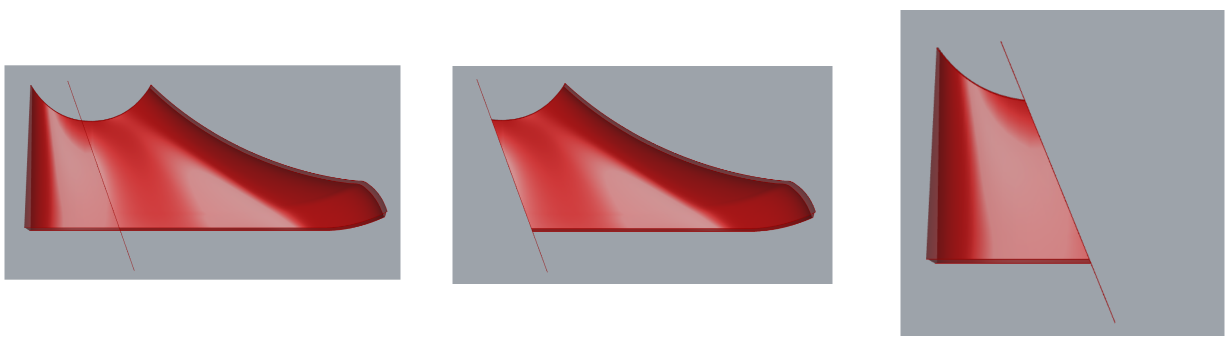


Figure 10.1: Before and after of upper with line for cutting.

Along with the heel model, some modifications were made to facilitate the adhesion necessary to stick to the midsole; this was done through a slight ridge being created along the bottom wall as mentioned in section 9. During the design process, it was also identified that the majority of applied stress would be taking place at the bottom further-most point of the heel model due to the lever action and moment that is created during the operation of the mechanism.

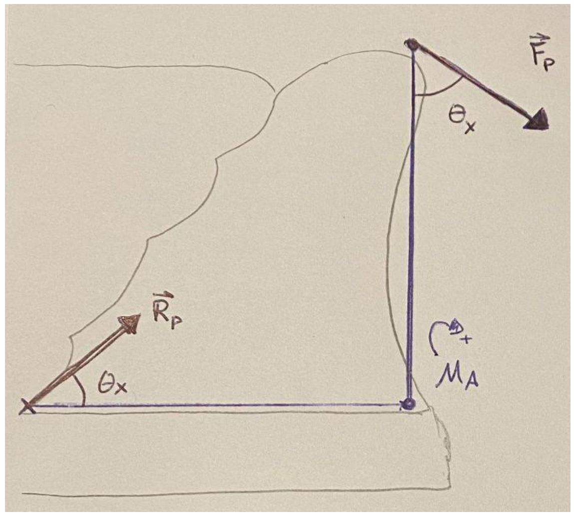


Figure 10.2: The point of action generated during operation of the accessibility mechanism.

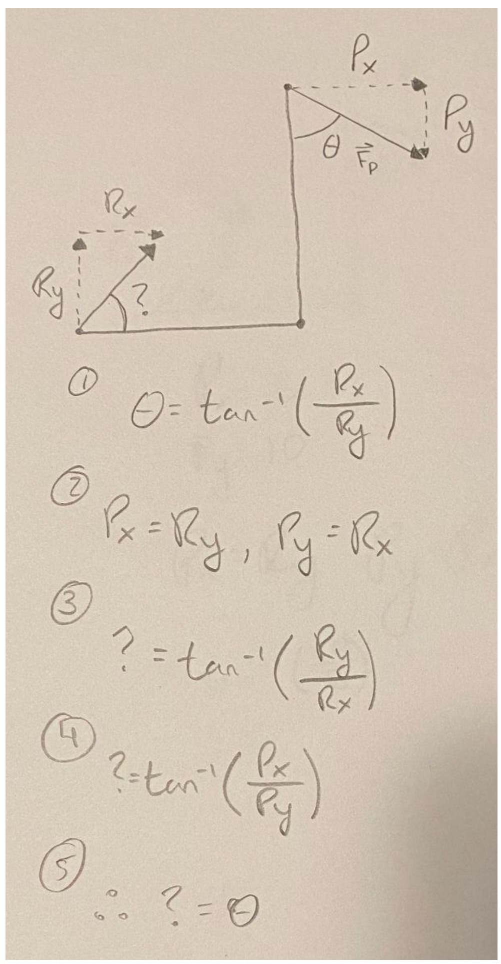


Figure 10.3: The physics of the stress point.

Staples, nails, and other stronger adhesives were considered to properly affix that point to the shoe, further securing the mechanism, but a preliminary test involving silicon caulking and other forms of adhesive was to be conducted first. Having these considerations in mind, the first prototypes were created and the scenarios described were conducted at length.

10.1 Heel Design Conclusion

The selected heel design integrates the accessibility mechanism through a tensive action, widening the entrance for the shoe by physically moving material out of the way. In order to facilitate this mechanism, it was identified that the heel required the same opposing force to be applied at the end of a lever arm of the heel base. Staples, nails, and other adhesives were considered for the role, but a silicon caulking was chosen as the first test to be conducted.

11. Preliminary Design and Concept Refinement

Both preliminary design and concept refinement go hand-in-hand when taking a holistic design approach, as this report does. The preliminary design, and associate drawings, display the intention behind the design and stylistic choices, whether that be for youth, everyday people, or seniors. These preliminary sketches orchestrate an important role in the design process, defining the path towards the completed modeling in CAD. This section follows the initial design drawings to the completed first iterations of the CAD model.

11.1 Preliminary Design

As the goal of creating accessible shoes is to address multiple user groups, three preliminary shoe designs were selected, one for each group; children, seniors, and everyday aesthetic wear. Each group's design focuses on qualities within the design that would be important to their wearer. Multiple iterations were ideated and discussed for each user group. Those iterative designs can be found in Appendix D**.**

11.1.1 Children Shoes

As children tend to like more dramatic and stand-out designs, very exciting and bold looks were created. This design is very similar to that of a look from Hasbro's *Transformers* and can be colored brightly to be more inviting to kids. The heel features a compressive foam spring design that allows a child's foot to easily slip into the shoe by increasing the size of the neck momentarily as a small force is applied from body weight. This spring then quickly returns to its original shape and secures the foot inside the shoe. Vents are included on the side of the shoe to facilitate breathability and keep the foot within the shoe cool; these vents are the shaded portions on the middle walls of the sketches below. The shaded portions on the heel are the slits cut to allow movement in the compressive heel mechanism.

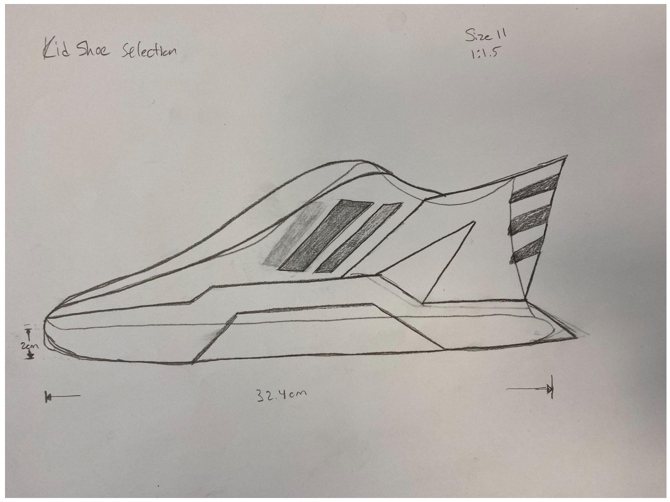


Figure 11.1: Base sketch for a size 11 men's children shoe.

A colored version of the sketch is included to showcase how eye-catching a design such as this can be for children.

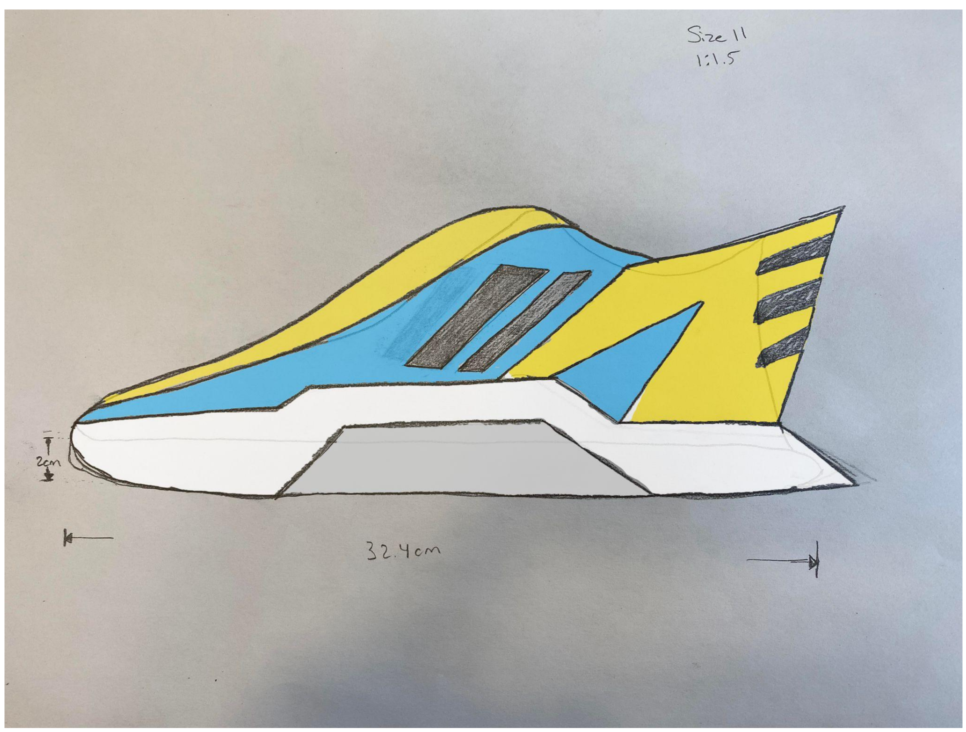


Figure 11.2: Coloured-in sketch of the above base design.

11.1.2 Senior Shoes

A tempered and more organic look was elected to be the design chosen for seniors for its simplicity and high comfort. This design is very easy to model and print since it does not incorporate any dramatic design features or overhangs that would prolong or complicate prints. This design is similar to that of a standard Vans shoe. This design features a tensile heel that pulls back as body weight is applied, widening the hole and allowing for a smooth entrance into the neck. It is then quickly brought to its original shape and secures the foot in place. Small slack parabolic cuts are made into the heel to allow tensile movement for the accessibility mechanism. A single, thin, linear bent is cut on the bottom of the shoe to allow for ample airflow to cool the feet.

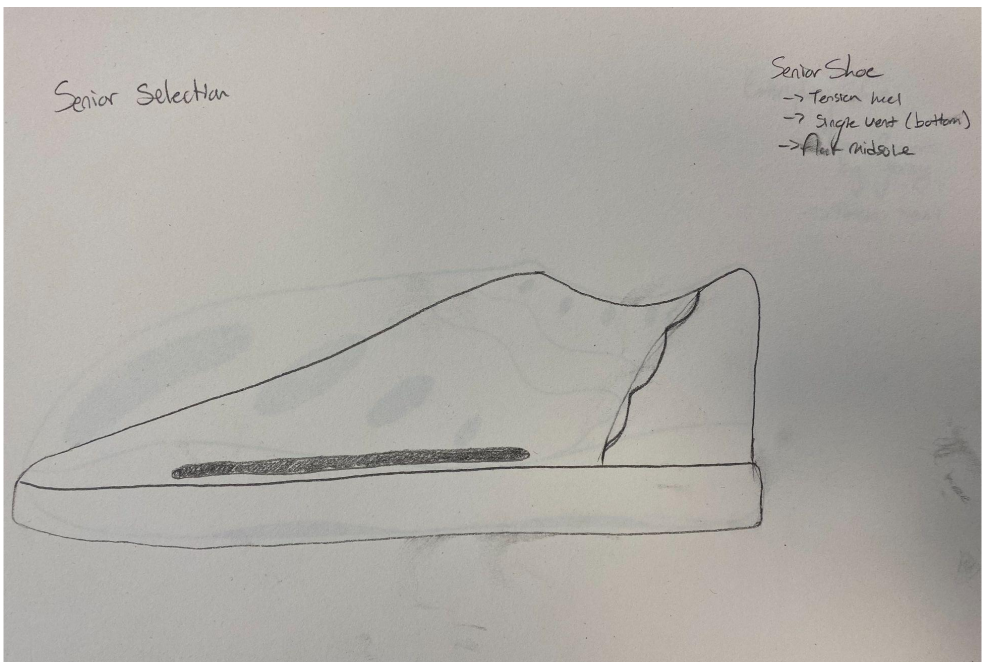


Figure 11.3: The senior shoe selection base sketch.

A simply colored design sketch is included to showcase the simplicity of the design and organic nature of the concept.

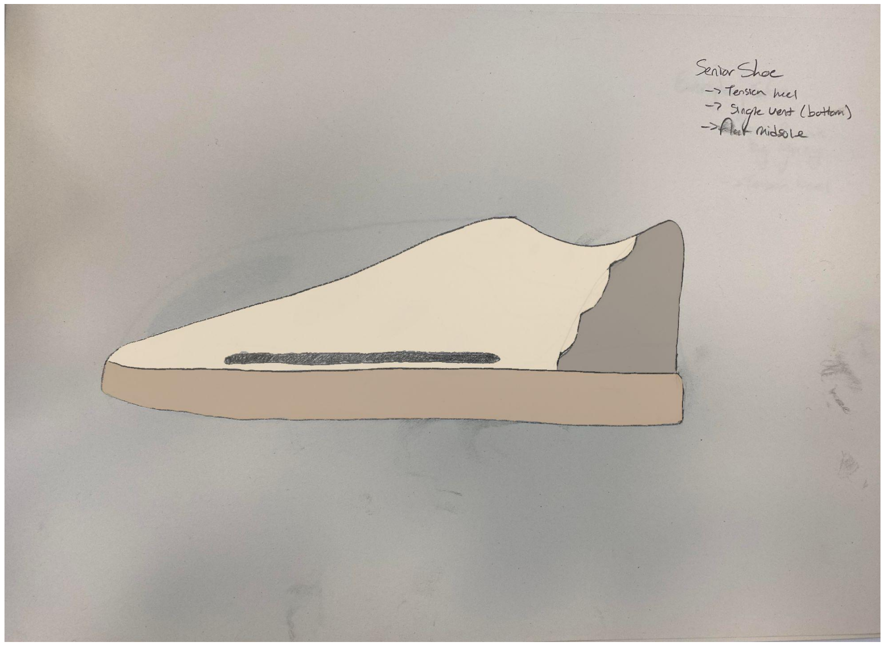


Figure 11.4: Coloured senior shoe design concept.

11.1.3 Everyday Shoes

Creating a design that is modern and aesthetically pleasing to the average consumer is an invaluable step in the creation of marketable footwear. The goal is to create a shoe for the everyday activities one may find themself doing, whilst also introducing the accessibility ease and 3D printing design novelty. The shaded areas are holes cut in the shoes for vents, and parabolic slits are integrated into the design to allow the tensile heel locking mechanism as discussed at length above.

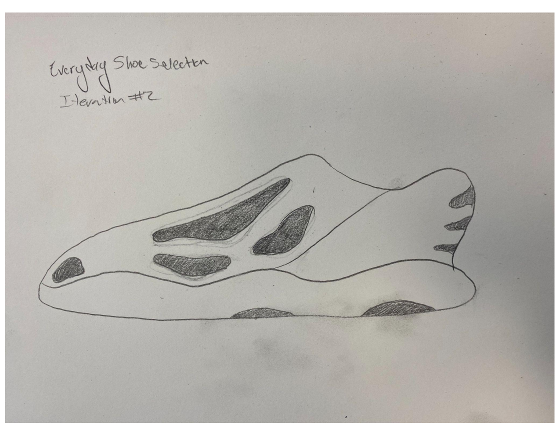


Figure 11.5: Everyday shoe base sketch, iteration #2.

A single color was added to the design to exemplify a pure and simplistic look, a very modern aesthetic for footwear at the current time.

Figure 11.6: The colored everyday shoe sketch.

11.2 Dimensioned Drawings

The tempered and organic senior shoes were chosen as the design that would be modeled and focused on throughout the remainder of this report. This was decided upon since the primary audience the project targets is geriatric patients and seniors. In order to appropriately model the design, dimensioned drawings were created of the sketches; many of the dimensions included were measured and compared to existing shoes, namely Vans for their striking resemblance. The following sketches are the preliminary dimensioned drawings for further refinement.

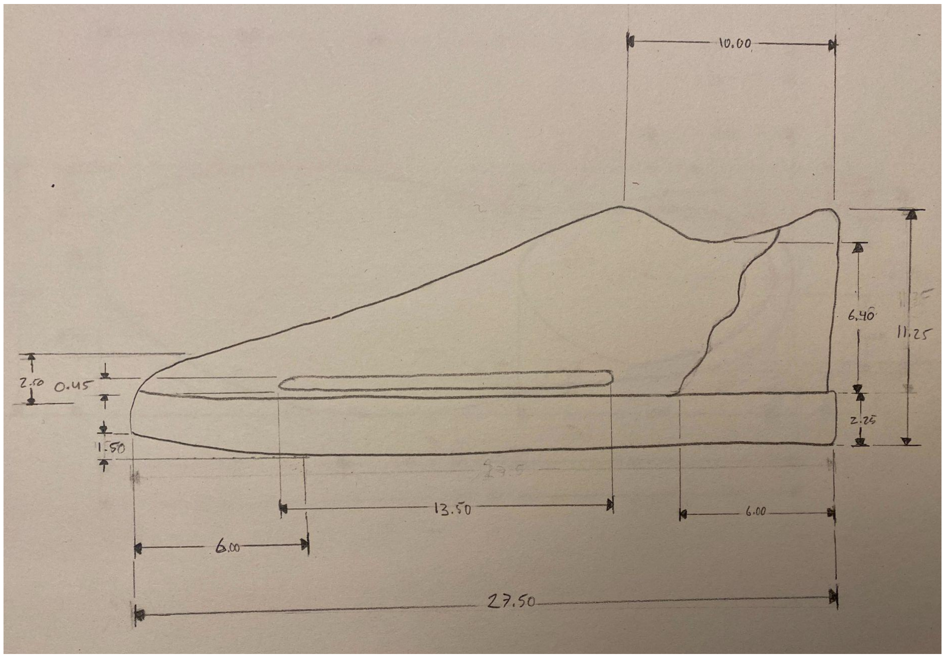


Figure 11.7: Dimensioned front view of the senior shoe.

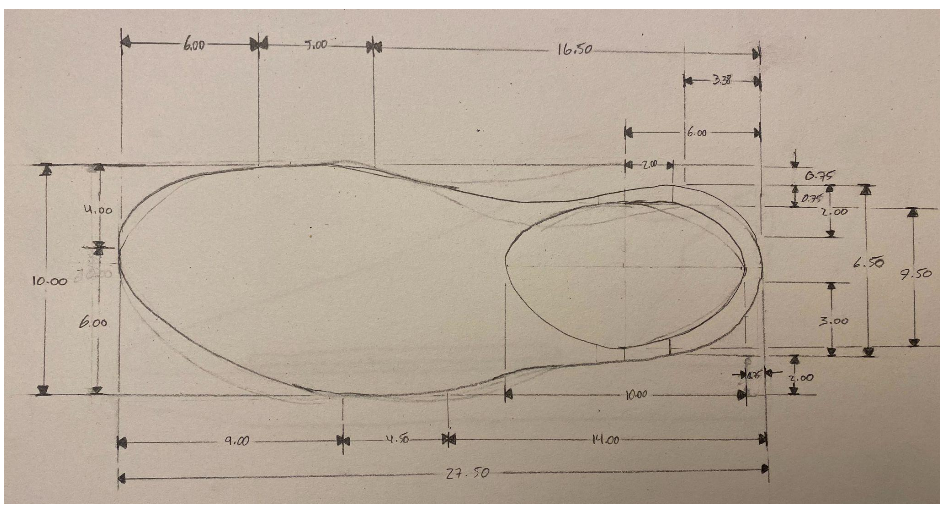


Figure 11.8: Dimensioned top view of the senior shoe.

11.3 Concept Refinement

With the senior shoe chosen as the focus of the report, the midsole, upper, and heel were redesigned to match the preliminary design specification. The upper remains mostly the same, with the exception of two added vents and tweaks to the dimensions. Additionally, the heel of the upper is cut away to make room for the separate heel as described in section 7.3. The two vents are added to the side by drawing out the slot geometry on the side of the upper and cutting out that material from it. The heel of the upper is cut away using the same method as described in section 10.

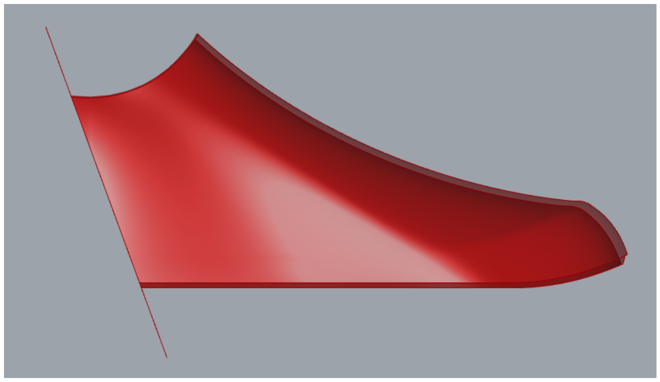


Figure 11.9: Upper with no heel.

Since the preliminary design calls for a heel that bends backwards (tensile heel), the heel is detached from the upper. The heel is made wider to allow the heel to hug the upper, as shown in the preliminary design. This is done by creating a second, wider midsole. An upper is made from the wider midsole, and the heel is extracted from the upper using the same method described above. However, instead of using a straight line to cut the upper, a wave pattern is used instead to match the preliminary design. Figure 11.10 below shows the resulting wavy heel, while figure 11.11 shows how it wraps around the upper.

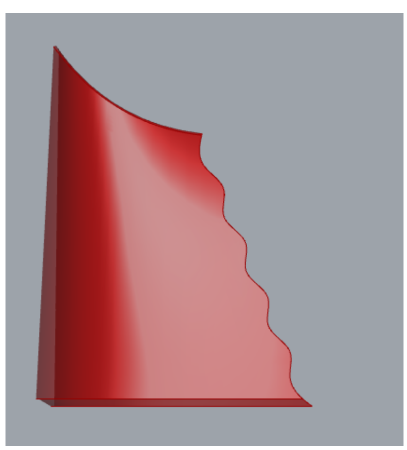


Figure 11.10: Heel with wavy pattern.

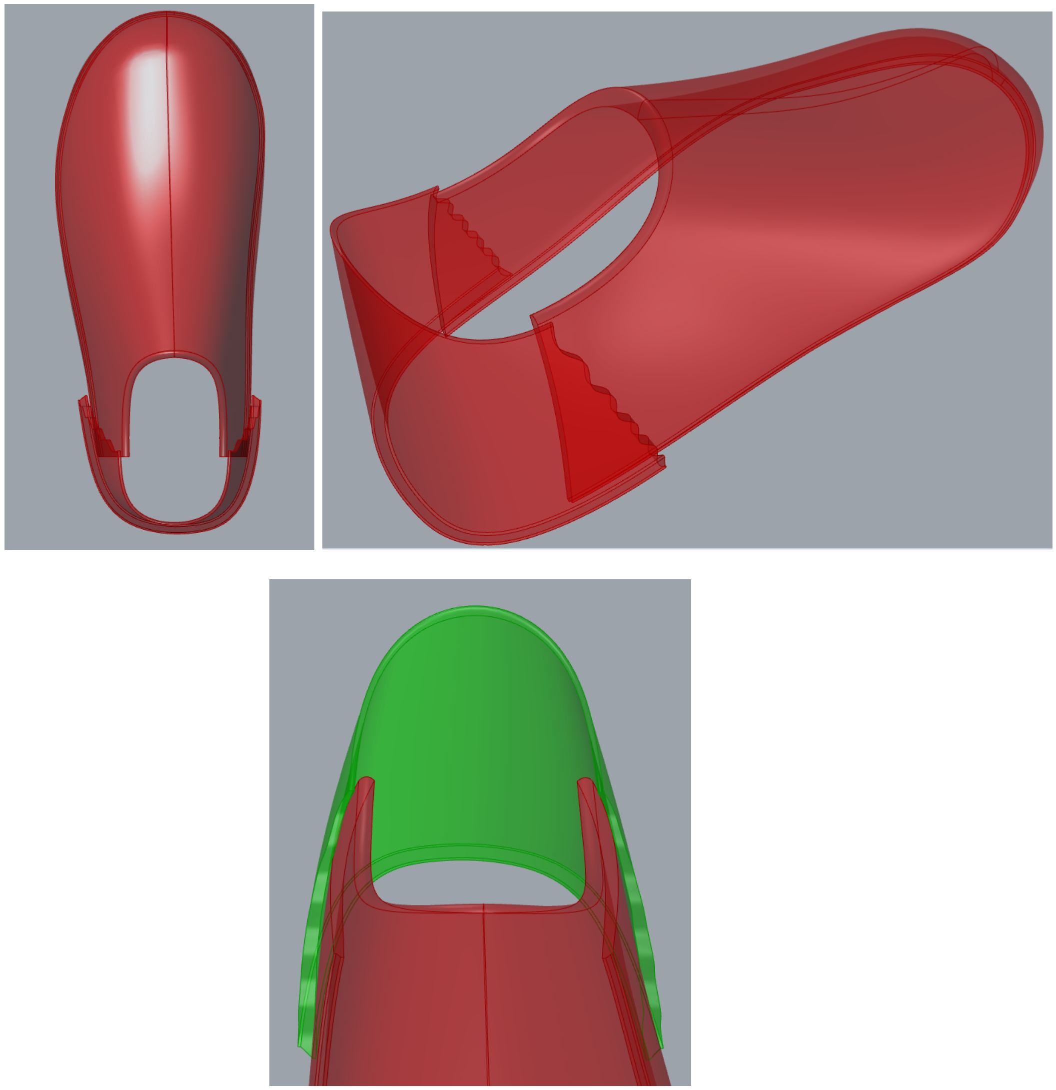
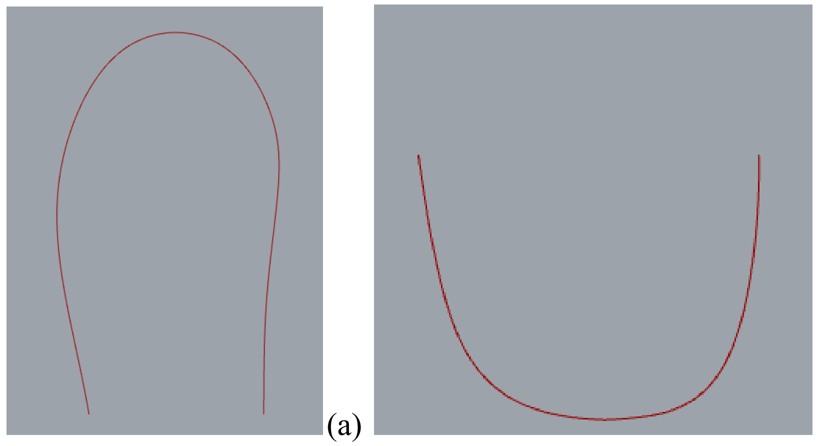


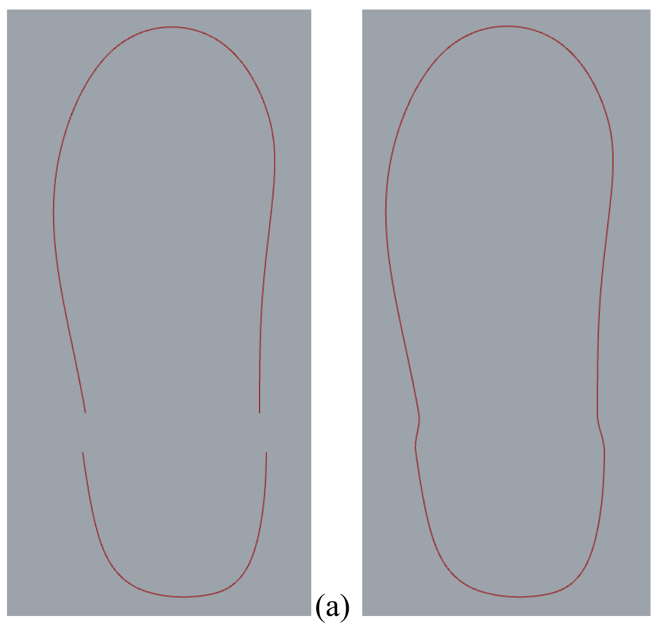
Figure 11.11: Heel hugging the outside of the upper.

Starting with the midsole, not much is changed with the design. Because the preliminary design is focused on seniors, the midsole remains flat and plain, meaning only tweaks to the dimensions of the midsole are required. This includes changing the dimensions of the toe box and thickness of the midsole. However, the midsole is made wider at the heel to accommodate for the larger heel size. This is done by taking the larger midsole curve and cutting it at the heel, and doing the same for the upper. A slight gap between the two is created to make space for a new curve to connect the two disconnected curves. Figure 11.12 and 11.13 below provide a visual representation of this process.



(a) (b)

Figure 11.12: (a) Upper curve with no heel from original midsole (b) Heel curve from new wider midsole curve.



(a) (b)

Figure 11.13: (a) Curves from figure 11.12, disconnected (b) Upper and heel curves connected to create the new midsole shape.

The new midsole is created from the new midsole curve shown above. This midsole is wider at the heel to accommodate for the separate heel. Figure 11.14 shows a rendering of the new midsole, while figure 11.15 shows a rendering of the whole shoe put together. Note the ridge on the midsole, which is there to facilitate adhesion between the upper, heel, and midsole.

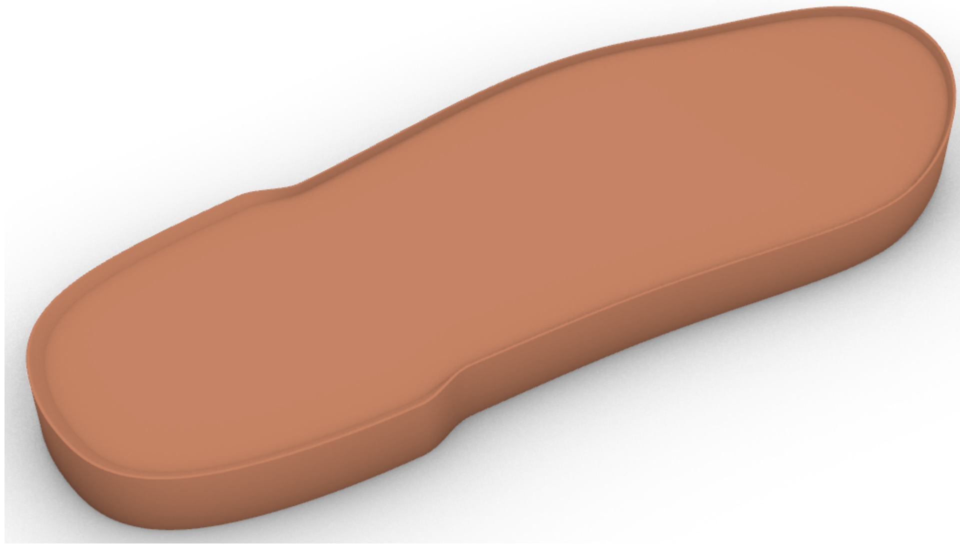


Figure 11.14: New midsole.

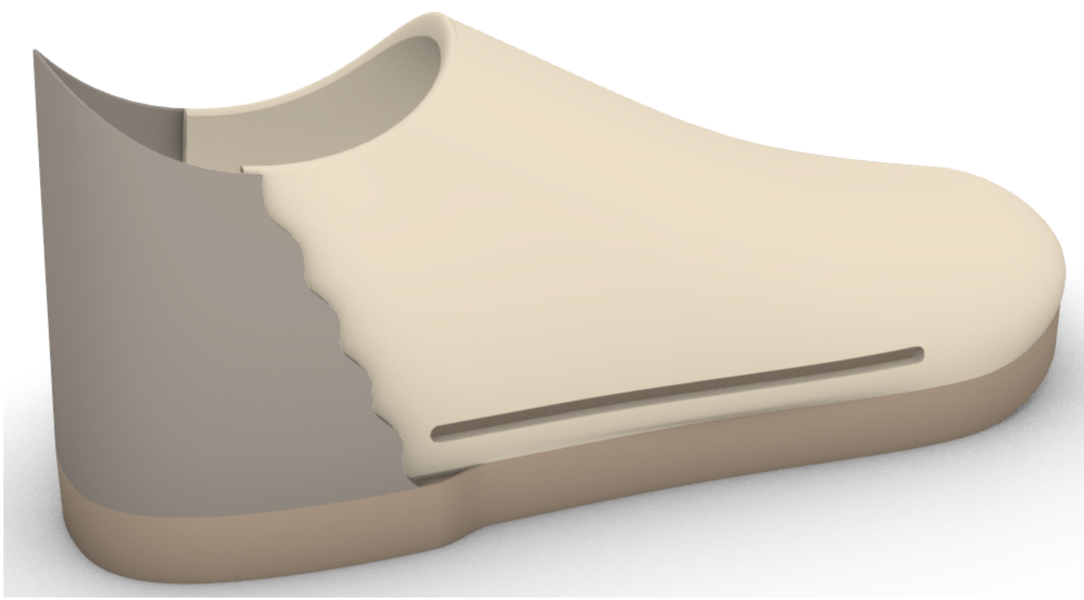


Figure 11.15: Senior shoe concept renderings.

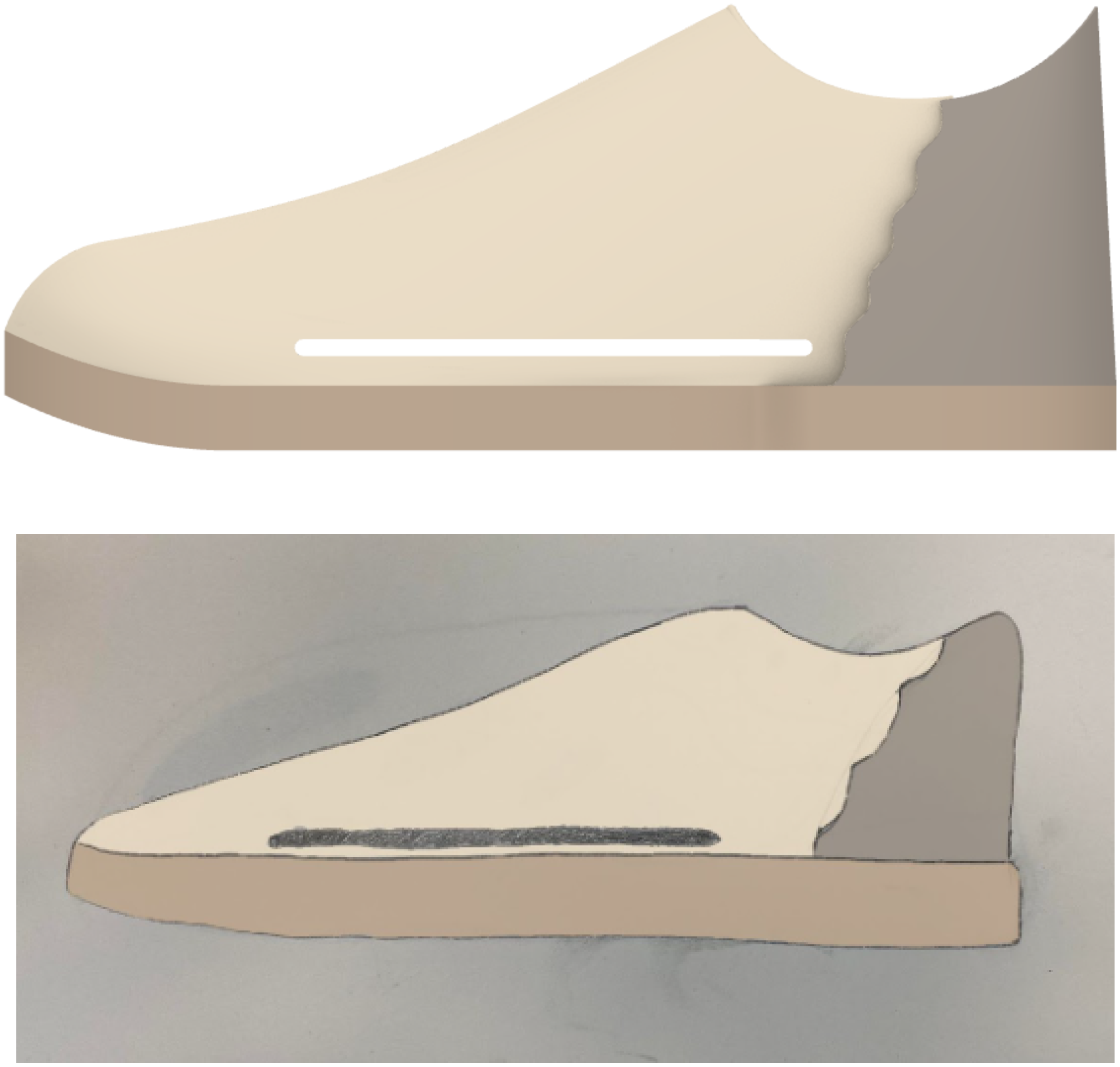


Figure 11.16: Side-by-side comparison of sketch and rendered model.

11.4 Preliminary Design and Concept Refinement Conclusions

The tempered and organic senior shoe was selected as the primary design for this report and was dimensioned for CAD, as a result. This selection was made since the primary objective was to create a shoe for geriatric patients and seniors. The midsole, upper, and heel used a double drawing method of creating interconnecting parts to complete the design of the shoe. These CAD drawings were turned into a complete model, which is used throughout the report.

12. Prototyping and Iterative Design

No first draft is perfect, and this shoe is no exception. However, with 3D printing, prototype designs can be quickly manufactured and tested. Furthermore, improvements on the design and further design iterations can be completed in only a matter of hours thanks to 3D printing. The use of flexible filaments requires slower printing speeds which increases the amount of time required for each print, but when compared to traditional manufacturing methods, 3D printing is an efficient method to quickly produce prototypes.

To take the design from the CAD software to the 3D printer, the model was first exported from the software as an STL file. An STL file takes the original CAD file and triangulates the surface, converting it into many different triangles. A slicing software is then required to convert the STL file into gcode for the printer. The slicing software controls nearly everything that can be controlled with the 3D printed; this includes layer height, printer speed, printer temperature, infill density, etc. For this project, Ultimaker Cura was used as the slicing software. Along with Cura, a printer controller called Octoprint was used to remotely control and monitor the printer via a web interface, and allows for various plugins to be installed, such as cost estimation and g-code optimizers.

The prototypes were printed in the order that they were designed. Therefore, the insole was the first model to be prototyped, followed by the midsole, upper, and finally heel. Naturally, the larger the volume of the model, the longer it takes to print. This meant it took on average 9h to print the insole, 20h to print the midsole, 16h to print the upper, and 4h to print the heel. While the upper has a lot less volume than the midsole, it does not have much empty space between the walls of the upper. This means the upper is essentially printed as one solid piece. The same goes for the heel, as it is a thin-walled model. The insole, however, has about 3mm - 4mm empty space in between top and bottom layers. This gap is what gives the insole its cushion, and by keeping it small but increasing infill density, the model becomes optimized for rapid prototyping.

12.1 Insole

The first insole prototype was printed in 87A TPE and was successful in matching the foot dimensions of the intended user. A photo of the first prototype is shown below in figure 12.1. The dimensions of the first prototype are shown in table x. Arch x-position refers to the millimeter distance between the midpoint of the insole and the furthest x-position on the arch. Arch y-position refers to the millimeter distance between the lowest point of the insole and the furthest y-position on the arch. The y-axis runs lengthwise through the insole while the x-axis runs widthwise.

Table 12.1: Insole dimensions - first prototype

Sole length	Ball width	Ball thickness	Heel width	Heel thickness	Arch heig/ht	Arch x-position	Arch y-position
280mm	110mm	5mm	70mm	5mm	20mm	55mm	145mm

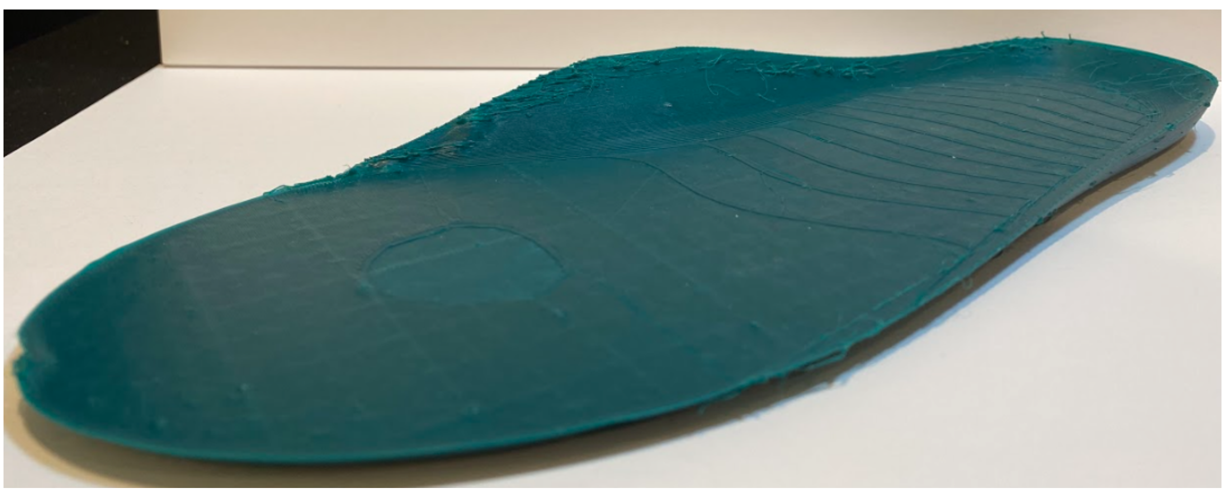


Figure 12.1: First insole prototype.

After wearing the insole for just a few minutes, the team realized that the contours around the heel served no immediate purpose, and noted that the heel did not provide enough support or cushion. Furthermore, the arch was not at the right location and did not provide enough support. A new design was created, making the top of the insole flat, and increasing the thickness of the heel. The arch location was also adjusted. The new dimensions of the second prototype are shown below in table x.

Table 12.2: Insole dimensions - second prototype

Sole length	Ball width	Ball thickness	Heel width	Heel thickness	Arch heig/ht	Arch x-position	Arch y-position
280mm	110mm	5mm	70mm	10mm	20mm	38mm	106mm

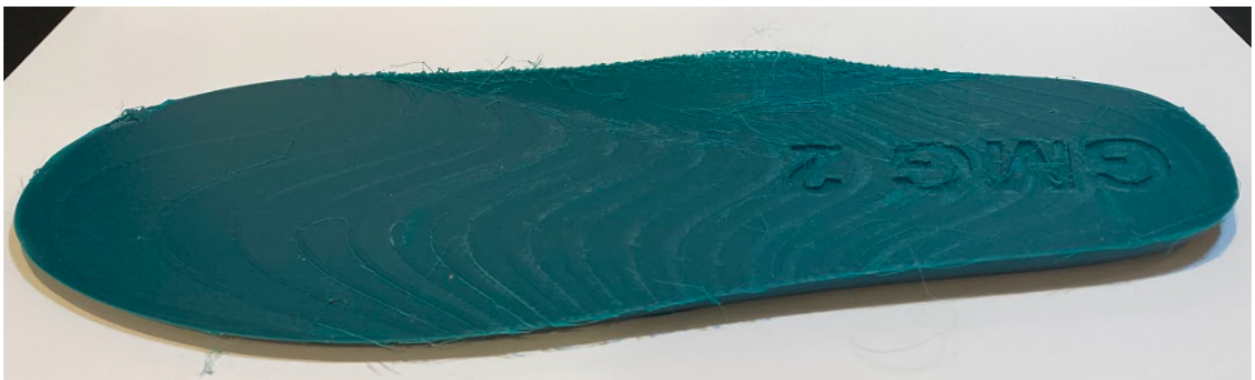


Figure 12.2: Second insole prototype.

The second insole prototype was printed for each group member using 87A TPE and was tested for several days. After wearing the insole for a few days, the team noted that the insole had a few problems, most notably with the arch. The design of the arch provided too much support. As seen in figure 12.3 below, the arch of the second prototype runs straight down and connects to the bottom of the insole. This removes flexibility in the arch and prevents the arch from matching the shape of the foot. After a few hours of using the insole, members of the team reported pains in their achilles tendon. The insole was also too soft, and this could have been caused by two factors; the overall thickness of the insole and the slice settings when printing the insole. Insole thickness at the ball of the foot is not as important as thickness at the heel. This meant that the heel would have to be more firm than the ball. This change would have to be made in slicing for the print.

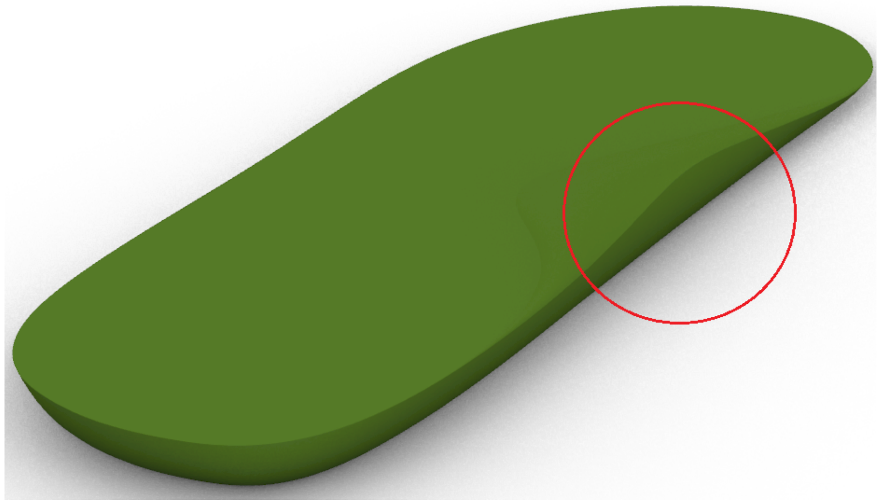


Figure 12.3: Second insole prototype arch concerns.

Changes were made to the insole to address these problems in hopes of remedying these issues. The thickness of the insole was dropped to 5mm thickness on the heel and 3mm thickness on the ball of the foot. One team member took to cutting the arch on the second prototype to try to increase its flexibility and tested it out. The team member did not experience any achilles pain after hours of testing and so the shape of the arch was adjusted such that it now had no support material beneath the arch. This allowed the arch to be more flexible and better fit the shape of the foot of the user. With these changes made, the third insole prototype was printed with 75A TPE to test its feasibility as a potential material. The new dimensions of the third prototype are shown below in table x.

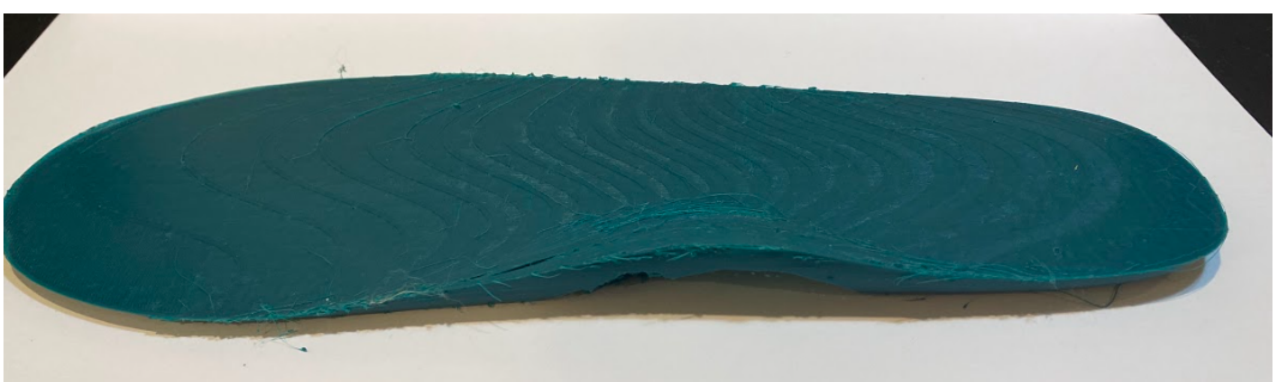


Figure 12.4: Second insole prototype with the arch cut to increase flexibility.

Figure 12.5: Third insole prototype.

Table 12.3: Insole dimensions - third prototype

Sole length	Ball width	Ball thickness	Heel width	Heel thickness	Arch heig/ht	Arch x-position	Arch y-position
280mm	110mm	2.5mm	70mm	4.5mm	20mm	38mm	106mm

The 75A TPE material was significantly softer than 87A TPE, but did not provide enough support due to its cloth-like feel. A fourth design was constructed, this time changing the thickness to 5mm at both the ball and the heel of the insole. The heel would be printed at a higher infill than the ball to give more support for the heel while not making the ball of the insole too firm. This fourth design would go back to 87A TPE since it felt comfortable during the testing. At the time of submitting this report, the fourth design was not prototyped, however the team is confident that these would be the last changes required for the insole.

12.2 Midsole

The midsole is the largest part by volume on the shoe, but it is also the simplest part in terms of shape and design. Since the midsole size was designed to be larger than the insole, the team was confident that it would fit over the foot of the test user, but it was unknown what the right infill density would be. The first midsole prototype was printed using red 95A TPU with a gyroid pattern (like all other prints) and a 6% infill. No supports were used at the toe box or for the outsole. The outsole was modified from a triangle pattern seen in section 8, to a square pattern to optimize print time.

Figure 12.6: First midsole prototype.

The print quality of the top and bottom surface was excellent. The ridges printed perfectly and the top layer had a very smooth finish. The side walls were also printed in great condition. The midsole had quality defects at the toe box due to the lack of support under the overhang, but it still resembled the shape of a shoe. The lack of support also meant the toe box sank slightly during the printing process. When looking at the midsole alone, this is not noticeable, but when combined with the prototype upper, there was a very noticeable gap between the two. This is discussed more in section 12.3. The 6% gyroid infill was too little and the midsole had too much cushion to it; it was like standing on gel. The midsole also looked very thick and did not look aesthetically pleasing.

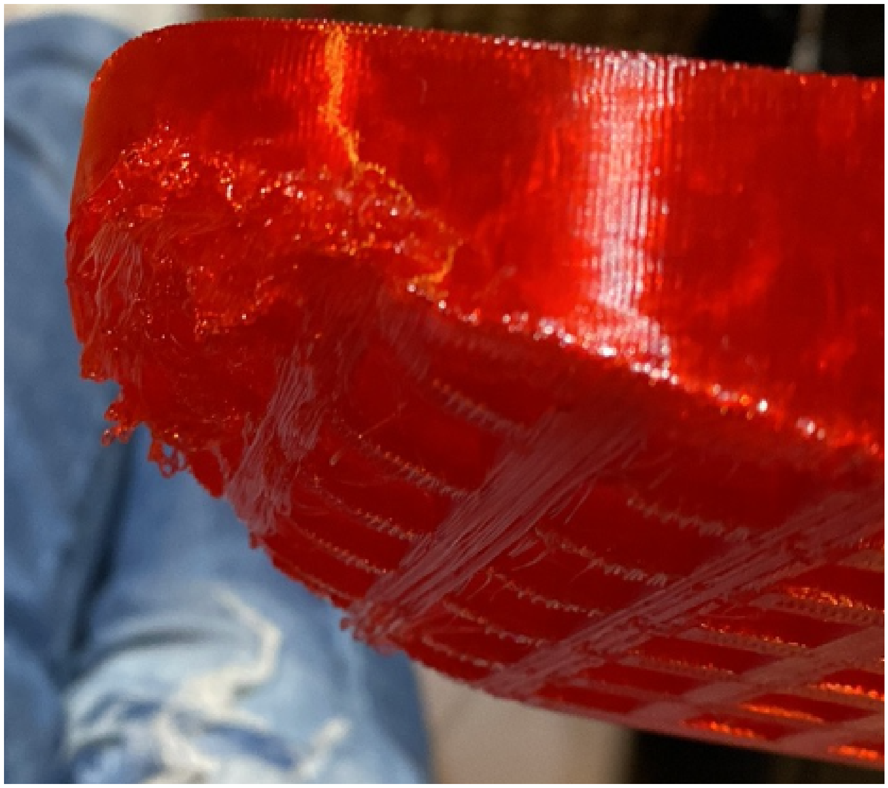


Figure 12.7: First midsole prototype toe box issues.

A second prototype was printed soon after the first. The infill was increased to 18%, thickness dropped from 22mm to 17.5mm, and support was added for the toe area. The result of these changes was a thinner midsole with a better quality finish for the toe box. The 18% infill density was too much and made the midsole too ridge to the point where there was no cushion. A major factor the team noted however was that 95A TPU is not flexible enough to use as a midsole, or any other part of a shoe for that matter, and since each midsole takes 20h to print, doing the trial and error process of finding the right infill density of a 95A TPU midsole would be pointless since a different material (85A) would be used for the final product.

Figure 12.8: Improved toe box on the second midsole prototype.

The print quality of the second midsole prototype was excellent and showed to the team that not much further work was required, especially since a different, softer filament, was to be used for the final product. With all this in mind, the team was ready to begin printing upper prototypes. This was a very important part of prototyping, not only because the upper makes up the majority of the shoe, but it would show if the ridges of the midsole and upper would be perfectly aligned like the CAD models suggested.

12.3 Upper

The first upper prototype was printed using red 95A TPU and represented the first full print involving significant overhang unsupported. The overhang was at the upwardly curved toe area, the slight ridges along the base, and the overall ceiling of the part. The print was estimated to take 18 hours to complete, so scaled down versions of the upper were first printed to test the overall design and rigidity.

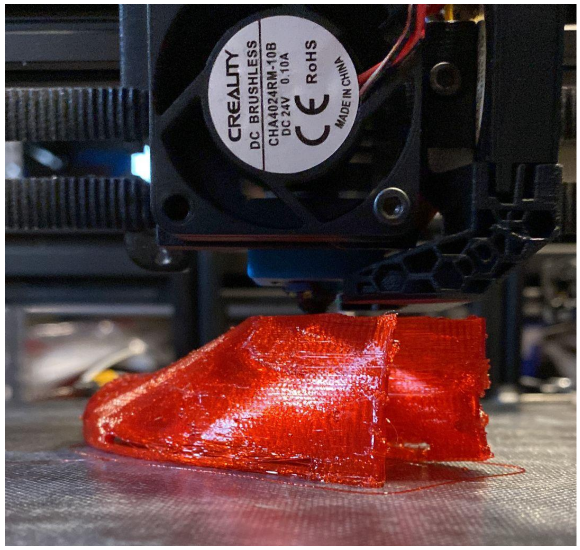


Figure 12.9: A scaled down print of the upper.

These prints offered a narrow view of the overhang capabilities, and so the first 18 hour print was conducted, unsupported. The final print came out surprisingly well and offered a great perspective on the successes the printer would have manufacturing designs that used many overhangs. While the print was beyond acceptable, there were small improvements to be made; namely, the instep height had to increase by 10mm, the curvature needed altering, and the team opted to include supports to clean up edges and provide greater resolution on the overhangs of the side vents and toe area. The toe area also exhibited issues with bending upwards, resulting in a slight gap between the upper and midsole; the supports would likely fix this issue.

Figure 12.10: The first full size upper print.

Figure 12.11: The slight gap between upper and midsole.

The above changes were made to the part and the design was sent to the printer once again, boasting a similar print type of just under 19 hours. Once again, the print was successful on the first attempt and provided a fantastic real world test of adding TPU supports.

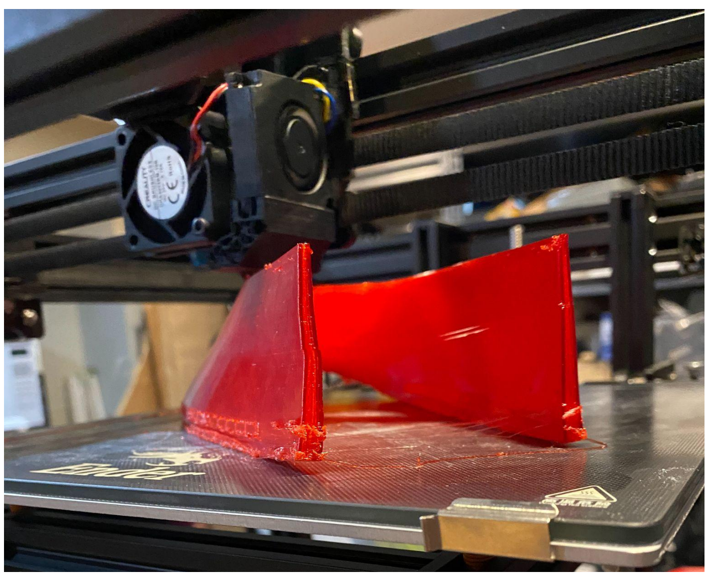


Figure 12.12: The second upper on the print bed.

Once the supports were removed and the stringing was cleaned up, the upper was fit tested against the midsoles that had been previously printed. The ridges fit well and the toe area was able to properly fit into the second midsole prototype, as expected. This upper was then used for the final design concept, which illustrated other issues that had to be addressed; these included a slight increase in instep height, an extra 10mm being added to the width, vent removal, and a drop to 85A TPU.

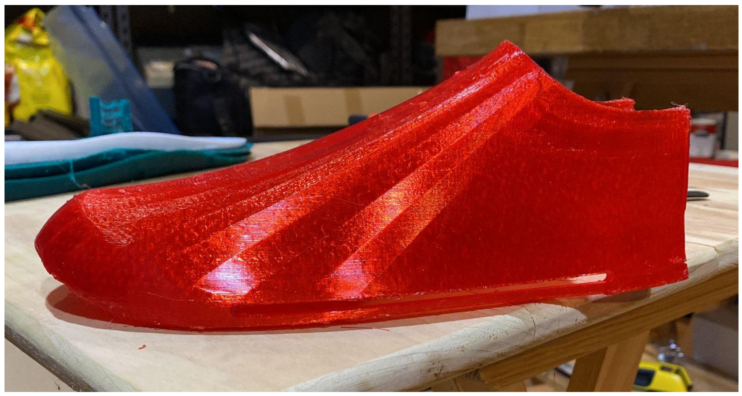


Figure 12.13: The second upper after vent removal.

12.4 Heel

The first prototype of the heel was printed using 95A TPU, the same red filament in much of the other initial part prototypes. With the design of the heel being relatively simplistic compared to parts that involved overhang, the first prototype was to test the accessibility portion, which involved experimenting with the part's willingness to bend. The first prototype was printed using a gyroid pattern at 12% infill and with walls of 3 layer thickness. This created a much firmer heel than desired and the result did not bend to facilitate the accessibility mechanism. This is due to a static amount of material being used for the solid walls which prevents stretching in the required direction. Relief cuts were suggested as a suitable fix, however the team attempted a lighter print with an infill of 6% and razor thin walls as a second prototype.

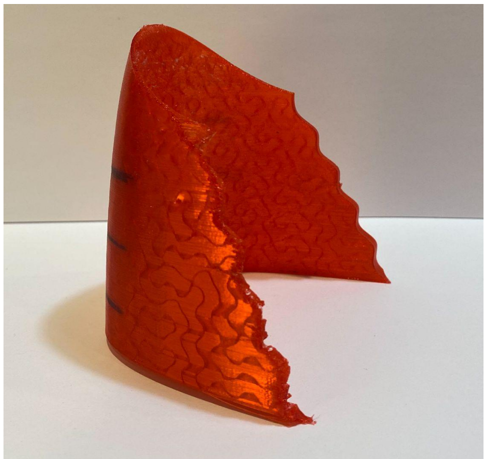


Figure 12.14: The first prototype of the heel.

Figure 12.15: The first prototype of the heel with the suggested relief cut lines marked on the part.

This second prototype was significantly thinner than the first, and as a result was much more compressible. However, due to the nature of the firm walls, the mechanism was unable to hinge as expected. As a final experiment, the 87A TPE was used to make a slightly softer heel, which was expected to make it even more compressible and bendable, leaving ample play room to add the final touch of relief cuts to the part. This final heel was printed and the relief cuts were added using an exacto knife and a soldering iron to close up the exposed areas; a process that would later be baked into the design on Grasshopper.

Figure 12.16: The first and second prototypes, side by side.

As a final prototype, a heel made of TPE 75A was printed to see if the softer, more fabric-like, material would be a suitable choice for the heel. However, due to the complexity of printing such a soft material, the resulting heel was too structurally incapable to act as the accessibility mechanism and heel of the shoe. The 87A TPE heel remained the top contender.

12.5 Prototyping and Iterative Design Conclusions

Each of the parts designed were independently printed as prototypes, tested to identify potential issues, and iterated on to solve mechanical challenges immediately noticed. For the insole, this included changing the infill pattern and density, reducing the width, raising the arch, and adding a gap below the arch. The midsole underwent similar changes with the infill density, reducing the overall thickness, and adding supports to create a cleaner print. Supports were added to the upper to tighten tolerances and prevent dropping in areas like the toes or vents. Four iterations of the heel were designed, varying in material, infill densities, and introducing after-print modifications through the relief cuts to facilitate the accessibility mechanism. These parts were then split into two categories: 1) primary prototypes, those that were the second best version of the parts, and 2) final prototypes, those that were the best version of the part. These categories were each used in the final design concept portion to test adhesives.

13. Final Design Concept

With the above prototyping stages concluded, it was time to affix each of the manufactured parts together, finally creating the final shoe. To bond the parts together, the team opted to try two adhesives, Gorilla Glue and a silicone caulk. The more promising adhesive, the caulking, was selected to be used on the final parts, with the Gorilla Glue being used on the previous prototypes.

Figure 13.1: The shoe bonded by Gorilla Glue and using primary prototypes.

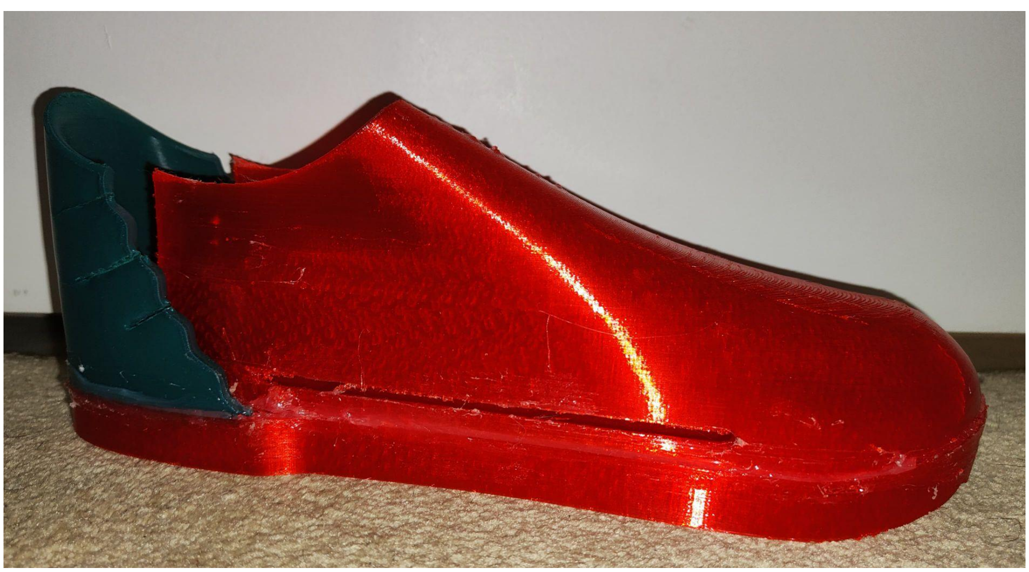


Figure 13.2: The shoe bonded by silicone caulking and using final prototypes.

After allowing both shoes to set, the bonding agents were tested side by side by trying to wear the builds. Immediately, the Gorilla Glue bonded shoe gave up and fell apart; this bonding agent was not suitable for the project needs, as expected. The silicone caulking shoe was then tested, and miraculously worked on the first attempt. The heel, having the aforementioned relief cuts added, allowed for a flawless placement on and removal from the foot.

Figure 13.3: The accessibility mechanism bending and in proper use.

Figure 13.4: The user wearing the silicon caulking shoe.

After thorough testing of normal wear, it was found the upper of the shoe was far too stiff to be comfortably worn; this began the list of adjustments that included a slight increase in the instep and width of the shoe. Additionally, as the caulking set, it began to emit an odor analogous to a molding orange mixed with a strong vinegar. The desire to remove this as a factor in the experience of the shoe was necessary to create a successful product. If the caulking could be omitted from the final design process, it would also allow for a more seamless assembly experience requiring no extra work beyond the FDM manufacturing process. As the goal was to create a seamless end-to-end process of manufacturing without human intervention, the decision to create the entire shoe in one print job was agreed upon.

Figure 13.5: A stiff upper significantly impaired the ability to walk, a horrible trait for a shoe to have.

The next design consisted of the instep and width adjustments, as well as a multi-infill single part print manufactured from 85A TPU. 85A TPU was selected as it was a great all-round material for each individual part of the shoe which required a different comfort and cushioning profile. The midsole of the shoe was printed using a 22% infill, the heel with 16%, and the upper with 16%. These percentages were estimates for the new 85A material, but remained closely defined to the previous 87A TPE and 95A TPU tests, respectively. The resulting shoe took a total of just under 50 hours to print. The print quality was excellent and exceeded expectations, however stringing within the shoe remained a large issue. While cleanup was relatively easy to conduct, there were still many strings from within the shoe that were inaccessible. These strings are covered by the insole, so they should not affect the experience of the shoe. Furthermore, with more time and testing, further calibrations could be done to determine the optimal print settings to eliminate stringing. However, there was simply not enough time to do so.

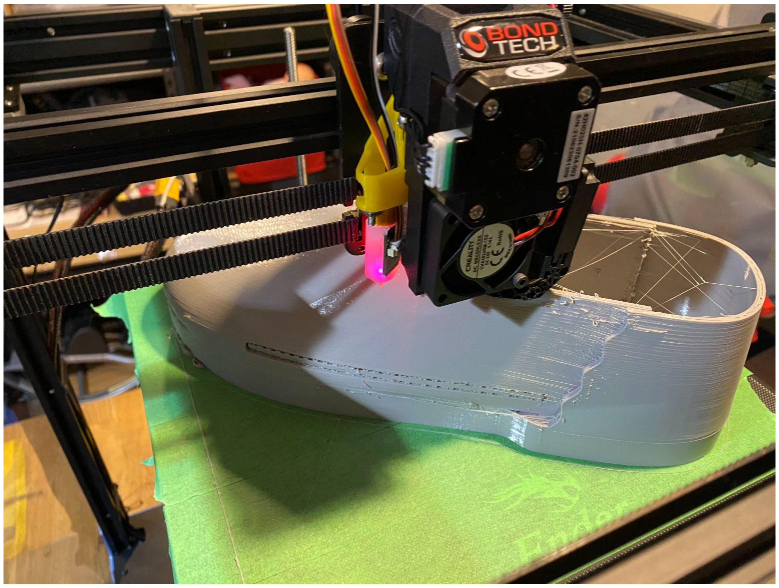


Figure 13.6: The printing of the single part shoe.

Figure 13.7: The single part shoe being worn.

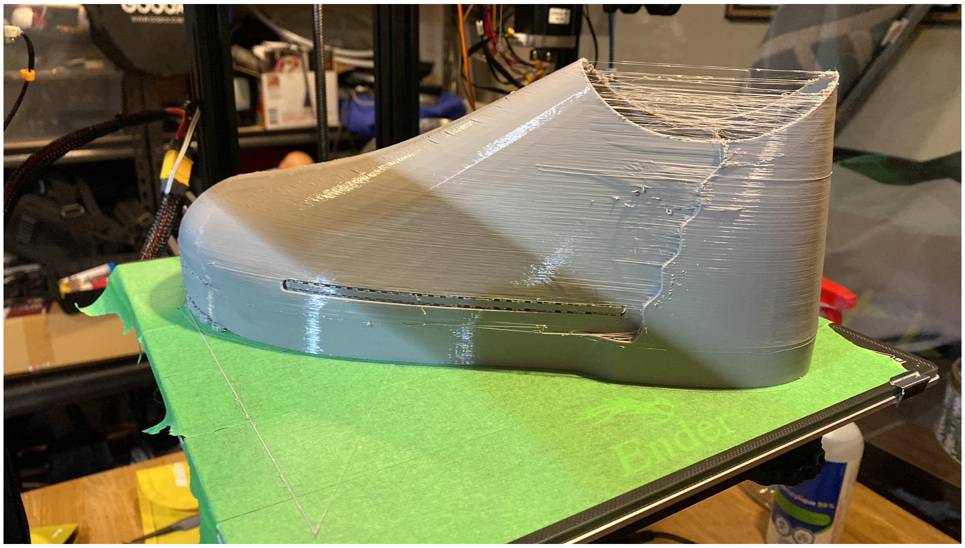


Figure 13.8: The single part shoe stringing issue.

The accessibility action, once relief cuts were added to the heel, worked well and provided the expected result similar to that of the final prototyped heel. The shoe was comfortable to wear, for the most part, but required slight modifications to further improve the wearing experience. These were expanding the width by 1 cm, removing the vents to increase structural integrity, adding a thicker tongue area to the upper, increasing the rigidity of the bottom of the heel, and adding additional supports for the toe area to improve print quality. These modifications were made and continue to be made to improve the design.

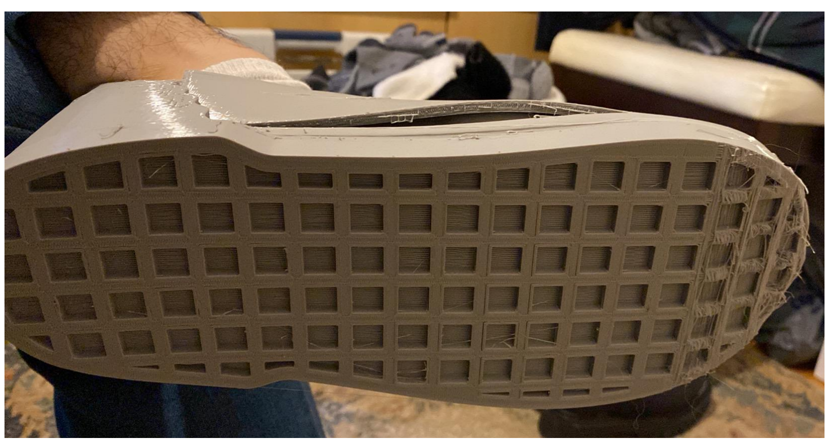


Figure 13.9: The width of the shoe is too small.

Figure 13.10: The print quality degrades at the toe area.

Other considerations were made to solve a toe bending issue experienced when walking the shoes; the leading contenders as of this report are to create relief cuts along the top, add vents along the top, or slice a pseudo-tongue from the upper. Printing the heel sideways may also offer better bending action since the FDM lines will align in the direction of applied force when placing or removing the shoes. These are modifications that should be made to future prototypes to find what may, or may not, work.

Figure 13.11: The toe bending issue.

13.1 Final Concept Conclusions

The final concept saw the decision to 3D print the entirety of the shoe within one single print, ridding the need of an adhesive or further assembly after the print. While ultimately the single printed shoe was a success in a lot of ways, there were a few key takeaways that inform future developments on this project. Namely, the reduction of stringing should be explored further, alternative heel relief cut strategies, the removal of the side vents to improve structural integrity, slight width expansion, increasing structural integrity of the heel bottom, slight relief cuts in the upper to reduce toe bending issues, and the addition of extra supports to improve the quality of the print. Additionally, further experiments can be conducted to identify if printing the heel sideways and aligning the FDM lines with the user applied forces increases the bending action made necessary by the accessibility mechanism.

14. Cost Analysis

A necessary step in every engineering project is cost analysis. Both to understand the practicality of the existing design but also determine improvements that can be made to make the product more cost effective. In order to perform the cost analysis, it is important to understand that the envisioned approaches to marketing and commercializing these shoes differs from what is considered conventional. These approaches are detailed further below. An initial cost analysis is performed followed by a direct comparison to the cost of simply buying existing hands-free shoes.

14.1 Commercial Viability & Strategy

There are two options for the commercialization of the project; the first is through the licensing of custom software that enables users to print the shoes on-demand using their hardware, or by outfitting a distribution center following an end-to-end human-free manufacturing process.

Through the first method, institutions like hospitals will be able to purchase their own 3D printers, set up their own small manufacturing facility, take the required measurements from their patients, input them into supplied software, and have a custom printed pair of shoes shortly thereafter. The software would exist as a portal, letting administrators at an institution input required information and generate a ready-to-print file to be sent to their printers, enabled by the parametric design. The only concern these institutions would have is the maintenance of the machines and ensuring they have enough material on hand, which could be an additional vertical a commercial entity undertaking this project could offer.

Creating a business-to-consumer product by running both the manufacturing and distribution could also be a viable option if the entire process is near human-free. Since the model was made to be parametric, it is within reach to create an end-to-end process that is entirely digital, requiring only a human to intervene to ship the product. The only paid positions required to run such an operation would be the designers that create the single parametric model per SKU, and the logistics team that removes the manufactured shoes from the print beds and places them into the shipping boxes to be delivered to customers. This greatly reduces the cost to run the operation by removing expensive human intervention from the equation. The consumer side of the process would begin by data collection, either through a simple web portal that collects required measurements, or through the use of a mobile app that utilizes smartphone cameras to measure and collect needed dimensions. Selecting standard shoe sizes could also be an alternative option available to the customer through one of these two data collection streams. The consumer would then simply select the style of shoe they wish to receive, and the order will be placed and delivered at a later date.

While both options are potentially viable, the aforementioned strategy of licensing the software to institutions, along with a support plan, is likely the better strategy in terms of value for both the commercial entity undertaking this venture and the institution making use of the product and process.

14.2 Cost Analysis & Comparison

In the case of hospitals and institutions being tasked with initially investing in the printers and materials, there's an initial investment for them that needs to be taken into account. Using the same printers and filaments used during prototyping these costs are tabulated below.

Table 14.1: Initial Investments

Component	Cost
3D Printer: Ender 6	$799.95 + tax ($103.99) [55]
Auto bed leveler + Micro Swiss Nozzle + Bondtech DDX v3	$223.88 + tax ($29.10)
DDX Adapter + Micro Swiss All Metal Hot Rod	$131.90 + tax ($17.14)
Total Initial Investment	$1305.96

The total initial investment at the bare minimum for institutions or individuals interested in printing the shoes themselves using an Ender 6 would need to be at least $1305.96. The next step is to determine the cost to print one individual shoe and one pair of shoes. This value comes out to $34.16 per shoe and $68.33 for a pair of shoes, with primary contributors to this cost being cost of materials and electricity. The derivation of these costs can be found in Appendix F.

Paying upwards of $1375 for one pair of shoes or even a couple is clearly impractical. The option of manufacturing the shoes themselves will most likely only be exercised by institutions such as hospitals and retirement homes that know they will print at least 20 pairs of shoes. It then becomes important to compare the costs between going this route opposed to simply buying existing hands-free shoes. Table x below documents the break even point when the cost is compared to buying pairs of the Nike FlyEase (retail price of $160) and the Kizik Men's Pragues (retail price of $147). The break-even points for the Nike FlyEase and the Kizik Men's Pragues are 14 and 17. At and after these respective points, investing in a 3D printer and printing the shoes becomes more cost effective than simply buying the existing products on the market. With some market research, an acceptable price for licensing can then be determined to effectively match competitive options. For example, buying 50 pairs of Nike FlyEase would cost $8000. Initial investments and printing 50 pairs of shoes would cost $4722.46. That is over a $3277 difference that can be made profitable through licensing.

Table 14.2: Break-even point.

Principal (Pairs of Shoes)	3d printed Shoes ($)	Nike FlyEase ($)	Kizik Pragues ($)
0	1305.96	0	0
1	1372.61	160	147
2	1439.26	320	294
3	1505.91	480	441
4	1572.56	640	588
5	1639.21	800	735
6	1705.86	960	882
7	1772.51	1120	1029
8	1839.16	1280	1176
9	1905.81	1440	1323
10	1972.46	1600	1470
11	2039.11	1760	1617
12	2105.76	1920	1764

13	2172.41	2080	1911
14	2239.06	2240	2058
15	2305.71	2400	2205
16	2372.36	2560	2352
17	2439.01	2720	2499
18	2505.66	2880	2646
19	2572.31	3040	2793
20	2638.96	3200	2940

The table below breaks down how many pairs of shoes could be printed using one printer in a single year ideally. The final result is roughly 19 pairs. As mentioned, conducting analysis such as this but in greater detail facilitates the avenues that can be explored for licensing and making this a profitable idea.

Table 14.3: Estimated number of pairs printed in one year.

Time required to print one shoe	50 hours
Time required for the shoe to cool down	0.17 hours (10 minutes)
Time required to remove the shoe and clean the print bed	0.083 hours (5 minutes)
Process is repeated for the second shoe	
Time required to print one pair of shoes	$2 \times (50 + 0.17 + 0.083) = 100.5\ hours$
Assuming 2000 work hours in a year	
Estimated number of pairs of shoes that can be printed in one year	$\frac{2000}{100.5} = 19.9 \sim 19\ pairs$

14.3 Cost Analysis Conclusions

As mentioned in commercial viability and strategy, there are multiple routes to making this idea profitable and commercializing it. The cost analysis primarily focused on the route of licensing the idea with proprietary software and allowing institutions and individuals to print the shoes themselves. This initial cost analysis showed promise, however, it is inconsistent and needs to be further evaluated and perfected. The cost analysis made a presumption that all attempts to print a shoe would be successful, essentially a failure rate of 0%. In the real world, especially with something as innovative on multiple fronts such as this project, this is optimistic at best and delusional at worst. A more thorough cost analysis would require a well reasoned failure rate that's taken into account within the calculations. Furthermore, the human labor that would go into finalizing each pair of shoes needs to be clearly quantified and considered into the cost analysis. Financial cost analysis is simply one fraction of the pie when it comes to the cost analysis of products and services. Oftentimes, people are willing to financially pay the price in return for ease of mind, ease of assembly, ease of use, among other things. However, this preliminary cost analysis clearly shows the viability and competitiveness of this idea. Cost analysis for more conventional distribution networks and methods can also be of utility in a true understanding of the profitability of this idea.

15. Discussion

The development of 3D printed accessible footwear has its design philosophy spanning tens of thousands of years, incorporating everything from biomechanics and ergonomics to modern and innovative design. This report has explored the foundations for developing footwear far beyond that of the 3D printed variety, offering insight into design choices and considerations made by some of the largest manufacturers of footwear. This deep insight acts as fundamental guidance to selecting materials and identifying their environmental impact, exploring engineering implications far beyond the scope of this project, and developing a framework for troubleshooting issues with the equipment, which are all explored in greater detail below.

15.1 Environmental Impact

In terms of environmental impact, there are several significant advantages to 3D printing compared to conventional manufacturing practices. The vast majority of manufacturing practices can be categorized as subtractive, this is especially true when it applies to the textile and fashion industry as a whole. Subtractive manufacturing, the process of starting with a base amount of materials then cutting/burning the excess away, results in significant waste at worst and at best is recycled. However, recycling itself requires vast amounts of energy and resources. In theory, 3D printing produces little to no waste. The process of designing something geared towards 3D printing is a grueling process with various stages of printing and prototyping, which does invariably produce a considerable amount of waste on its own. However, once designs are finalized and the product is ready to truly be manufactured, it without question produces significantly less waste than conventional subtractive manufacturing. It also must be emphasized that designing and prototyping, regardless of whether it is geared towards 3D printing or not, will always create some amount of waste product.

Usually when considering environmental impacts of products, individuals are inclined to look at its recyclability or the processes that go into producing the product. However, just as importantly, transportation and the resulting emissions make a significant impact on the environment. This is why 3D printing holds so much potential. It has the potential to eliminate or significantly reduce the transportation needs for products. Even if the products are not printed by the consumer themselves, the infrastructure necessary to manufacture using 3D printing can be more easily established in various locations with differing climates and resources than current manufacturing options.

When 3D printing, there are numerous direct and indirect environmental consequences. When the filament is heated to around 200 degrees Celcius to print, the first thing that comes to mind is the emissions. When printing with filaments like ABS, Nylon, and PETG it is recommended to use an enclosure for the 3d printer with a filtration system to minimize direct emission of fumes that cause fatigue, headaches, and in some cases, respiratory tract irritation.[56] TPU is synthesized when a di-isocyanate reacts with one or more diols in a polyaddition reaction.[57] Isocyanate-containing compounds have harmful effects on human health and the environment, like the ones mentioned above.[58] These problems only occur when the bond isn't complete and the TPU is manufactured poorly.[59]

TPU was selected for this project because it is a highly durable and flexible material, which are properties that are necessary for many applications in today's world. Additionally, TPU is an environmentally friendly polymer that can be recycled into fundamental chemical components and maybe even used to produce new raw materials or TPU. TPU is also biodegradable, which means it can degrade completely in less than 6 years with no harmful environmental impacts in the process.[60]

The filaments come with a filament spool by default, this keeps the filament neatly wrapped while it is mounted on the 3d printer for printing or saved for later use. Depending on the manufacturer, these spools are composed of various materials. Most manufacturers choose polypropylene and a PC-ABS (PolyCarbonate-Acrylonitrile Butadiene Styrene) blend; unfortunately, these polymers are not biodegradable.[61]

Filament spools add up over time without the user's notice, and their disposal might be hazardous to the environment. A few tips for minimizing the effects are listed below:

- Getting creative is the most fun way to go. Many users repurpose the spools for various projects, such as storage cabinets, lamps, and spin tables to display their other models.

- Choose the spool-less form of filament when purchasing or ordering it for little to no extra cost.
- In situations where a spool-less solution isn't possible, a cardboard spool will work just as well.
- Some manufacturers and distributors have created incentive programs for returning empty spools that they can reuse
- Cutting and grinding empty spools into pellets can be used to make filaments and a spool of a custom design to hold filaments. [62]

15.2 Engineering Implications

Great engineering projects have an ability to transcend their initial scope. Simply the inception of one idea breeds another. Various aspects of this project can be applied to not only footwear but also other completely unrelated industries. Simply creating a 3D printable hands-free shoe forces one to ask what possibilities lie out there when it relates to engineering and innovation.

The initial vision for this project was creating a parametric design that could be easily distributed to those with the 3D printing infrastructure and materials necessary to readily print these shoes themselves. This vision alone introduces a new approach to engineering, innovation and product manufacturing and distribution. Vast amounts of resources of many companies are diverted to optimizing manufacturing and distribution. Not only is this financially costly, it's also costly in terms of time and energy. Time and energy that could be better used creating the best possible product that best suits the customers needs. Introducing a route to focusing on primarily engineering and still making a product available for a significant number of people is a necessary step to moving away from conventional ideas of manufacturing and distribution.

Utilizing 3D printing also does not need to be limited to entire products themselves. Utilizing 3D printing in conjunction with a flexible filament like TPU for replacements or repairs of existing products is also something companies have to seriously take into consideration. Instead of utilizing resources to manufacture and distribute a small part, they may see more benefit in utilizing those resources in making that part 3D printable. During the preliminary research stage of the project, various companies specializing in simply 3D printed customizable orthotics and insoles surfaced. Perhaps the solution to improving the accessibilities of shoes doesn't lie in creating entirely new shoes but creating a 3D printable attachment that can be used on pre-existing shoes. These are all conversations that can only be made possible by introducing the idea of improving the accessibility of shoes utilizing 3D printing.

The vision for this project includes a world where hospitals and other healthcare institutions are actively investing in 3D printing technologies. It is only right that 3D printing in the biomedical industry specifically be explored further. There are currently four primary applications of 3D printing in the biomedical field; creating tissues and organoids, surgical tools, patient-specific surgical models and custom-made prosthetics[63]. One of the primary benefits attributed to 3D printing surgical tools is significant reductions to production/distribution costs along with being able to readily innovate existing tools. Similarly for prosthetics, 3D printing enables more cost effective and customizable prosthetics that are produced faster than traditional methods. Companies exist that are geared towards 3D printing for these applications. However, very few are designing with the prospect of hospitals and institutions having the capabilities to print designs on their own.

During the prototyping phase, it was surprising how similar the ninjatek 75A TPE material felt to cloth, immediately sparking discussions surrounding its applications for other pieces of clothing. During the environmental section, it was documented how one of the primary positive contributions 3D printing makes is it significantly reduces the amount of waste created from conventional manufacturing processes. The textile industry is one of the most glaring examples of the problems with excess waste production with modern manufacturing. The primary reason for attempting to make this hands-free shoe 3D printable is to greatly improve customizability. With the growing demand for customizability, the solution clearly lies in additive manufacturing. Parametric designs will become the new norm for vast sectors of the clothing industry, at least those that want to provide their customers with a more custom and catered experience. Current practices in the fashion industry result in customization being an expensive process. Once again it must be emphasized that the utility of 3D printing is not limited to 3D printing entire articles of clothing, even just making small progressions by 3D printing some aspects of it is a move in the right direction.

15.3 Troubleshooting & Challenges

Designing and 3D printing a shoe and its components does not come without its challengers or hiccups. Throughout this project, the team has encountered numerous challenges with respect to designing and 3D printing the shoe. This has made the team somewhat experts on a variety of challenges that users may come across. This section will cover solution ideas to potential problems users may face when attempting to 3D print their own shoe.

15.3.1 Printer Problems

This section explores considerations users should keep in mind in regards to their 3D printer and how it can affect printing their very own shoe.

15.3.1.1 Printer Bed Size

The printer bed size is the most important thing users should pay attention to before printing their own shoe. A bed size of 260 x 260 x 400 mm is sufficient to print shoes up to and including size 13. Many popular printers such as the Prusa i3 and the Ender 3 have bed sizes smaller than this, so users are aware of their bed size.

15.3.1.2 Printing with Flexible Filaments

Printing with flexible filaments requires patience and more patience. Calibration prints should be done before printing full sized models. Users should follow the temperature guidelines listed on their filament spool, and users *must* print very slowly, on the scale of 15-30 mm/s. The lower the shore hardness of the material, the slower users should print. Furthermore, while it is possible to have success printing flexible filaments like TPU 95A using bowden extruders (discussed in section 6), materials like 85A and 75A will benefit greatly from direct drive. A glass heated bed should be used for adhesion, but a glue stick or painters tape also works.

15.3.1.3 Bed Leveling

The first layer of a print is the most important layer. Flexible filaments have difficulty adhering to the bed, hence why glue or a heated bed is required as mentioned above. A level print bed helps to make sure that the first layer is printed flat, and reduces the chance of problems with the first layer.

15.3.1.4 Third-Party Hardware and Software Support and Online Support

3D Printers are still relatively new technology. It is guaranteed users will run into problems with their printer at some point or another. The online 3D printing community is huge and there are many forums for users to look for help and guidance. However, if a user has a relatively new printer model or an obscure printer model, online support may be scarce. This is especially true if users want to do hardware and software upgrades such as installing a direct drive extruder, or updating their machine firmware. Users should try to pick a 3D printer that is relatively popular and has been on the market for a few years to give third-parties time to release upgrades to printer hardware and software.

15.3.2 User Challenges

This section will explore the various problems users will run into when it comes to 3D printing flexible filaments, and what they can attempt to mitigate these problems.

15.3.2.1 Poor Print Quality

Poor print quality is an issue that can be caused by many factors. The biggest one is print speed. A print speed of 15-30mm/s should be used, with a travel speed of roughly 1.5x print speed. Temperature can also cause problems too; users should follow their filament guidelines and perform test prints before printing full sized models. A high temperature can cause zits or blobs to appear on the bed, while a low print temperature can cause poor adhesion between the layers. Layer height should be kept standard or fine, but no higher than 0.24mm. Layer height of 0.16 or 0.20 is ideal.

15.3.2.2 Poor Bed Adhesion

Glue sticks or painters tape is key in getting good bed adhesion. A heated bed helps as well, although it is not required. First layer print temperature and fan settings are also very important. It is key that the fan does not turn on until the third or fourth layer, since cooling the first layer down too quickly can cause it to lift off the print bed.

15.3.2.4 Retraction and Stringing

Unfortunately, retraction and stringing is inevitable with 3D printing flexible filaments. Users can play around with their retraction speed and length to try to find the settings that will reduce the amount of stringing, but it is inevitable. On Cura, combing mode can be turned on to try to reduce the stringing. Because flexible filaments are flexible (as the name implies), extruders have a hard time retracting enough filament to eliminate stringing problems. In any case, users should try to keep retraction speed slow and around 20-30mm/s, while retraction length depends on the shore hardness of the filament being printed. With enough calibrations and testing, it is possible to significantly reduce stringing.

15.4 Discussion Conclusions

This report goes over the design process in excruciating detail at points, but this information is intended to foster the realization of these core fundamentals to scopes beyond that of an accessible 3D printed shoe. The benefits of additive manufacturing, transportation and logistics, emissions, and the recyclability of packaging materials were explored in depth, providing a methodology of consideration for the environment that can be applied elsewhere. Likewise, the implications of being able to 3D print parts on-demand for healthcare applications is an area that has endless potential for further research, and this project takes a small jab at a consumer oriented product. Exploring the ability to expand 3D printing more cloth like materials, such as the 75A TPE, is also a derivative of the engineering side of the project. Finally, while much of the printer troubleshooting was geared towards printing with flexible materials, the framework laid out offers invaluable insight into tried and true methods of working with 3D printers; a market that is likely to continue to expand. These focus areas can be applied far beyond this project, and will assist in the development of future ideas and design processes.

16. Conclusions and Recommendations

This project documents the process of designing and creating a 3D printable accessible shoe; initially stemming from the intersection of genuine curiosity and one nurse at Sunnybrook Health Sciences Centre dealing with a shoeless patient. Engineering at its core is rooted in problem solving; with a clearly defined problem, goals were set by the team for what the solution should consist of: factoring in functionality, usability, producibility, maintainability, durability, and sustainability into each and every step of the design process. The final product has met a considerable amount of the goals within these six categories, and in some areas it has fallen short due to various challenges experienced along the way. Suggestions on the future of the design and thoughts on where this idea can be taken from this point are included.

In terms of functionality, the final prototype falls short in being overtly comfortable to wear, which comes as a fault of the materials used and can likely be fixed through experimentation of other materials and infill densities. Usability saw all but one of the goals accomplished, with the subjective point of creating an aesthetically pleasing shoe for all age groups falling short due to time constraints. With more time, sophisticated and modern designs could be made. Producibility saw all the goals achieved, completely eradicating the need for assembly, minimizing production costs significantly, and effectively creating only a single part that requires manufacturing. Maintainability and durability share much of the same fanfare, with all the goals of each being met or surpassed. Finally, sustainability sees only the optimization of print time falling below the target; with further tweaking to the model, printer, and gcode, this could be improved upon greatly.

From this point forward, iterations to the design should be considered to achieve those remaining goals and to continue the development of a feasible shoe product. It is recommended that creating custom lattice structures within Grasshopper for both the mid and insole are looked into to improve the ergonomics and biomechanical nature of the product. Adding these custom lattices will aid in the compressibility and give a finer level of control to the designer to account for specific health conditions that may have been otherwise overlooked by this report. Further experimentation is required within the scopes of vents, identifying if they are required and where they should be placed, if so. The upper requires changes, as described above in the design iteration portion of the report, to account for the bends that are required for day-to-day wear. Work on the heels to improve the bending action to facilitate better accessibility could be investigated as well, including the printing of compressive heels and comparison against tensive heels, as described in the preliminary designs section. Finally, further work into expanding the scope of the project to include fashionable everyday wear and kids shoes should be a priority to broaden the audience of this product. For every shoe that is tired and worn, an opportunity emerges to further our understanding and ability to innovate beyond the status-quo, empowering us to make a world where shoes are easily accessible for all.

References

[1] Picone, K. (2018, May 11). *The fascinating history of Footwear*. All That's Interesting. Retrieved February 10, 2022, from https://allthatsinteresting.com/fascinating-history-footwear

[2] "How long does it take to make a pair of shoes?," *How Shoes are Made: The Sneaker Factory*, 20-Jul-2020. [Online]. Available: https://www.sneakerfactory.net/2017/09/shoe-production-timing/. [Accessed: 10-Feb-2022].

[3] "18 shoes that work well for older adults and the elderly," *greatseniorliving.com*, 01-May-2018. [Online]. Available: https://www.greatseniorliving.com/articles/shoes-for-seniors. [Accessed: 10-Feb-2022].

[4] T. Lemke, "Why do older people have more foot problems?," *HealthLocal*, 04-Jan-2018. [Online]. Available: https://health-local.com/healthy-body/2018/01/why-do-older-people-have-more-foot-problems/. [Accessed: 10-Feb-2022].

[5] "Mobility impairments," *Mobility Impairments | Disability Resources & Educational Services - University of Illinois*. [Online]. Available: https://www.disability.illinois.edu/instructor-information/disability-specific-instructional-strategies/mobility-impairments. [Accessed: 10-Feb-2022].

[6] "Shoe tips and suggestions (updated)," *Cerebral Palsy Society*, 19-Dec-2019. [Online]. Available: https://cerebralpalsy.org.nz/shoe-ttips-and-suggestions/. [Accessed: 10-Feb-2022].

[7] "Nike's first hands-free shoe: Go FlyEase," *Nike.com*. [Online]. Available: https://www.nike.com/ca/flyease/go-flyease. [Accessed: 18-Feb-2022].

[8] "Nike flyease," *Nike.com*. [Online]. Available: https://www.nike.com/ca/flyease. [Accessed: 18-Feb-2022].

[9] "Friendly shoes - the shoe for all abilities," *Friendly Shoes - The Shoe for All Abilities*, 22-Nov-2021. [Online]. Available: https://friendlyshoes.com/. [Accessed: 18-Feb-2022].

[10] I. Servantes, "How a Nike-backed brand ensures its hands-free shoes go to people with disabilities," *Input*, 23-Nov-2021. [Online]. Available: https://www.inputmag.com/style/kizik-hands-free-shoes-nike-go-flyease-accessibility-sneakers-people-with-disabilities. [Accessed: 10-Feb-2022].

[11] M. Pratt, "Rapid-Entry Shoe," 30-Jan-2018.

[12] "Men's athens - watermelon," *Kizik*. [Online]. Available: https://kizik.com/collections/mens-new/products/mens-athens-watermelon. [Accessed: 10-Feb-2022].

[13] "Checkerboard slip-on: Shop shoes at Vans," *Vans*. [Online]. Available: https://www.vans.com/shop/shoes-classics-classic-slip-on/checkerboard-slip-on-black-off-white-check. [Accessed: 18-Feb-2022].

[14] "Sustainably made sneakers," *Unis Footwear*. [Online]. Available: https://www.unisfootwear.com/. [Accessed: 18-Feb-2022].

[15] "Scry shuttle 'shadow' beta," *SCRY*, 2021. [Online]. Available: https://scccccry.com/shop/shuttle. [Accessed: 18-Feb-2022].

[16] "Introducing Adidas 4DFWD, the future of running shoes," Carbon, 13-Aug-2021. [Online]. Available: https://www.carbon3d.com/adidas-4dfwd/. [Accessed: 18-Feb-2022].

[17] "4DFWD: Data-driven 3D printed performance technology designed to move you forward," adidas News Site | Press Resources for all Brands, Sports and Innovations, 05-May-2021. [Online]. Available: https://news.adidas.com/running/4dfwd--data-driven-3d-printed-performance-technology-designed-to-move-you-forward/s/514baddb-1029-4686-abd5-5ee3985a304a. [Accessed: 18-Feb-2022].

[18] S. Sheth, “This parametric 3D printed sneaker is made entirely out of one single flexible material - yanko design,” Yanko Design - Modern Industrial Design News, 14-Jan-2022. [Online]. Available: https://www.yankodesign.com/2022/01/14/this-parametric-3d-printed-sneaker-is-made-entirely-out-of-one-single-flexible-material/. [Accessed: 18-Feb-2022].

[19] M. Acer, “DESIGN AND MODELING OF A COMPLIANT MECHANISM,” thesis, 2007.

[20] *Why Machines That Bend Are Better*. Youtube, 2019.

[21] S. A. Zirbel, K. A. Tolman, B. P. Trease, and L. L. Howell, “Bistable mechanisms for space applications,” *PLOS ONE*, vol. 11, no. 12, 2016.

[22] “Bistable compliant switch by BYU_CMR,” *Thingiverse*, 24-Jul-2018. [Online]. Available: https://www.thingiverse.com/thing:2988576. [Accessed: 18-Feb-2022].

[23] “Innovation in every step,” *HandsFree Labs*. [Online]. Available: https://www.handsfreelabs.com/. [Accessed: 10-Feb-2022].

[24] “Women's Athens - Sunrise,” *Kizik*. [Online]. Available: https://kizik.com/products/womens-athens-sunrise. [Accessed: 10-Feb-2022].

[25] A. Jurca, J. Žabkar, and S. Džeroski, “Analysis of 1.2 million foot scans from North America, Europe and Asia,” *Scientific Reports*, vol. 9, no. 1, Dec. 2019.

[26] C.-Y. Yu and H.-H. Tu, “Foot Surface Area Database and estimation formula,” *Applied Ergonomics*, vol. 40, no. 4, pp. 767–774, 2009.

[27] B. Shuter and A. Aslani, “Body surface area: Du Bois and Du Bois revisited,” *European Journal of Applied Physiology*, vol. 82, no. 3, pp. 250–254, 2000.

[28] Du Bois and Du Bois, “A formula to estimate the approximate surface area if height and weight be known. 1916,” *Nutrition (Burbank, Los Angeles County, Calif.)*, 1989.

[Online]. Available: https://pubmed.ncbi.nlm.nih.gov/2520314/. [Accessed: 18-Feb-2022].

[29] "The engineering behind Shoe Design," *Illumin Magazine*, 26-Oct-2017. [Online]. Available: https://illumin.usc.edu/the-engineering-behind-shoe-design/. [Accessed: 10-Feb-2022].

[30] "Girth," *How Shoes are Made: The Sneaker Factory*, 13-Jun-2021. [Online]. Available: https://www.sneakerfactory.net/Shoe_Terms/girth/. [Accessed: 10-Feb-2022].

[31] K. Kirby, "The biomechanics of running shoes ," *PodiatryM*, Sep-2017. [Online]. Available: https://www.podiatrym.com/cme/CME1_917.pdf. [Accessed: 10-Feb-2022].

[32] D. C. Dombroski, "When to replace worn out footwear: Solescience Custom Orthotics," SoleScience, 25-May-2020. [Online]. Available: https://www.solescience.ca/how-worn-is-worn-out. [Accessed: 18-Feb-2022].

[33] C. Bintcliffe and R. Bintcliffe, "Anatomy of the Shoe," *Shoe Guide*, 07-Jun-2020. [Online]. Available: https://www.shoeguide.org/shoe_anatomy/. [Accessed: 10-Feb-2022].

[34] J. Flynt, "The Pros and cons of every 3D printing filament material," The Pros and Cons of Every 3D Printing Filament Material, 23-Jul-2020. [Online]. Available: https://3dinsider.com/pros-and-cons-3d-printing-filaments/. [Accessed: 17-Feb-2022].

[35] J. C. Horvath and R. Cameron, Mastering 3D printing a guide to modeling, printing, and Prototyping. New York: Apress, 2020.

[36] M. Mayer, "Is PLA heat resistant? ABS, ASA, PETG and more!," 3D Solved. [Online]. Available: https://3dsolved.com/is-pla-heat-resistant-abs-asa-petg-and-more/. [Accessed: 18-Feb-2022].

[37] L. Gregurić, "Pla+/plus filament: What is it & is it worth it?," All3DP, 01-Jun-2020. [Online]. Available: https://all3dp.com/2/pla-plus-filament-what-is-it/. [Accessed: 18-Feb-2022].

[38] M. Mayer, “3D solved,” What is PLA+ and how is it different from regular PLA? [Online]. Available: https://3dsolved.com/what-is-pla-and-how-is-it-different-from-regular-pla/. [Accessed: 18-Feb-2022].

[39] “Nylon filament - features, properties, and techniques on printing nylon,” AllThat3D, 29-Dec-2021. [Online]. Available: https://www.allthat3d.com/nylon-filament/. [Accessed: 18-Feb-2022].

[40] A. Danis, “Nylon filament: Properties, uses & benefits,” Filaments.ca, 09-Jul-2020. [Online]. Available: https://filaments.ca/blogs/3d-printing/nylon-filament-properties-uses-benefits. [Accessed: 18-Feb-2022].

[41] “TPE filament - learn everything about the TPE material for 3D Printing,” Tractus3D, 15-Jul-2021. [Online]. Available: https://tractus3d.com/materials/tpe/. [Accessed: 18-Feb-2022].

[42] H. Kondo, “TPE Filament: The Basics & Best Brands,” All3DP, 28-Jan-2021. [Online]. Available: https://all3dp.com/2/tpe-filament-explained-and-compared/. [Accessed: 18-Feb-2022].

[43] “TPE filament - durable, elastic, versatile material [date],” AllThat3D, 29-Dec-2021. [Online]. Available: https://www.allthat3d.com/tpe-filament/. [Accessed: 18-Feb-2022].

[44] Y. Chen, “TPE vs TPU Flexible filament: The differences,” All3DP, 20-May-2020. [Online]. Available: https://all3dp.com/2/tpe-vs-tpu-flexible-filament-the-differences/. [Accessed: 18-Feb-2022].

[45] “What is the difference between TPE and TPU in 3D printing?,” Beamler, 27-Dec-2020. [Online]. Available: https://www.beamler.com/difference-between-tpe-and-tpu/. [Accessed: 18-Feb-2022].

[46] “What is 'shore hardness'? -,” Recreus, 01-Sep-2021. [Online]. Available: https://recreus.com/gb/noticias/learn-with-recreus/what-is-shore-hardness-. [Accessed: 18-Feb-2022].

[47] “Ender 5 Plus 3D printer,” *Creality*. [Online]. Available: https://www.creality3dofficial.com/products/creality-ender-5-plus-3d-printer. [Accessed: 10-Feb-2022].

[48] T. Hullette, “Direct drive vs bowden extruder: The differences,” *All3DP*, 17-Aug-2021. [Online]. Available: https://all3dp.com/2/direct-vs-bowden-extruder-technology-shootout/. [Accessed: 10-Feb-2022].

[49] Josef Průša September 22. 2017 and J. Průša, “Original prusa i3 mk3 is out! and it's Bloody Smart!,” *Prusa Printers*, 23-Oct-2017. [Online]. Available: https://blog.prusaprinters.org/original-prusa-i3-mk3-bloody-smart_7201/. [Accessed: 10-Feb-2022].

[50] “Choosing the right 3D printer: FDM vs sla,” *MakerBot*, 19-Apr-2021. [Online]. Available: https://www.makerbot.com/stories/engineering/choosing-the-right-3d-printer-fdm-vs-sla/. [Accessed: 10-Feb-2022].

[51] “Bondtech DDX Direct Drive extruder for Creality Ender / CR-10(S) 3D printers,” *Bondtech DDX Direct Drive eXtruder for Creality Ender / CR-10(S) 3D P*. [Online]. Available: https://www.dold-mechatronik.de/Bondtech-DDX-Direct-Drive-eXtruder-for-Creality-Ender-CR-10S-3D-Printers_1. [Accessed: 10-Feb-2022].

[52] “I3 Mega,” *ANYCUBIC 3D Printing*. [Online]. Available: https://www.anycubic.com/products/anycubic-i3-mega. [Accessed: 10-Feb-2022].

[53] J. Bartosch, “Do our feet change in middle age?,” *UChicago Medicine*, 03-Oct-2019. [Online]. Available:

https://www.uchicagomedicine.org/forefront/orthopaedics-articles/do-our-feet-change-in-middle-age. [Accessed: 10-Feb-2022].

[54] D. R. Bonanno, K. Ledchumanasarma, K. B. Landorf, S. E. Munteanu, G. S. Murley, and H. B. Menz, “Effects of a contoured foot orthosis and flat insole on plantar pressure and tibial acceleration while walking in defence boots - scientific reports,” *Nature*, 08-Feb-2019. [Online]. Available: https://doi.org/10.1038/s41598-018-35830-5. [Accessed: 10-Feb-2022].

[55] 3D Printing Canada, “Creality Ender 6 (250x250x400mm),” 3D Printing Canada. [Online]. Available: https://3dprintingcanada.com/products/creality-ender-6?gclid=Cj0KCQjwl7qSBhD-ARIsACvV1X3dM7cwmfc9JVYf5gMZAzTYvMZ6q5ctZ4YltWKR9OhHs6zctHGsEEIaAkA3EALw_wcB. [Accessed: 08-Apr-2022].

[56] D. Miller, “Should you worry about 3D printer fumes?,” io3dprint.com, 02-Mar-2021. [Online]. Available: https://io3dprint.com/should-you-worry-about-3d-printer-fumes/. [Accessed: 08-Apr-2022].

[57] “Complete Guide on Thermoplastic Polyurethanes (TPU),” Thermoplastic Polyurethane (TPU) Material: Properties & Applications. [Online]. Available: https://omnexus.specialchem.com/selection-guide/thermoplastic-polyurethanes-tpu. [Accessed: 08-Apr-2022].

[58] “Department of Labor Logo United Statesdepartment of Labor,” Isocyanates - Overview | Occupational Safety and Health Administration. [Online]. Available: https://www.osha.gov/isocyanates#:~:text=Isocyanates%20include%20compounds%20classified%20as,nose%2C%20throat%2C%20and%20skin. [Accessed: 08-Apr-2022].

[59] E. Clark, “TPU filament 3D printing material – The Complete Guide [date],” AllThat3D, 05-Apr-2022. [Online]. Available: https://www.allthat3d.com/tpu-filament/. [Accessed: 08-Apr-2022].

[60] “What is TPU - uses of thermoplastic polyurethane in Sporting Goods,” Eco Sports. [Online]. Available: https://ecosports.com/pages/what-is-tpu-thermoplastic-polyurethane-sporting-goods. [Accessed: 08-Apr-2022].

[61] “How to recycle old filament spools into filament,” Filabot. [Online]. Available: https://www.filabot.com/blogs/news/how-to-recycle-old-filament-spools-into-filament. [Accessed: 08-Apr-2022].

[62] “How to avoid wasting empty filament spools,” 3D Insider, 15-Sep-2020. [Online]. Available: https://3dinsider.com/empty-filament-spools/. [Accessed: 08-Apr-2022].

[63] A. Nawrat, “3D printing in the medical field: Four major applications revolutionizing the industry,” *Medical Device Network*, 02-Feb-2022. [Online]. Available: https://www.medicaldevice-network.com/features/3d-printing-in-the-medical-field-applications/. [Accessed: 08-Apr-2022].

[64] “Ninjaflex 85a TPU filament - 1.75mm - 2KG,” Filaments.ca. [Online]. Available: https://filaments.ca/collections/all/products/ninjaflex-85a-tpu-filament-snow-white-1-75mm-2kg. [Accessed: 08-Apr-2022].

[65] “Electricity rates,” Electricity rates | Ontario Energy Board. [Online]. Available: https://www.oeb.ca/consumer-information-and-protection/electricity-rates. [Accessed: 08-Apr-2022].

[66] “Creality Ender 6: Review: Features, Specs, Pros & Cons,” The 3D Printer Bee, 26-Nov-2021. [Online]. Available: https://the3dprinterbee.com/ender-6-review-specs/#:~:text=Creality%20specifies%20the%20maximum%20power,print%20bed%20is%20heated%20up. [Accessed: 08-Apr-2022].

Appendix A - Foot Measurements Database

Stature height group	Measurement	Body Weight Group						Sub-total	
		Slim BMI < 18.5		Medium 18.5 < BMI < 27		Fat BMI > 27			
		Range	Mean (S.D.)	Range	Mean (S.D.)	Range	Mean (S.D.)	Range	Mean (S.D.)
(a) Male ($N = 135$); unit: cm									
XL	Foot-length	26.52–26.59	25.63 (0.89)	25.2–28.15	26.3 (0.74)	24.81–27.38	24.75 (0.36)	24.81–28.15	25.64 (0.91)
	Ball-breadth	10.5–10.88	10.66 (0.19)	10.2–11.49	10.91 (0.57)	10.13–11.15	10.59 (0.52)	10.13–11.49	10.74 (0.45)
	Ball-girth	24.99–25.66	25.28 (0.34)	23.93–27.32	25.95 (1.49)	23.88–26.41	25.18 (1.27)	23.88–27.32	25.52 (1.12)
	Instep-girth	24.42–27.71	25.69 (1.77)	23.61–26.99	25.36 (1.4)	24.81–27.27	26.05 (1.23)	23.61–27.71	25.67 (1.33)
	Ankle-girth	21.47–21.76	21.57 (0.17)	20.85–24.54	22.97 (1.59)	23.63–25.36	24.28 (0.94)	20.85–25.36	22.94 (1.51)
L	Foot-length	24.34–25.02	25.38 (0.76)	23.75–26.63	25.08 (0.21)	25.17–26.82	24.36 (1.09)	23.75–26.82	24.95 (0.82)
	Ball-breadth	10.2–10.49	10.39 (0.16)	10.2–11.13	10.71 (0.29)	9.98–11.56	10.85 (0.6)	9.98–11.56	10.65 (0.38)
	Ball-girth	24.74–25.21	25.01 (0.24)	24.35–27.15	25.44 (0.8)	24.19–27.47	26.05 (1.24)	24.19–27.47	25.5 (0.91)
	Instep-girth	23.99–25.33	24.56 (0.69)	24.21–26.74	25.24 (0.8)	25.61–27.55	26.93 (0.79)	23.99–27.55	25.56 (1.13)
	Ankle-girth	20.76–21.12	20.92 (0.18)	21.01–25.46	22.39 (1.18)	23.77–25.19	24.68 (0.58)	20.76–25.46	22.65 (1.57)
M	Foot-length	23.22–25.4	23.88 (0.25)	24.35–26.97	23.7 (0.2)	24.88–25.29	23.93 (0.16)	23.22–26.97	23.82 (0.21)
	Ball-breadth	9.18–10.01	9.7 (0.45)	9.63–10.72	10.32 (0.32)	10.79–11.7	11.31 (0.47)	9.18–11.7	10.43 (0.64)
	Ball-girth	22.23–23.74	23.16 (0.82)	22.71–25.91	24.73 (0.97)	25.99–27.39	26.83 (0.74)	22.23–27.39	24.89 (1.47)
	Instep-girth	23.2–23.75	23.39 (0.31)	23.05–25.5	24.79 (0.76)	24.87–26.77	26 (1)	23.05–26.77	24.73 (1.1)
	Ankle-girth	19.29–20.73	20.17 (0.77)	20.79–23.18	21.74 (0.88)	23.19–24.11	23.68 (0.46)	19.29–24.11	21.85 (1.38)
S	Foot-length	23.79–24.11	26.9 (1.31)	23.59–24.19	26.29 (1.32)	23.47–23.84	26.55 (0.03)	23.47–24.19	26.56 (1.02)
	Ball-breadth	9.35–9.93	9.73 (0.33)	9.28–9.84	9.52 (0.23)	10.44–10.93	10.74 (0.26)	9.28–10.93	9.97 (0.6)
	Ball-girth	22.52–23.74	23.27 (0.66)	22.58–23.54	22.87 (0.45)	24.98–26.33	25.69 (0.68)	22.52–26.33	23.88 (1.39)
	Instep-girth	21.53–23.35	22.45 (0.91)	22.05–24.72	23.2 (1.12)	22.66–24.7	23.68 (1.02)	21.53–24.72	23.12 (1.04)
	Ankle-girth	18.95–20.58	19.59 (0.87)	19.26–22.29	20.46 (1.3)	22.68–23.93	23.43 (0.66)	18.95–23.93	21.11 (2.03)
XS	Foot-length	23.59–24.87	23.87 (1.05)	22.31–24.51	25 (0.24)	24.76–25.25	24.05 (0.71)	22.31–25.25	24.37 (0.87)
	Ball-breadth	9.52–9.87	9.64 (0.2)	8.8–10.24	9.67 (0.62)	9.98–10.05	10.01 (0.04)	8.8–10.24	9.76 (0.41)
	Ball-girth	22.79–23.43	23.07 (0.33)	21.15–24.12	23.12 (1.34)	23.89–24.98	24.36 (0.56)	21.15–24.98	23.48 (1.03)
	Instep-girth	21.5–22.97	22.24 (0.74)	22.31–24.05	23.15 (0.97)	23.08–25.73	24.08 (1.44)	21.5–25.73	23.16 (1.21)
	Ankle-girth	19.07–20.14	19.47 (0.58)	19.11–21.88	20.12 (1.23)	22.35–24.78	23.36 (1.27)	19.07–24.78	20.9 (1.92)
Sub-total	Foot-length	23.22-26.59	25.11 (1.25)	22.31–28.15	24.89 (1.17)	23.47–27.38	24.74 (1.11)	**22.31–28.15**	**24.91 (1.21)**
	Ball-breadth	9.18–10.88	9.94 (0.5)	8.8–11.49	10.22 (0.6)	9.98–11.7	10.91 (0.57)	8.8–11.7	10.35 (0.61)
	Ball-girth	22.23–25.66	23.79 (1.1)	21.15–27.32	24.44 (1.41)	23.88–27.47	26.06 (1.19)	21.15–27.47	24.73 (1.41)
	Instep-girth	21.5–27.71	23.53 (1.59)	22.05–26.99	24.45 (1.22)	22.66–27.55	25.52 (1.61)	21.5–27.71	24.5 (1.55)
	Ankle-girth	18.95–21.76	20.26 (0.97)	19.11–25.46	21.57 (1.48)	22.35-–25.36	23.88 (0.89)	18.95–25.46	21.87 (1.79)
(b) Female ($N = 135$); unit: cm									
XL	Foot-length	22.61–24.19	23.25 (0.74)	23.2–26.18	23.08 (1.03)	24.32–25.06	22.83 (0.75)	22.61–26.18	23.06 (0.77)
	Ball-breadth	9.08–9.99	9.52 (0.46)	8.92–10.46	9.65 (0.64)	9.99–10.54	10.25 (0.28)	8.92–10.54	9.79 (0.55)
	Ball-girth	21.65–23.48	22.45 (0.94)	21.43–24.66	23.56 (1.47)	24.19–25.52	24.69 (0.72)	21.43–25.52	23.56 (1.37)
	Instep-girth	21.32–23.24	22.12 (1)	20.83–24.36	22.71 (1.49)	24.54–26.02	25.15 (0.77)	20.83–26.02	23.26 (1.69)
	Ankle-girth	18.09–21.78	20.22 (1.91)	20.36–23.55	21.71 (1.41)	23.18–25.09	23.88 (1.05)	18.09–25.09	21.91 (1.99)
L	Foot-length	21.88–24.25	22.7 (0.91)	21.41–24.36	22.32 (1.04)	21.89–23.77	21.82 (0.76)	21.41–24.36	22.28 (0.92)
	Ball-breadth	8.34–9.5	9.12 (0.34)	8.74–10.23	9.6 (0.45)	9.89–10.16	10.06 (0.15)	8.34–10.23	9.6 (0.48)
	Ball-girth	20.18–22.57	21.77 (0.67)	20.96–24.53	22.83 (0.96)	23.83–24.37	24.09 (0.27)	20.18–24.53	22.89 (1.07)
	Instep-girth	20.3–21.91	21.32 (0.47)	20.43–23.65	22.38 (0.86)	22.38–24.68	23.69 (1.18)	20.3–24.68	22.46 (1.04)
	Ankle-girth	17.5–20.43	19.15 (0.82)	18.75–23.15	20.78 (1)	23.15–23.74	23.37 (0.32)	17.5–23.74	21.08 (1.5)
M	Foot-length	20.75–22.82	22.25 (0.72)	21.22–23.87	22.13 (0.87)	21.66–23.52	22.56 (1.02)	20.75–23.87	22.29 (0.77)
	Ball-breadth	8.27–9.1	8.69 (0.35)	8.47–9.94	9.25 (0.48)	9.59–9.95	9.83 (0.21)	8.27–9.95	9.25 (0.55)
	Ball-girth	19.62–22.15	20.86 (0.93)	20.46–23.59	22 (1.03)	22.89–23.69	23.39 (0.44)	19.62–23.69	22.07 (1.25)
	Instep-girth	17.98–21.45	20.07 (1.39)	20.29–23.75	21.74 (0.97)	20.85–23.33	22.13 (1.24)	17.98–23.75	21.36 (1.36)
	Ankle-girth	17.12–20.66	19.04 (1.31)	18.6–21.51	20.21 (0.92)	21.77–22.55	22.21 (0.4)	17.12–22.55	20.46 (1.43)
S	Foot–length	21.57–23.61	24.59 (1.23)	21.15–23.25	24.79 (0.41)	21.17–22.87	23.57 (0.84)	21.15–23.61	24.35(1)
	Ball-breadth	8.61–9.26	8.88 (0.33)	8.98–9.79	9.41 (0.32)	9.5–10.18	9.8 (0.35)	8.61–10.18	9.37 (0.44)
	Ball-girth	20.48–22.32	21.39 (0.92)	21.36–23.07	22.33 (0.69)	22.81–24.29	23.37 (0.8)	20.48–24.29	22.36 (0.99)
	Instep-girth	20.29–21.74	20.93 (0.74)	20.26–22.72	21.82 (0.95)	20.57–23.73	22.05 (1.59)	20.26–23.73	21.62 (1.07)
	Ankle-girth	19.02–20.43	19.56 (0.76)	18.78–21.89	20.39 (1.15)	20.87–22.18	21.65 (0.69)	18.78–22.18	20.52 (1.18)
XS	Foot-length	20.28–20.91	21.22 (0.63)	20.59–21.8	21.11 (0.23)	20.88–21.33	20.62 (0.32)	20.28–21.8	21 (0.49)
	Ball-breadth	7.92–8.69	8.39 (0.41)	8.66–9.13	8.92 (0.21)	9.17–9.48	9.34 (0.15)	7.92–9.48	8.88 (0.46)
	Ball-girth	19.39–21.34	20.42 (0.98)	20.48–21.63	21.18 (0.54)	21.89–22.48	22.28 (0.34)	19.39–22.48	21.28 (0.96)
	Instep-girth	18.09–21.18	19.65 (1.55)	18.68–21.04	19.77 (1.08)	19.95–20.48	20.14 (0.3)	18.09–21.18	19.84 (0.99)
	Ankle-girth	18.47–20.64	19.27 (1.19)	18.56–21.31	20.07 (1.28)	20.87–21.33	21.14 (0.24)	18.47–21.33	20.15 (1.21)
Sub-total	Foot-length	20.28–24.25	22.93 (1.14)	20.59–26.18	22.77 (1.43)	20.88–25.06	22.5 (1.11)	**20.28–26.18**	**22.74 (1.19)**
	Ball-breadth	7.92–9.99	8.88 (0.47)	8.47–10.46	9.37 (0.48)	9.17–10.54	9.87 (0.38)	7.92–10.54	9.37 (0.55)
	Ball-girth	19.39–23.48	21.3 (0.97)	20.46–24.66	22.32 (1.1)	21.89–25.52	23.57 (0.96)	19.39–25.52	22.39 (1.26)
	Instep-girth	17.98–23.24	20.71 (1.18)	18.68–24.36	21.83 (1.22)	19.95–26.02	22.57 (1.98)	17.98–26.02	21.71 (1.49)
	Ankle-girth	17.12–21.78	19.3 (1.09)	18.56–23.55	20.48 (1.11)	20.87–25.09	22.4 (1.19)	17.12–25.09	20.71 (1.53)

Stature height group	Measurement	Body Weight Group						Sub-total	
		Slim BMI < 18.5		Medium 18.5 < BMI < 27		Fat BMI > 27			
		Range	Mean (S.D.)	Range	Mean (S.D.)	Range	Mean (S.D.)	Range	Mean (S.D.)
(c) Total ($N = 270$); unit: cm									
	Measurement	Range	Mean (S.D.)						
	Foot-length	**20.28–28.15**	**23.83 (1.72)**						
	Ball-breadth	7.92–11.7	9.86 (0.76)						
	Ball-girth	19.39–27.47	23.56 (1.78)						
	Instep-girth	17.98–27.71	23.1 (2.09)						
	Ankle-girth	17.12–25.46	21.29 (1.8)						

Figure A-1: Database of foot measurements used by Yu & Tu in Foot Surface Area Database and Estimation Formula [27]

Appendix B - Team Insole Sizing Chart

Table B-1: Team's insoles sizing chart

Size	Sex	Brand	Ball Width	Arch Width	Heel Width	Length	Length to Mid Heel	Length to Ball Width
13	Male	Steve Madden	10.0cm	7.2cm	6.8cm	30.3cm	4cm	9cm
13	Male	Nike	10.2cm	7.5cm?	7cm	30.9cm	3.8cm	9.5cm
13	Male	adidas	10.5cm	6.9cm	6.5cm	29.8cm	4cm	8.5cm
11.5	Male	adidas	9.5cm	6cm	6cm	28cm	3.5cm	6cm
11	Male	Nike	9cm	7.5cm	7cm	28cm	4cm	7cm
11	Male	Polo	8.5cm	5.5cm	6cm	29cm	4cm	7cm
11	Male	Asics	9.5cm	6cm	6cm	27cm	3.5cm	7cm
11	Male	Vessi	9.5cm	5.5cm	5.5cm	27cm	3cm	8cm
11	Male	New Balance	9.5cm	6.5cm	6.5cm	28cm	3.5cm	8cm
10.5	Male	Saucony	9.5cm	5.5cm	6cm	26cm	3.5cm	7cm
10.5	Male	Nike	9.7 cm	7 cm	6.5 cm	28.8 cm	3 cm	8 cm
10.5	Male	Nike	10 cm	7.5 cm	6 cm	29 cm	2.5 cm	8 cm
8	Female	Nike	8cm	6cm	6cm	23cm	3cm	7.5cm
7	Male	Steve Madden	9.7cm	5.5cm	5cm	26cm	3.5cm	8cm

Appendix C - Insole Sketch Grasshopper Formula

The insole sketch consists of six points which are then transformed into 12 points; two points for each original point. A curve is constructed through the 12 points to create the shape of the insole. To construct a set of *parametric* points from an original point, the following steps are performed:

1. Sole length is multiplied by an empirical factor.
    a. The empirical factor is found by deciding on the desired distance between the two new points and dividing it by the sole length. Therefore by multiplying the factor with sole length, the distance between the two points is returned. This helps make the design parametric.
2. The result is divided by two
    a. This represents the distance between the original point and the two new points
3. A right triangle is created using the distance between the original point and the new point as the hypotenuse, and an angle found empirically.
4. Portions of the x and y coordinates of the new point are extracted using the constructed right triangle.
5. The coordinates of the original point are deconstructed into x,y,z coordinates.
6. For the upper new point, the x,y coordinates found via the right triangle are added together with the deconstructed x,y coordinates of the original point.
7. For the upper new point, the x,y coordinates found via the right triangle are subtracted from the deconstructed x,y coordinates of the original point.

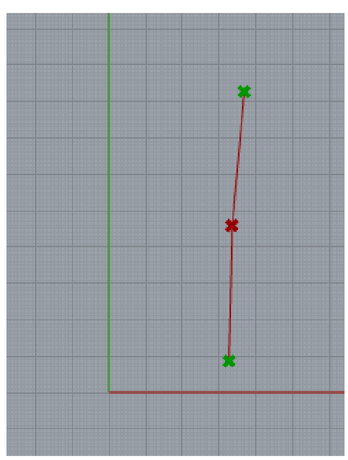


Figure C-1: Two new points in green while the original point is shown in red, with connecting lines added for clarity

Figure C-2-4 shows how these steps are translated into a Grasshopper script. An optional division component can be added to make fine adjustments to the new point coordinates if required.

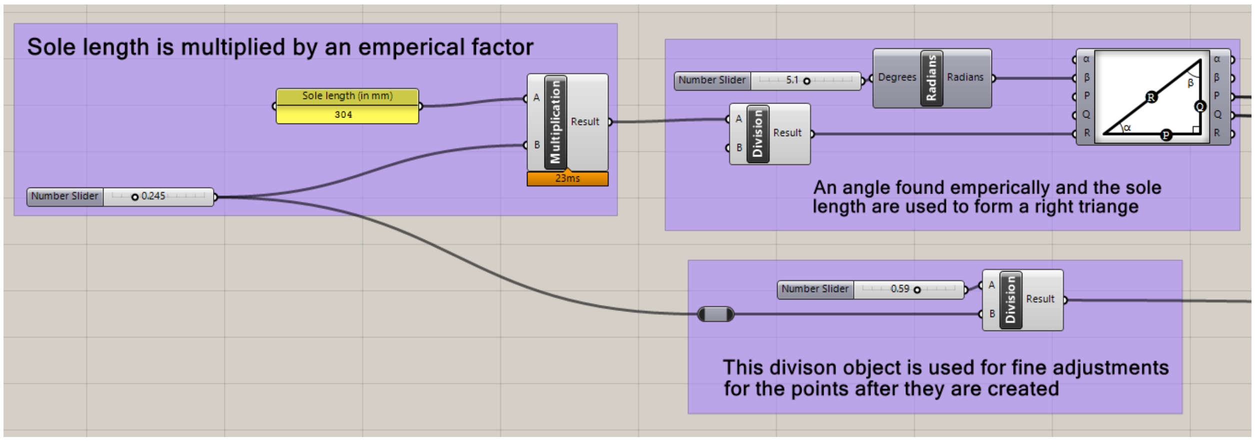


Figure C-2: First half of the example Grasshopper script

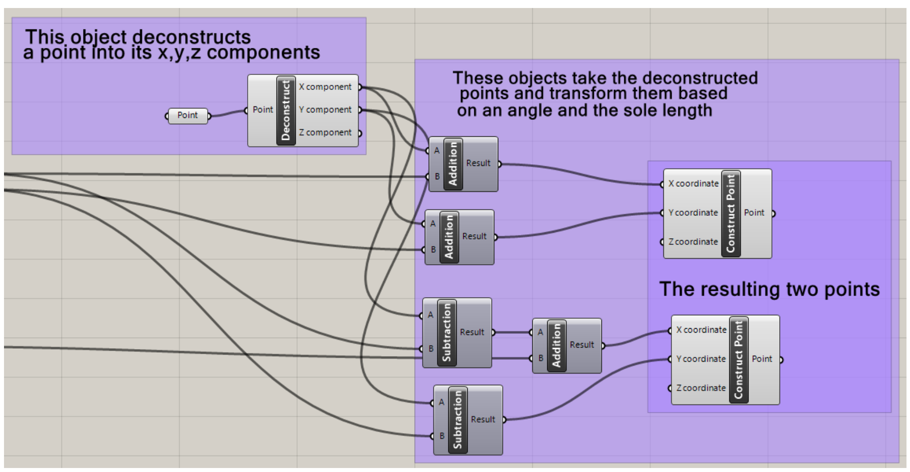


Figure C-3: Second half of the example Grasshopper script

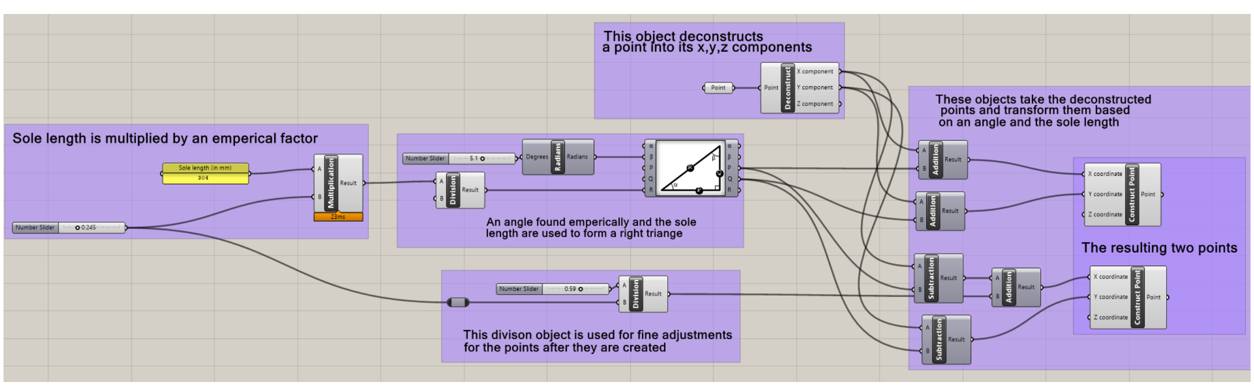


Figure C-4: Full view of the Grasshopper script with all components visible

Appendix D - Shoe Designs

Kids

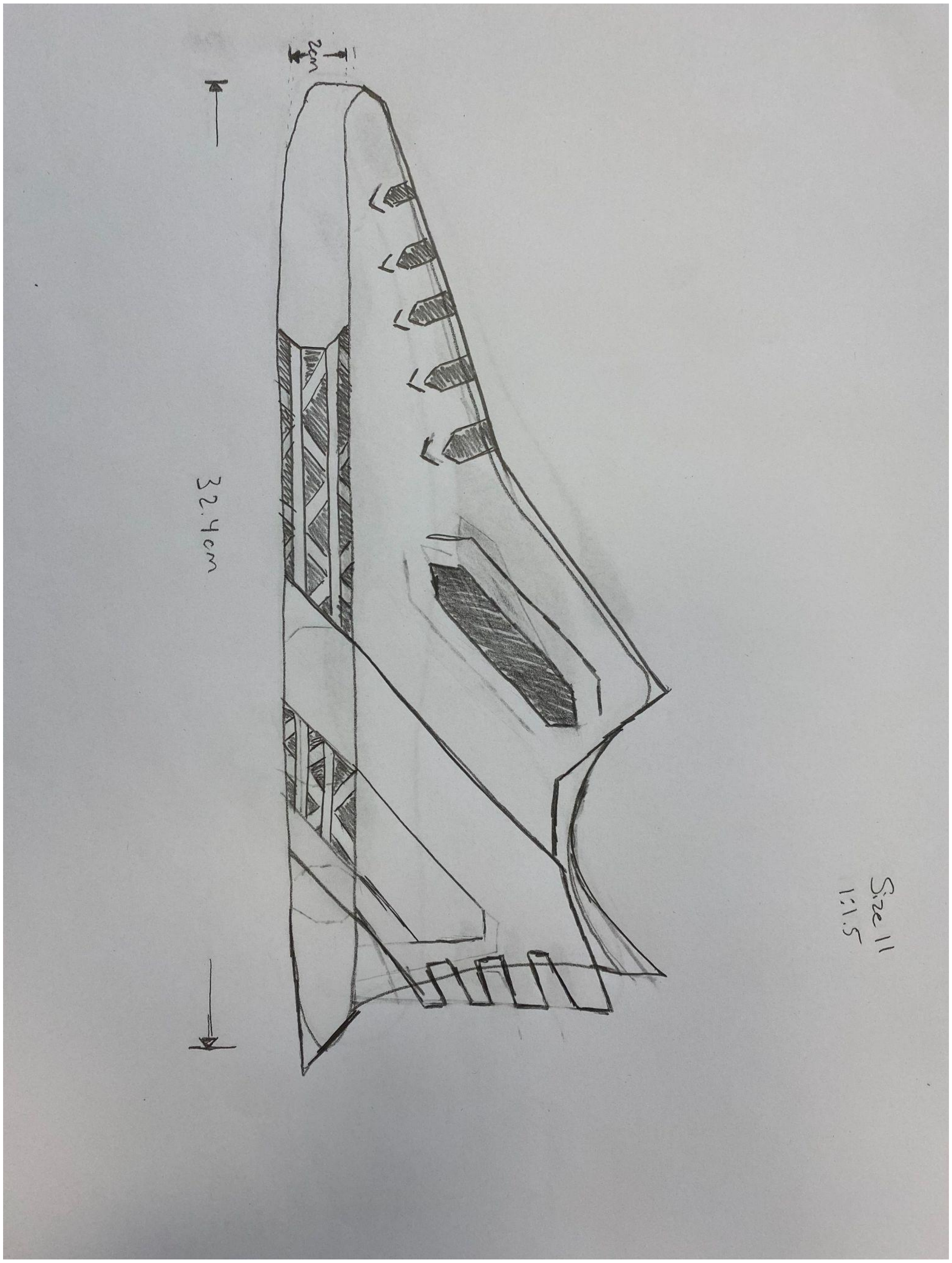


Figure D-1. Kids Shoe Design I

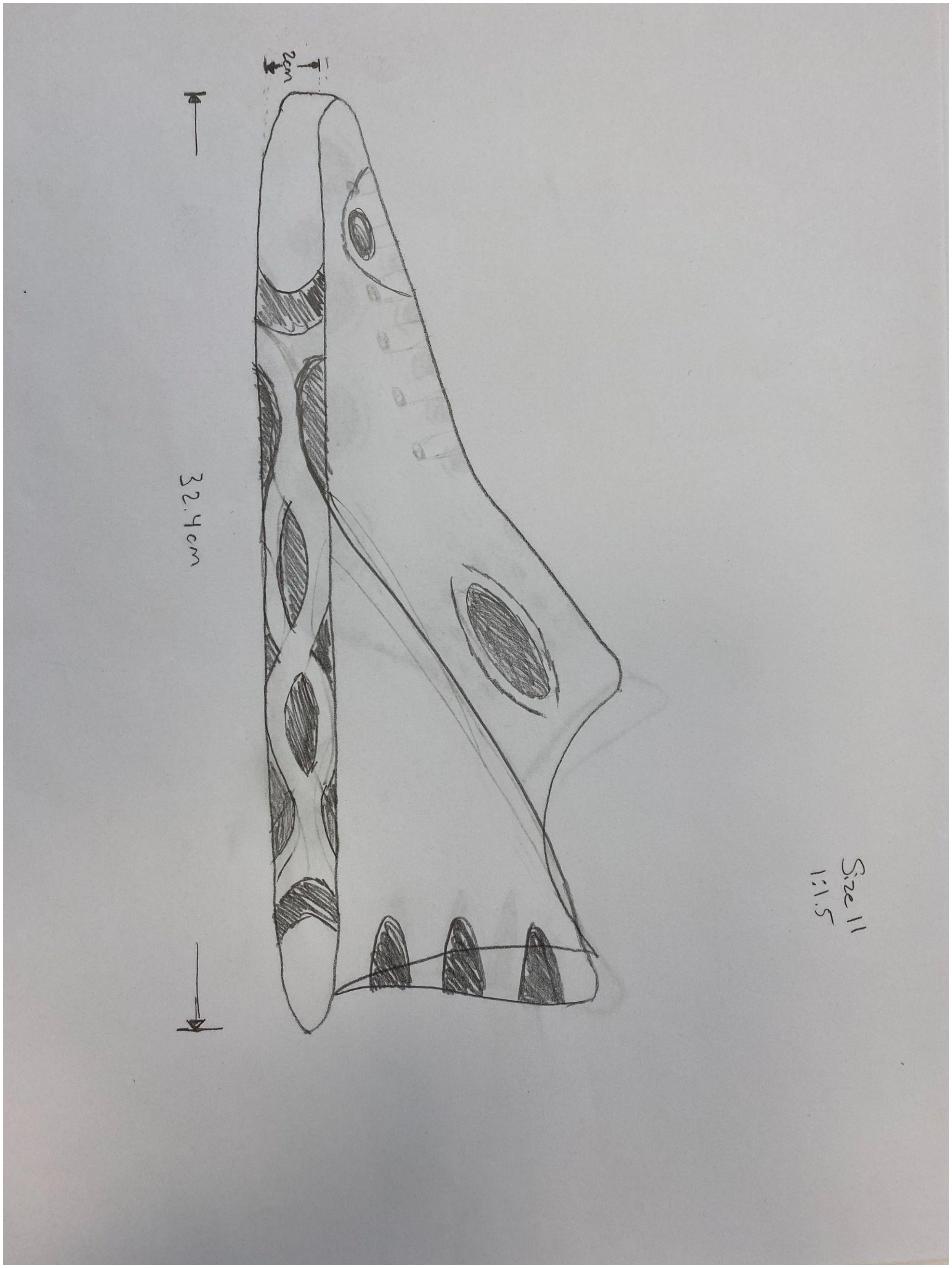


Figure D-2. Kids Shoe Design II

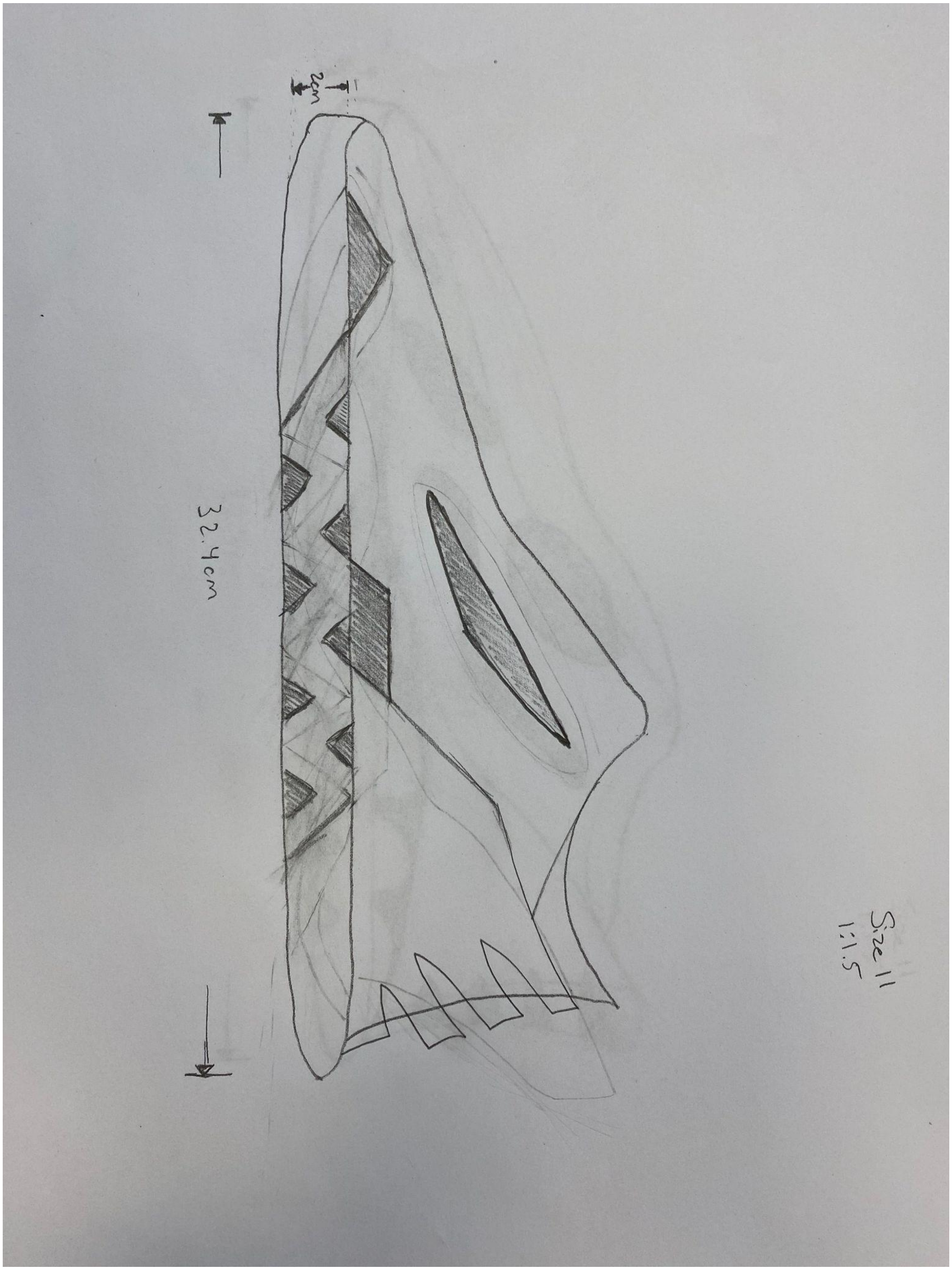


Figure D-3. Kids Shoe Design III

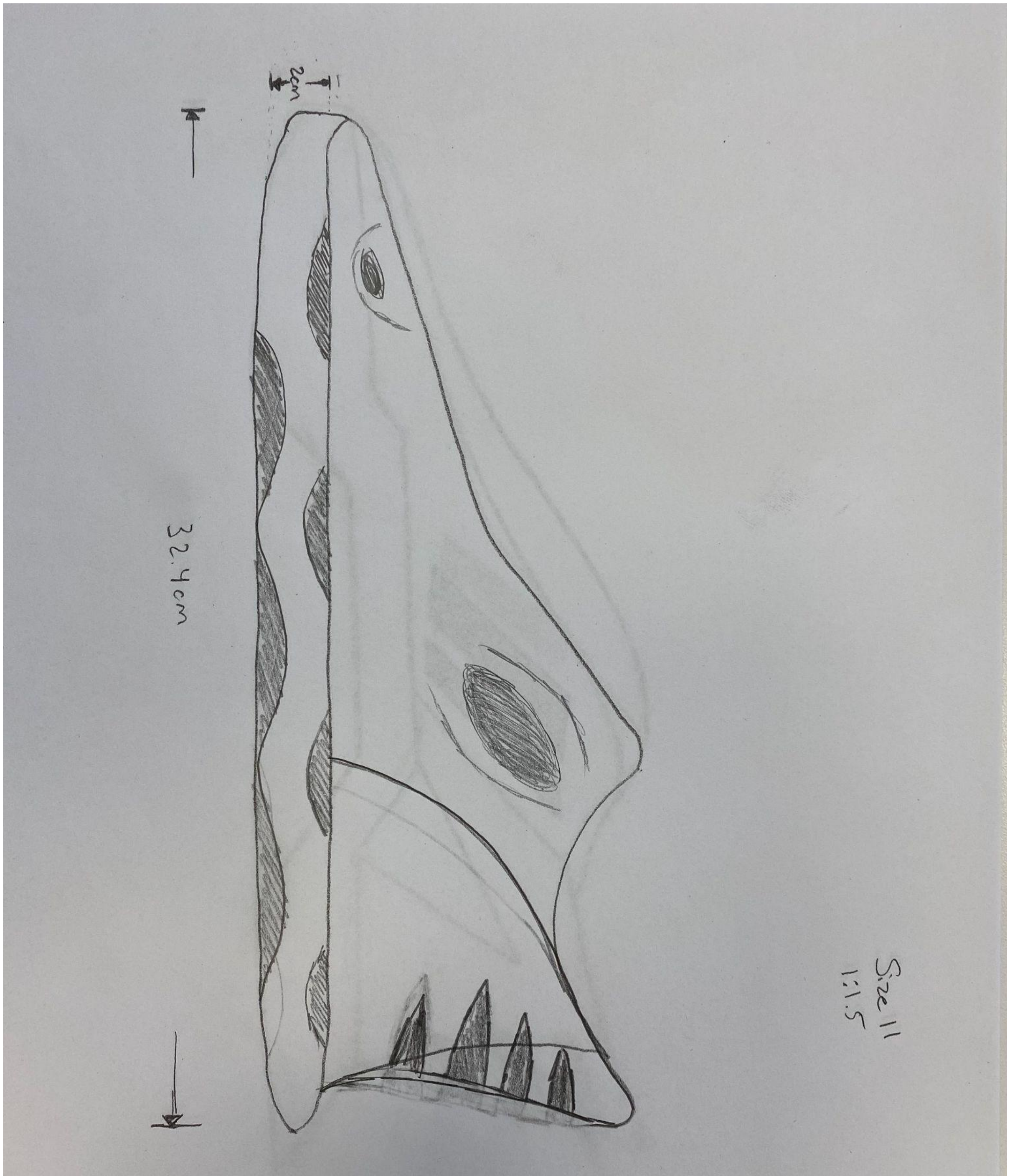


Figure D-4. Kids Shoe Design IV

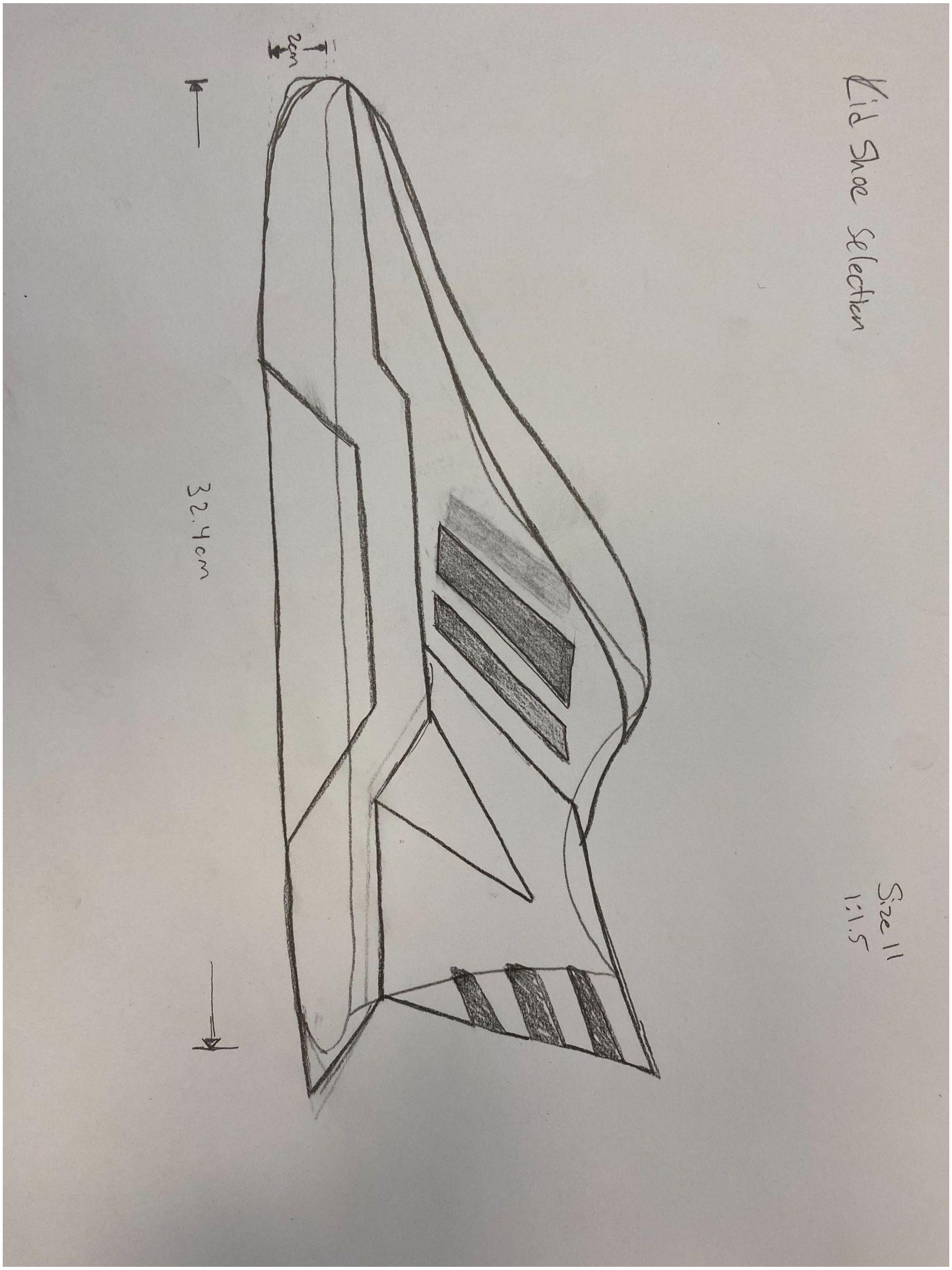


Figure D-5. Kids Shoe Design V

Seniors

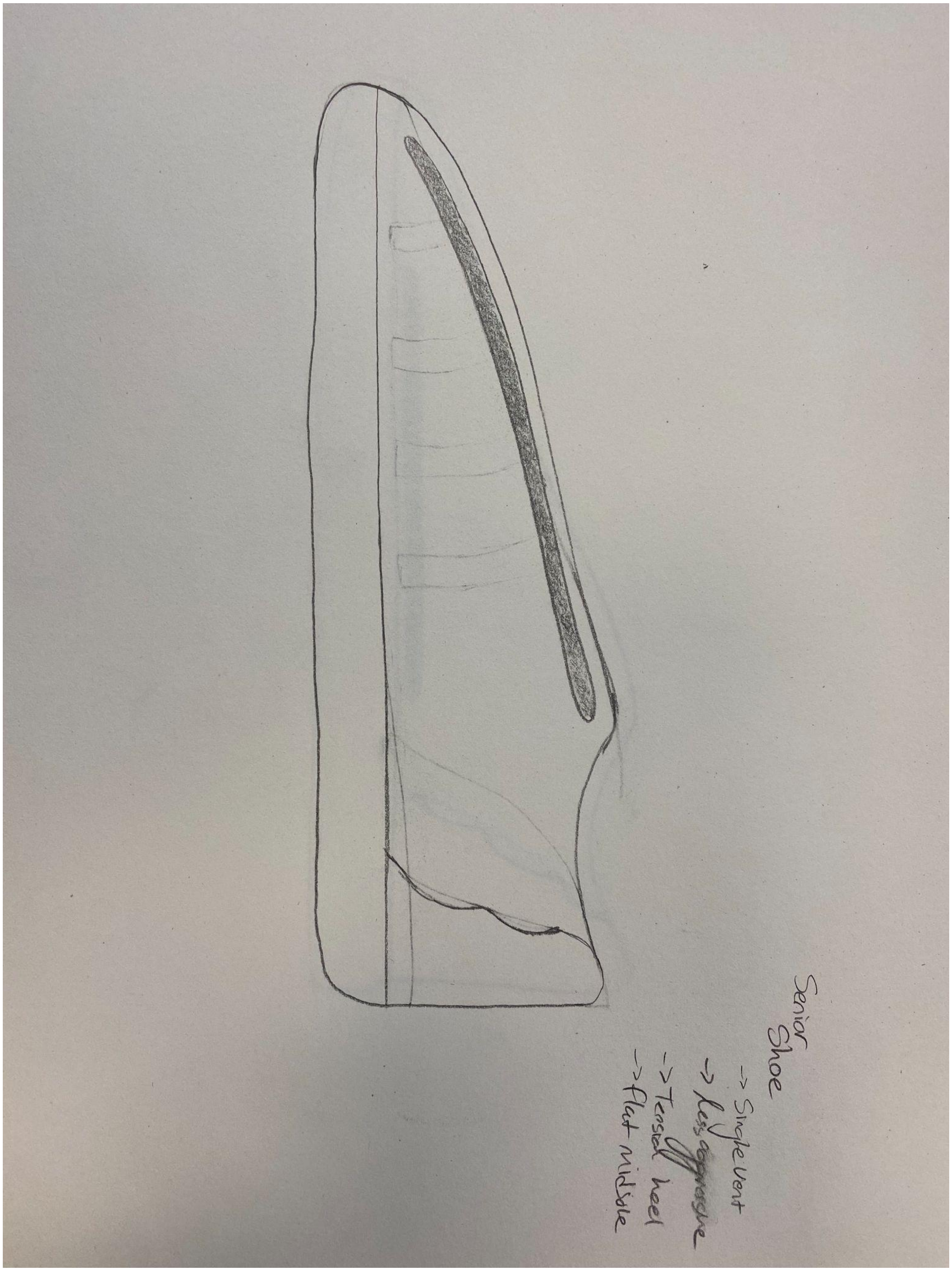


Figure D-6. Seniors Shoe Design I

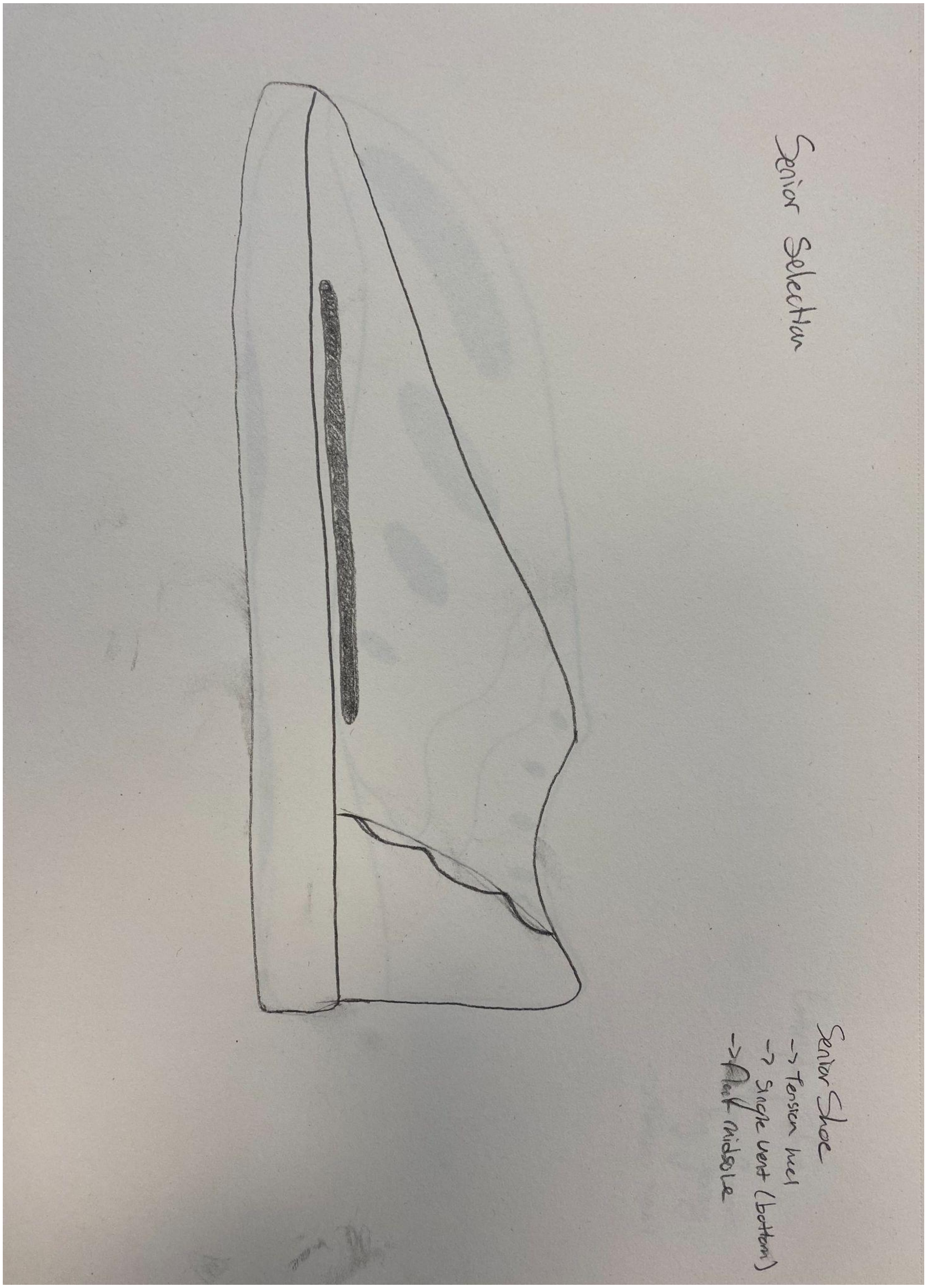


Figure D-7. Seniors Shoe Design II

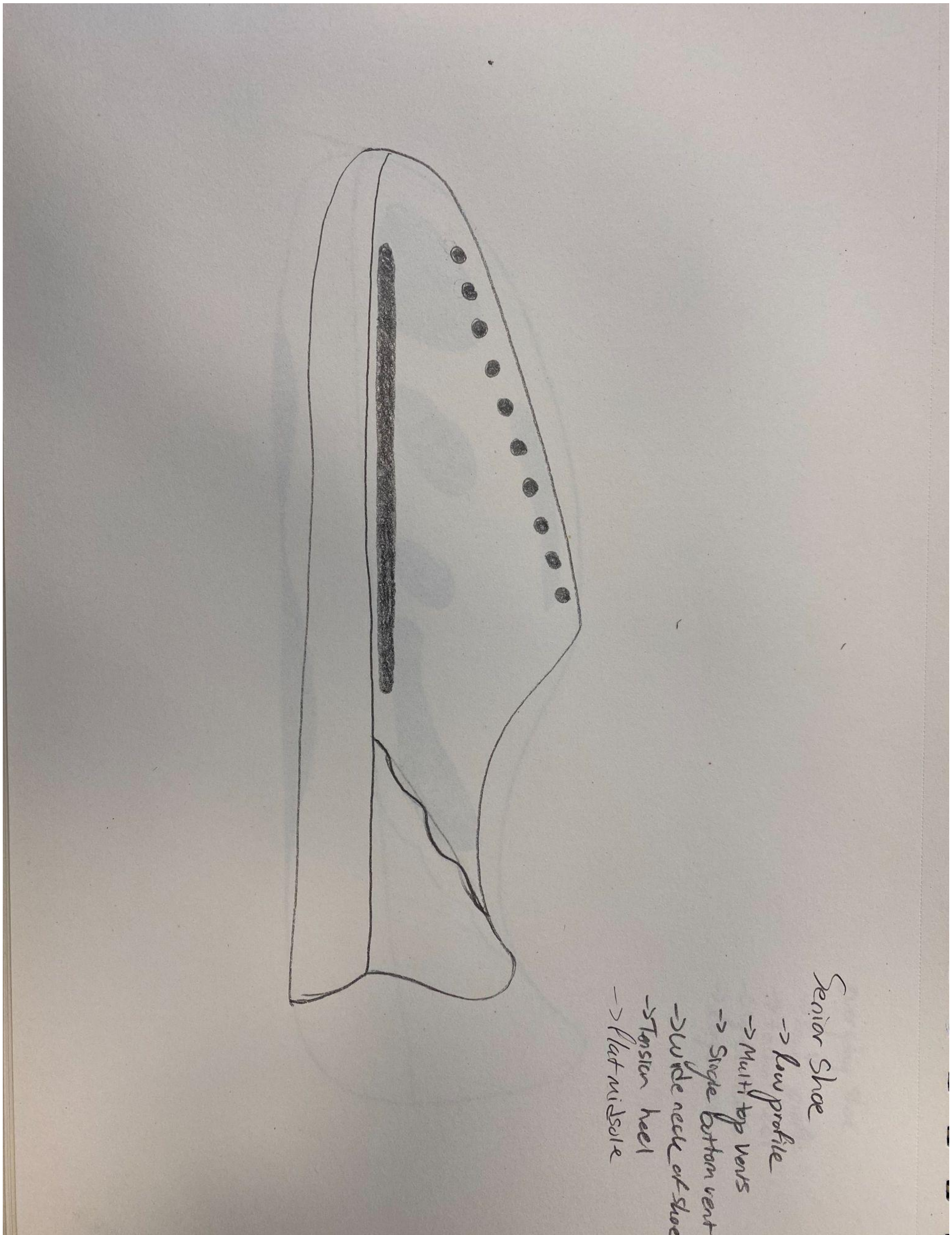


Figure D-8. Seniors Shoe Design III

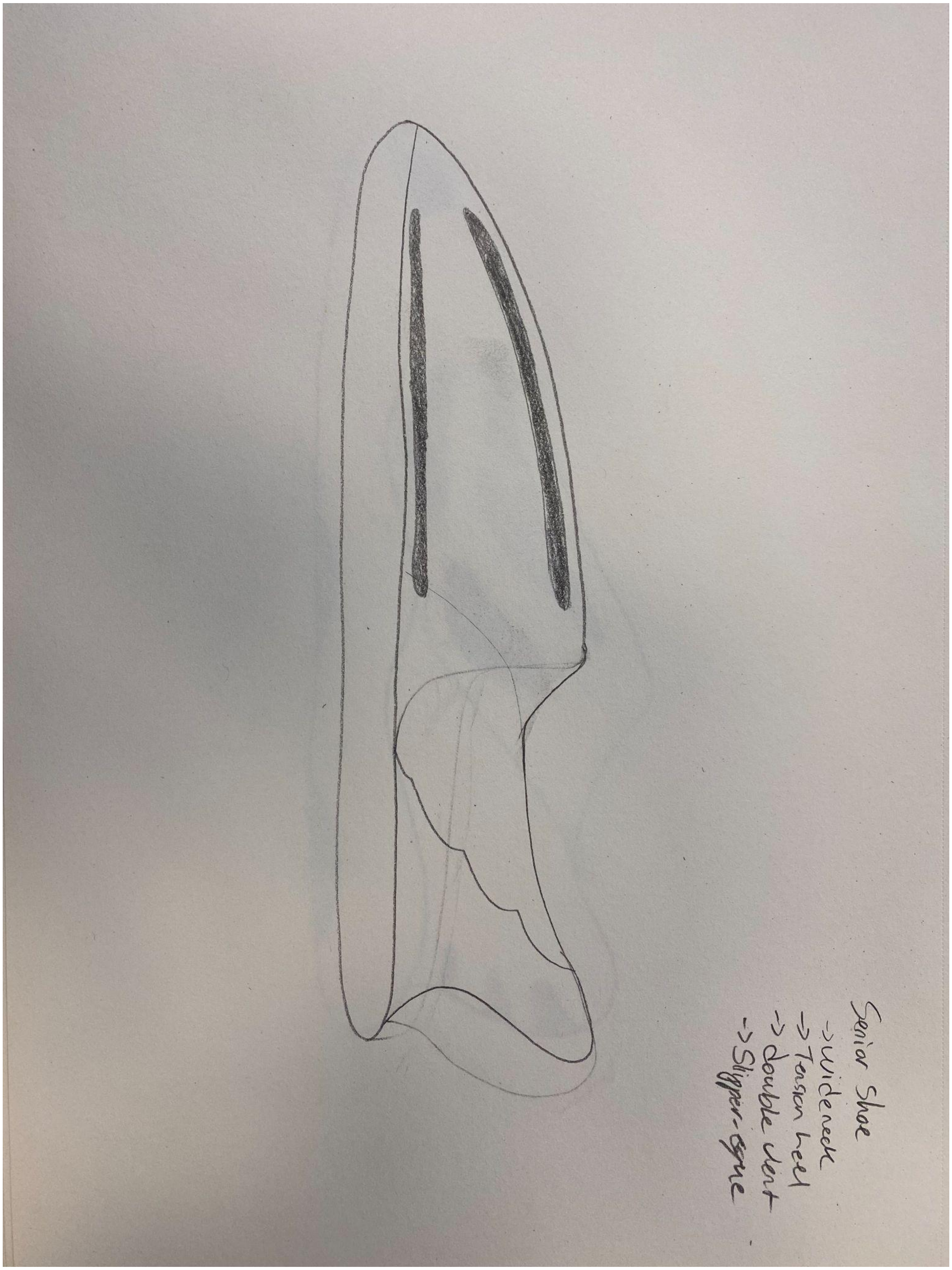


Figure D-9. Seniors Shoe Design IV

Everyday

Figure D-10. Everyday Shoe Design I

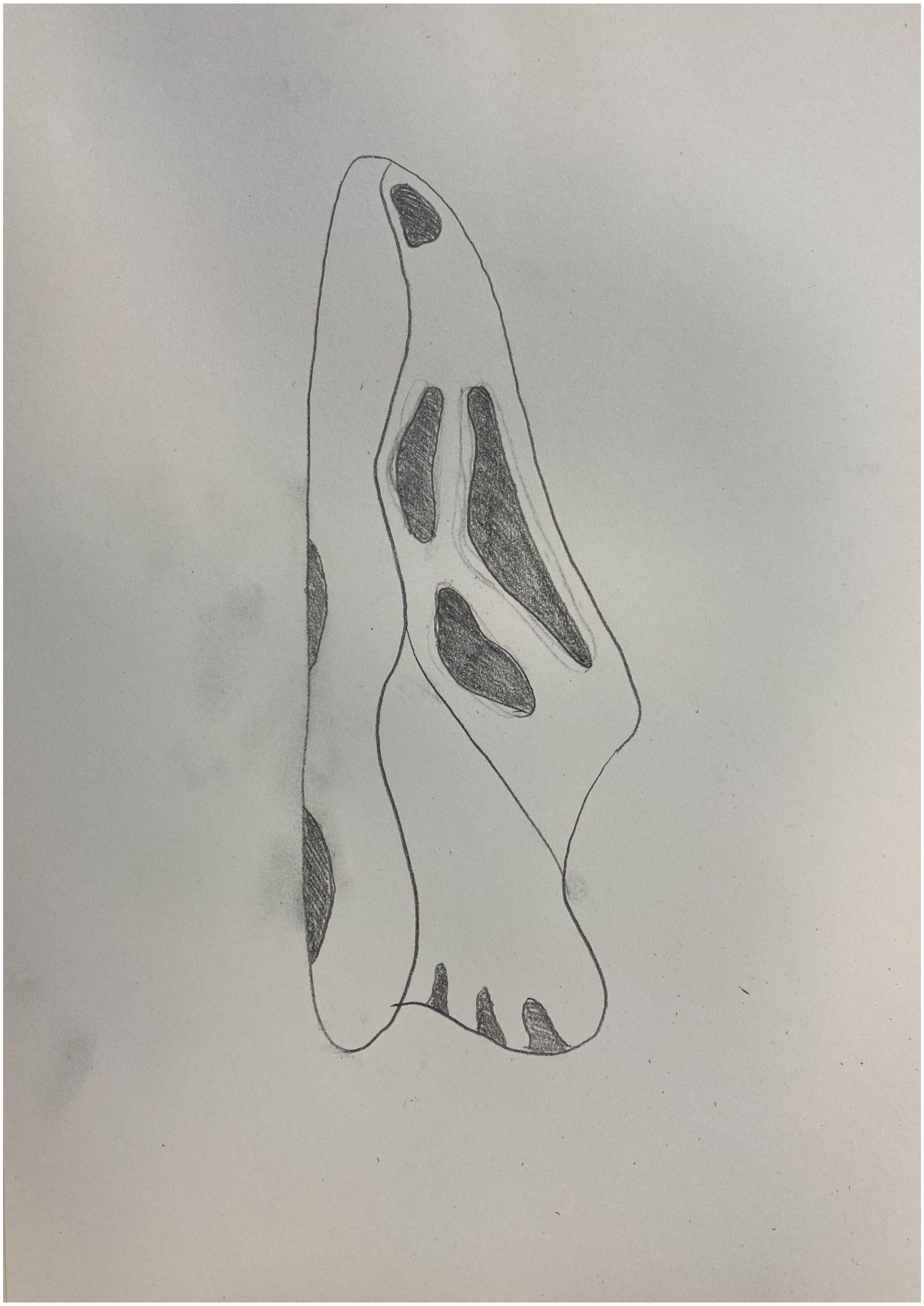


Figure D-11. Everyday Shoe Design II

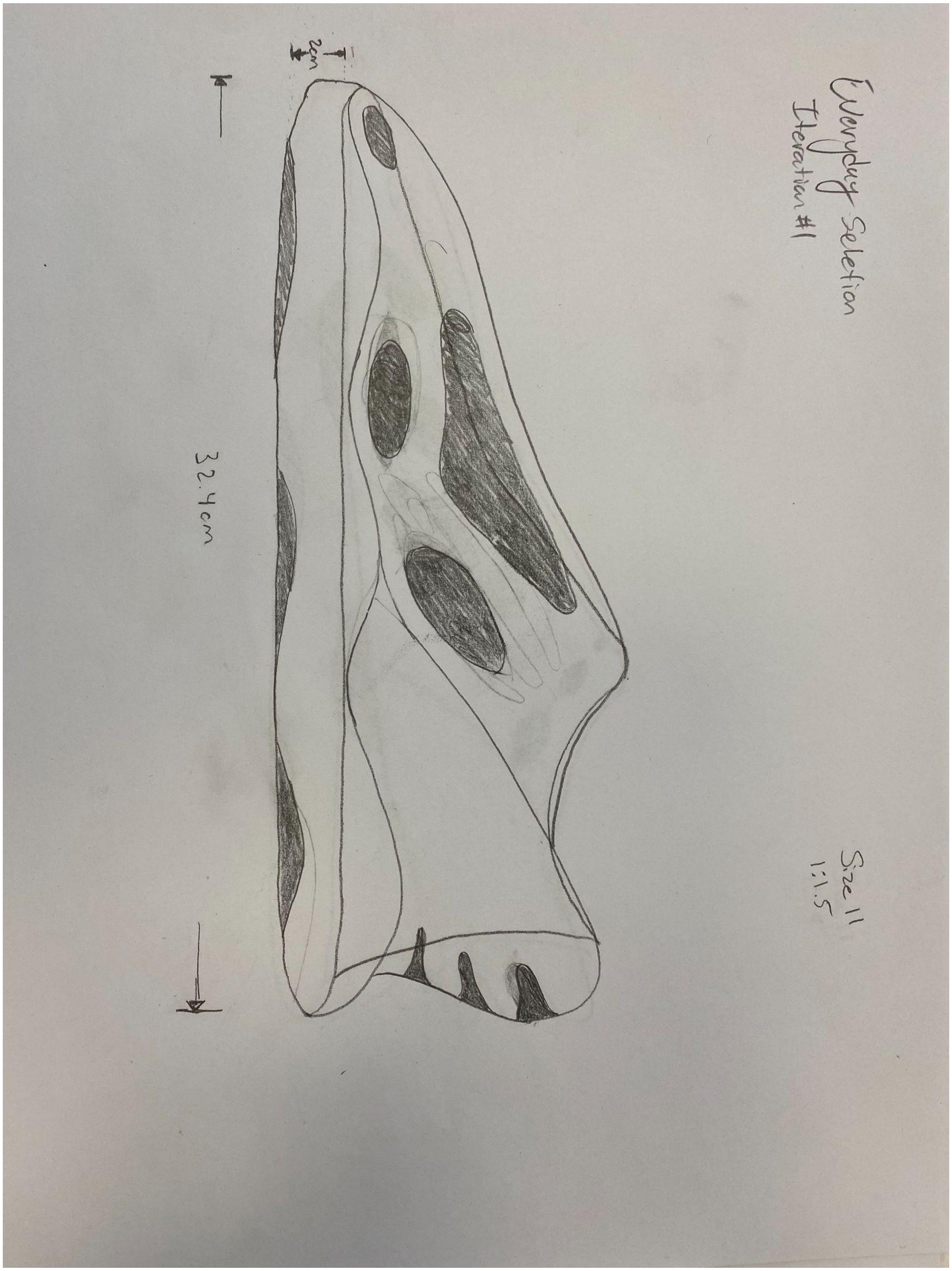


Figure D-12. Everyday Shoe Design III

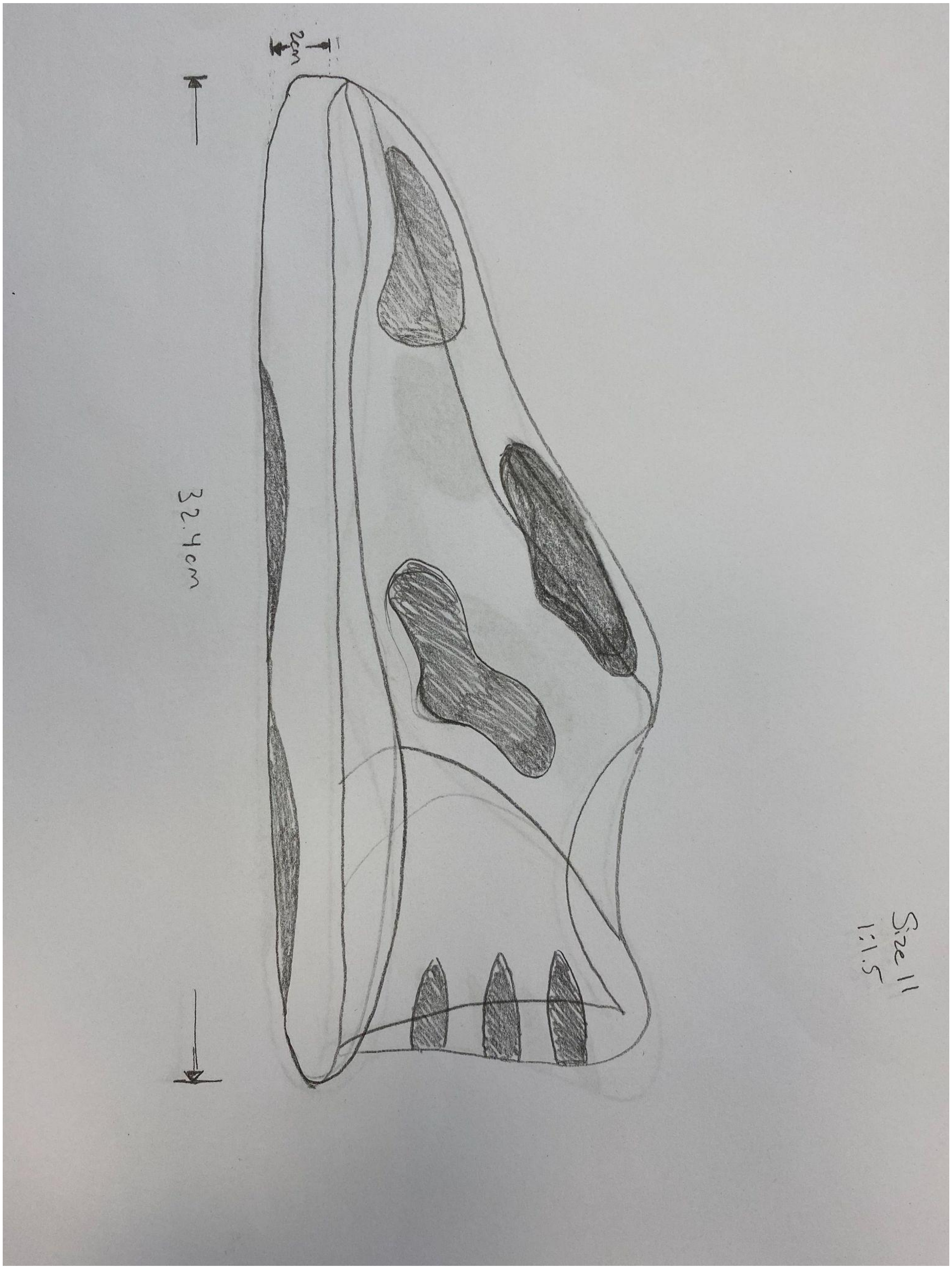


Figure D-13. Everyday Shoe Design IV

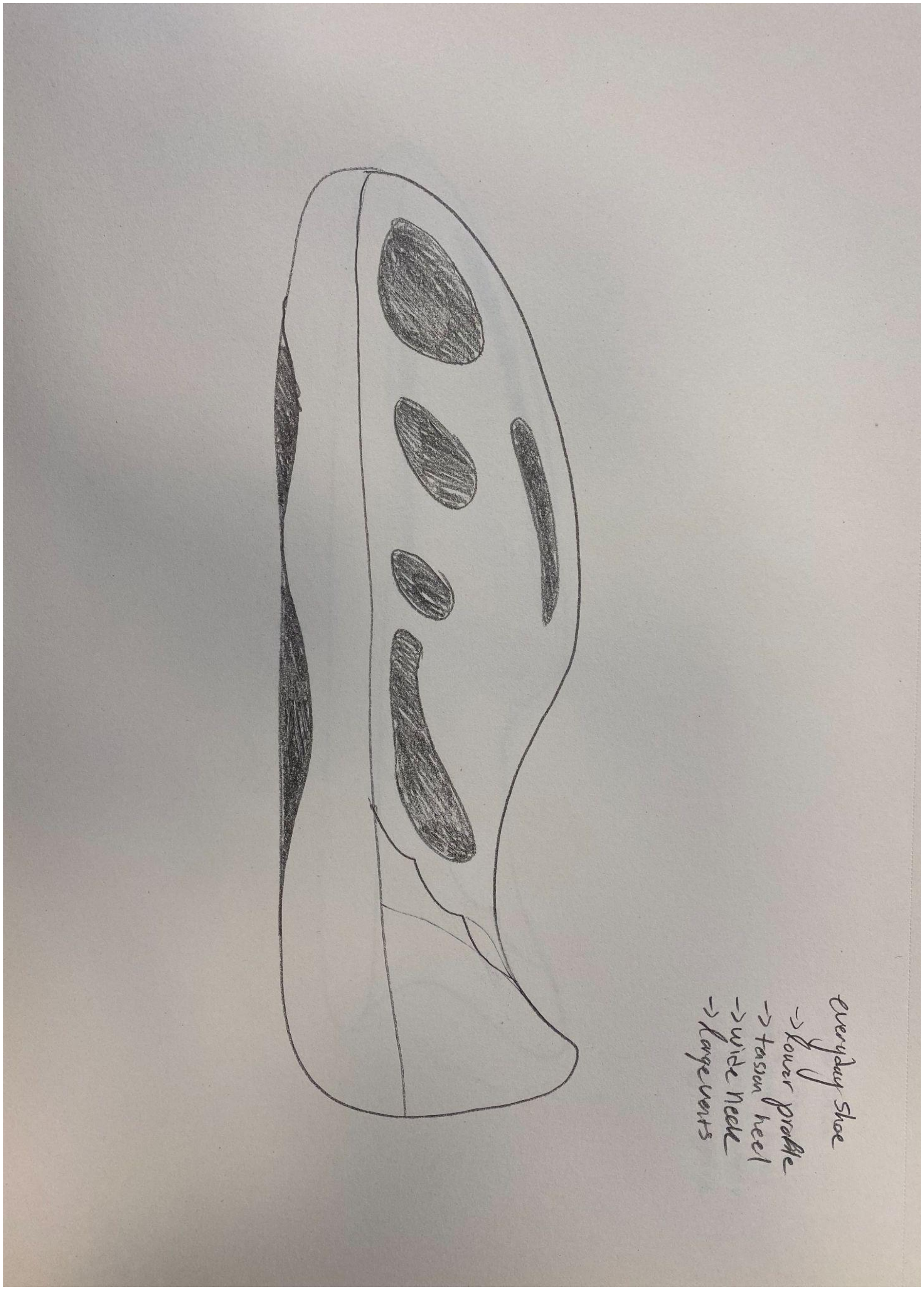


Figure D-14. Everyday Shoe Design V

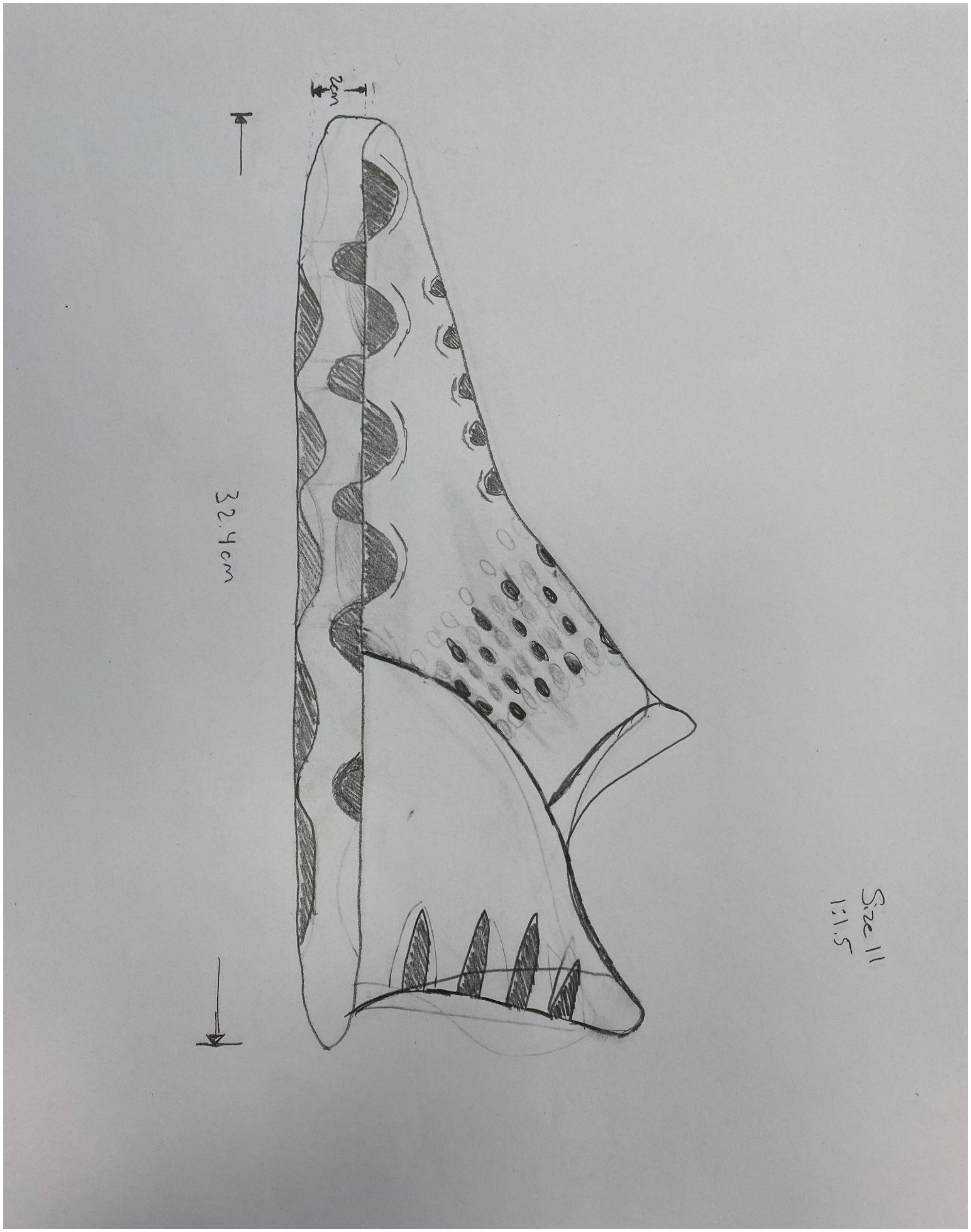


Figure D-15. Everyday Shoe Design VI

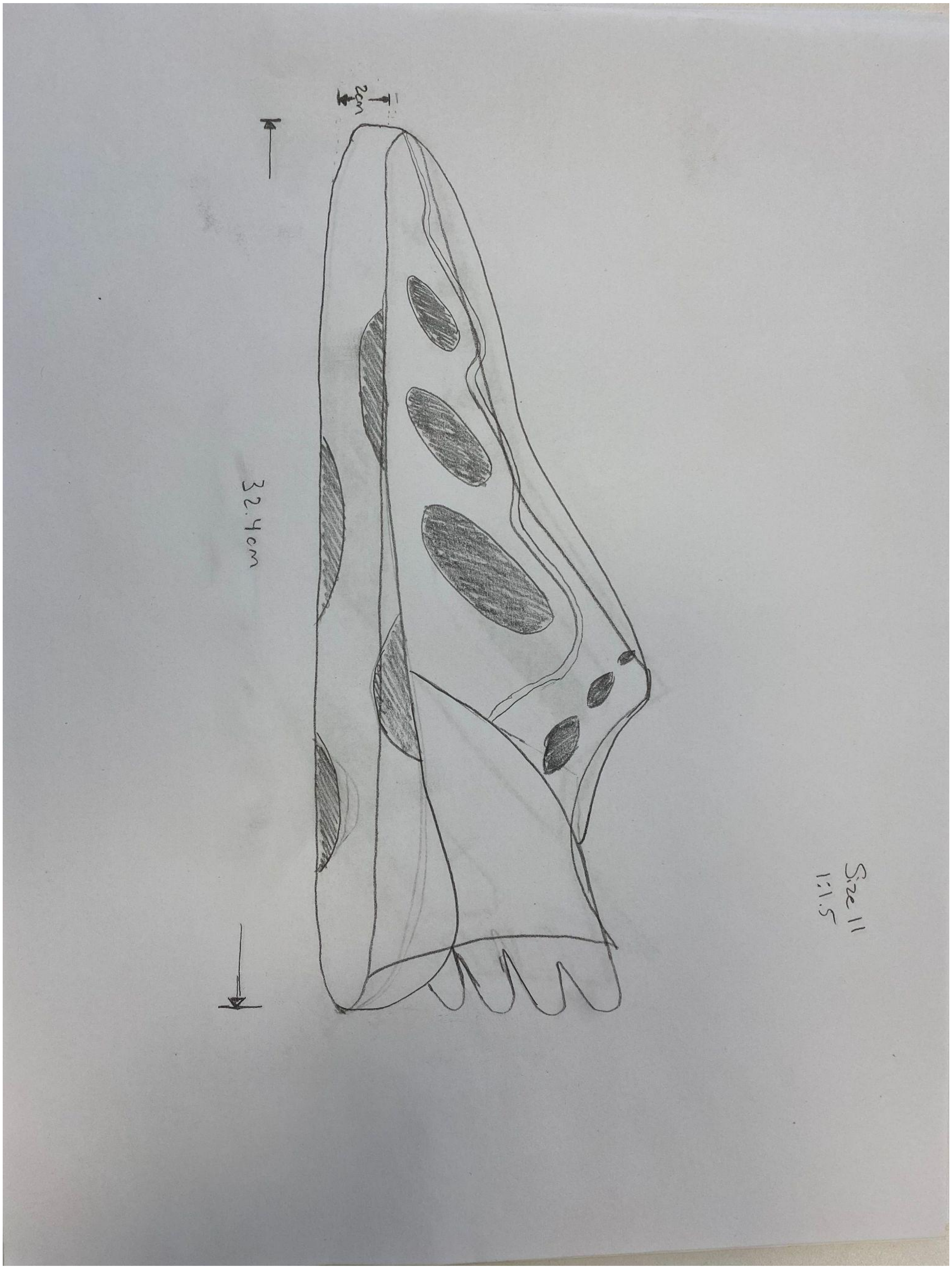


Figure D-16. Everyday Shoe Design VII

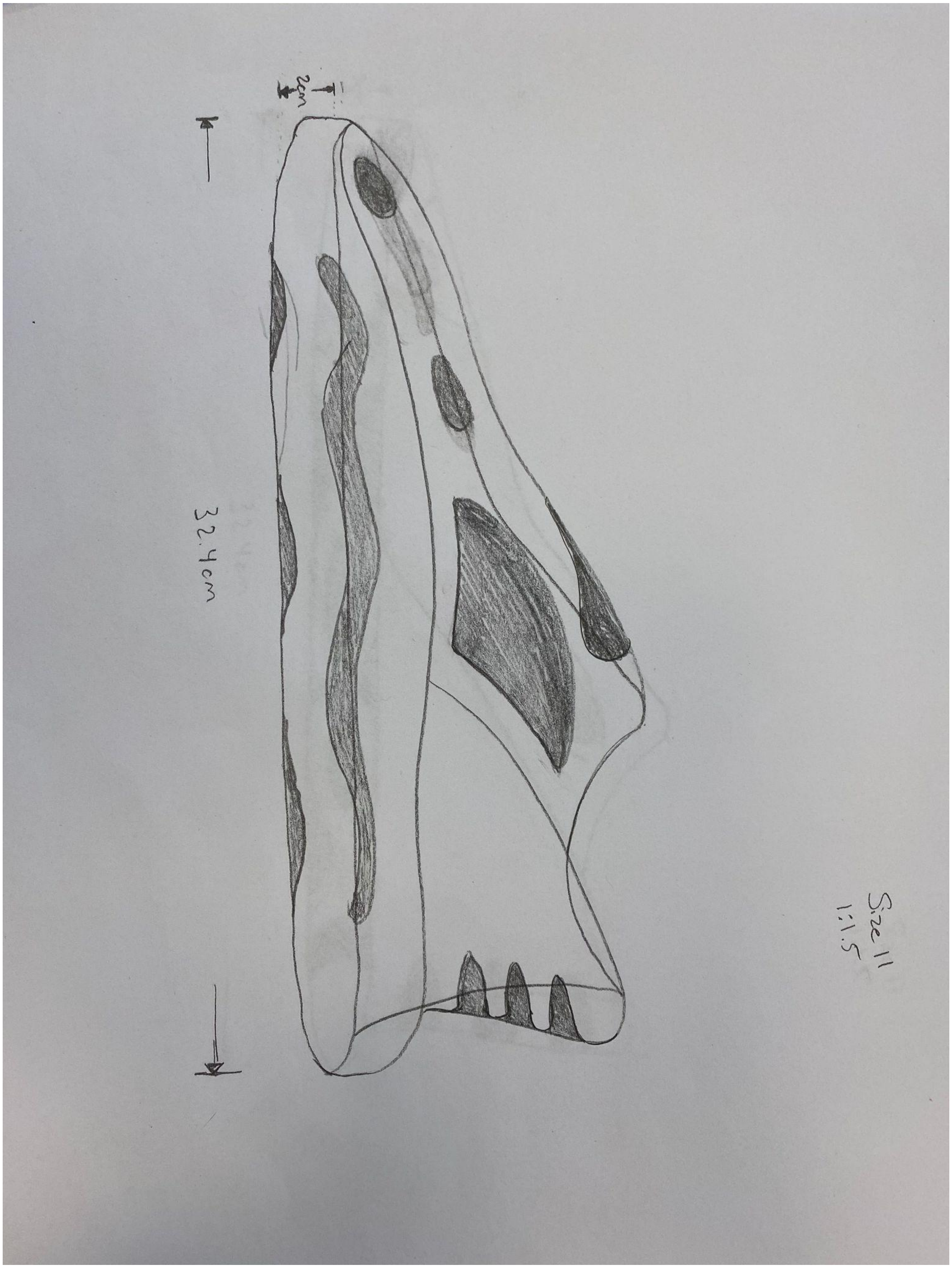


Figure D-17. Everyday Shoe Design VIII

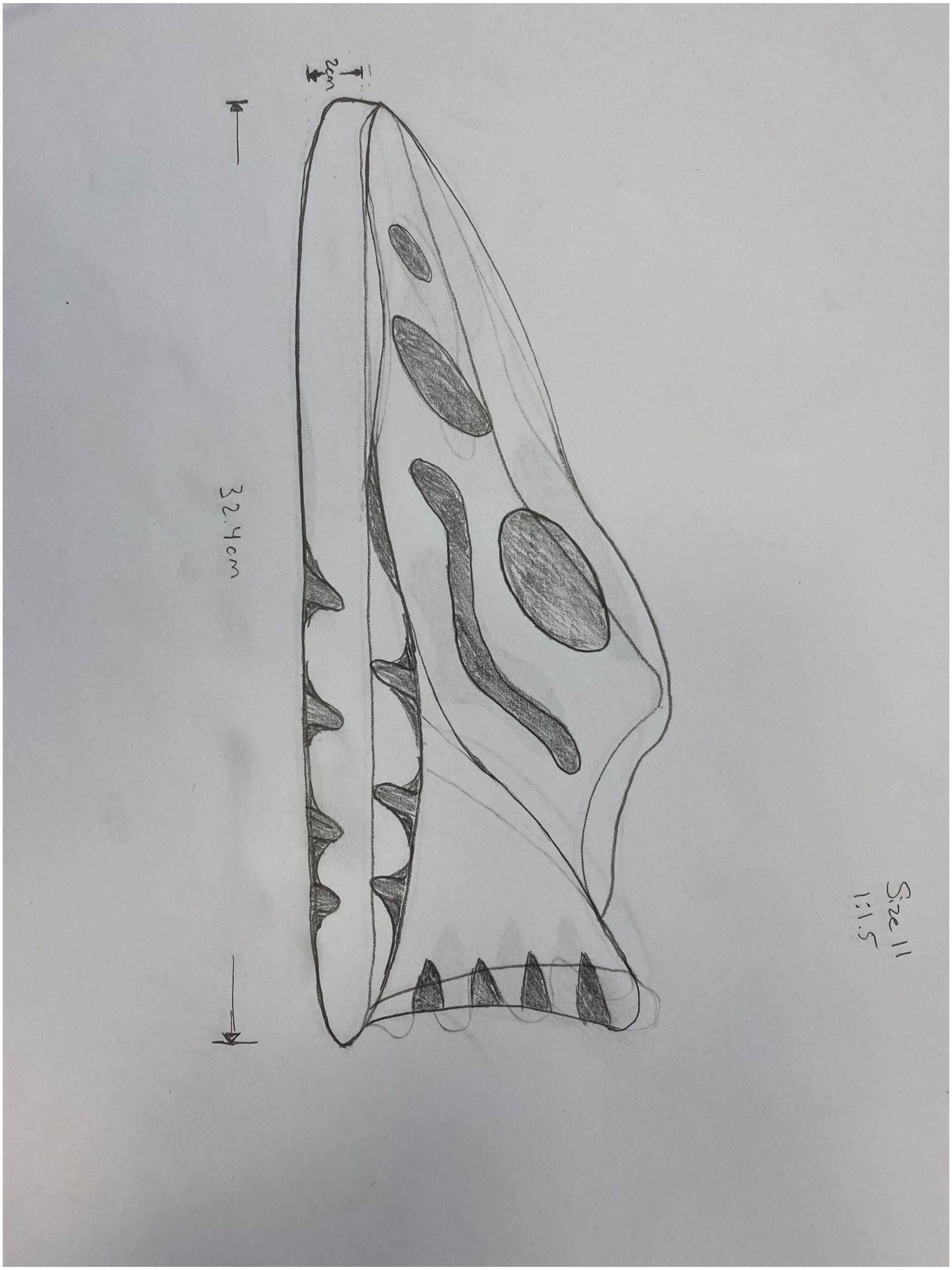


Figure D-18. Everyday Shoe Design IX

Figure D-19. Everyday Shoe Design X

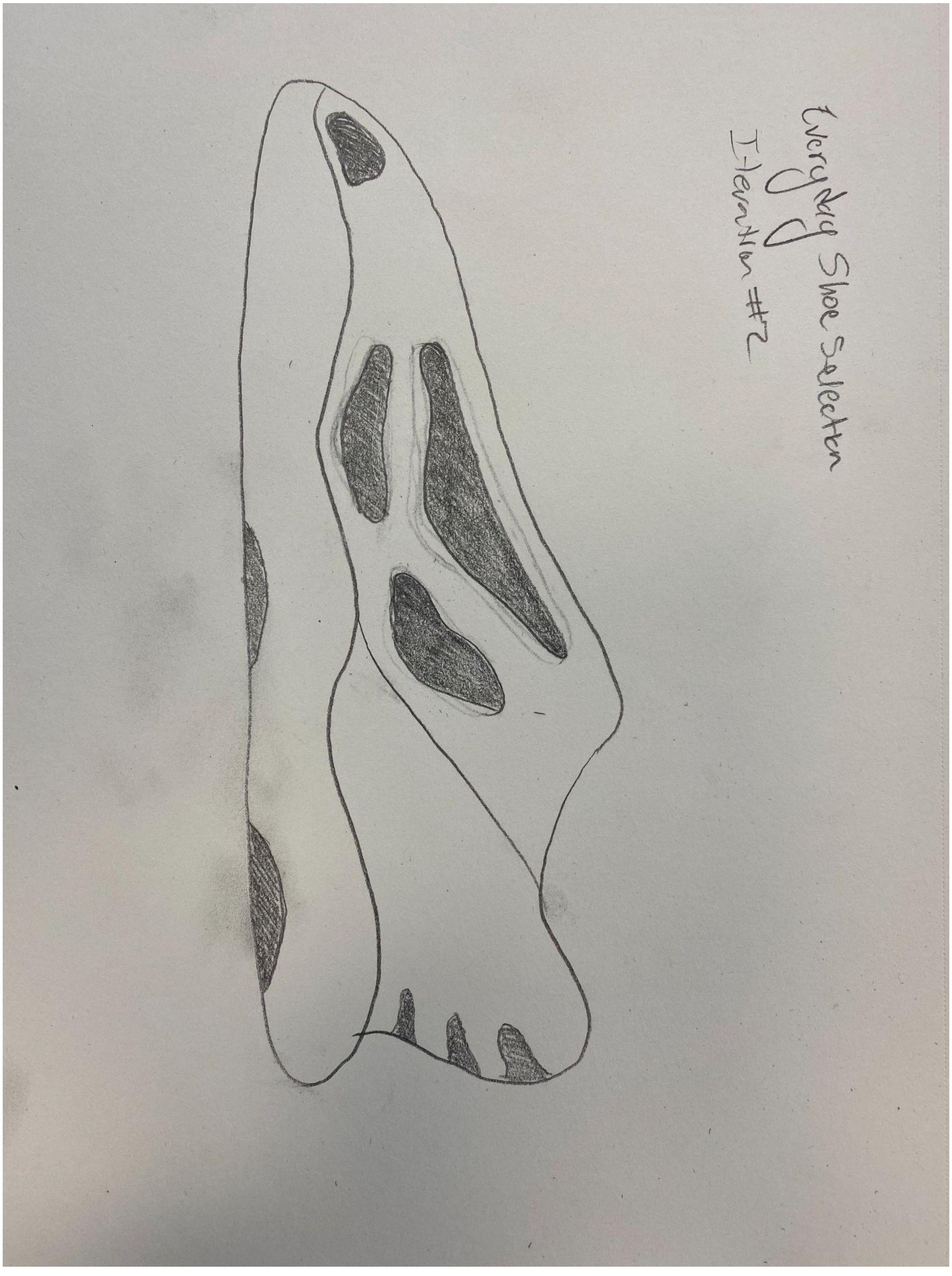


Figure D-20. Everyday shoe design XI

Additional Coloured Sketches

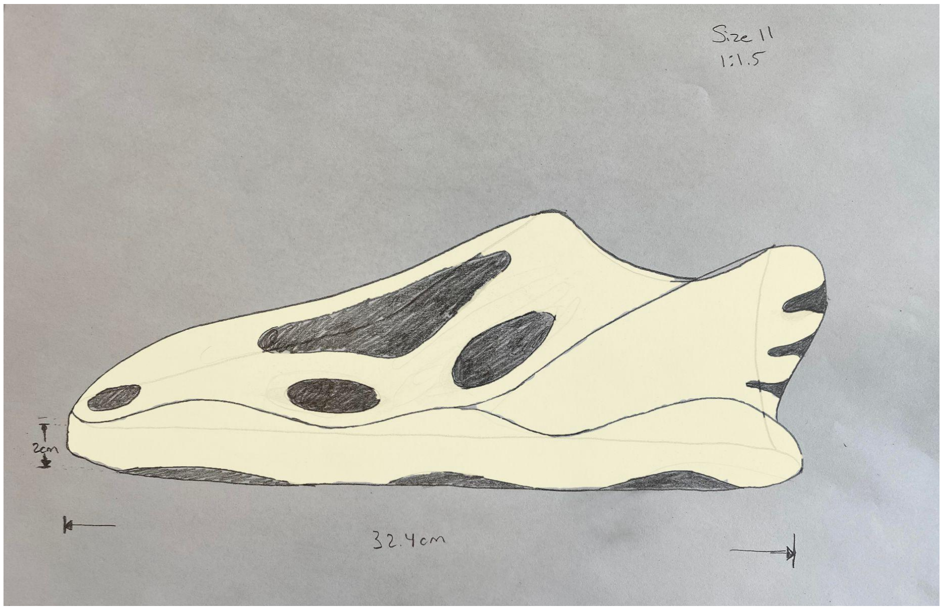


Figure D-21. Everyday shoe III colored sketch

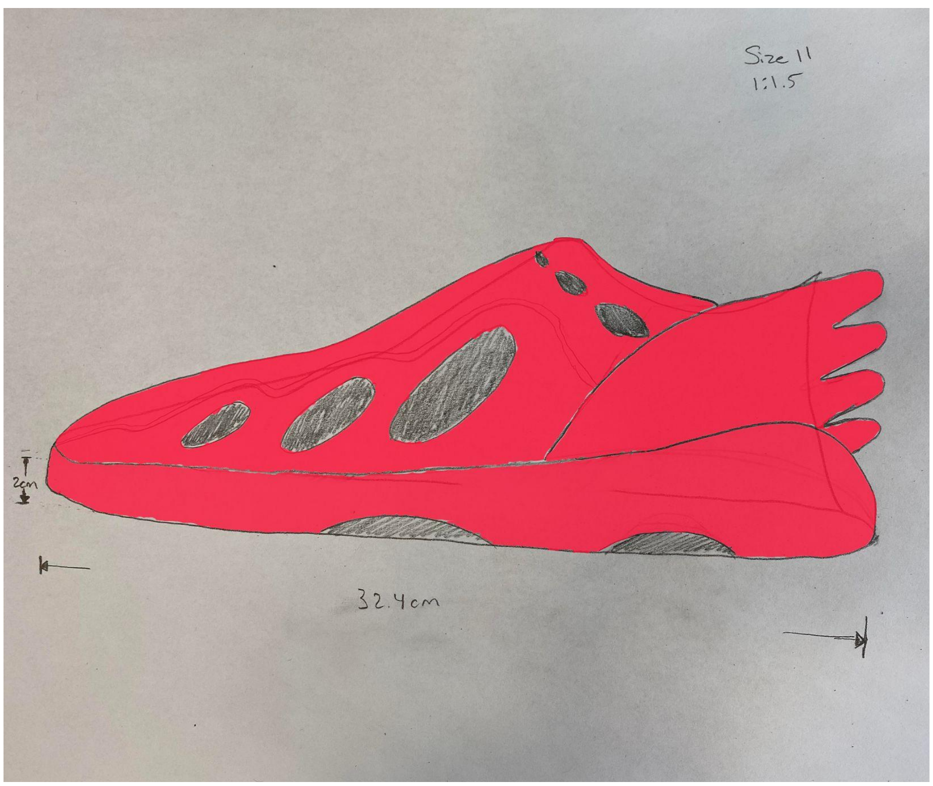


Figure D-22. Everyday shoe VII colored sketch

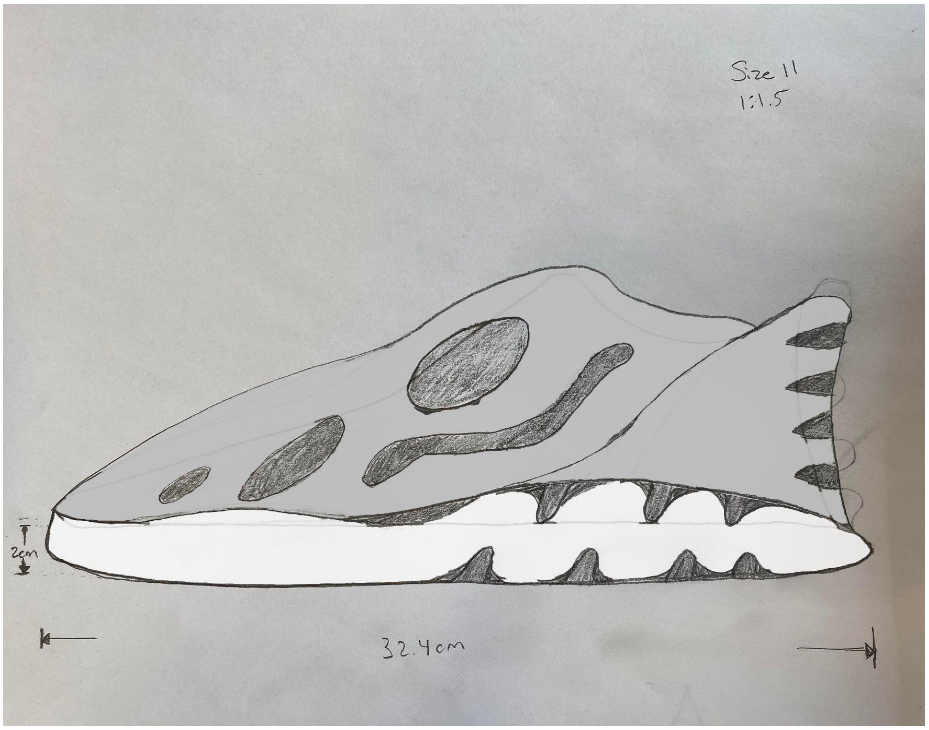


Figure D-23. Everyday shoe IX colored sketch

Appendix E - Insole Grasshopper Script

Screenshots of the insole script are shown below in Figures 80- 84

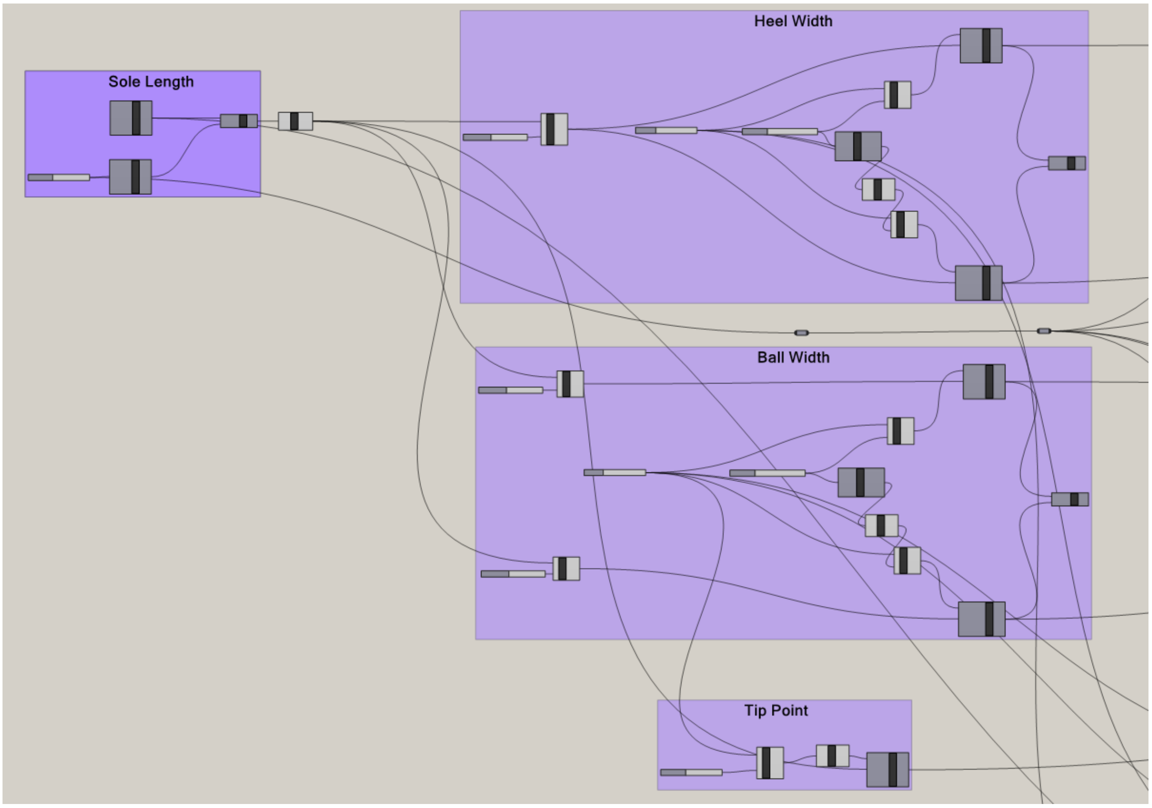


Figure E-1: Section of script for sole length, tip point, and heel and ball width

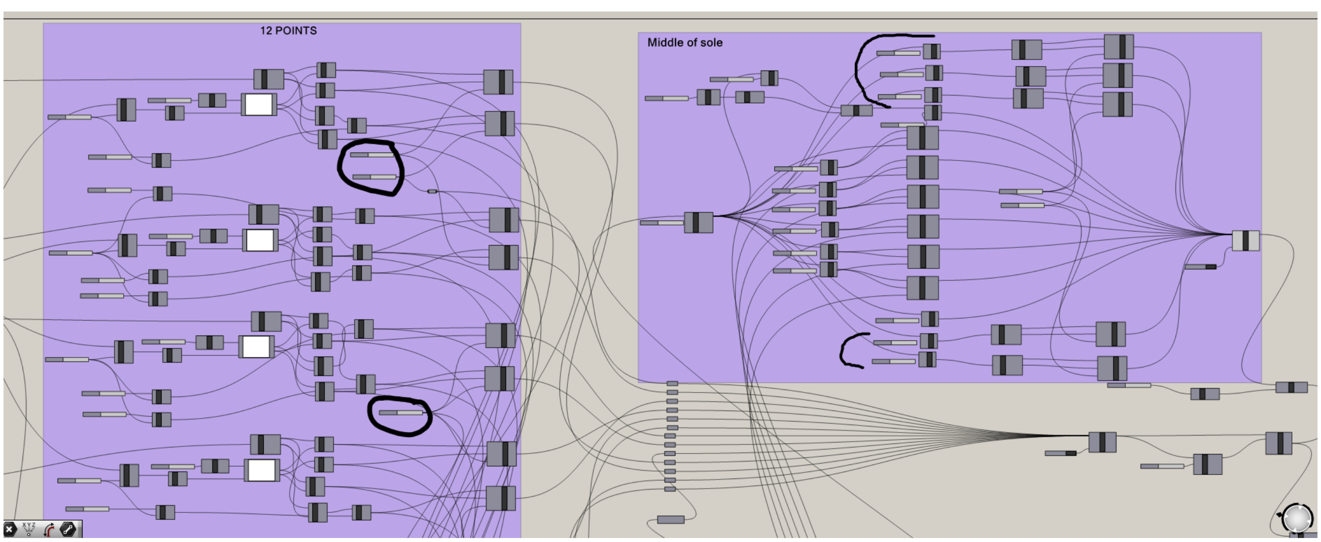


Figure E-2. Section of script for the 12 points and the middle-sole surface

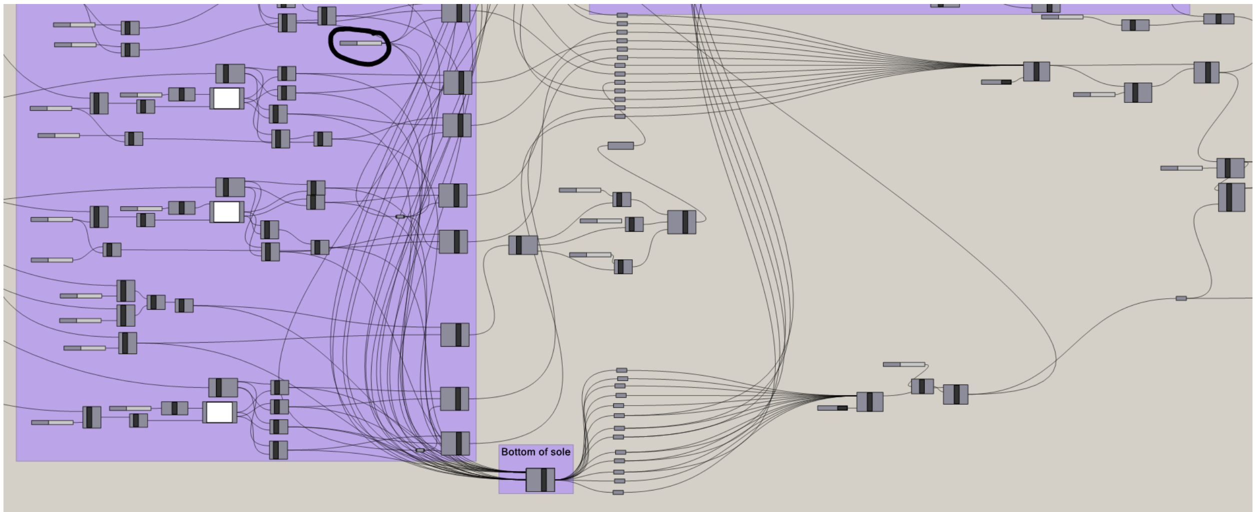


Figure E-3. Section of script for the 12 points and bottom-sole surface

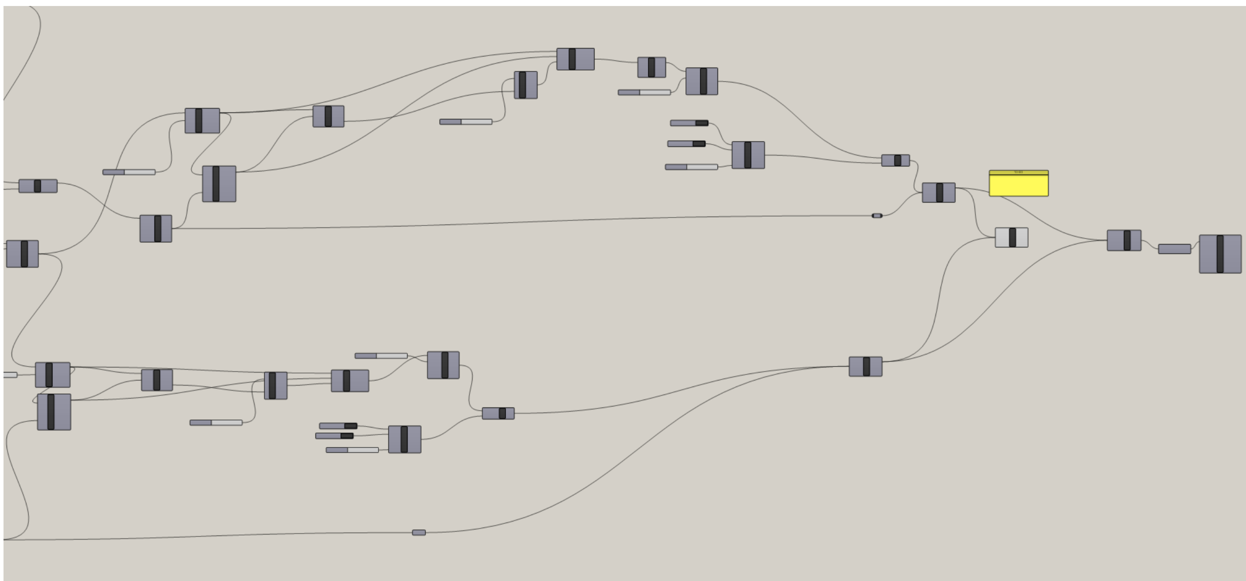


Figure E-4. Section of script for lofting unconnected surfaces together to form the final product

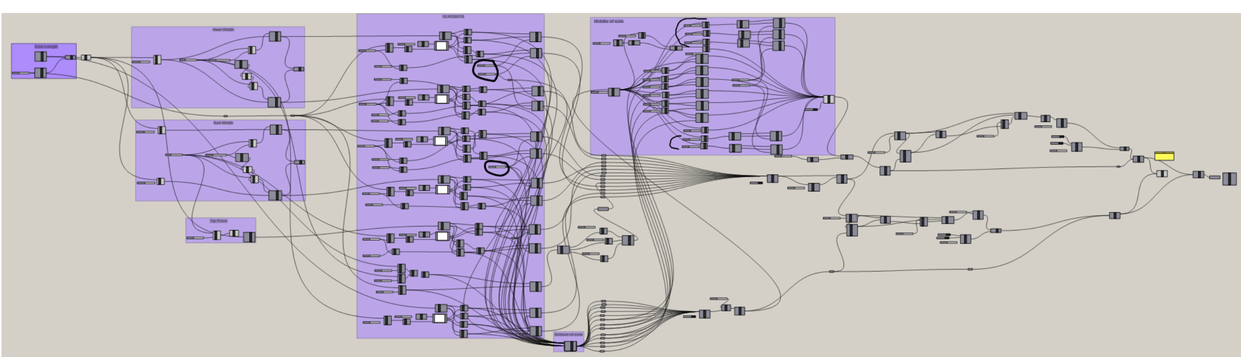


Figure E-5. Full view screen capture of the insole grasshopper script

Appendix F - Cost Analysis Calculations

Cost of NinjaTek Ninjaflex 85A TPU 2kg 1.75mm = $204.95 + tax [64]

Weight of one shoe = 0.286 kg

Weight of supports/waste from one shoe = 0.02 kg

Total weight of material needed to print one shoe = 0.306 kg

Total weight of material needed to print a pair of shoes = 0.612 kg

3.2 pairs of shoes can be manufactured using 2 kg of material

Materials cost:

$\frac{\$204.95}{3.2}$ = $64.05 per pair of shoes or $32.02 per shoe

Electricity cost:

0.35 (max power consumption of ender 6) x 50 (print time hrs) x 0.1217(average electricity cost) = $4.28 per pair or $2.14 per shoe [65][66]

Total cost of production:

Per shoe = $34.16

Per pair of shoes = $68.33

Table F-1: Shoe handling time (post print).

Time to remove supports and clean strings and excess material	0.5 hours
Time to add new spool	0.25 hours
These times do not affect printing time as the task can be completed while the next shoe is being printed.	

Appendix G - Miscellaneous Images

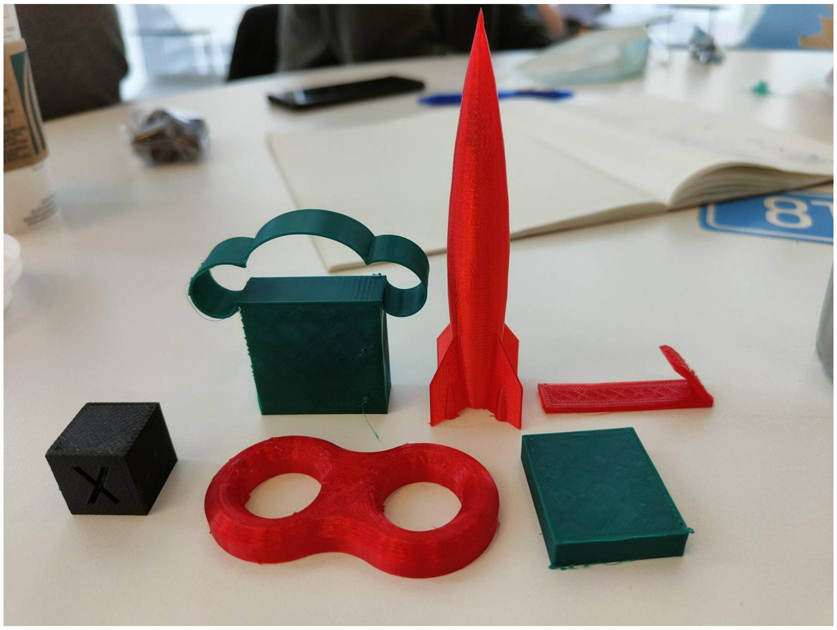


Figure G-1: Miscellaneous calibration prints made from TPU and TPE.

Figure G-2: Mahdi in protective gear before cutting our bracket.

Figure G-3: Mahdi using a dremel to cut a bracket used for the modification of the AnyCubic i3.

Figure G-4: James machining the same modification bracket.

Figure G-5: Girish soldering a new potentiometer onto the printer motherboard.

Figure G-6: Mahdi and Matthew working on the printer.

Figure G-7: Matthew and James playing with the calibration prints.

Figure G-8: Anupom measuring the adjustments required to the first insole.

Figure G-9: Mahdi and Girish taking a dinner break.

Figure G-10: Girish applying glue to the print bed for better adhesion.

Figure G-11: Max offering emotional support to the team.

Figure G-12: James, Matthew, and Girish posing with the first completed shoe.

Figure G-13: Mahdi wiring in the printer motherboard.

Figure G-14: Mahdi with the printer.

Figure G-15: James with the printer.

Figure G-16: Anupom and Mahdi weathering the storm.

Figure G-17: The team at 4am after spending 13 hours fixing the printers.

Figure G-18: Team meeting discussing the table of contents.

Figure G-19: The team working on the interim report.

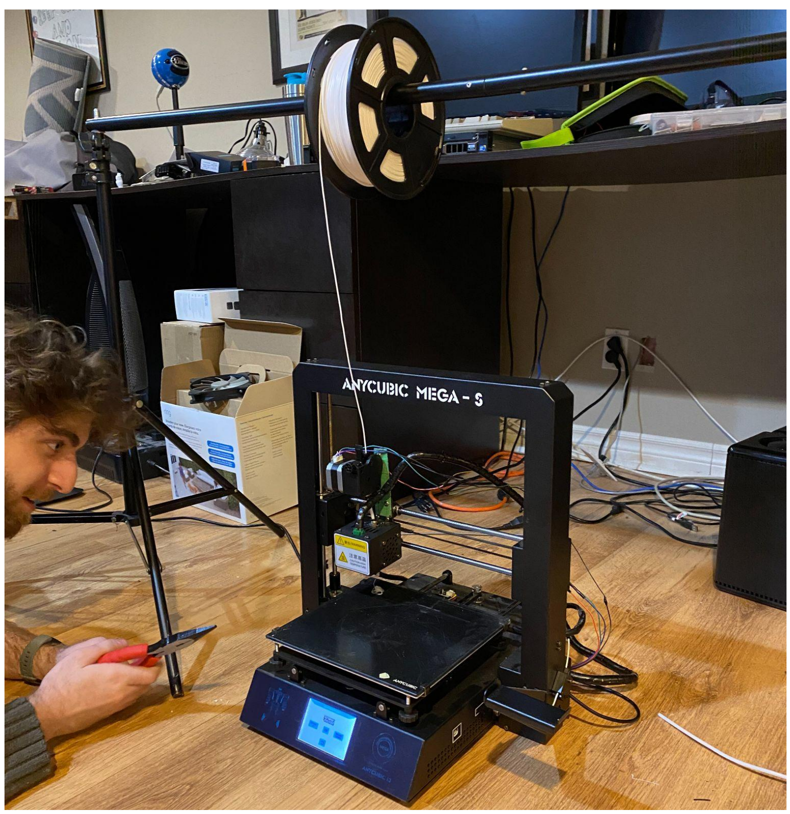


Figure G-20: Mahdi supervising the custom modification to the AnyCubic i3.

Figure G-21: Anupom helping hold the printer motherboard for Girish who is soldering in SLC8.

Figure G-22: Max verifying our shoe design.