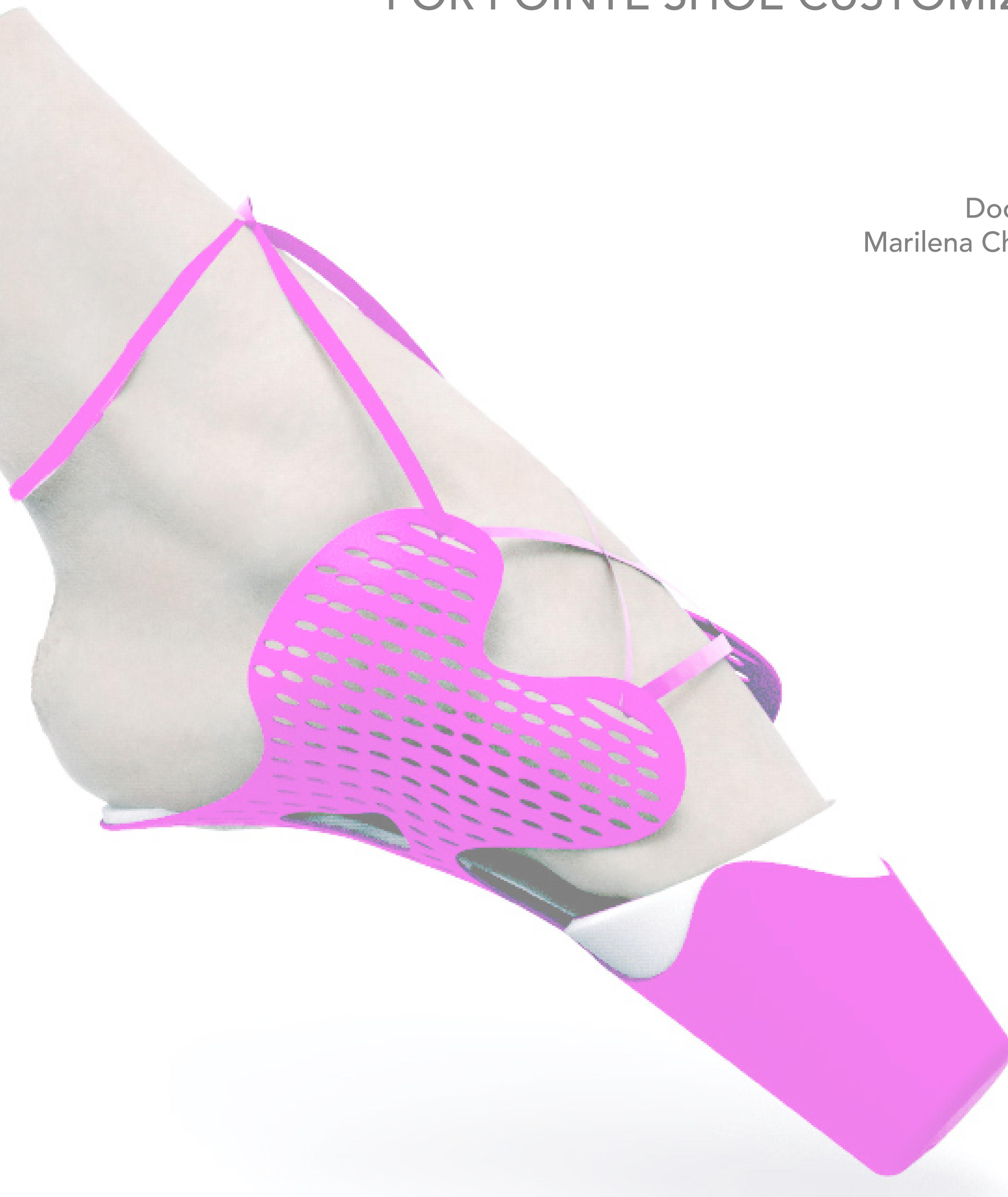
DEVELOPING A PARAMETRIC SYSTEM FOR POINTE SHOE CUSTOMIZATION



Doctoral Thesis

Marilena Christodoulou

Thesis presented for obtaining the doctorate title from the
Polytechnic University of Catalunya (UPC).

July 2021

DEVELOPING A PARAMETRIC SYSTEM FOR POINTE SHOE CUSTOMIZATION

Doctoral student: Marilena Christodoulou

Supervisors of the thesis:
Pau de Solà-Morales
Isidro Navarro Delgado

Program of Doctoral degree in Architectural, civil and urban heritage and refurbishment of existing buildings
ETSAB - Escuela Técnica Superior de Arquitectura de Barcelona
Universitat Politècnica de Catalunya

Thesis Title: Developing a Parametric System for Pointe Shoe Customization

ABSTRACT

A Pointe Shoe is worn by ballet dancers while performing “en pointe”. This fundamental ballet technique, which is performed by rising to the tips of the toes, enables dancers to create the illusion of incredible lightness and sylph-like appearance. However, pointe work causes pain, blisters, calluses, and disfigurement of the feet. Dancers, pointe shoe fitters, and podiatrists agree that finding Pointe Shoes which fit correctly and adjust throughout your career could help to avoid feet injuries. The different parts of the shoe require different performance, depending on the different parts of the foot. Each dancer has particular feet, with variations of toe length and shape, arch flexibility, and mechanical strength. Instead of having the dancer’s feet adjusted on the point shoes, the idea is to have the shoes, uniquely ‘adapt’ according to the morphology of the feet. The foot is not just a passive weight-bearer, it must assume positions and execute movements beyond its normal limits. Therefore, the parameters to take in account are classified in anatomical, mechanical, assembly and material.

From the study, it is deduced that the above parameters may be the key to define a proposal for a solution to the design of Pointe shoe.

Keywords: Parametric design · Algorithm · Mass customization · Pointe Shoes

ACKNOWLEDGMENTS:

Although it has been a quite lonely experience due to the circumstances, this thesis couldn't be completed if it wasn't for the contribution and support of many people.

First of all I would like to express my deepest appreciation to my three tutors:

Above all, Pau de Solà-Morales who believed in me and the project since the first moment, has always motivated me in his own way and has always been a great teacher, mentor and inspiration.

Isidro Navarro Delgado who, even if he accompanied me only the last two years, his contribution to the project and thesis has been of a great significance, as well as his patience, trust, dedication and determination.

Joaquin Manuel Regot Marimon who believed in the project and gave me the opportunity of making this real.

A very big gratitude I owe it to my parents, Joana and Mario Christodoulou, for their trust, for not letting me quit in the most difficult moments, but mostly I owe it to my sister, Areti Christodoulou who even in distance has always been by my side offering me a great moral and intellectual support.

I would also like to extend my deepest gratitude to Marcel Bilurbina Camps for his patience and contribution to the project as a professional, a teacher and above all a friend.

I am also deeply indebted to:

Jordi Truco for the support and all the knowledge he shared with me in many years, but specially for his mentoring during the first months of the project.

Robert Brufau for helping me making the project richer by introducing physics and structural principles to it.

Bernhard Spanlang for introducing me to the 3D scanning world and teaching me so many valuable things.

Juan Antonio López Vidal for all the knowledge he had the kindness to share with me about shoe designing and making.

My ballet teacher and RAD (Royal Academy of Dance) exterminator Meritxell Paradell who has been a great inspiration and who has taught me so much about dance anatomy.

My former ballet teachers Eleni Vaka and Elisenda Tarragó for, without them I wouldn't be a ballet dancer and the idea of this project could never been conceived.

ELISAVA School of Design and Engineering for all the knowledge and the recognition I received from them, that motivated me for converting this idea to a project.

ATTA33 workshop for their help and advising about digital fabrication.

I would like to extend my sincere thanks to all the people who offered themselves for scanning their feet but special thanks to Barbara Pla and Laura Stramacchia for their patience during the scanning process.

Last but not least I would like to thank all my friends and family who believed in me and without them I would never be able to complete this thesis. Special thanks to Katerina Papaionannou for all the love and moral support, Marianna Legaki, Angelos Shiamaris, Zorana Melovic, Shashank Shrivastva and Cristina Centeno.

Table of Contents

Chapter One: Introduction

1. Chapter 1: Introduction

1.1 Motivation

Besides my background in Architecture and design, for the last 28 years I have been practicing ballet and I am considered as a proficient ballet dancer. Since I was a child, I remember that, the moment of buying a pair of pointe shoes was very crucial and significant. The length of the shoe, the width, the size of the box, the rigidity and so many other factors that you should take in account while trying out the shoes at the shop. That was just the start. Thinking that you had bought the shoe that fits you the best, before even wearing the shoes, you had to sew the ribbons at the right position and then start hitting the shoe on the floor, or crushing it in the door so that the shank[1] would gain some flexibility. I also remember that the first years of dancing on pointe, as there wasn't any silicone cushion in the market, we would even add cotton in the box so that would make the shoe a bit more comfortable. Besides all these manual adjustments, when removing the shoes after dancing for an hour or two, the toes would be full of blisters and wounds.

Dancing on pointe shoe is like playing tennis with a racket. It's the most important tool for ballerinas. The idea of designing a new pointe shoe that could adapt to every foot was sparked by my passion for ballet and design.

My relationship with contemporary design strategies within the Masters Degree of Advanced Design and Digital Architecture in Elisava, UPF, with the logic of emerging systems, biomimetics, efficiency and adaptability, supported by the new paradigms of digital tools and media, helped me to change the way I think about the design process and how to conceptualise a project. It made me realise the new possibilities that technology offers us as designers and that, as a designer that studies the capacities of the new design methods with softwares based on algorithms and digital fabrication, it is almost an obligation trying to apply these design methods to every part of life.

1 Shank: the reinforced sole of a pointe shoe that stands between the inner and outer sole of the shoe.

1.2 Hypothesis:

Until now, due to the high cost, custom made Pointe Shoes were considered a forbidden fruit for an everyday dancer. The cost alone is the sole reason that only professional dancers or "prima" ballerinas use custom made Pointe Shoes. Common dancers, spend money buying Pointe Shoes that need "customization" by removing or adding material, in order to make them softer and thus usable. For that reason, one part of the investigation is the customization of the shoe using digital technologies. The hypothesis of this project is to study if it is possible to develop a parametric system that can be used for designing a pointe shoe adaptable to all feet.

Sports shoes and especially in this case point shoes are driven by highly specialized performance. Working on a project like this, it is impossible not to come across with the new concept of the product commercialisation and mass customisation. In the old days, the shoemakers would design and make the shoes for each person individually. Later on, with the mass production this became impossible (Boër & Dulio, 2007). However, the new technologies nowadays, allow us to have a production of non-normalized repetitive components directly from the digital data. This realization led me to the second part of the project that is the functional customization using new materials and new manufacturing techniques to help the user, reach the highest level of performance.

1.3 Objectives:

The main objective of this project is to study well the geometrical and structural parameters that need to be considered while designing a pointe shoe, and using a graphical algorithmic editor, to develop a parametric system for designing and making pointe shoes that will be adaptable to all feet.

In order to achieve this objective, the study is divided in five individual subsections:

I. Using 3d scanning technology and the theoretical background related to foot and dancing anatomy, define the geometrical variables that need to be taken in account while designing a pointe shoe and its specific parts.

II. Study the applied forces that take place while dancing and dancing on pointe, specially the ones that need to be consider while designing a pointe shoe. Study the impact that these forces have on the shoe and eventually on the feet of the dancer.

III. Taking in account the forces that are being applied on the shoe while dancing, investigate on which materials respond better to the requirements of a pointe shoe in order to help the dancer to reach the top of her performance.

IV. Using generative algorithms and 3d modeling tools, develop a parametric system for designing a pointe shoe that geometrically and structurally can be adaptable to all feet.

V. Once a parametric system is developed, produce prototypes using digital fabrication. These prototypes can be parts of the pointe shoe or even a complete shoe and they need to be structurally tested before being used.

1.4 Innovation:

Following a centuries' tradition, point shoe making process it's an artisanal craftsmanship. With the exception of Gaynor Minden[1] that in the last years started introducing machines in a specific part of the manufacturing process, pointe shoe making industries work with specialised, trained and hard to replace, artisans. The need for modernising also stands for the material that is being used. The traditional pointe shoes' section, answers to cardboard, paste, burlap, little nails, and even newspaper. On the other hand, customized point shoes it is not an option for the majority of dancers.

The integration of digital technologies in the designing process, as well as the digital fabrication in the manufacturing process, implies the introduction of new materials. The objective of this thesis is to try and implement digital design and manufacturing to the pointe shoe making process, opening in this way the door for redefining the design, ergonomics and comfort of the shoe. The use of 3d scanning technology and parametrics it's an important part of the investigation, as it will allow to personalise the design of the shoe for every individual according to his/her anatomical characteristics or even, personal taste.

1 https://dancer.com/about-gaynor-minden/about-our-shoes/from-the-designer/

Note:

The following dissertation is a work based on a quite wide theoretical background but mainly it is focused on a primary research that has been practically evolved through the years. This dissertation is a transcript of a practical work that has been done using different kind of instruments, between them a 3D scanning, computer, design softwares, 3D printers etc. The theoretical part of this thesis has been very important for laying the foundations of the work that followed in the workshop and for developing the practical part of the investigation, which forms the biggest part of this dissertation and that was documented with prototypes, images, diagrams, tables etc.

Chapter Two: History

2. Chapter 2: History

The world of Ballet dance has very strict and rigid principles that are not easy to change. Tradition and change are almost always in conflict. This is one of the reasons that pointe shoe industry has been incapable of changing the shoe making process and materials through out the centuries. Pointe Shoe making has a long history, beginning in 1832 when Marie Taglioni appeared for the first time dancing on pointe. Studying the origins of ballet and ballet shoes and what pointe shoes represent in the Ballet world, it has been very important for this thesis in order to understand the functionality and symbolism of the shoes.

Additionally, the world is changing very fast and as designers it is almost impossible not to think about integrating digital technology in every part of the designing process. That is the reason why in this chapter you can also find a brief history of how digital technologies and fabrication penetrated architecture, design and more particularly shoe design.

Figure 2.1. (left) Anna Matveyevna Pavlovna Pavlova performing The Dying Swan on pointe.

2.1 History of Pointe Dancing

Ballet dance was formed in the Italian and French Renaissance courts back in the 15th and 16th centuries for aristocrats, whose need for entertainment and political propaganda, made court ballet a combination of art, politics and entertainment (Au, 2012). At the beginning it was nothing more than a court performance formed by amateur dancers and the king or the queen. As the dancers performed on ballroom floors, the audience would view the spectacle mostly from above giving more importance to the geometrical symbolic shapes and patterns that dancers would create by moving around. In those years, dancers were only men and not highly skilled professionals. Through out the 17th century, court ballet, coincided with the birth of opera in Italy and the opening of the first public theaters in France, changing in that way its inspiration sources. Pantomimic dance with acrobatic elements also started appearing. All these elements together, transformed ballet into a professional art and the grotesque or acrobatic dancers, were replaced by professional dancers (Au, 2012).

In 1661, King Luis XIV *(Fig. 2.2-3)* founded the Royal Academy of Dance. Until then, dancers performed on ballroom floors. With the foundation of the Royal Academy of Dance they were raised up on the stage. This fact changed the audience's perception and dancers' feet became more important. The stages started growing larger and choreographers became more concerned with sideways movement, so they created the concept of turned-out[1] legs. The height of the

1 Turnout is an external rotation of the stretched leg in the hip joint. Nowadays is a part of many dance styles and very essential for ballet. It is common that a forced turnout in order to achieve 180° causes a numerous of over-stress syndromes and injuries. See Simmel, 2014 pg. 63 for further information.

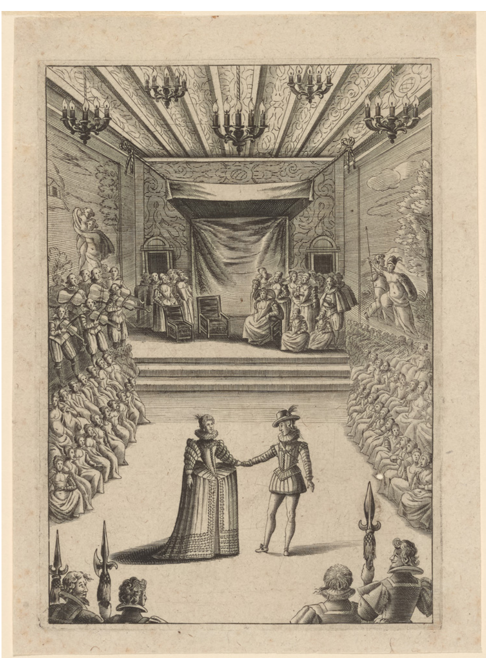


Figure 2.2. (left) Luis XIV was the King of France from 1643 to 1715. Not only he loved watching dance he also liked to dance. He integrated so much ballet in life at court that it became a symbol and a requirement of aristocratic identity.

Figure 2.3. (right) King Luis XIV as the Sun god, Apollo in Le Ballet de la Nuit, at the age of 15 that´s why he was also known as Sun King.

Figure 2.4. Marie Anne de Cupis who was born in Brussels in 1710, is consider to be a pioneer not only for the way she changed the ballerina's dress and shoes but also because she introduced steps in her dances that by then only males could perform. She had altered not only ballet as an art but also the position of women in ballet.

proscenium[2] inspired a new movement vocabulary of elevated steps. Professional dancers began to evolve technical feats that demanded a high degree of training and skill, such as pirouettes[3], cabrioles[4] and entrechats[5]. In 1681, four pioneering, female professional dancers appeared for the first time, dancing in the ballet Le Triomphe de l'Amour, at Paris Opéra. These ballerinas, led by Mademoiselle de Lafontaine (1655-1738), wore shoes with heels, constricted bodices, voluminous skirts, unwieldy headpieces and enveloping shawls. Female dances, mostly because of their costume restrictions, were more serious and serene.

During the eighteenth century dance evolved rapidly and many spectacular dancers made their debut. It was a time when both dancers and choreographers began to let go the social dancing and they aimed to give importance not only to the technique but also to the dramatic dimension of ballet. In 1714, Françoise Prévost and Claude Balon, were the firsts to performed a dramatic dance in France. Prévost was the teacher of two of the most famous dancers of the 18th century, Marie Camargo and Marie Sallé. In 1726, Marie Camargo *(Fig. 2.4)* made her debut at the Paris Opera Ballet with her teacher´s solo. Camargo was a brilliant technician and one of the firsts of introducing the entrechat and cabriole steps. These beaten steps needed rapid changes of her feet from fifth position

2 Proscenium stage, was the most common form of theatre building in the 18th, 19th and 20th centuries

3 A pirouette is a ballet term meaning to whirl or spin while balanced on the toes.

4 A cabriole is a ballet step in which a dancer jumps in the air off one leg as the other is thrown upwards, as the bottom leg raises to meet and beat with the top leg, the top leg continues to go higher as the bottom leg returns to the floor.

5 An entrechat is a ballet step in which a dancer jumps vertically while repeatedly crosses the feet and beats them together.W

front to back and front again, so it was then when female dancers' skirts gotten shortened. For the same reason, even though at the beginning of her career she danced with the commonly heeled shoes, later on she started wearing flatter shoes to make easier the fast footwork. Camargo also devised an undergarment to wear beneath her petticoats, from which tights later evolved.

Unlike Camargo who devoted her career in perfecting her technique, Marie Sallé *(Fig. 2.5)* was more interested in exploring the dramatic potential of dance. In 1734, she appeared at the Drury Lane Theatre in London, performing in a ballet called Pygmalion for the first time. This ballet was based on a greek myth and the greek robes she wore, with a simple muslin dress that followed the lines of her body replaced the corset that the dancers used to wear. That was the initiation for rethinking ballet costuming (Barringer & Schlesinger, 2004). Until then, the costumes used to be extremely stylised and rich, trying to please the vanity of the aristocrats.

Although there is not exact date of the first use of pointe shoes, in 1712-22, a dancer called Mr Sandham who used feature Commedia characters, performed a play named "Dutch Skipper", "upon his Toes" at Lincoln´s Inn Fields in London (Hammond, n.d.). Around 1779, Antoine-Bomaventure Pitrot who was a performer and a ballet master, was seen to be dancing on his toes. According to Gennaro Magri's texts, he "hoisted up his whole body on the big toe of the foot" (Hammond, 1987).

The French Revolution brought a lot of changes. Ballet as an art tried to get closer to the audience and connect with common people and not just with

Figure 2.5. (left) Marie Sallé, who was born in 1707 in Paris, France, was the first female choreographer. She was one of the firsts who took of the mask while dancing, giving more importance in this way to the expression.

Figure 2.6. (right) Didelot's flying machine challenged technically the dancers, who soon looked in new ways to dance in an elevated position. This was when they discovered that by rising higher and higher on half pointe, they could balance on the ends of their fully stretched toes.

Figure 2.7. (left) Lithography of Marie Taglioni dancing the Flor et Zéphire (1831) which was one act with choreography and libretto by Didelot, music by Cesare Bossi, and design by Liparotti. The story is based on the myth of Zéphire and his wife Flor who was a nymph.

Figure 2.8. (right) Marie Taglione in La Sylphide. Eugène Fresnay was the designer of the muslin dress, that later became theuniform of the classical dance (tutu).

the court life. Costumes became lighter and shoes became more flexible. This change, allowed to the female dancers to develop more demanding steps and movements.

Charles Didelot[6], during the Revolution left the Paris Opera to perform in England and other parts of Europe. In 1795 he introduced the concept of a flying machine (*(Fig. 2.6)* in a production in Lyons. A year later his work Flore et Zéphire, was deified because of this new invention. The concept of the flying machine enabled dancers to stand on their toes for a moment, creating the illusion of lightness as they portrayed the ethereal, unreal characters of classical ballets. The audience loved Didelot´s flying machine, watching the dancers perform feats like for example crossing the stage with the help of hidden wires, giving the illusion as if they were flying, it was something completely new and exciting. When the dancers landed on their toes, the audience reacted with enthusiasm. This fact, encouraged choreographers to look for ways for the dancers to linger in an elevated position and it was then when the introduce of pointe work became a reality. After that, the next step was to try and on pointe without the support of wires, which lead the dancers to give emphasis on their technical skills. In 1815 Geneviève Gosselin, a french dancer of the Ballet de l'Opera de Paris, appeared to be dancing the role of Flore on her toes (Jowitt, 1988).

In 1823 Amalia Brugnoli danced on full pointe in Vienna while in 1832, Marie

6 Charles-Louis Didelot (1767-1837) was a Swedish dancer, choreographer and teacher who was born in Stocholm. He started studying dance with his father at the Royal Theater in Stocholm. In 1790 he made his debut in Opera de Paris. From 1816 until the end of his life he lived and worked to St. Petersburg. Didelot was famous for his inventions and important costume and scenographic innovations. For further information look in Au, 2012 pg. 47

Taglioni *(Fig. 2.7)*, an Italian ballet dancer, performed on pointe at the first performance of La Sylphide (*Fig. 2.8)* at the Paris Opera (*Fig. 2.9*). Marie Taglioni was the daughter of the famous choreographer Filippo Taglioni[7] and his work La Sylphide gave a boost to the Romantic ballet in the 19th century. Taglioni's light and fluid movements inspired a lot of people and dancers who started imitating her style. The use of pointe shoes was done precisely for giving a weightless illusion and an artistic and ethereal element to the performance. Her costume that had the shape of a bell-skirt, was made of many layers of white transparent muslin was the precursor of what we call a "tutu" today (Au, 2012).

The pointe shoes she used, were made of satin fabric, sewed up at the tip (*Fig. 2.10)*. The box was not rigid in order to protect the toes and so the feet could not be well supported, instead the sole was made of a flexible leather. They were darned along the sides and over the toe in order to form the slippers (Barringer & Schlesinger, 2004). Pointe shoes of that time were one sized obligating the toes to be squeezed into a uniformly narrow pointe that was almost irrelevant with the shape of the foot. As it was so difficult to dance with these such soft shoes, they used to padded their toes in order to give some protection to their feet. As a result of their uncomfortableness and inefficiency, there was an obvious limitations of the steps and technique. Despite of this limitations, Marie Taglioni changed the image of her concurrent ballerinas, by adding the ingredient of innocence and perfectionism.

7 Filippo Taglioni was born in Milan and trained by Carlos Blasis and Jean-François Coulon. La Sylphide was first presented at Paris Opera Ballet on the 12 of March 1832 choreographed by Taglioni to music of Jean Madeleine Schneitzhoeffer.

Figure 2.9. Salle Le Peletier, which was the home of the Paris Opera from 1821 to 1873 and where Taglioni performed. The Paris Opera Ballet (Ballet de l'Opéra national de Paris) is a French ballet company that forms part of Paris Opera, was founded in 1713 by Louis XIV.

Figure 2.10. (left) Marie Taglioni's pointe shoes who look like normal ballet slippers with reinforcement in the block of the shoes

Figure 2.11. (right) Pierina Legnani as Odette (1895) in Swan Lake that was the first ballet by Peter Ilyich Tchaikovsky .The plot is based on an ancient German legend in which Princess Odette and her companions are turned into swans and she is found in the forest and loved by Prince Siegfried.

Dancing on pointe gained a lot of popularity during 18th century creating in that way the need of improving the technique and defining exercises for strengthening the feet and legs. Many steps required balancing on one foot or on half pointe, obligating in this way the ballerinas to work their turnout. In order to improve pointe work, by the mid of 18th century dancers started collaborating with shoemakers for manufacturing better shoes (Clifton, 2009). Italian pointe shoes manufacturing became famous and travelled to many other places like Russia.

Ballet started expanding across the world and by the end of the 19th western Europe had nothing more to offer. Great talented choreographers and dancers of the Romantic times were fading out until they disappeared. By the beginning of the 20th century the ballet scene was transferred to Russia and although the history of "Russian Ballet" goes back in time, it was then (1910s and 1930s), when Russia became the epicenter. In 1890s and 1910s decades, the choreographer Marius Petipa (1818-1910) who got inspired by the Italian ballet dancers, marked the beginning of a new era with his works like The Sleeping Beauty and Swan Lake (*Fig. 2.11)*. Sleeping Beauty's premiere was in 1890 at the Imperial Mariinsky Theater with the music of Tchaikovsky and it was a play that was performed entirely on pointe shoes with complicated steps. The fairy variations that the dancers performed on their toes started spreading. The shoes were no longer the soft slippers, instead, the toe box was made of layers of newspaper and floured paste that it was reinforced by a midsole made of a light cardboard (Barringer & Schlesinger, 2004).

While in America and Europe ballet was giving its place to contemporary dance in the beginning of the 20th century, in Russia a new ballet legend was getting born. Anna Pavlova had a great expression and technique and was able to seduce her audience *(Fig. 2.12)*. The dying swan, that was choreographed by Michel Fokine (1880-1942) was the role that followed her throughout her life and was danced on pointe featuring bourrée, constantly. Her art and love of ballet, made her an inspiration for many dancers and choreographers. It is said that Pavlova used to prepare her pointe shoes on her own. She would have a student breaking them in and then she would pull out the cardboard, fabric and leather in order to replace them with an inner sole that she would design. It is also said that, because of her big foot arc she wore shoes with a wide platforms in order to balance better. In fact, she used to ask from photographers to edit her photographs so that her shoes would look narrower (Barringer & Schlesinger, 2004).

Even before the end of the 19th century, many pointe shoe manufacturing companies, like Capezio, were founded and opened the possibility to the dancers of having pointe shoes better fitted to their feet. The majority of companies, like Freed of London that was founded in 1929, worked and still works with the "turnout" process. That means that using a shoe last of the shape of the foot, the shoe is constructed inside-out and turned right-side-out at the end (Clifton, 2009). As the century passed by, the pointe-shoe manufacturers kept experimenting and the shoe boxes became harder in order to make pointe dancing more comfortable and to respond to the needs of the pointe technique. The harder they got though, the more they weighted and the less flexibility they had, having as a result the absence of the contact between the dancer's feet and the floor.

Figure 2.12. Anna Matveyevna Pavlovna Pavlova was born on February 12, 1881 in St. Petersburg, Russia. The Dying Swan became Pavlova's signature role. Her legacy still inspires many ballet dancers even nowadays.

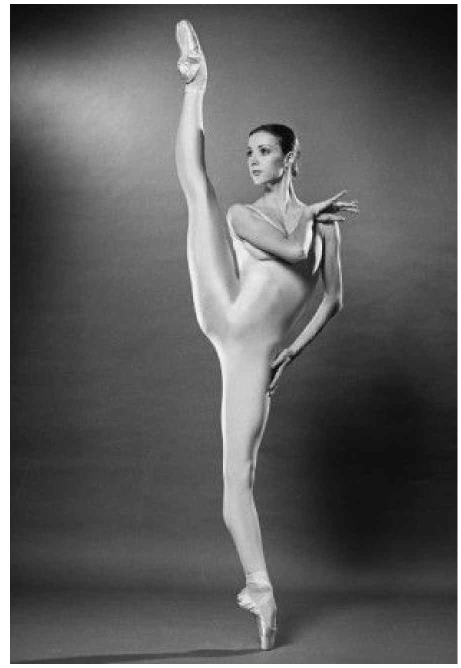



Figure 2.13. (left) Svetlana Yuryevna Zakharova a Russian prima ballerina of Bolshoi Ballet, performing Odile (Black Swan) in Swan Lake.
Figure 2.14. (right) Sylvie Guillem is a French ballet dancer, considered to be one of the best of the 20th century. Nowadays pointe shoes are also introduces in contemporary plays as well.

Nowadays, pointe dance is big part of classical ballet dancing and although time has passed by and romantic choreographs gave their place to new and contemporary performances, a ballerina on pointe shoes is still a magical thing to watch *(Fig. 2.13-14)*. Although it has been questioned weather it's a part of the past, many dance companies and classical ballet education are focused on pointe shoe techniques making them the most important tool of a ballet dancer.

2.2 Shoe and Footwear Manufacturing History

Designing and making shoes it is not an easy task. It requires a lot of diverse knowledge in many aspects that may affect the quality, the aesthetics and the functions of the shoe.

The first evidence of footwear, were found in the remains in Tianyuan Cave and belonged to humans of Middle Upper Paleolithic. Shoes were not found but the anatomical characteristics of their skeletons indicated supportive footwear. Although shoes are mainly used to ease the motion and to prevent injuries, they are also used for fashion and adornment and many times for indicating the status of the person within a social structure. Footwear used to differ a lot between cultures, mainly because of weather and landscape conditions, material disposition and tradition. For example, the paintings inside the Cave of Altamira in Spain that belonged to 15000 BC founding, represent hunters wearing boots made (Carolina, 2015) of animal leather and fur. The first shoes ever found though, came out in 1938 in Fort Rock Cave in Oregon *(Fig. 2.15)*. These were sandals made of twined shredded sagebrush bark and were dated to more than 9000 years old. In Armenia were found the first leather shoes, dated to 5500 years old. The first shoes that were found in Egypt between 1550 and 1070 BC were made out of reed and they had the shape of a boat (Bossan, 2012). Then the first shoes that were found in China in 68 BC were made out of several layers of hemp.

Leather sandals was the basic foot protection in the Mediterranean until Middle Age when wooden shoes were spread around Europe. They were made from a single piece of wood roughly cut into shoe form. The most famous shoe worn in Europe during Middle Age was called patten *(Fig. 2.16)*. Patten lasted up until the early 20th century. They were shoes worn over a normal shoe for the outside and they looked like wooden platforms, usually with a metal base. Their purpose was to protect the shoes and clothes from mud and dust.

Little by little leather started being added and by the 1600s, leather shoes came in two main types. Turn shoes that were put together inside out, and then was turned right-side-out once finished and another type in which the upper was united with an insole, which was subsequently attached to an out-sole with a raised heel.

Heels initially, were invented from Persians for helping men riding their horses. When heels came to Europe they were not designed for practical reasons. Instead, they were an extravagant status symbol and they were mostly worn along socialites. By the late 1700s, heels became more related to feminine fashion.

Chopines, were some sort of ridiculously high platform shoes that were used

Figure 2.15. The first shoes ever found, in Fort Rock Cave in Oregon in 1938.

Figure 2.16. Patten shoes were used as a protective mechanism against the unwanted dirt and mud.

as an overshoe for protecting their dresses from dust and mud (Bossan, 2012b). Although they were invented in the 15th century in the Ottoman Empire, they were worn mostly in Venice all throughout the Renaissance period. Their height could reach up to 50cm.

Up until 19th century, shoemaking process was a traditional handicraft. The shoemaker would measure the feet and cut out upper leathers according to the required size. Later on the process was almost completely mechanized, and the production was happening in large factories. Although industrial revolution, brought the benefit of mass-production. On the other hand, with mass production, the individual needs and physiology that the shoemaker was able to provide, disappeared as he knew everything about his clients feet.

The shoe designer appeared in the early 1900s, while shoe design appeared as a discipline in the 20th century (McDowell, 1989).

As mentioned before, the shoemakers would design and make the shoes for each person individually, something that later on changed because of the mass production. Recent developments though, of 3D technology and computer graphics have changed the way of product designing, allowing us to have a production of non-normalized repetitive components directly from the digital data. 3D printing as an addictive manufacturing processes allows us to transform digitally developed 3D models into physical objects. Footwear companies taking advantage of the new trend and technology, started looking for further customisation by investing in 3D printing.

Although throughout the beginning of human history, shoe have been worn for protecting the feet and making it easier to walk, nowadays have gone beyond this. Nowadays, apart of being a protective barrier, they also represent a fashion statement or a status symbol.

2.3 History of Parametric Design and its Applications in Footwear Design

2.3.1. History of Parametric Design

The term "parametric" has its origin in mathematics. A parametric equation employs one or more independent variables that is called a "parameter", in which dependent variables are defined as continuous functions of the parameter and are not dependent on another existing variable. The first intentions of expressing geometry with parametric equations were done in the first half of the 19th century, while a half century later, Antonio Gaudí started designing architecture using parametric catenary curves and parametric hyperbolic paraboloids.

Parametric architecture is a non-linear design method that is based on pre-defined parameters that serve to control the relationships between them and thus, define a geometry. In parametric design, the designer defines some parameters, within which he can adjust and control the geometry of his work in such a way that allows him to have innumerable variations and solutions. Gaudí, for example, could experiment with natural models to obtain the best possible results

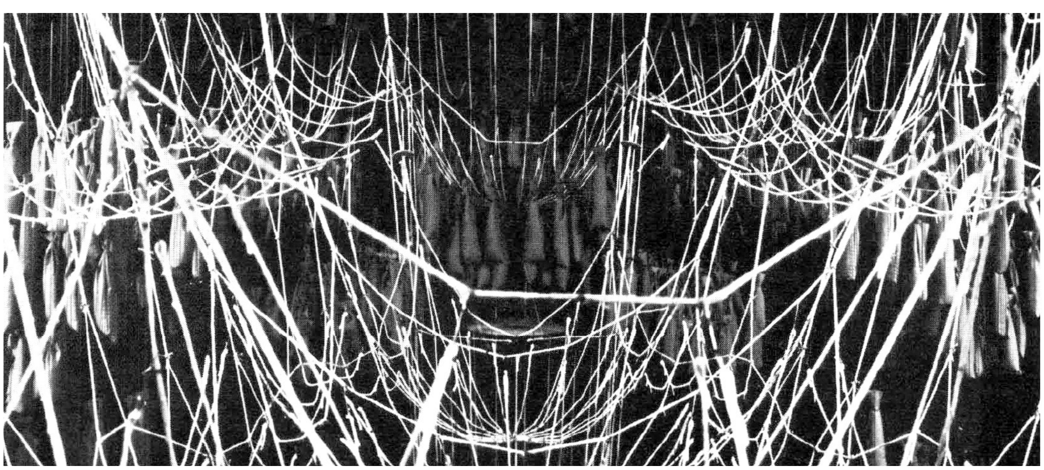


Figure 2.17. Antonio Gaudí used to work with upside-down physical models of hanging chains.

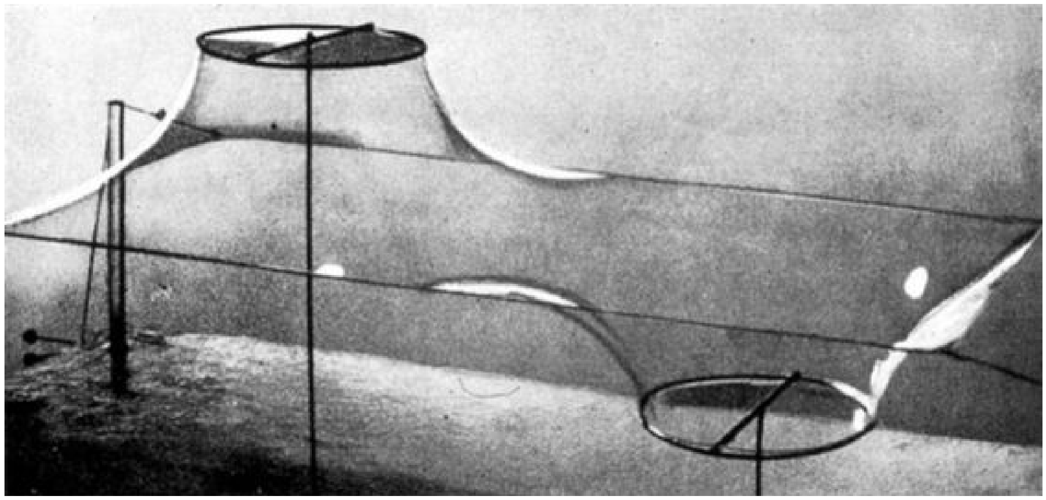


Figure 2.18. The same as Gaudí, the soap bubble experiments of Frei Otto were fundamental for he was able to create forms and structures that were considered to be imposiible before.

(Fig. 2.17). He used hanging chain models (catenaries[8]) to design the roof of the Colonia Guel church, which was later used as an exemplar for the design of the Sagrada Familia church (Burry & Burry, 2010). Using various weights (sandbags) that were hanging on to the ends of the chains, the calculations could be done automatically and thus change the roof geometry without having to do the calculations manually. This prototype design and proportioning method was later copied by Frei Otto for the design of the stadium in Munich for the 1972 Olympic Games. In 1961, Frei Otto began to experiment with soap bubbles *(Fig. 2.18)*. His experiments were based on suspending soap film and dropping a looped string into it in order to form a perfect circle, which by trying to pull it out, he was able to create a minimal surface[9]. This way of designing was called "form finding".

More or less at the same time, the first attempts at using the computer during the design process were made (Sketchpad[10], 1963). During the 1960s and 1970s, various architects, mathematicians, computer scientists and physicists made major progress with computer science, which had major consequences, and as it was revealed a few years later, sealed the development and evolution of parametric design. Postmodernism and deconstructivism were the transitional movements that led designers to a new era of research and innovation. William J. Mitchel[11],

8 The catenary is a mathematical curve, which, when rotated around its X-axis, gives the catenoid, or minimal surface (Burry, 2010)

9 Minimal surface's technical definintion is a surface of vanishing mean curvature (for example plane).

10 Sketchpad is considered to be the ancestor of Computer-Aided Computer programs and who lead the road for Human-Computer Interaction. It was developed by Ivan Sutherland.

11 William J. Mitchel was an architect and an urban theorist who contributed in computational design, specially with his book "The logic of Archicteure".

with his Computer Aided Design; John Von Neumann, with automata cellular; George Stiny[12], with shape grammars; the development of Bézier curves[13]; and the ideas of the philosopher Jacques Derrida, are a few of the artefacts that set the foundations of what we today call parametric design.

By the 1980s, with the release of AutoCAD, computational design started affecting architecture. The development of CATIA facilitated the work of the deconstructivist architects. For many years, engineers told Frank Gehry that the geometries he was designing could not be built, until new computers and software were developed, allowing him and his partners to materialise their ideas and drawings *(Fig. 2.19)* (Taylor, 2003). Frank Gehry wasn't the only one; CAD penetrated architecture for good, while the work of Peter Eisenman, Frank Gehry, Daniel Libeskind and Zaha Hadid are some of the most important examples of deconstructionism and the precursor of parametricism (Lee, 2015).

According to Patrik Schumacher, the parametric style came as a response to the needs of the post-fordist society (Schumacher, 2008). The need for uniqueness that rose from the industrial society, driven by the demands of capitalism for mass production and mass consumption (Taylor, 2003), led architects and designers in search of a new style. Striving for globalisation and trying to break

12 George Stiny was a design and computation theorist, who created the concept of "shape grammars". He defined a powerful type of grammar known as a parametric shape grammar. Shapes, according to Stiny, consist of points, lines and labels. Rules specify how sub shapes of a composition in progress may be replaces by other shapes.

13 Bezier curve is named after Pierre Bézier and is a parametric curve used in computer graphics. It's the result of linear interpolations.

Figure 2.19. The Guggenheim Museum Bilbao that is a museum of modern and contemporary art designed by Frank Gehry who achieved the impossible by setting forms in motion and giving movement form (Taylor, 2003)

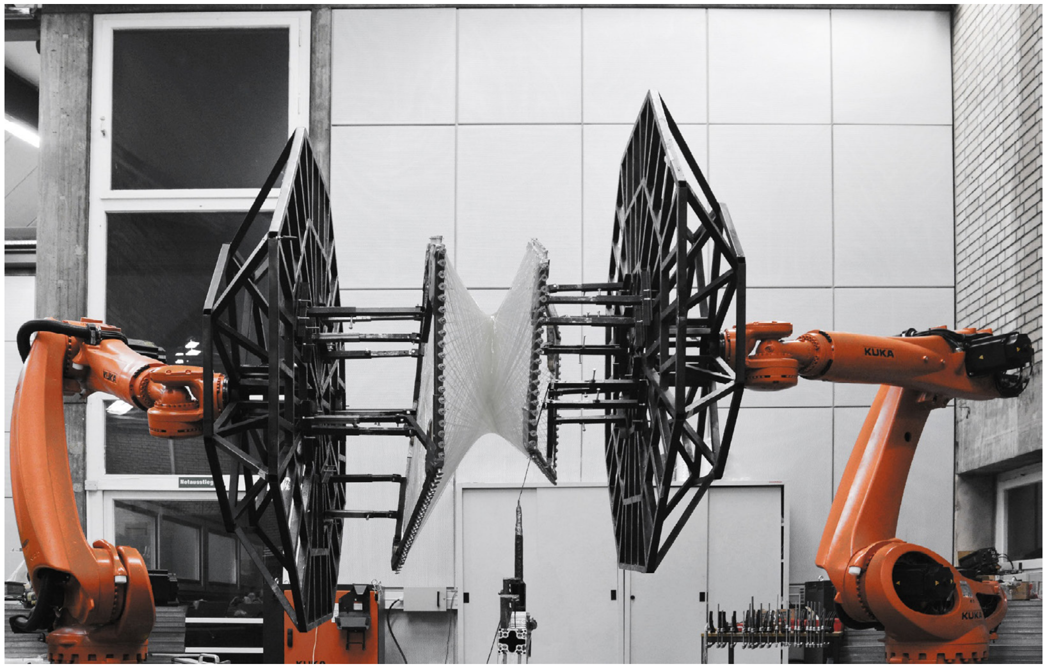


Figure 2.20. Sychronized robots winding a core-less filament for the creation of the Elytra Filament Robotic Pavillion by Achim Menges and ICD Stuttgart institute.

past traditions, modern industrialism was characterised by a homogeneous and universal consumption pattern. However, the new network culture was evolving through the complexity of globalisation into a heterogeneous society, demanding uniqueness and diversity, to which architecture and design were responding with a new style that was called Parametricism (Schumacher, 2009).

Electronic computation offered high-speed, automated ways of deploying different families of algorithms to undertake this reversible form-finding exercise.

Parametric design opened the doors for more research and innovation. The intention of engineers for manufacturing complex geometries, led them to the development of digital fabrication tools *(Fig. 2.20)*. Digital fabrication machines are controlled by a computer which is programmed to make products directly from digital designs. The most common forms of digital fabrication are the CNC machine, 3D printer and Laser Cut. This new way of manufacturing required the search or even the composition of new materials.

Furniture, fashion and product design did not remain unaffected. The new possibilities that computer aided design offered, changed the scenery of fashion and product design. A new era was awakened, where product commercialisation moved from a universal mass production to mass customisation and personalisation (Piroozfar & Piller, 2013). Thus, a progressive movement towards an era whereby the consumer would be able to have their products according to their needs, taste and measurements.

The footwear industry, in the last ten years, has been characterised by a new movement of research and innovation. Great architects and designers, realising the potentiality of parametric design and digital fabrication, have been making intentions to change the concept of footwear consumption. On one hand, new possibilities of the new design style allows designers to change the conventional look of shoes as we know them today, by experimenting with new forms, geometries and materials. On the other hand, parametric design is creating a new level of product customisation by linking human data directly into the design, engineering process and manufacturing.

2.3.2. Parametric Design: A New Design Style in the Footwear Industry

Designing and making shoes is not an easy task. It requires a lot of diverse knowledge in many aspects that may affect the quality, aesthetics and the functions of the shoe. Up until the 19th century, the shoemaking process was a traditional handicraft. The shoemaker would measure the feet and cut out upper leathers according to the required size. Later on, the process was almost completely mechanised, with production taking place in large factories, and in this way, generalising the needs and the particularity of every user. Although the industrial revolution has brought about the benefits of mass-production, the future may allow us to return to the craft production of the past by using the advantages of modern manufacturing. The expression of the ideals of craft production could come into reality through contemporary industrial technology. Recent developments in 3D technology and computer graphics have changed the way of product designing, allowing us to produce non-normalised repetitive components

Figure 2.21. Data-driven midsoles by New Balance and Nervous System.

Figure 2.22. Morphogenesis project of 3D printed shoes by the fashion designer Pauline Van Dongen.

directly from digital data *(Fig. 2.21)*. Footwear companies, taking advantage of new trends and technology, have started looking for further customisation by investing in 3D printing. 3D printing as an additive manufacturing processes allows us to transform digitally developed 3D models into physical objects.

In the last ten years, many fashion designers have realised that the study of natural sciences like biology, chemistry and physics have a strong impact on the aesthetics of clothing and footwear. For this reason, many of them have become researches, providing a more scientific approach to their designs and use of materials. At the same time, as mentioned earlier, computer aided design and digital fabrication have facilitated the exploration of new forms and geometries. The following case studies show the latest trends and how technology and material science have affected footwear design.

Pauline van Dongen:

Pauline Van Dongen, a Dutch fashion designer and innovator, was one of the first designers that started introducing 3D printing into her design process. Van Dongen has been experimenting with wearable technology and hi-tech materials for years.

In 2010, her project the "Morphogenesis" shoe collection, was a collaboration with 'Freedom of Creation', a design and research company that was specialised in 3D printing technologies *(Fig. 2.22)* (Smelik, 2010). With technology as a major ally, Van Dongen was able to give an architectural approach to her design, and managed to create new spatial forms. The innovative aspect of her designing was that the entire design process was carried out using a computer, meaning that the use of a mould, prototype or a moulage was not necessary. The virtual design was directly transferred from the computer to a three-dimensional geometry, through a 3D printer. One disadvantage of her designs was that the choice of materials were quite limited in those years. Polyamide material was too hard and rigid for creating a wearable shoe. Additionally, 3D printing was a very expensive technique used to make a commercial production. Despite these disadvantages, the 'Morphogenesis' project received various awards for shoe design.

Iris van Herpen

Iris van Herpen is also a Dutch fashion designer and one of the first to start introducing digital fabrication techniques to her designs. She often refers to her designs as 'organic futurism', as she often works with high technology techniques trying to imitate nature, but she also uses natural materials or traditional techniques to represent something artificial or imagined. As she has confessed, she starts her design process with a simple sketch and with the help of architects that are skilled at computer-aided design and programmers, her drawings are then translated into software code (Tonkin, 2019). Looking at her work, her ambition to explore the aesthetic and performance boundaries of synthetic polymers is very obvious (Doubrovski and Verlinden, 2018). Her collaborations with companies that specialise in additive manufacturing (for example Materialise), have helped her to produce innovative and dynamic garments and shoes.

In July 2013, van Herpen collaborated with Rem D Koolhaas, founder of the shoe brand United Nude, and Stratasys 3D printing company, to create 12 pairs

Figure 2.23. 3D printed shoes presented at the Wildness Embodied fashion show, designed by Iris van Herpen.

Figure 2.24. (left) UNX2 3D printed shoes, designed by Ben Van Berkel for the Re-inventing Shoe Project.

Figure 2.25. (right) Flames 3D printed shoes designed by Zaha Hadid for her participation in the Re-inventing Shoe Project.

of 3D printed shoes for Paris Fashion Week at van Herpen's Couture show "Wildness Embodied" *(Fig. 2.23)*. Trying to mimic nature once again, the design of the shoe was inspired by the roots of a tree. Twisted and detailed lattices embrace the foot to form the shoe, imitating the roots. The shoes were 3D printed with the multi-material Stratasys Objet Connex and Objet Eden 3D Printers.

Van Herpen's designs have not only been challenging for additive manufacturing companies, but also for material engineers, as additive manufacturing is trying to respond and adapt to the demands of mass-production. The solidification of the polymeric material and the formation of the geometries of the objects at the same time, helps designers to maintain quality control both during and after the production of their creations, despite the lack of information about the natural ageing behaviour of the materials that are used in these processes.

United Nude - The Re-inventing Shoe Project

The Re-inventing Shoe project that was organised by United Nude in 2015, was a project that was focussed on the exploration of 3D printing being applied to footwear design. Five designers and architects were invited: Ben van Berkel (architect), Zaha Hadid (architect), Ross Lovegrove (product designer), Fernando Romero (architect) and Micheal Young (product designer).

UNX2, designed by Ben Van Berkel and his studio Unstudio, was conceptualised in such a way that it featured the mechanics of the foot and visual effects while the shoe was in motion *(Fig. 2.24)*. When the user was not moving, for example, the silhouette of the foot would come into sight through the vertical ribbons that embraced it. Once the user began to move, different levels of transparency were created by the vertical lines, giving the illusion of rhythmical motion and creating, in this way, patterns of movement. The designers developed a parametric workflow that would allow them to update the geometric model of the foot, any time there was a need for changes in the shoe size, heel height, formal shape and the patterning.

Flames, designed by Zaha Hadid, imitated flickering flames, featuring strips that looked like flames that started from the heel and covered up the foot *(Fig. 2.25)*. The insole was ergonomically studied and designed in such a way as to provide support and comfort.

Ilabo, designed by Ross Lovegrove and his computational design team, was formed by a mesh designed in Grasshopper, that covered the sole and the user's foot like a curtain that opened at the toe and heel *(Fig. 2.26)*. Describing this transmission from analogue to digital design as a second renaissance, Lovegrove found it essential to scan the foot in order to maintain and to use as input for the 'sophisticated surfaces' of a female foot.

Ammonite, designed by Fernando Romaro, was inspired by fossils, making very obvious the desire of the designer to study the mathematical relations of this organic geometry and attempt to integrate them into his shoe design *(Fig. 2.27)*.

Young Shoe, designed by Michael Young, gave the opportunity to the designer and his team to explore the boundaries of 3D software and the associated material by creating a heeled boot of lattice visuals.

Figure 2.26. (left) Ilabo 3D printed shoes, designed by Ross Lovegrovel for the Re-inventing Shoe Project trying to imate curtain.
Figure 2.27. (right) Ammonite 3D printed shoes designed by the designer Fernando Romaro for the Re-inventing Shoe Project.

Figure 2.28. 3D printed midsoles for running shoes design by New Balance and Nervous System.

The purpose of the project, as mentioned previously, was to push the limits of rapid prototyping and apply it to footwear design. The production method was the highest quality of 3D printing (Selective Laser Sintering), with a hard nylon and-all new soft rubber material being used. United Nude was able to come up with a way to combine harder and softer 3D printer parts in order to create fully functioning shoes.

2.3.3.Parametric Design and Mass Customisation in Footwear Design

Until now, in mass production systems, the consumer/user remained anonymous, as well as their personalised needs. The aim of companies was to sell as much standardised products as possible, in this case shoes, without getting to know the user, their needs, or demands. One of the advantages of parametric design and digital fabrication is that the manufacturer can have a direct link with the anatomical and aesthetic demands of the user, opening up new possibilities for product customisation. Mass customisation is about producing goods with a high degree of personalisation with near industrial efficiencies. Many footwear companies are moving towards the future by experimenting and trying to get closer to satisfying consumer needs using contemporary technology and adjusting to new design techniques.

New Balance and the Nervous System

New Balance have collaborated with Nervous System in order to develop 3D-printing midsoles for running shoes *(Fig. 2.28)*. The innovation of this design stands behind the introduction of underfoot pressure data from runners as the parameter for the design of the midsole. In this way, the designers are able to generate variations of the cushioning density, allowing them to customise the way that a runner performs.

These midsoles, instead of a uniform foam, form a structure that can be adapted to the performance data of different runners *(Fig. 2.29)*. The basic data used, is the pressure data from a foot strike by the user, that is recorded by a grid of sensors under the foot, demonstrating the force as the foot hits the ground and pushes off over time. Nervous System, instead of dealing with structural optimisation, decided to create a platform that allowed them to experiment with variables that would respond to the data in several ways. They started testing different ideas of how this midsole would be, getting runners to try them in order to check how they performed and felt. Dealing with the midsole as a foam structure was one of the approaches that they followed. Their idea was to develop a foam structure that would perform as a natural foam structure. The artificial foam structures are usually limited by their uniformed structure and thus performance. On the contrary, foam structures found in nature, like wood, corals, sponge, plant leaves, bone, etc, are anisotropic[14], which helps them to increase their mechanical efficiency by placing material where it is most needed in order to resist applied forces (Gibson, Ashby & Harley, 2005). In the same way, Nervous System's idea was to create an anisotropic, macroscopic foam structure that would be

14 Anisotropic material: a material, which is considered to be a three-dimensional solid, is called isotropic when it exhibits the same properties (e.g., mechanical) regardless of the direction of loading. On the contrary, if the material exhibits different (mechanical) behaviour in different directions, it is called anisotropic.

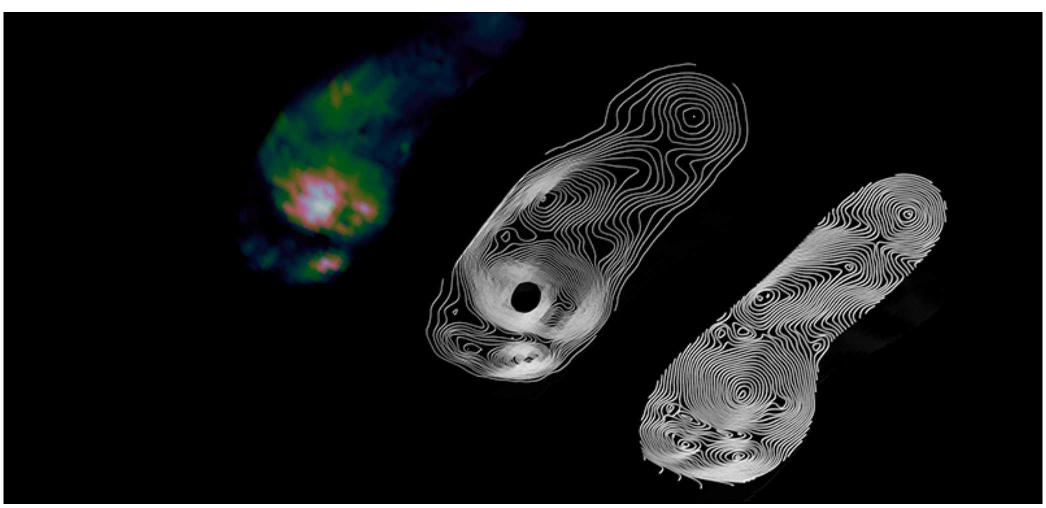


Figure 2.29. The innovation of these midsoles is that they form a structure that can be adapted to the individual performance data of every runner.

Figure 2.30. Futurecraft is an innovative project from Adidas that seeks to introduce the 3D printing technology in the footwear industry.

controlled according to the running data, with its geometry to be adapted to different forces.

The interpretation of the data in a midsole was studied in many ways. For example, they tried generating directional structures following the gradient of the pressure data, unveiling in this way the anatomy of the foot or generating less interconnected structures based on the Hyphae system.

Adidas

Since 2015, Adidas has been working on their “Futurecraft” project, introducing the future in sports footwear, with the ambition that customers, in a few years, will be able to enter an Adidas store, run on a treadmill, and leave the store with an instantly 3D-printed shoe *(Fig. 2.30)*. Futurecraft is an open source collaboration and craftsmanship that consists of a series of 3D-printed prototypes of a running shoe midsole that try to imitate a runner’s footprint. Scanning a runner’s foot, getting their footprint and pressure points, would allow for every athlete to have their midsoles personalised in order to help them reach their peak performance.

Adidas collaborated with Materialise for the release of Futurecraft 3D, with an attempt to create a lightweight 3D printed midsole with variations of flexibility and rigidness. The midsoles were laser sintered[15] in TPU[16] material.

15 Laser Sintering: is an additive manufacturing technique that uses laser for the fusion of material particles, usually nylon or polyamide.

16 TPU material: Thermoplastic Polyurethane or TPU is rubber-like material, with flexibility and durability as its main properties.

As a result, a couple of years later, with their collaboration with Carbon company, Adidas launched Futurecraft 4D. Carbon is a company that specialises in 3D-print lattice structures *(Fig. 2.31)*. A customised midsole requires a cushioning with a variation of properties that can be adapted to the needs of every athlete and to its anatomical characteristics. Carbon's technology helped Adidas to create a digitised footwear design process. Using a mixture of UV curable resin and polyurethane, they were able to print a midsole with a variation of lattice structures in the heel and forefoot in such a way that it responses to the different cushioning needs for the above parts of the foot while running.

The introduction of new technologies in all fields of industry it's a reality that can not be avoided. Footwear industry, in particular, for the last decade has been experimenting using computational design on a design level but also for trying to achieve mass customization. Even though pointe shoe making follows a centuries' tradition of artisanal craftmanship, the introduction of new ways of designing and customizing will be inevitable for the needs and the requirements of 21st century's dancers are also changing and need to adapt to the new reality.

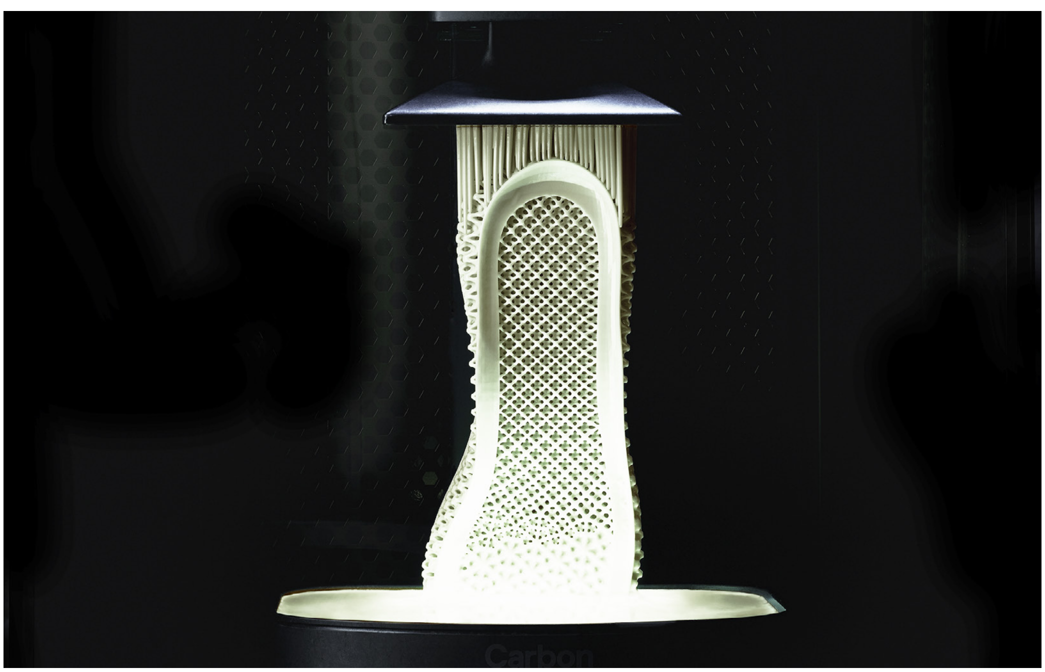


Figure 2.31. With the Futurecraft project Adidas wants to experiment with different materials and 3D printing techniques.

Chapter Three: Anatomy


1 new, 1 old

3. Chapter 3: Anatomy

Dancing on pointe it is not just about bearing passively the weight of the body, while dancing on pointe the foot, also, has to confront the extreme demands of the movements. For that reason, the feet have to be very strong but at the same time sensitive (Chatfield, 1993). Ballerinas, in order to be able to dance on pointe, they need to have very strong feet. In fact a ballerina should be able to stand on pointe with a naked feet, the pointe shoe is there just to cover the foot.

It was very essential for this investigation, to study the kind of movements that a ballerina has to do while dancing on pointe. Study the movements, understand the structure of the human body, understand which parts of the body or even which parts of the foot are participating while dancing on pointe. How is the weight of the body being distributed and most importantly, which is the role of the shoes? How is the traditional pointe shoe design and for which reason? Could we change the structure of the shoe? Which materials of the shoe could be replaced?

In order to answer all the questions above, it is also essential to study and understand well the anatomy of the shoes and how each part is being related to each part and movement of the foot.

Figure 3.1 (left) X-ray of a dancer while standing on pointe shoes.

3.1 Dance Anatomy & Anatomy of the Foot

3.1.1.Dance Anatomy:

Dance is defined by a rhythmically motion usually followed by a music. Aristotle who considered to be the father of biomechanics, in his work, “Motion and its place in Nature” uses the term “motion” (κίνησις / kinesis) with a much wider significant than the one we use nowadays. According to Aristotle, this term can mean:

- Change of the substance (genesis and decay)
- Change of the size (increase and decrease)
- Change of the quality (alteration)

Aristotle, describes the movement of animals and treats bodies as mechanical systems *(Fig. 3.2)*. During the Renaissance, Leonardo da Vinci, was the one who studied the mechanics of the bodies of living organisms in great detail and in a scientific way. He studied in depth the anatomy and he came to early conclusions about the transmission of forces from the muscles but also the function of joints (Klenerman & Wood, 2006). In many of his inventions, he imitated nature to design animated machines. Another great personality of the Renaissance, Galileo, was particularly interested in the strength of and the bone structure. Galileo was the first who assumed that the bones are not solid but they have resources to ensure maximum strength with minimum weight.

The execution of a movement is directly dependent on the structure and

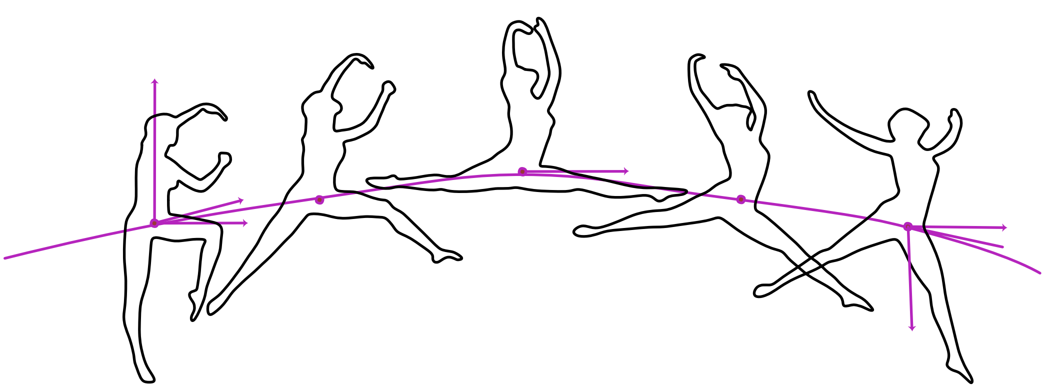


Figure 3.2 Dancer perfoming a “grand jete” - Biomechanics study the structure, function and motion of the mechanical aspects of biological systems.

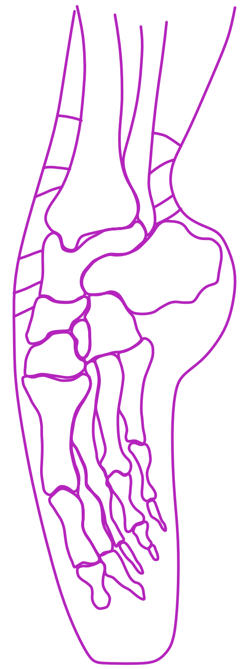


Figure 3.3 The bones of the feet need to adapt to the shape of pointe shoes.

properties of the human body. The complexity of the structure and the functions of the human body makes the movement to be even more complex and complicated procedure.

The kinetic mechanism of a human includes:

- the muscles (assets part-forces)
- the bones and joints (passive part-levers)

This mechanism is a part of the complex system of the human movement that includes:

- the energy source
- the motor mechanism
- the motion object
- their address system (controls organs: brain, nerves, sensory)

In order to understand movement, it is fundamental to study well the structure of bones, joints and muscles, which all of them together form the musculoskeletal system *(Fig. 3.3)*. The musculoskeletal (locomotor system) system is responsible for the form, stability and motion of the human body. It is subdivided into skeletal and muscular system.

Skeletal system consists of the 206 bones of our body, which besides of shaping us, providing protection to our organs (like the heart) and support, they also connect with our muscles, functioning as levers and helping us in that way to move (Haas, 2010). Bones are also responsible for storing minerals and lipids, while some of them they are responsible for the reproduction of the red blood cells. Bones articulate with each other through joints. Joints, apart from linking the bones together, they also provide us with the flexibility that is needed for featuring a movement (Simmel, 2014).

The muscular system contains all types of muscle of the human body and they are responsible for all kind of movements of our body. There are the smooth or involuntary muscles that are controlled by autonomous nerves that executive movement without the conscious order of ours[1], there is the heart muscle that is also controlled by the autonomous nerve system and at last there are the skeletal muscles that are the ones that are attached on the bones through the tendons and the ones that consciously with the help of the nerve system, are responsible for moving the skeleton *(Fig. 3.4)* (Simmel, 2014).

3.1.2.Anatomy of the Foot

A healthy foot is the basis of a dancer and although we don't pay enough attention to our feet, they are the barriers of our weight. Ballet teachers usually say that if you have strong feet you don't even need pointe shoes. The foot and every muscle of it needs to be strong, flexible and sensitive. The foot has a complex

1 The nervous system could be distinguished, depending to its function into the somatic or voluntary nervous system and the autonomic nervous system. The first one is responsible for linking us to our environment by connecting with the skin, sensory organs and our skeletal muscles. It's responsible for our voluntary movements and for processing sensory information. The autonomic nervous system it's responsible for all the unconscious functions of our body such as heart beat, breathing or digesting. For more information look in (Simmel, 2014)

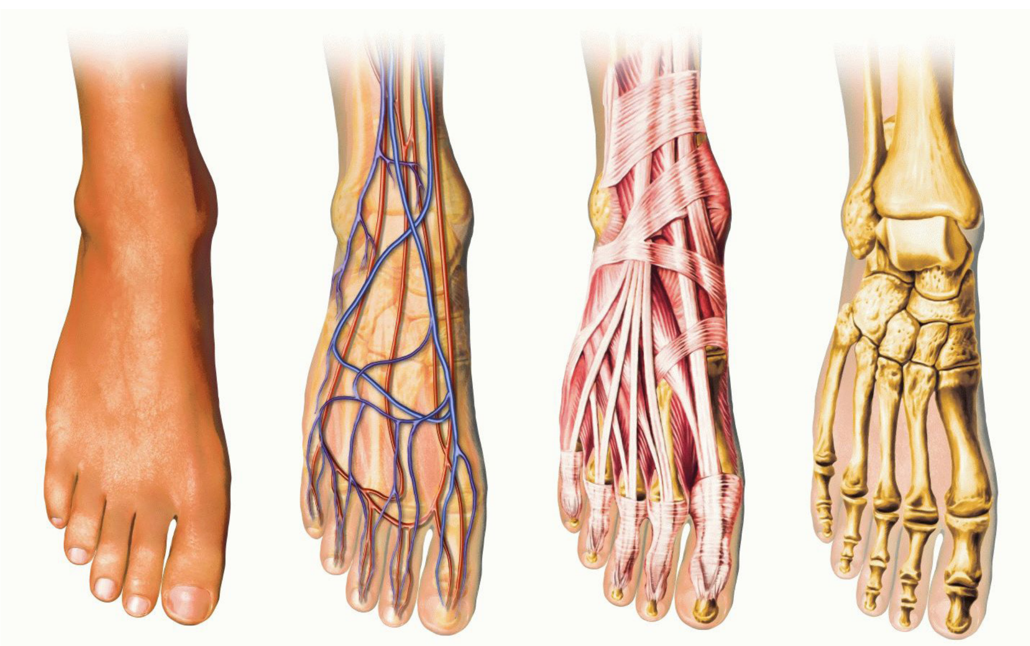


Figure 3.4 Anatomy of the foot - Skin, Nerves, muscles and bones form the foot which is the base of the whole body.

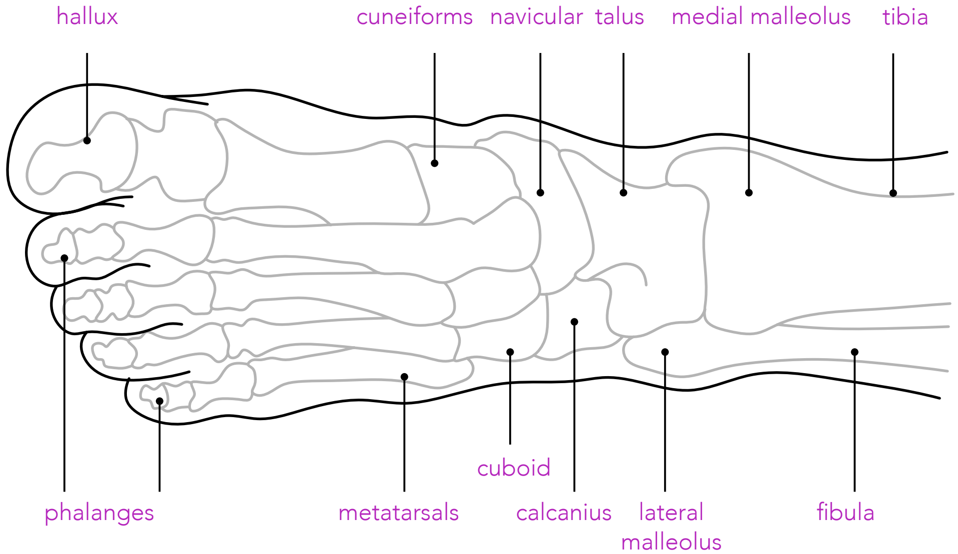


Figure 3.5 Anatomy of the foot: Bones in the foot and ankle of the left foot.

structure that contains:

- 26 bones (one quarter of the bone of the human skeleton is at the feet)
- 33 joints
- over 100 muscles, tendons and ligaments;
- a very complex network of vessels, nerves and tissues

All the above work together in order to provide the body with the support, balance and mobility it needs. A structural anomaly in any of the above may result in the onset and development of problems in some part of the body, such as back pain (Haas, 2010).

Bones:

As mentioned above, the foot consists of 26 bones and it is structurally subdivided into three parts: the hind-foot, the mid-foot and the forefoot.

The hind-foot (or tarsus) consists of the talus bone, the calcaneus (heel bone), the navicular, the cuboid and the three cuneiforms. The mid-foot consists of the five metatarsal bones that have the shape of a tube. The metatarsals are always counted from the inside outwards, the metatarsal of the big toe is counted as “no1” while the metatarsal of the small toe as “no5” (Simmel, 2014). The forefoot consists of the phalanges (toe bones). Except from the big toe (or hallux) all other toes are formed by three phalanges. The hallux has only two phalanges *(Fig. 3.5)*.

The talus (or ankle bone) it´s the main connector between the foot and the leg and it´s responsible for transferring our weight to the foot through the tibia bone as well as transmitting the impact from the foot to the body while none muscle it´s attached on it. It has a trapezoidal shape, which helps it to fit into a concave mortise formed by tibia and fibula and it is covered with articular cartilage allowing it to move against the other bones.

The calcaneus is the largest tarsal bone and forms the heel that we can see and feel. The cuboid is a squared-shaped bone, situated between the calcaneus and the two outer metatarsal bones and it forms a joint with the outer cuneiform and navicular. The navicular (named by its shape which looks like a boat) is situated on the inside of the foot and it forms a joint with talus to the back and to the front with the three cuneiforms. These last three form a joint with each other, the three metatarsals in the front, the navicular and the cuboid behind.

The foot has to be stable but at the same time flexible and elastic. For that reason, the bones of the foot form two kind of arches (the longitudinal and the transverse arch) which can easily be compared to a spiral. The longitudinal arch runs from calcaneus to the ball of the big toe, while the transverse runs between the metatarsal bones.

Joints:

The foot bones are articulated with both tibia and fibula and as well as between them, forming 57 joints, allowing the foot to have a facility of movements.

Metatarsophalangeal joints:

Figure 3.6 The lateral ligaments of the foot that stabilize the ankle joint

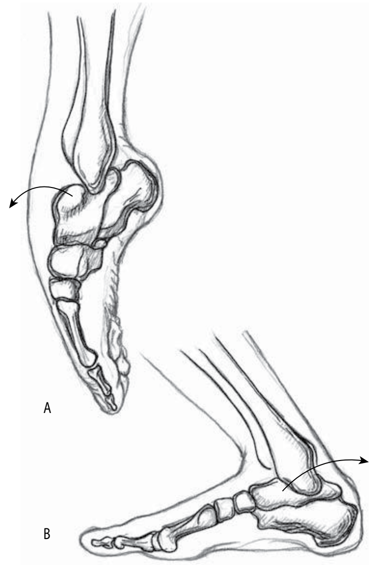


Figure 3.7 A: in plantar flexion the talus slides forwards, B: in dorsiflexion the talus slides backwards.

The metatarsophalangeal joints (MTP joints) are the condyloid joints between the metatarsal bones the foot and the proximal bones of the toe (Simmel, 2014).

The ankle joint:

The ankle is the joint that joins the tibia bone and fibula with the foot (talus). It allows us to raise and lower the foot (bending / extension). Right under the ankle, there is another hinge, the torso joint, which allows the feet to move to the left and right (rotary movements). The hip joint protects the ankle joint by absorbing the vibrations. Anatomically, the ankle joint is divided into two part: the lower and the upper ankle joint *(Fig. 3.6)*. The lower ankle joint stands between the talus, calcaneus, navicular and cuboid bones. Because of its shape, it is consider to be a very complex joint. The rotation of the foot around the sagittal axis takes place at this part. Supination[2], we call the raising of the inner side of the foot, and pronation, the raising of the outer side of the foot[3].

The upper ankle joint lies between the talus and the lower leg and is located between the two bony prominences (malleoli) on either side of the ankle joint. The outer malleolus is formed by the end of the fibula, the inner malleolus by the end of the tibia. These two bones form the ankle "mortise", into which the talus fits. With each plantar flexion[4] the posterior part of the talus is held in the mortise,

2 Supination trauma or twisting of the foot is a very common injury in ballet. This can happen while landing from a jump or when losing balance.

3 Pronation and Supination affects the arch type of the dancer and it's one of the parameters that a dancer takes in account when trying on pointe shoes.

4 In dance this movement is called "point" position.

and the joint is less stable. In dorsiflexion[5] the anterior part of the talus is held in the mortise, and the joint is more stable *(Fig. 3.7)*.

The ankle functions as the foundation between vibration absorption and kinetic thrust. In other words, the ankle is a body-promoting machine with anti-vibrational features. An ingenious system of ligaments protects and supports the upper ankle joint.

Muscles:

Muscles of the foot depending on the location of their outgrowth are divided in the intrinsic muscles, which are located within the foot, and the extrinsic muscles, which extend from the lower leg across the ankle joint into the foot (Grivas, 2002).

Intrinsic muscles:

The intrinsic muscles are muscles are located within the foot and are responsible for the fine motor actions of the foot, for example movement of individual digits. They have both their origin and insertion on the foot and thus have no influence on movements within the ankle joint. They connect the hindfoot with the proximal phalanges and flex or extend the toes. They are also responsible for stabilizing the foot and its arches. For the dancer, the short flexor and the extensor muscles of the toes are very crucial. They run from the hindfoot to the proximal phalanges and flex or extend the toes. Together with the long flexor

5 In dance, this movement is called “flex” position.

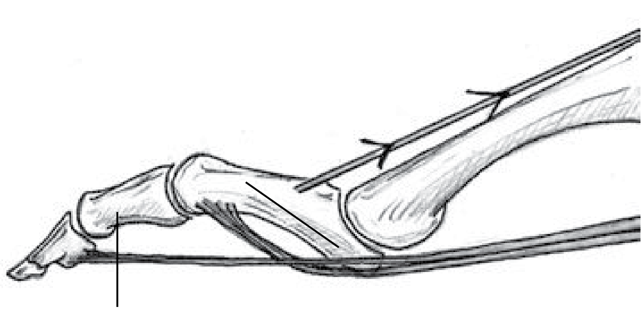


Figure 3.8 Claw toes are problematic for they reduce the force of the muscles of the foot.

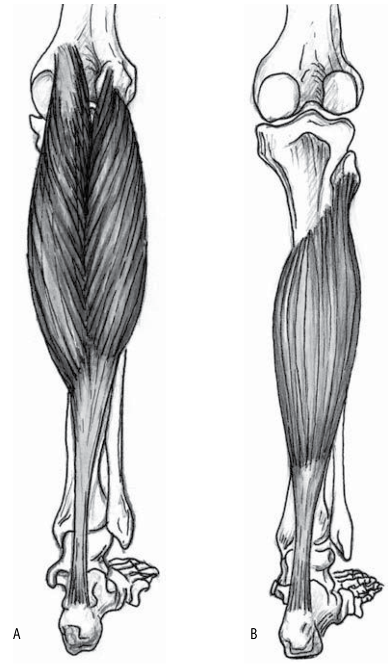


Figure 3.9 The calf muscle consists of A: gastrocnemius and B: soleus

and extensor muscles they are responsible for the movement and strength of the toes. Strong toes in ballet are very important. While standing on demi-pointe or even just standing on a lower heel position, toes have to be attached to the ground in order to grow the surface and thus the dancer is being better supported (Pearson and Whitaker, 2012). Strong toes help the dancer to have a better control of the movement of the toes, thus helping him/her to avoid curled toes. Curled toes is very bad for ballet dancers because they reduce the mobility in the ankle joint as well as the arch of the foot *(Fig. 3.8)* (Simmel, 2014).

Extrinsic muscles:

All muscles originating on the lower leg except the popliteus muscle are attached to the bones of the foot. The tibia and fibula and the interosseous membrane separate these muscles into anterior and posterior groups, in their turn subdivided into subgroups and layers. Some of these long muscles are attached to the hindfoot or midfoot; they move the foot at the ankle joint and affect the position of hind- and midfoot. Other muscles, like the long flexor and extensor muscles of the toes, continue past the hind- and midfoot to the distal phalanges of the toes. Their main task is to move the toes.

The calf muscle is located on the back of the lower leg and it is formed by two muscles. The gastrocnemius and the soleus *(Fig. 3.9)*. The gastrocnemius is larger and it connects into the Achilles tendon. It is a two-joint muscle, one hand helps the bending of the knee and on the other it controls the movement within the ankle joint. The soleus stands underneath the gastrocnemius and it is smaller. Soleus also connects into the Achilles tendon[6]. It is also responsible for the movement within the ankle joint.

The Tibialis Anterior (AT) runs from the front of the tibia down to the front of the shin where it wraps around the medial arch at the first cuneiform and the base of the first metatarsal. It is responsible for dorsiflexing the ankle and invert the foot.

The Extensor Digitorum Longus (EDL) lies deep to the anterior tibials. It is more of a lateral muscle, it origins on the lateral tibia and fibula. It's related with four tendons and it's responsible for the movement of the 2-5 toes. The EDL it is directly attached to two intrinsic muscles on the top of the foot.

The Fibularis Tertius (FT) is the lower part of the EDL muscle. It runs from the fibula to the 5th metatarsal but it does not impact the EDL tendon to the 5th toe. Its responsibility is the dorsiflexion of the ankle and the eversion of the foot.

The Extensor Hallicus Longus (EHL) is the most lateral of the shin muscles, it lies to both AT and EDL and it runs from the fibula, over the tibia to the big toe. EHL is responsible for extending the big toe[7].

3.2 Anatomy of the traditional Pointe Shoe

6 Achilles tendon is the biggest and strongest tendon in our body and it can withstand 12 to 15 times, the weight of our body, mechanical rubbing though of shoe ribbon can cause its inflammation.

7 In ballet EHL is a very important muscle because it helps the dancer to have a powerful push off while jumping but also it offers stability while on pointe.

Figure 3.10 A section of the conventional pointe shoe where they can be seen the different parts of the shoe.

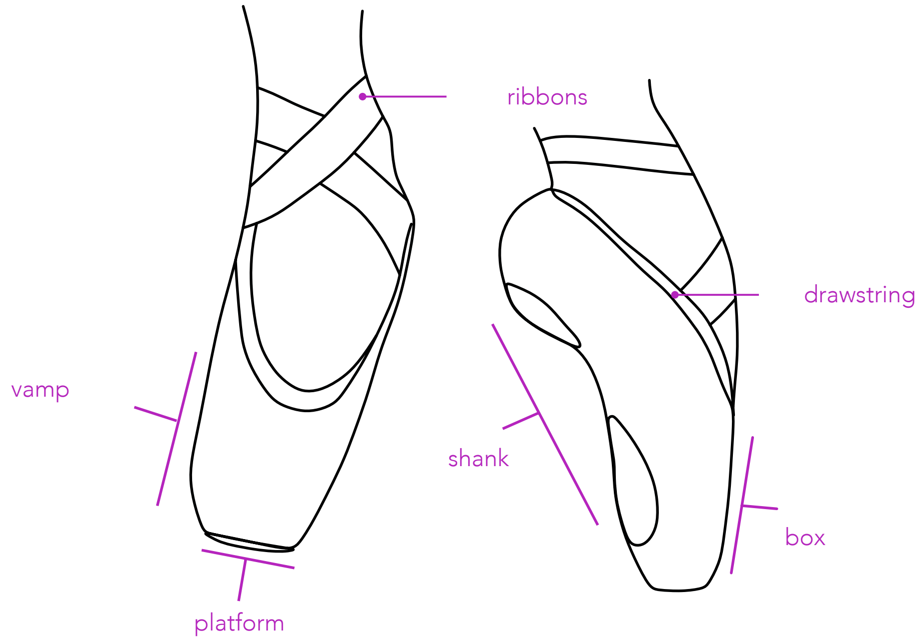


Figure 3.11 Anatomy of the traditional pointe shoe.

The Box or Block is usually made from densely packed layers of fabric and paper, which are shaped and dipped in glue. It is this hardened glue that makes the shoe stiff *(Fig. 3.10)* (Barringer & Schlesinger, 2004). This box of fabric and glue extends over the phalanges, encasing, protecting and supporting the toes and keeping them straight *(Fig. 3.11)*. The box is flat on the front end, forming a platform for which the dancer to stand and balance on. Although it appears very hard and it is not solid but layered when the dancer wears the shoes and the warmth of her foot expands the air, it is not rigid anymore.

The platform is the outer, flat tip of the box, which contacts the floor when the ballerina rises on pointe. The blocking is thickest at the tip but extends as far as halfway down the shoe in a thinner form, providing a sturdy structure under a skin or upper of satin, canvas, or leather.

Shoe blocks come in varying degrees of hardness and varying widths and vamp lengths. The vamp covers the tops of the toes and foot. The vamp supports the dancers toes, but most importantly their metatarsals; the vamp can be shaped differently, allowing for higher sides, or a higher throat in the front, ensuring that all of the flexible joints are supported and encased within the box.

The outer sole is the bottom part of the shoe and it is made by thin leather allows for flexibility and contact with the floor. Although most of these outer soles are made in one piece, a few companies have introduced split outer soles to provide more flexibility in the shoe. The outer sole usually is made of synthetic or leather. A sturdy but pliable insole made of various combinations of leather and fibre reinforces the dancer's arch. Between the outer and inner sole, there is a thin supportive stiff sole that is called shank. The shank of a pointe shoe is supple but the sturdy support the arch needs to hold a dancer's body weight. Usually, the shank the sole of the shoe corresponds in shape with hardened pieces of leather, card-stock, or hardened burlap.

The ribbons are what make the pointe shoes' design so famous and although they seem to be there just as an ornament, their purpose is to give security and to keep the pointe shoe on the foot. This is achieved by wrapping across the arch of the foot and tiding above the ankle. In the last years an elastic is also usually sewn to the heel of the pointe shoe to keep the shoe in place. The drawstring might be either cotton or elastic and it is placed around the shoe encased on the edge of the fabric.

Chapter Four: Manufacturing Process

4. Chapter 4: Manufacturing Process

Traditional pointe shoes are usually manufactured with a method that is called turnshoe. This means that the shoes are sewn inside out on a last and then turned through. Manufactures use a standardised, common last for both left and right shoes. In this chapter will be studied which manufacturing process of pointe shoes is being used in almost every pointe shoe company and mostly, will be studied the example of Gaynor Minden, a company that has broken the tradition by adding machines in some parts of the process and has replaced some of the materials of the traditional pointe shoe.

Ballet dancers need to mold their shoes to their feet in order to make them more comfortable by adding or removing materials. This technique, is called "Breaking In" and it is very important to understand this as a part of the manufacturing process.

Figure 4.1 (left) A pointe shoemaker forming the box with layers of paper, burlap (hessian), fabric and glue.

4.1 The pointe shoemaking process

The shoe is made with a method that is called turnshoe. This means that the shoes are sewn inside out and then turned through. Until 1870s, all shoes were made with this method, nowadays only pointe shoemakers use this technique. This happens because dancers cannot afford to have the stitches outside. The shoe can be light and flexible while very strong. For a dancer, working the shoes it's what builds up the strength in the foot to enable them to move into more demanding dancing.

The pointe shoemakers are usually men. Women often work in the preparation or finishing stages of the process. They are trained for doing this job and many of them they do this job for a lifetime. As they are highly skilled craftsman they are often irreplaceable unless they train their replace.

Some of the phases the shoemaking process, like cutting and sewing, have been automated but the majority of the pointe shoemaking process is still done by hand.

The pointe shoemaking process is divided into eleven steps:

1. Cutting or Clicking: The exterior or upper of the toe shoe that is formed by the vamp section, quarter sections and lining[1], are sewed using satin and lining material *(Fig. 4.2)*. They cut these pieces using a hydraulic press equipped with a metal mould in order to cut many layers at a time. Lining is used in order

1 Lining in sewing it's the process where a piece of a fabric it is added on the inside of a garment.

Figure 4.2 Sewing the satin for forming the outer shoe.

Figure 4.3 Clipping the sole on the last
.

to protect dancers from irritations.

2. Sewing or Closing: The seamstresses extend the V (vamp) by attaching the quarter sections to it and sewing the satin and cotton lining sections of the upper together. Then they sew the ends of the V together, making a heel seam which it's being reinforced with ribbon. The same type of ribbon it's fit through a special machine that it folds it in half over a drawstring. They stitch it to the top perimeter of the shoe. This drawstring enables dancers to pull the shoe tidily around their feet.

3. Preparing the Insole, Shank and Outer Sole: The insole is made of rigid cupboard for support, imbued from plastic for flexibility. In some factories, the insole, shank and outer sole are made of leather. In fact, for some companies the use of leather iss undoubted and is very difficult to find a regular supply for leather *(Fig. 4.3)*. On the soles and insoles, a channel or a groove is cut into it about 2mm, around the perimeter of them, using a machine that looks like a sewing machine. This groove will later be the stitching line of the assembling of the shoe. On the outer sole they usually engrave the brand, the size and the last information.

4. Pulling Over: The upper of the shoe is attached/stretched inside out over the last. The last is a foot-shaped form mold that varies in sizes. The shape of the last represents something between a flat and an arched foot and it's what defines the size and the specifications of each shoe. Usually, the professional dancers have their own last molded to their feet, while common student dancers have to compromise with stock shoes shaped in standard lasts in size, shape and style. In

some cases, the last is covered with tissue paper for making the removement of the shoe, easier.

5. Blocking: After the upper is placed over the last, the shoemaker starts forming the "block" by using layers of paper, burlap (hessian), fabric and a special glue in order to build up the inside of the box. This part of the process differs from a manufacturer to manufacturer, mostly as far as it concerns the materials that they use. The glue for example is made of bread flour and starch but the specific recipes are usually kept top secret. In many cases they pay a lot of attention at this stage in order to make sure that the shoe will be "noiseless" or according to the dancer's specifications.

6. The Lasting Step: at this point, the block is pleated tightly around the last *(Fig. 4.4)*. This is the step when the shoemaker molds the up to this point soft block into its pointe (square, long, flat, oval or curved) shape by pulling. Once the pleats are formed, the maker holds them using his thumb while tying them at the right position. The fit and flexibility depends on this particular step, while shoemakers claim that this is the most difficult part of the process.

7. Stitching and Turning: at this step, the shoemaker stitches down the pleats with a linen threat and he cuts off the surplus cloth. The upper it is stitched to the sole in the pre-cut groove. Once this is done, they turn the shoe right side out.

8. Insole Insertion: after turning the shoe right side out, they place the insole and the shank inside the shoe, attaching it with nails and glue. Then they stamp and they shape the inside of the shoe, while they glue a softer inner sole or lining.

Figure 4.4 A shoemaker stitching and turning the pleats.

Figure 4.5 A shoemaker hitting the platform with a hammer to make the surface as planar as possible.

9. Hammering Out: this is the part where the shoemaker reinserts the last but this time in the right side, using a big shoehorn *(Fig. 4.5)*. This happens in order to shape the shoe from the outside. For this job, they use a smooth-edge hammer and they hit the box to take the shape of the last and they try to maximize the smoothness of the pleats. In this way they are able to get rid of any bumps or anomalies[2].

10. Drying: once the shoes are done, they are placed in a hot air-oven over night in order to dry and become more rigid. In some factories they are just placed on a rack to dry for two to four days.

11. Inspection: when the shoes are dried they are inspected for quality. They then prepare them for shipping or they keep them in the warehouse.

4.2 Preparing the Pointe Shoes:

When a dancer gets a new pair of pointe shoes, she needs to mold them to her feet and make them more comfortable. Dancers wear through their pointe shoes very quickly, although they have to spend extensive amounts of time modifying them before they use them. Professional dancers use numberless pairs of pointe shoes a week during heavy performance period or even more than one

2 The Freed industry's shoemakers at this point they stamp their mark on the sole. This mark is known as the "Maker Mark" and it was invented by the owner Fredrick Freed in order to determine who made malfunctioning shoes. In this way he knew whom to blame when shoes were returned with a complaint. For some Ballerinas it was obvious that certain shoes suited them better than others and they became aware of the significance of this mark on the shoes they preferred. They were then able to recognize the mark and get their preferred shoes.

pair during a single performance.

Even though, most of them don't have the time to modify their shoes, dancers came up with many "breaking in" techniques. These are treatments that dancers can apply to their pointe shoes before wearing them for the first time. These treatments may include, pounding them with a hammer, smashing them in a door, wetting them and many other techniques in order to smooth the box and the shank. The purpose of this it is to try to compound the original rigidity of the shoe, which is needed for support and the right amount of give needed for fluid motion.

Protective padding:

There is a big debate among ballerinas and ballet teachers weather a protective padding is necessary while wearing the pointe shoes *(Fig. 4.6)*. The most common reasons for using one are the blisters, breaking nails or wounds on the toes. The protective padding should never be thick or bulky as the dancer should be able to "feel" the ground. Their purpose is to prevent and not to fill in the box of the shoe. The most common paddings are made of foam or silicone gel although it is believed that still, these types of padding do not allow them to feel the floor. The most recommended is a small amount of lamp's wool that could even be wrapped around individual toes. The lamp's wool allows the toe to slip slightly agains the soft fibers, avoiding in this way the contact with the canvas lining.

In the past years, even though protective padding was a taboo, ballerinas

Figure 4.6 Protective paddings made of foam for avoiding blisters and wounds.

Figure 4.7 Even though pointe shoes are not sold with the ribbons, they are very important and every dancer needs to sew them on her own on their shoes.

used foam rubber or fur toe pads. Their disadvantage was also that they would not allow to the toes to move freely in the shoe and thus not contacting properly with the floor.

Sewing and tying the ribbons:

The first thing that a dancer does when she gets her shoes, is to sew on the ribbons *(Fig. 4.7)*. The ribbons are usually made of polyester satin with either a shiny or matte finish[3]. They are one and a half or two centimeters wide and 50-60cm long. The length depends on the size of the dancer's ankle. To attach the ribbons, the dancer folds the heel of the shoe against the sole and towards the front. They place the ribbons inside the shoe in the angles that are made by the folding heel and they mark it with a light pencil. The ribbon is usually folded by at least one centimeter before sewing and then using a strong thread (or dental floss) they sew the ribbon securely onto the shoe using whip stitches and in a square pattern. Many dancers apart from the ribbons they also sew elastics, usually where the ribbons are sewn. Elastic is to provide more support, specially if the dancer has highly developed arch and not very strong ankle (Barringer & Schlesinger, 2004). Elastic can also be sewn at the back of the heel in order to provide more support to the Achilles tendon.

The way that ballerinas tie their ribbons is very important because even though they are the ones that hold the shoe on the feet in any position and the ones that give security to the dancer while preventing injuries, they should never be very

3 https://dancer.com/ballet-info/about-pointe-shoes/sewing-ribbons/

tight for they could hurt the Achilles tendon or limit the mobility of the ankle. There are many ways of tying the ribbons. While tying them up, the dancer has to be kneeling on one knee while leaning a bit backwards. The knee of the other leg is bend while the foot is placed flat on the floor. In this way is given the maximum flexibility to the ankle. On the contrary, if the foot is on pointe position or the leg straight the ribbons are tied very tight making it difficult for the dancer to pass from fully on pointe to demi-pointe position. They then take the inside ribbon and they wrap it around their foot and the back of the ankle, then wrapping it around through the front of the ankle and the back again and stopping at the inside of the ankle. The ribbon has to lie flat on the foot. The second (outer) ribbon is wrapped over the foot and around the back of the ankle, bringing it around to the front to meet the inner ribbon at the inside of the ankle, between the ankle-bone and the Achilles tendon. They are tied in a small, tight double knot[4] that they hide under or between the ribbons so that their ends are invisible. The know should never go directly on the Achilles tendon or the shinbone in order to avoid pressure and thus inflammation.

Some shoes they do not have a drawstring, or it is made of elastic. In general, drawstring in front of the shoe is tightened in pointe position, until the shoe feels secured. Again, it should never be very tight because it could dig into the Achilles tendon, causing inflammation in this way, or it could put too much pressure and cause bursitis.

4 Ribbons are never tied up in a bow in order to point out that the ribbons are there for support and preventing injuries and not for excessive look. They have to have a clean and dignified look.

Figure 4.8 Dancers need to search for ways for breaking the box of the pointe shoe in order to make it a bit more flexible and comfortable.

Figure 4.9 Breaking in the shank is the first thing that a dancer does once she buys new pointe shoes, for their rigid material do not allow them to bend the foot and perform a full plantar flexion.

Softening the box:

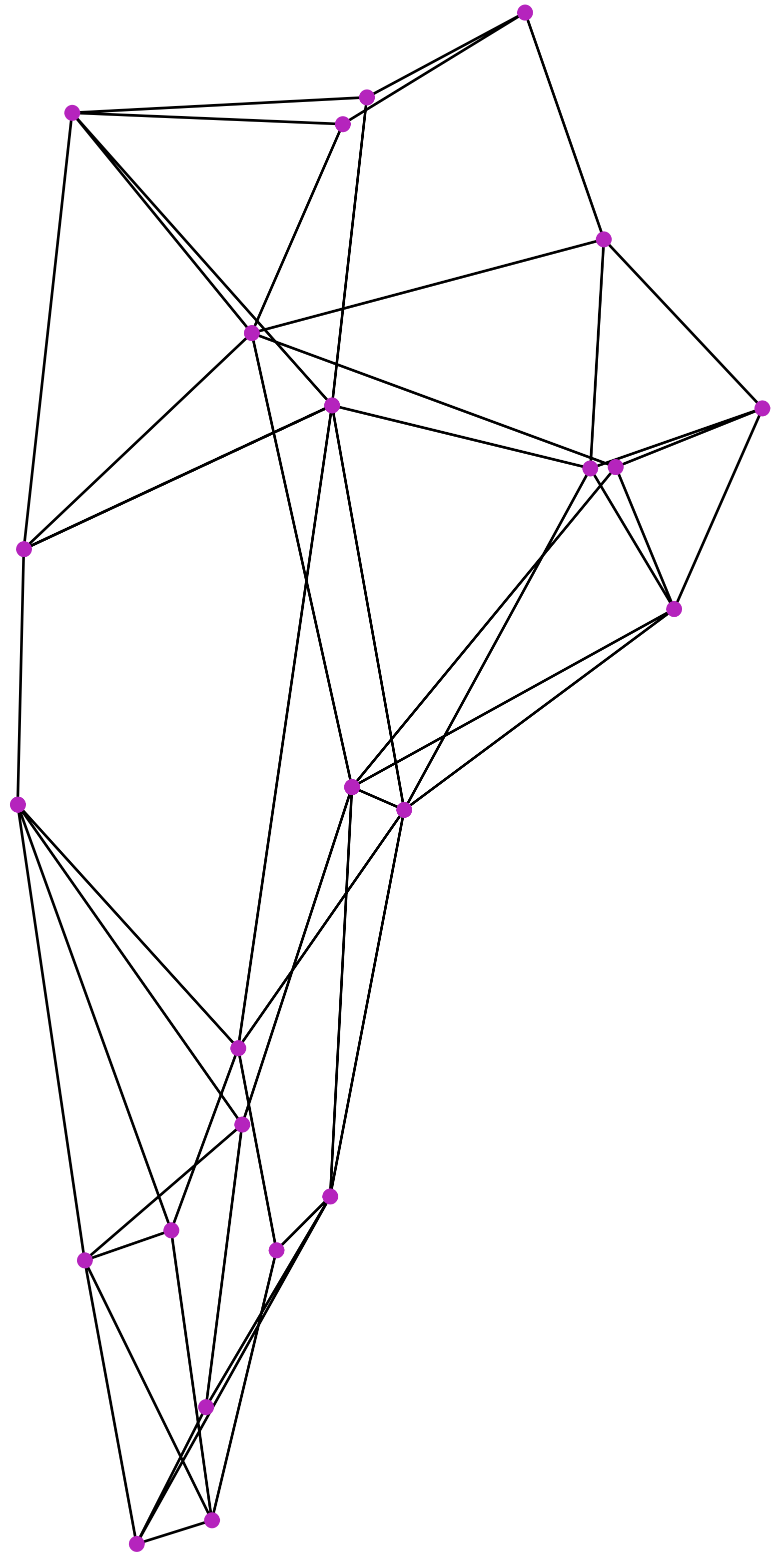
Most of the dancers wear their new pointe shoes around the house and rising from quarter- to demi- and three quarter pointe to mold them to their feet. They even rise to full pointe many times on each foot and turn the toes back and forth. They also work the shoes with the hands. Sometimes they step on the box with their heel in order to crush the box and reduce its stiffness *(Fig. 4.8)*. Another trick for softening the box is to rub the shoes with alcohol or water. The ones that are more experienced they even slam them in the door.

Adjusting the shank:

Some dancers, have ankles that are not very flexible and instep and for that reason they find it difficult to break in the shanks of their shoes. That's why they have come up with many of clever ways to bend, cut, score and tape their shanks. These adjustments can significantly improve a shoe's performance. This is a highly personalised process. One of the things that they do, is to try and bend the shoe by hand or even cut off the inside of shank very carefully, layer by layer so that the small part at the back of the heel is removed *(Fig. 4.9)*. Some companies have modified the shoes and now they make three-quarter shanks.

It is important here to mention that the moment of buying a new pair of pointe shoes it is very crucial. Nowadays in the market there are plenty of variations of the width of the vamp, the depth of the box or the flexibility of the shank (we will analyze it on the next chapter).

Chapter Five: Areas of Investigation



5. Chapter 5: Areas of Investigation

In order to be able to investigate as deeply as possible all the involved disciplines for pointe shoe designing and making, the scope of the study has been divided into four subchapters:

- Geometrical Approach: In this first part of the investigation is concentrated on the geometrical aspect of the problem. That means that after studying well the different parts of the feet that affect the geometry of the pointe shoe is needed to set up carefully the variables that have to be taken in account at the moment of the design. It is also important to define what is topology and understand the variations of the feet that could be found in nature.
- Structural Approach: While a dancer is dancing, there are outside forces that act on her/his body. These forces help the dancer to do the movements technically correct. In this section, will be studied the applied forces that have a major impact on the feet while dancing on pointe.
- Material Approach: As mentioned before, pointe shoe making process is an artisanal craftsmanship working with the same materials for at least two centuries. In this chapter will be studied the performance of the traditional materials to try and understand their properties in order to be able to propose new materials.
- Digital Fabrication Approach: One of the advantages of the digital era is that you can link human data to the design and manufacturing. 3D printing as an addictive manufacturing process, allows us to transform digitally developed 3D models into physical objects. This possibility along with other computer aided manufacturing processes will be studied in this chapter.

Figure 5.1 (left) Diagram of the foot in plantar flexion with the most important points.

5.1 Geometrical Approach

5.1.1.3D Scanning:

As explained before, the human foot is considered to be the base and the barrier of our body. Its shape and form is related to the complexity of its bio-mechanical functionality. The shape of the foot, the shape of each muscle and bone of the foot keeps adapting to every movement. Additionally, each one of us, has a different foot that is designed and built in such a way that is unique and corresponds only to the body structure of each one of us. In order to study well the geometry of a variation of feet we needed to get samples of different feet using a 3D scanner (Piperi, Spahiu and Galantucci, 2014).

A 3D scanner is a device that analyses an object or environment and collects data about its shape and possibly its appearance (e.g. color). Its functionality is very similar of a camera. The most important common thing, is that they both collect information about surfaces that are enlightened and not obscured. On the other hand, cameras collect color information about surfaces while 3D scanners collect distance information about surfaces that are included in their field of view. The result image of a 3D scanner is nothing more but the description of the distance to a surface at each point of the image (Ebrahim, 2011).

The first 3D scanner technology was created in the 1960s where they used a combination of lights, cameras and projectors in order to complete the process. In 1980s, the first contact 3D scanners were developed but as the accurate replication of an object, required a lot of effort and time because of the complexion

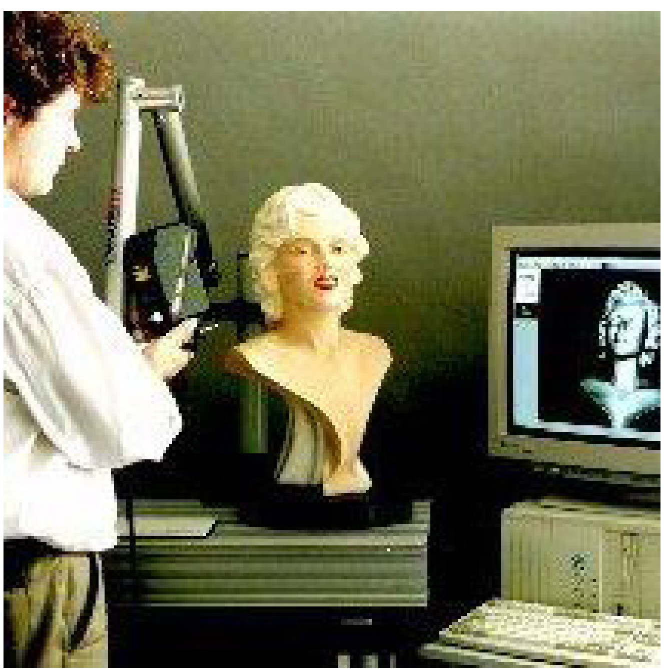


Figure 5.2 Manually operated arm and strip 3D scanner

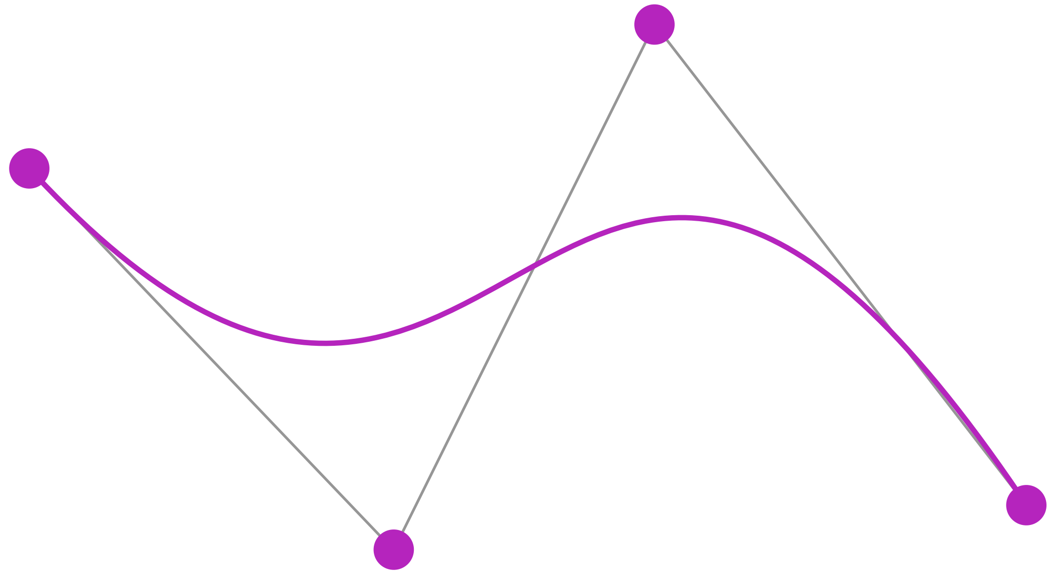


Figure 5.3 NURBS curve can be easily modified by moving its control points.

of the scans, soon they started using optical technology. By 1985 3D scanners began to use white lights, lasers and shadowing in order to collect data points of an object's surface *(Fig. 5.2)*.

Non-contact 3D scanners do not require a physical contact with an object. Their functionality stands on some active or passive techniques. For example, one of the techniques is the emission of light or some sort of radiation (ultrasound, x-ray) and the detection of its reflexion on an object. In this way, we are able to collect a very accurate cloud of points that can be used for measurement and visualization in many fields.

There are many ways of reconstruction of a model. One of the them is the reconstruction from point clouds that is usually used in architecture or construction world. Another way is the reconstruction from a set of 2D slices that are put together to produce a 3D representation and are used mostly by Computed Tomography and MRI.

As most applications use polygonal 3D models, NURBS[1], surface models or editable feature-based CAD models, the collected point clouds are usually translated into polygon mesh models, surface models or solid CAD models *(Fig. 5.3)*. A mesh model, is a polygonal representation of an object for example, imagine a curved surface that is described by as many small planar surface. Surface models

1 NURBS or Non Uniform Rational B-Splines are mathematical representations of any 3D geometry that are able to describe accurately, any shape, from a simple 2D line, circle, arc, or curve to the most complex 3D organic free-form surface or solid. NURBS curves and surfaces developed in the 1950s with the intention to introduce precision to the description of free-form surfaces mainly used in industrial design (for example, ship or car designing).

are built up using NURBS, T-splines or any other curved representation, while solid CAD models represent a digitized shape with an editable, parametric CAD model.

As the collected data can then be used to construct digital three-dimensional models and can give the exact model of any object, a 3D scanner was considered to be the most appropriate tool for scanning different types of feet in order to have a more complete topological analysis. The 3D models of the feet that were scanned, were not only used for analyzing and defining the variables for developing the parametric system, they were also used for the development of the parametric system.

For the 3D scanning it will be used a Structure Sensor connected to a computer along with the software SKANECT *(Fig. 5.4)*. Various feet had to be scanned including dancers but also people that have never danced in their lives. All feet scanned belonged to women. Scans were done with a naked foot, pointed as much as possible. In order for the scan to be done, the structure sensor had to be rotated 360 degrees around the foot to accomplishing the best result possible.

5.1.2.Defining variables:

Topology:

Ἀεὶ ὁ θεὸς γεωμετρεῖ[2] is a greek saying credited by the greek philosopher Pla-

2 The phrase is also used as a mnemonic of the irrational number pi (π the ratio of circle's circumference to its

Figure 5.4 3D scanner - Structure Sensor.

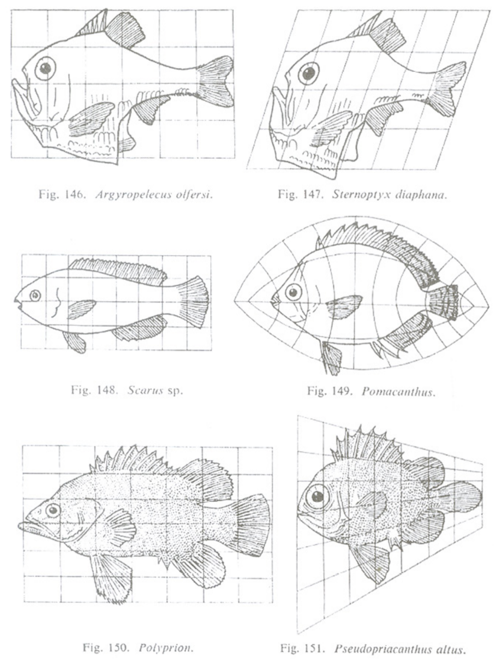


Figure 5.5 One of the famous Transformation Diagrams from On Growth and Form.

ton which means that "Always, the great god applies geometry to everything" and it outlines the importance of geometry in understanding the cosmos. In the beginning of 20th century many scientists started studying and writing down the linking lines between biology and mathematics (Weinstock, 2010). According to D'Arcy Thompson[3], the form of an object, living or dead and the changes of its form can be described as a "diagram of forces" that acted on it *(Fig. 5.5)* (Thompson, 1917). Form can be described by mathematical data, by mapping points in three-dimensional coordinate space, by dimensions, angles and curvature radii (Weinstock, 2010). In this particular thesis, a topological study of the anatomy of the foot was needed to be done in order to understand its geometry and the variations of its geometry in which can be found in humans.

The term topology in mathematics, refers to the study of the properties of objects that are preserved through deformations, twisting and stretching of the objects. It's the study of the flexible geometry. It is, therefore, a kind of a generalized geometry. However, we do not focus on the dimension or a generalized analysis but we concentrate on the continuity or not of some functions. Topology[4] is the Topological Space[5]. Topological spaces are found in mathematical analysis, algebra and geometry.

diameter) since the number of letters in each word give 3.1415

3 D'Arcy Wentworth Thompson was a Scottish biologist and a mathematician. His book On Growth and Form, set the boundaries of the scientific study of Morphogenesis. Morphogenesis comes from the greek words μορφή(shape) & γένεσης(creation) and it studies the biological process that makes a cell, tissue or organism to develop its form.

4 Topology (τοπολογία) comes from the Greek words τόπος (place, location) & λόγος (study).

5 A topological space is a set of points, together with a set of neighborhoods for each point, that satisfies a set of axioms relating to points and neighborhoods.

Fundamental concepts such as convergence, boundary, continuity, consistency, or compass meet their best formatting in topology. Topology[6] is essentially based on the concepts of topology and homogeneity.

In anatomy, topology refers to the topological approach in studying anatomy, i.e. studying based on anatomic regions and the relations between the structures, and is referred to as topographic anatomy. In this chapter thought, we are interested in the geometrical approach of the foot and the different variations of its form. At a first glance we all humans look the same, taking a more closer look though of the individual characteristics of each one of us, one can find many differences *(Fig. 5.6)*. One can have a small hand with short, chubby fingers, another one can have thin, long fingers, another can have short, very thin fingers and a big palm, etc. There are infinity combinations of characteristics that make each one of us unique. The same happens with our feet. Below, you can find an intention of cataloging the most important characteristics of a foot and in which way, each part of the foot relates with each part of the pointe shoe.

Types of foot:

Although in ballet the prevailing view is that the pointe is the foot and not the shoe, the different parts of the shoe require different performance, depending on the different parts of the foot. To meet the unique demands of the pointe

6 As a term it has been actively introduced into architectural discourse since the early 1990s but still lacks of a clear definition in architecture.

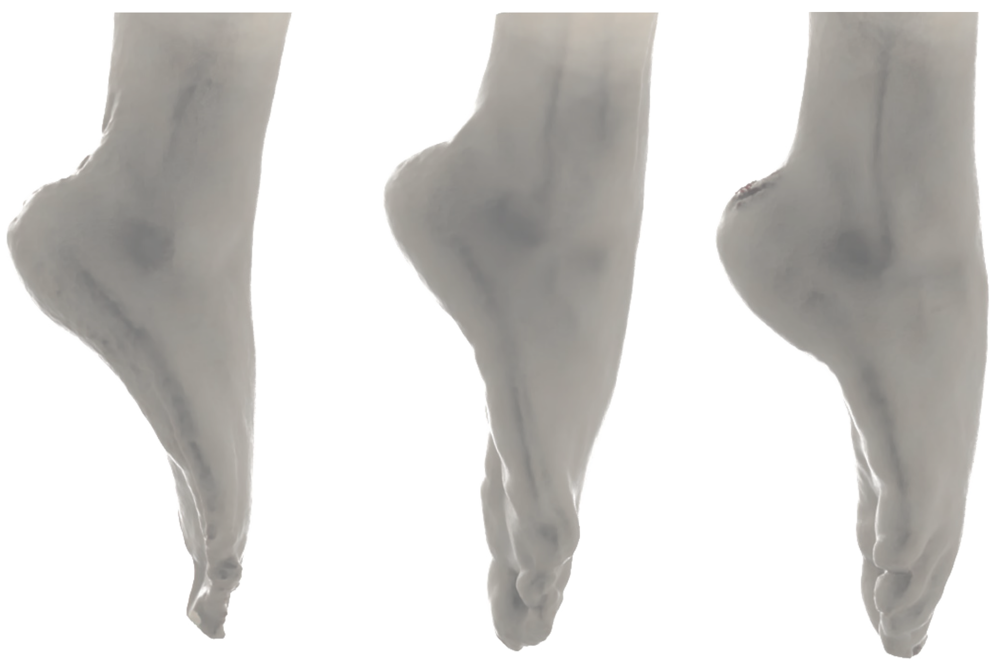


Figure 5.6 3D scans of different feet.

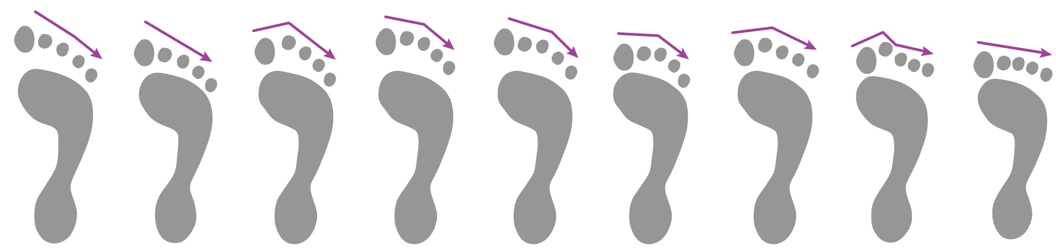


Figure 5.7 Toe shapes.

dancing, the foot has to be strong, supple and sensitive as the hand. Rather than serving as a passive weight-bearer, it must assume positions and execute movements beyond its normal limits.

The physical characteristics of a ballet dancer's foot can be either an advantage or a disadvantage when it comes to the pointe shoe dancing.

Toe shape:

The toe shape is related to the box shape of the pointe shoes *(Fig. 5.7)*. Box Shape is arguably the most important aspect of the pointe shoe fit. The wrong box shape can be the source of many frustrations, including big toe pain, zero metatarsal support, bruised toenails and more. There are three very generalized types[7] of toe shape, the Greek, the Egyptian and the Giselle/Peasant/Roman type.

The Greek or Morton´s foot is very easy to identify as there is an obvious difference of the length between the second and all other metatarsals, with the second one being the longest of all. Wearing a pointe shoe, this is quite problematic as it obviously means that the second metatarsal is also longer than the hallux, and when in pointe shoe is forced to curl (Oztekin et al., 2007). At the same time, even on demi-pointe because of its length, is forced to bear a disproportionate amount of weight ((Simmel, 2014). Ballet dancers with this anatomic problem, usually use a padding to fill in the gap between the first and second metatarsal

7 Even though there no serious scientific evidence, foot types are often labeled "Greek", "Egyptian", "Roman", "Celtic", or "Germanic", in an intent to relate the foot type with our ancestry.

or they even use a toe separator.

The Egyptian or tapered foot structurally may be the most functional in the day day life. Usually these feet are quite narrow with the hallux being the longest toe. Wearing a pointe shoe though, may cause hallux valgus (or bunions). This is a condition where the big toe bends towards the second one and it is usually combined with a bony bump that is formed on the joint at the base of the hallux. This can be provoked by genetic factors but from a dancing style as well[8]. Wearing the right shoes is important in order to try to align the hallux on its axis and avoid the deviation.

There are innumerable types of feet and each one of us has different characteristics, all the above are just some of the basic generalizations of the toe shape types but there are many more.

Toe Length:

The length of the toes is a very important parameter and is related to the part of the shoe that it's called vamp *(Fig. 5.8)*. The dancers who have long toes require a longer vamp than the ones who have short toes. The vamp needs to be long enough to cover the joint at the base of the hallux. If the vamp doesn't cover enough the toes, then there is the possibility that the toes fall out of the shoe. The center of the front part of the vamp should always reach as far as, or just beyond the third phalange of the first and second metatarsal. If the vamp is

8 "Rolling in" is a habit of many dancers that struggle with their turned-out position and they often force the ankles to roll in.

Figure 5.8 Toe Length

Figure 5.9 Foot width

too short it will cause the foot to fall over the toes. This not only makes the foot look ugly, it also makes it almost impossible for the dancer to maintain her weight at the right position. On the other hand, if the vamp is too long and covers the foot more than the necessary, it will throw the dancer backwards and prevent her from standing on a full-pointe position.

The length of the toes is also related to the box of the shoe. For example, dancers with long toes and narrow feet usually use a more pointed box and those with wider feet require a squarer box.

Foot Length:

In general, if a shoe is larger than it should, then the foot sinks into the shoe forcing the big toe to twist. Bigger shoes, could also be the reason of causing bunions, corns on the toes, blisters or bruised nails. On the other hand, if a shoe is smaller than it should be, then it might be the cause of discomfort on the Achilles tendon. Smaller shoes can also cause inflammation at the ends of the toes for putting much of a pressure. Usually foot length is proportioned to the height of a person. It is commonly known though, that most people have at least a very small variation of foot length or width. In that way, a shoe may be perfect on one foot and a disaster on the other.

Foot Width:

The foot width, affects the shape and the width of the box, the vamp and also the platform *(Fig. 5.9)*. The width of the foot changes according to the movement/position of the foot. For instance if you step your feet on the ground it gets the maximum width. On the other hand, in the pointe position, depending on the flexibility of the foot, the width becomes smaller. If a shoe it´s very narrow squeezes the toes and joints and it doesn't allow them to work properly. The shoe should hold the toes tide but not so tide that they are bunched together. They should be able to move just a bit side ways, but the most important is that the tips of the toes should just feel the ends of the shoes when the dancer's weight is evenly spread. The toes should not feel sore inside the shoe, instead, they have to be able to perform a demi-plie without the toes having a problem of expansion inside the shoe (Barringer & Schlesinger, 2004).

Arch Type:

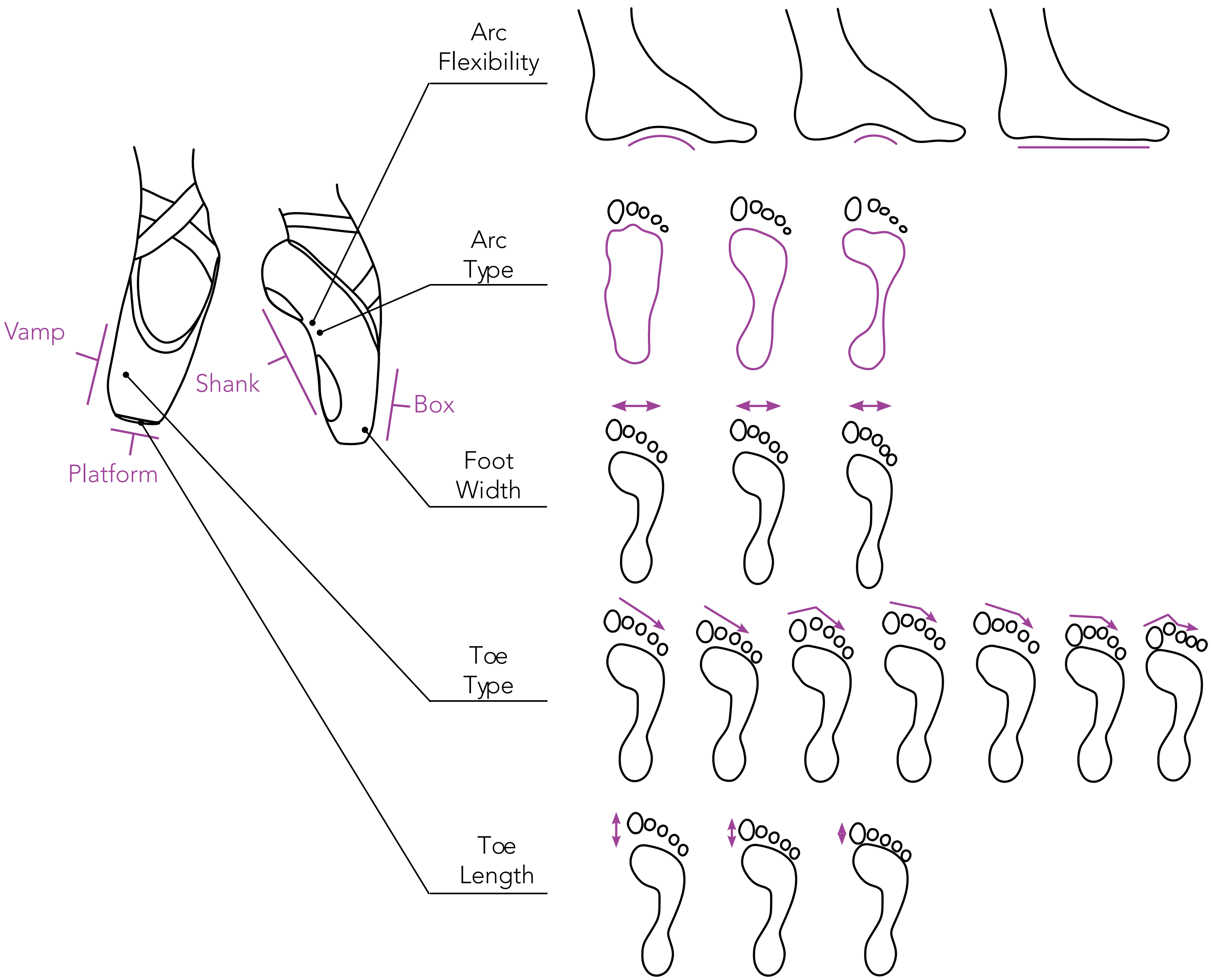
A high arch is especially important when dancing on pointe: tibia, talus, mid-foot and fore-foot should all be aligned in a vertical line, the optimal line of gravity *(Fig. 5.10)*. This allows the load to be axially applied to the bones of the foot that, bio-mechanically, provides the greatest stability. Some dancers (and people in general) have anatomically "flat feet". Some girls tend to have a flatter curve to their arch in standing due to the actual shape of the bones in their foot, and no matter how strong the small foot muscles get, the shape of the foot will not change significantly. In addition, some girls have a very high arch to their foot, yet are very weak in the small muscles of the feet, while it may appear that they have good control of the arch. This is one of the parameters that affects the rigidity of the shank.

Figure 5.10 Arch type

Figure 5.11 Arch flexibility

Arch Flexibility:

Arch flexibility is related mostly to the shank of the shoe, in addition, is one of the parameters that dancers are based to decide about the rigidness of the shoe *(Fig. 5.11)*. There is a big debate among ballerinas or ballet teachers weather a shoe should be very soft or very hard. It is suggested for beginners to have harder shoes for more support although they do not have the strength they need for bending the arch of the shoe. On the other hand, harder shoes make them work harder, thus they gain strength and flexibility. If a ballerina has a very flexible arch and a weak ankle, it is also suggested to have a harder shoe in order to control their balance better. Besides all these, it is believed that a ballerina should be able to depend on the strength of her feet and not her shoes. A weak ankle or weak foot with soft shoes, if there is absence of control, it could cause injuries such as a twisted ankle.


Arc
Flexibility
Arc
Type
Vamp
Shank
Box
Platform
Foot
Width
Toe
Type
Toe
Length

5.2 Structural Approach

While a dancer is dancing, there are outside forces that act on her/his body. These forces help the dancer to do the movements technically correct. In this chapter they will be studied the applied forces that have a major impact on the feet while dancing on pointe and what forces need to be taken in account while design a pointe shoe (Barber and Popalisky, 2008).

Gravity:

In physics, gravity is called the property of the material elements to attract and be attracted to other elements. The drawn bodies move in accelerating motion towards the attractor. The resistant forces are equal. The measure of resistance, which shows each body in the change in its kinetic state, is called the mass of a physical body. The pulling force, called weight, is greater when the bodies are closer or when they have a larger mass. Gravity on Earth attracts material elements and causes them to fall on its surface when released. In addition, it helps the dancer stay grounded by pushing her/him downwards.

The center of gravity of a physical body is the point at which the body will balance. In order to remain balanced, the center of gravity must remain directly above the area of contact with the floor. The gravity dragging downwards and the floor pushing up, both forces help the dancer to move around and balance .

Figure 5.12 (left) Each part of the pointe shoe sorresponds to a different part of the foot.

(Barber et al., 2007)

Support from the ground:

Newton´s third law of motion, states that for every action there is an equal and opposite reaction. When a physical body acts a force upon another body (action), then the second body exerts a force of equal measure and opposite direction in the first (reaction). Each action always has an opposite reaction. So, as for each action there is a reaction, it appears that in nature forces always appear in pairs. The action and the reaction act simultaneously upon two different bodies. The measure of action and reaction is the same, regardless of the masses of the bodies that interact. The law of reaction-action applies whether the bodies are immobile or move at a speed.

$FA = -FB$

It does not matter which of the two forces we call action and what reaction. In dance, as gravity pushes while the floor pushes up, the dancer is able to move.

Friction from the floor:

Friction is a resistance force that manifests itself against any movement of parts of the same material element or the relative movement of two elements with their surfaces touching. In the first case there is an internal friction, in the second (between elements) external friction *(Fig. 5.13)*. The direction of the friction is always opposite to the direction of movement. The frictional force is distinguished by static friction when the elements are balanced and in slip friction

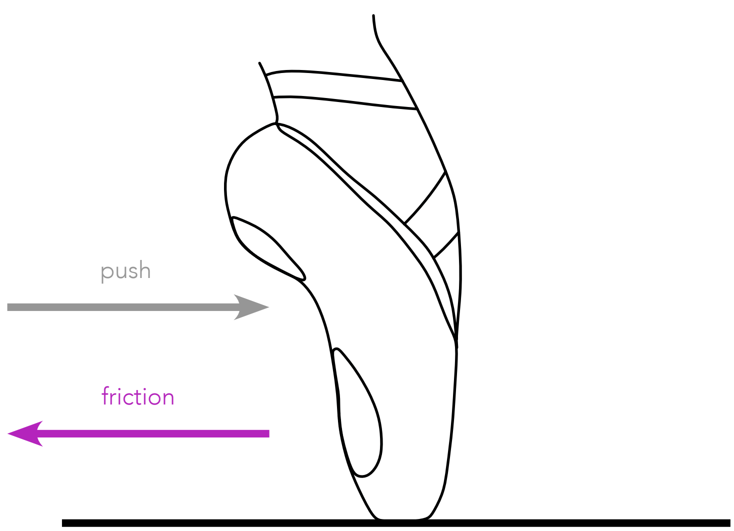


Figure 5.13 Friction from the floor is very importat for balancing while on pointe shoes.

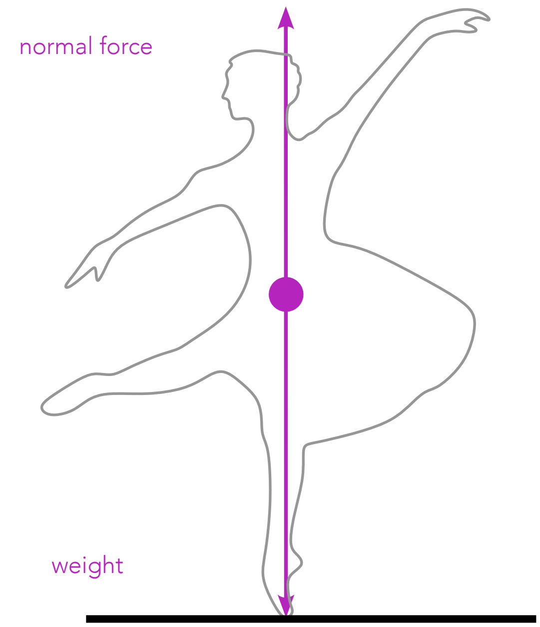


Figure 5.14 Center of gravity while standing on pointe shoes.

when the elements move between them. The frictional force is due to electrostatic forces between the two surface molecules.

Static friction is the force that prevents a physical body from moving even while the body is balancing. The measure is equal to the measure of the applied force that tends to move the body and can take values from zero Newton up to a maximum value equal to μs·FN. Where μs is a dimensionless size called static friction coefficient and depends on how rough a surface is. The coefficient of friction is calculated experimentally. FN is the force that develops between the adjoining bodies. When the external force exceeds the above value then the body begins to slide and is now exercised on this slip friction. Sliding friction is slightly less than the maximum of static friction, because when the body gains speed, the frictional forces are slightly reduced.

The weight of the dancer changes the amount of friction between her/her and the dance floor. Friction is needed to create the correct movements for each step. Without friction, it would be impossible for a dancer to stop her/him self from turning.

5.2.1.Applied forces while dancing on pointe shoes

While a dancer stands or even dance on pointe shoes there are many forces that act on the shoe from the dancer and the floor and forces that act on the dancer and the floor from the shoe. It has been very crucial the understanding of the different forces that are applied on the specific parts of the shoes.

Gravity:

In ballet, what we define as a "center of gravity"[9] is "that point where the downward force of gravity appears to act on the body as a whole" *(Fig. 5.14)* (Laws, 2002). While standing on one foot, the center of gravity lies on a vertical line that passes through the "area of support at the floor" (the contact area of the foot on the floor). When someone stands on pointe, the area of support is much smaller than standing on one flat foot and it´s much more difficult for the dancer to locate his/her gravity center. For the same reason, it is much easier if the tips of all toes are able to "touch" the floor than forcing the body to balance just on the big toe or the first two toes.

Additionally, when a dancer stands on a pointe shoe, apart from the box and the toes of the dancer, also the shanks holds some of his/her weight. The shank is the part of the shoe that bends and although the "center of gravity" should not pass through the heel of the dancer, some of the dancer's weight is being distributes also on the shank. In order for this to happen, the dancer needs to perform a complete plantar flexion of the foot and ankle and to try to combine an angle of 90 degrees. This is the reason why the shank needs to be made of a very resistant and flexible material.

Poisson's effect:

One of the most important realizations is that the box of the shoe, is nothing more than an application of Poisson's effect *(Fig. 5.15)*. Poisson's effect describes

9 Dancers usually call this as his/her "center".

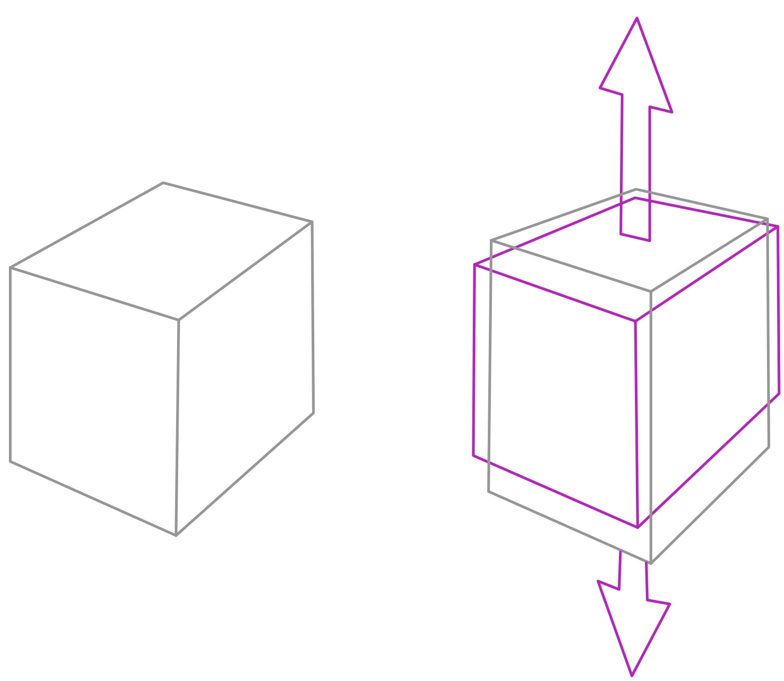


Figure 5.15 Poisson's effect is the phenomenon in which a material tends to expand in directions perpendicular to the direction of compression.

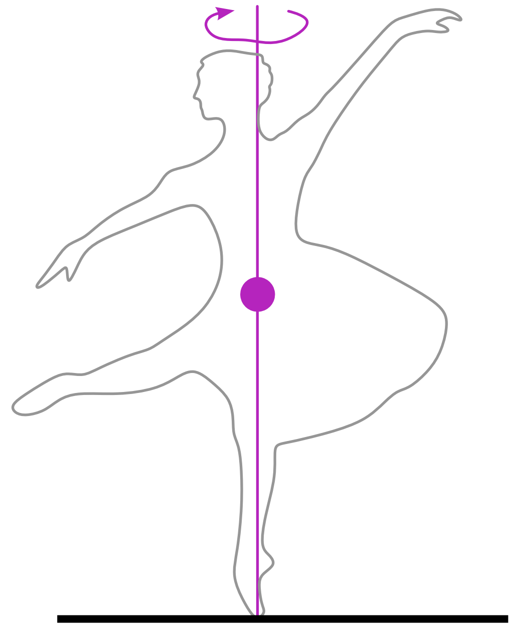


Figure 5.16 Torque is the force that enables dancers to perform pirouettes.

the expansion of a material in directions perpendicular to the direction of compression. The weight of the dancer, acts as a perpendicular force on the toes of the feet. For that reason, the box of the shoe works as a “confinement reinforcement" for the feet, tiding the toes together and not letting them to expand and thus, it helps the dancer keeping the axis of his/her body perpendicular. That’s why it is very important that the vamp covers the joint at the base of the toes and at the same time has to hold the toes tide but at the same time letting the minimum of space for the toes to move slightly sideways.

Traction:

Pointe shoes were invented from the desire of the ballerina to “fly”, to look weightless, balancing on an almost non-existent area. When a ballerina dances on demi-pointe (rising on the ball of the foot), the area of contact between the feet and the floor is bigger than when she dances on pointe and the area of the contact is just the small surface from the tapered box. As a result, the small contact area, reduces the rotational traction that can be used and it increases the possibilities of slipping. It is widely admitted by dancers that pointe shoes slip more easily than “flat” shoes and they require much less force to turn.

As the magnitudes of coefficient of static and kinetic friction depend on the chemical and mechanical properties of the surfaces, the properties of the materials of both pointe shoes (the area of the platform of the shoe) and the floor are very important parameters when dancing on pointe.

Torque:

If we exert a force on a body that has the ability to rotate around a fixed axis, then the body rotates unless the force carrier passes through the axis rotation, for example when the hand turns a screwdriver *(Fig. 5.16)*. This in physics is called torque. When turning on pointe (doing a pirouette), the dancer experiences a torque (Imura and Yeadon, 2010). Unlike ice skater though, that turn on an almost frictionless surface, ballerinas "need" the friction while experiencing a torque, in order to be able to slow down and finally to stop turning after a specific number of turn. In this case, the frictional force acts equally on each point of the contact area. If the contact area increases, then the torque also increases. For this reason the dimensions of the platform are a very important for having in mind for the design.

5.3 Material Approach

As mentioned before, every part of the shoe needs to perform in a specific way depending on the anatomical characteristic of the foot that corresponds to a specific part of it. The applied forces while dancing also impact the specific parts of the pointe shoe in a different way depending on the action that is being performed. Each part of the shoe requires specific material properties *(Fig. 5.17)*. Depending on the functionality of each part, some need to be resistant to fructure and others need to be resistant to friction. Some of them need to protect the toes and some others need to hold the weigh of the whole body. It has to be defined, which are the material characteristics that are needed for every part of the pointe shoe taking in account the health and comfort of the dancer as well as

Figure 5.17 Conventional pointe shoes are made of many and different materials because each part of the shoe needs to perform in a different way.

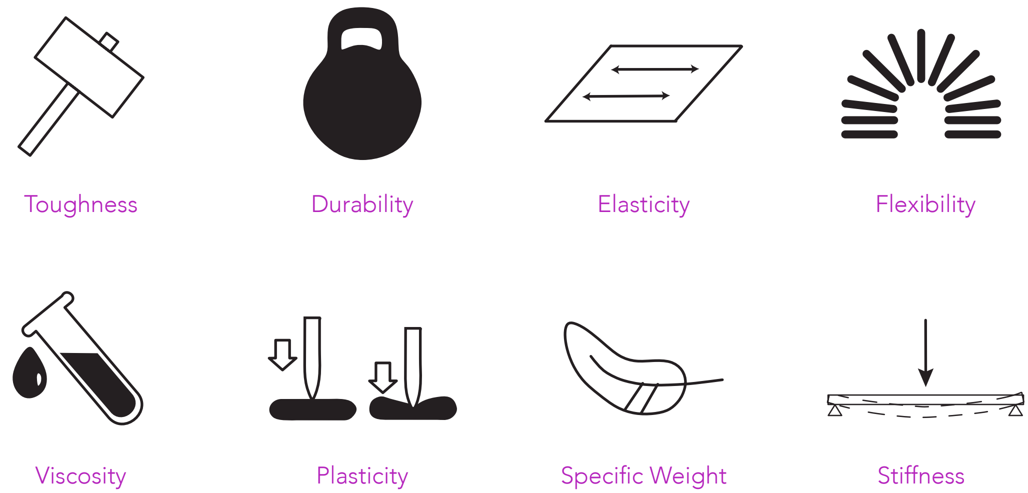


Figure 5.18 Mechanical properties of the different materials of the pointe shoes.

the structural requirements.

5.3.1.Mechanical properties:

Below we appose a list of the mechanical properties that are required for the different parts of the pointe shoes *(Fig. 5.18)*:

Durability: Ability to withstand wear, pressure or damage. Hard wearing.

Elasticity: Ability of a body to resist a distorting influence or stress and to return to its original size and shape when the stress is removed.

Flexibility: Ability of an object to bend or deform in response to an applied force, pliability, complementary to stiffness.

Plasticity: Ability of a material to undergo irreversible or permanent deformations without breaking or rupturing, opposite of brittleness

Specific weight: Weight per unit volume.

Stiffness: Ability of an object to resist deformation in response to an applied force, rigidity, complementary to flexibility.

Toughness: Ability of a material to absorb energy (or withstand shock) and plastically deform without fracturing (or rupturing)a material´s resistance to fracture when stressed, combination of strength and plasticity.

Viscosity: A fluid´s resistance to gradual deformation by tensile or shear stress, thickness.

5.3.2. Material properties for each part of the shoe:

(Table 5.1)

Platform:

The platform for instance, that is the flat surface on the tip of the shoe, is the part of the shoe that is in constant contact with the floor. As the platform forms part of the box, traditionally, is made of packed layers of fabric, cardboard and/or paper, dipped and hardened by glue and then it's covered by satin.

The platform, as it holds the whole body, needs to be really rigid and sturdy. On the other hand, the outer layer needs to be resistant to the friction with the floor and at the same time, the dancer needs to be able to perform pirouettes without slipping, otherwise there is the danger of falling out of balance.

Box:

The box, as already mentioned, is the part of the shoe that hold the toes together. The box determines fit and comfort. With the exception of the brand Gaynor Minden that is made from elastomeric materials layered with pieces of shock-absorbing foam, the box is traditionally made the same way as the platform, layers of fabric, paper and hard glue. The layered composition of the box also functions as an absorber of the forces that the foot is subjected.

Usually, the inside of the box it is just covered with a fabric for absorbing the

Part of the shoe	Material properties
Platform	Durability, Rigidity, Toughness, Resistance
Box	Durability, Rigidity, Stiffness, Plasticity, Viscosity
Shank	Rigidity, Flexibility
Vamp	Elasticity, Plasticity, Viscosity
Outer of the shoe	Elasticity, Resistance
Ribbons	Durability, Stability
Sole	Durability, Elasticity, Resistance

Table 5.1 The different parts of the pointe shoes and the mechanical properties that each part requires.

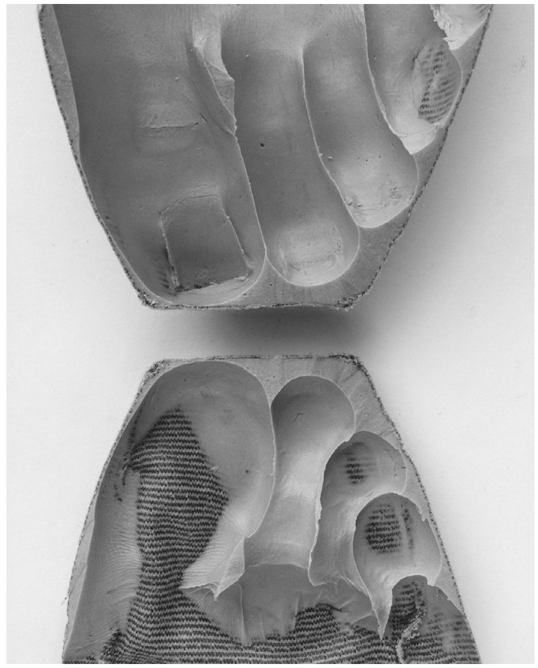


Figure 5.19 A protective padding made of silicone using a mold to create it.

sweat. The problem here is that the materials that are used are very rigid and stiff that not only makes it very heavy and uncomfortable, it is also the reason of many injuries, like bunions, callus, corns or even breaking of nails. Many dancers in order to avoid all these injuries, they use protective paddings made of cotton, fabric, foam or silicone *(Fig. 5.19)*.

Another problem that dancers face, is the short life of the shoes. The box of the conventional shoe after a short time of using the shoe, and if the dancer is very strong or has to perform very demanding steps and spends too much time en pointe, then the shoe degenerates quite fast. A professional dancer at the top of her career might wear out 65 pairs of pointe shoes a month (Cunningham et al., 1998). For that reason, the increased lifespan is another important parameter to take in account when deciding for the material of the box, as is one of the first parts of the shoe that begins to degenerate.

For all these reasons it would be suitable to use a hard material for the structure of the box that will offer durability, rigidity and stiffness and the inside of the box should be resolved by materials that offer viscosity and plasticity like maybe a material similar to a memory foam or silicone (Colucci and Klein, 2008).

Shank:

The shank plays a supporting role. In the conventional pointe shoes is a narrow spine that is placed between the inner and outer sole. Even though most of the dancer's weight is transmitted to the platform, her foot needs a support to push her against in order to be able to remain on pointe. It is placed under the arch of the foot and it has to be totally rigid along the sagittal plane of the foot and quite flexible along the transverse plane. This is one of the most crucial parts of the shoe because when the dancer stands on pointe, she needs a complete support for she is in complete plantar flexion and she needs to remain stable for maintaining her balance. At the same time though, when a dancer is rising from demi-pointe to a full pointe, or when she is landing on the ground, she needs to bend her toes to the opposite direction and thus, she needs to be able to bend the shoe in the opposite direction. In consequence, the design of the shank mush provide controlled flexibility in order to allow a smooth transition (from demi-pointe to full pointe and the contrary).

In addition, the thickness of the shank of the conventional pointe shoe, is equal, while it is observed that is not necessary to have the same support equally along the foot. The part where most support is needed is under the toes. It has to be noted that the shank and the box are created separately and it could be proposed to be designed as one piece.

Outer sole:

The outer sole is usually made of thin leather allowing flexibility and absorbing pulsations from the ground, specially when the dancer performs jumps.

Top and side of the shoe:

The top and side of the shoe are traditionally covered by cotton and an outer layer of satin, canvas or leather. This is the part that holds the whole shoe together and it has to be so elastic and flexible to fit the dancer like a second skin.

Figure 5.20 There are different kinds of ribbons, the most common are the satin ones.

Figure 5.21 There are at least 13 different materials in the conventional pointe shoes.

Ribbons:

The ribbons, even though they are usually sold as an extra part, they are very important for adjusting the shoe on the foot *(Fig. 5.20)*. It's a traditional ornament for the shoes and are not easily substituted because of the prestige they carry. The ribbons are the image of the ballerina. Every conventional shoe needs two pieces of 50-60cm long and 1,5cm width of a ribbon. The length truly depends on the size of the ankle of the dancer. There are plenty of types. Some of them are satin on one side and grosgrain or malt finish on the other. The reason they are made like this, it's because the grosgrain, as a rougher surface is placed toward the leg for gripping the tights and holding the shoe in place. Ballerinas usually tight their shoes too tightly. For this reason, they could be replaced by an elastic.

Every part of the shoe has its functions and requires materials with different properties *(Fig. 5.21)*. Having studied these requirements, along with the properties that are needed for better performance of the shoe, is easier to make a proposal for replacing some of them. The reason of invastigating new materials is because this project is proposed to be developed and to make various prototypes using digital fabrication techniques and tools.

5.3.3.Materials that can be used in Rapid Prototyping

Even though pointe shoe making process has always been a craftsmanship, in this investigation, additive manufacturing will be applied as the process for creating point shoe prototypes.

There is a lot of investigation going on the last 20 years studying the potentialities of the 3D printers. Scientists are experimenting with many materials. Up until today, the most studied and promising are polymers, ceramics and metal. The majority of 3D printers though is concentrated on polymeric materials because of their ease of manufacturing and manipulating.

There is a huge variety of polymeric materials that represent a very wide range of mechanical properties and applications[10]. As already mentioned, because of their processability and low cost, they are by far the most utilized class of materials for 3D printing. There are many types of polymers, like thermoplastics, elastomers, hydrogels, functional polymers, polymer blends and other composites that can be used for 3D printing *(Fig. 5.22)*.

Between the polymers that can be found in the market are Polycarbonate (PC), acrylonitrile butadiene styrene (ABS), poly ether ester ketone (PEEK), poly etherimide (ULTEM) and Nylon. These materials are usually used for processes that require thermoplastics or processes that require heating to a semi-liquid state and close to the melting point. Fused Deposition Modeling (FDM), Jetting (InkJet) and Selective Laser Sintering (SLS) are some of the additive manufactur-

10 They are used for fabricating bottles, toys, tools, bags, phones, computers, tools, cushions, electronics etc.

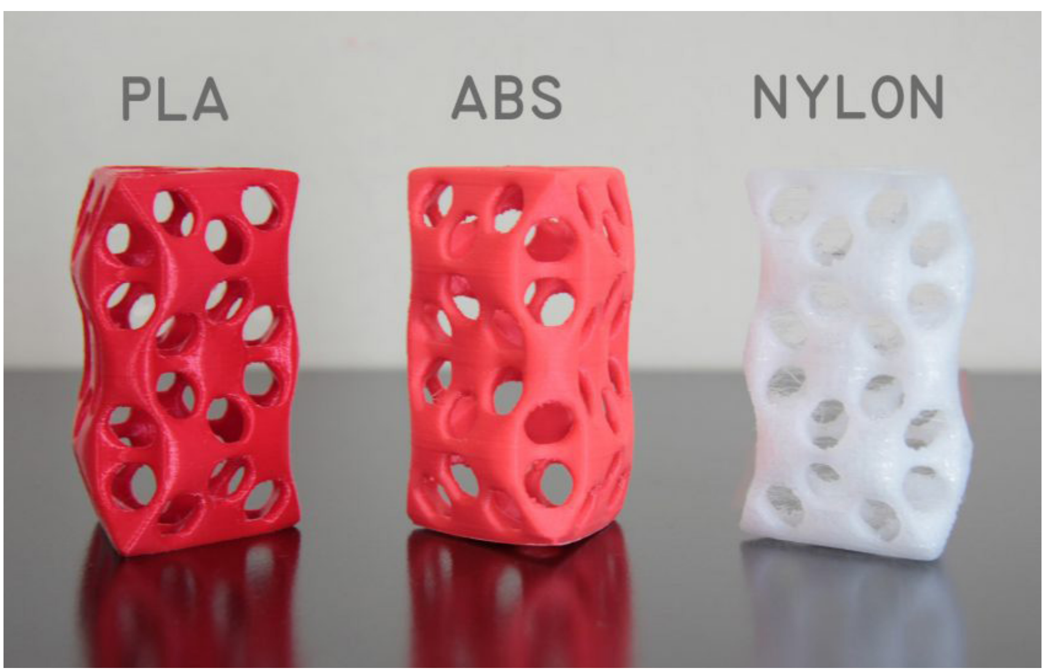


Figure 5.22 Thermoplastic polymers are the most common for additive manufacturing.

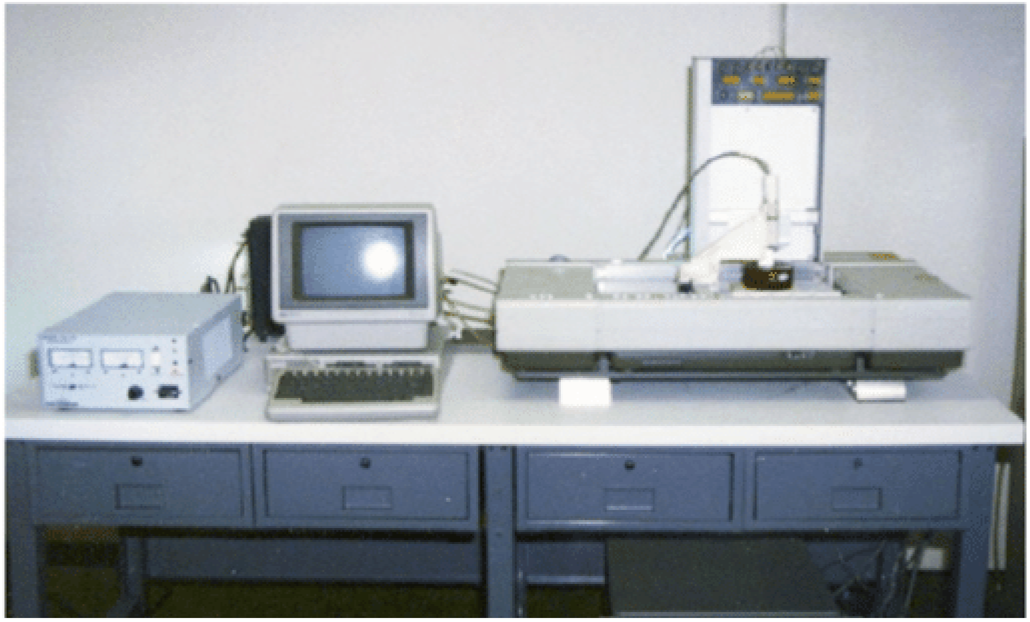


Figure 5.23 The Stereolithography Apparatus was invented by Charles Hull.

ing techniques that require thermoplastics. These materials become soft when they get heated and once they are extruded, they solidify. In this process, no chemical reaction occurs. They have low viscosity when heated and for that reason the extrusion is made through a nozzle. Some other techniques, they use polymers in their liquid state (resins) that they solidify after the process. These polymers are called Thermoset polymers and have been used in many high-technology applications because of their thermo-mechanical properties.

5.4 Additive Manufacturing (AM)

Additive manufacturing is also called as rapid prototyping or 3D printing. The term rapid prototyping (RP) is describing a process in which a quick prototype of a product or a part of a product is made[11] (Gibson et al., 2015). In AM a model is created using a three-dimensional Computer Aided Design (3D CAD) system. It functions by creating geometries by adding material in layers. Each layer is a thin cross-section of the geometry that is derived from the CAD data. The quality of the result is proportioned to the width of each layer. The thinner the layer is, the closer will look to the original geometry. One of the advantages of the rapid prototyping, is that mostly in the product industry the clients or the creator can test their ideas and have a feedback during the development process.

3D printing technology was first appeared in the 1980s. In 1982, Dr Hideo Kodana of Nagoya Municipal Industrial Research Institute invented the first layer by

11 This term is also used by management consultants and software engineers for describing a process of developing business and software solutions.

layer photopolymer rapid prototyping process but his method was not commercialized. Later, in 1983, Charles Hulls came up with his patent “stereolithography” *(Fig. 5.23)* . This is a technique where a 3D object is created by a computer that moves a laser beam that is able to build up a structure, layer by layer, from a liquid polymer that hardens when it gets in contact with UV light. Hull was also the developer of the STL file format, that is the most common file that 3D printers use nowadays.

In the late 1980s, the Selective Laser Sintering (SLS) was also invented. It was developed by Carl Deckard and it’s a technique where layers of powdered material (usually metal) are fused using a high-power laser. In the 1980s the Fused Deposition Modeling was also developed by Scott Crump and Lisa Crump. It’s a technique where an object is created layer by layer by a material that is heated and extruded through a nozzle. Up until today, this is the most common 3D printing technology. In the 1990s, engineers came up with the technology of Direct Metal Sintering and Binder Jetting. This was also the decade that scientists started developing Bioprinting for medical applications. From 2000 and up until today, various additive processes matured. Today, 3D printers have reached in such a level of quality and price that everyone could afford and be able to manage one *(Fig. 5.24)*.

AM as a process, involves a number of steps that begin from the virtual CAD description and they finish with the physical model *(Fig. 5.25)*.

1. The first step is the model designing that can be done by any CAD modeling software which can give as an output a 3D solid or a surface representation.

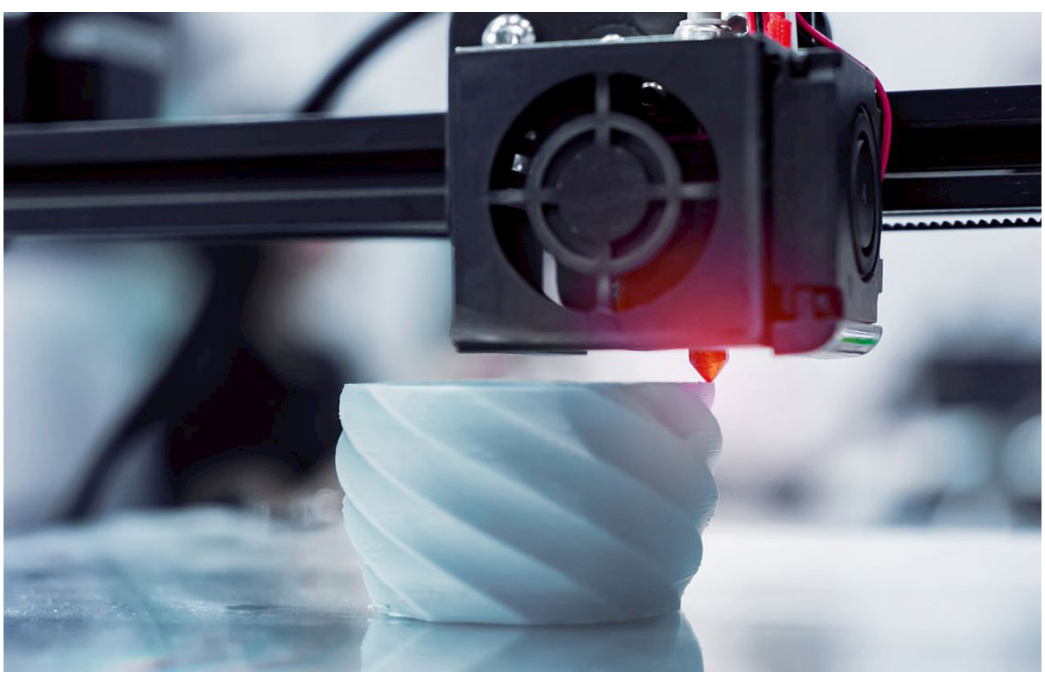


Figure 5.24 3D printer

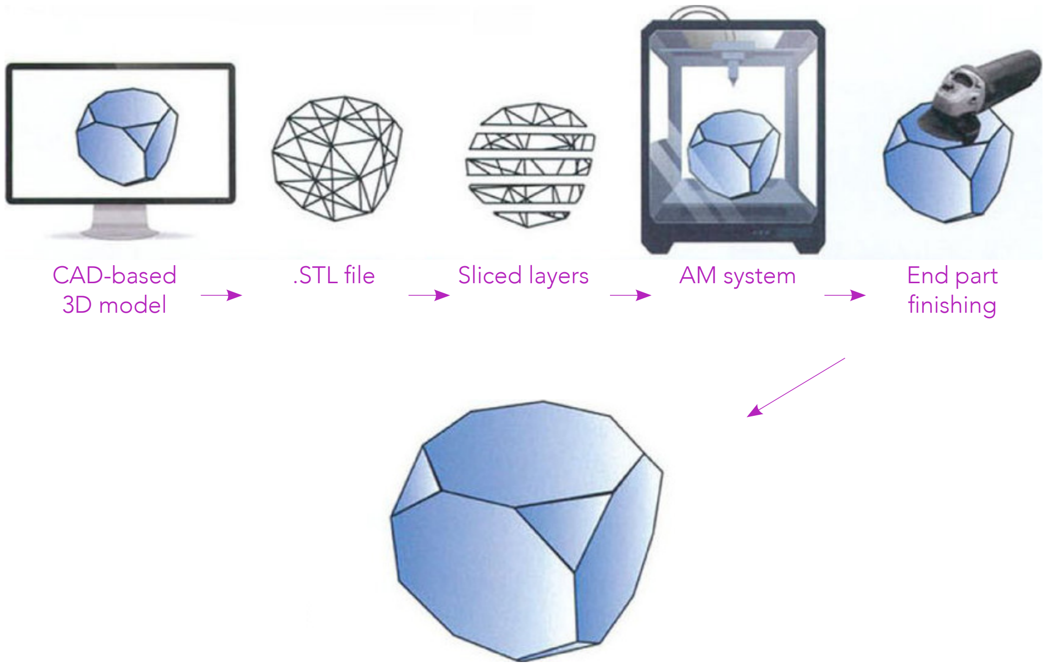


Figure 5.25 The steps of the process of 3D printing.

This representation can also be created by a 3D scanner.

2. The second step is the creation of the STL file format, that can be used by almost all 3D printers. This can be created by the same CAD modeling software or convert it using another program.

3. Then the STL file is transferred to an AM machine software where the STL can be manipulated and checked of the scale, rotation, etc.

4. Before starting the build up process is important to set up the settings that are related to the build up parameters, like for example the material constrains, energy source, layer thickness, building pattern, speed etc.

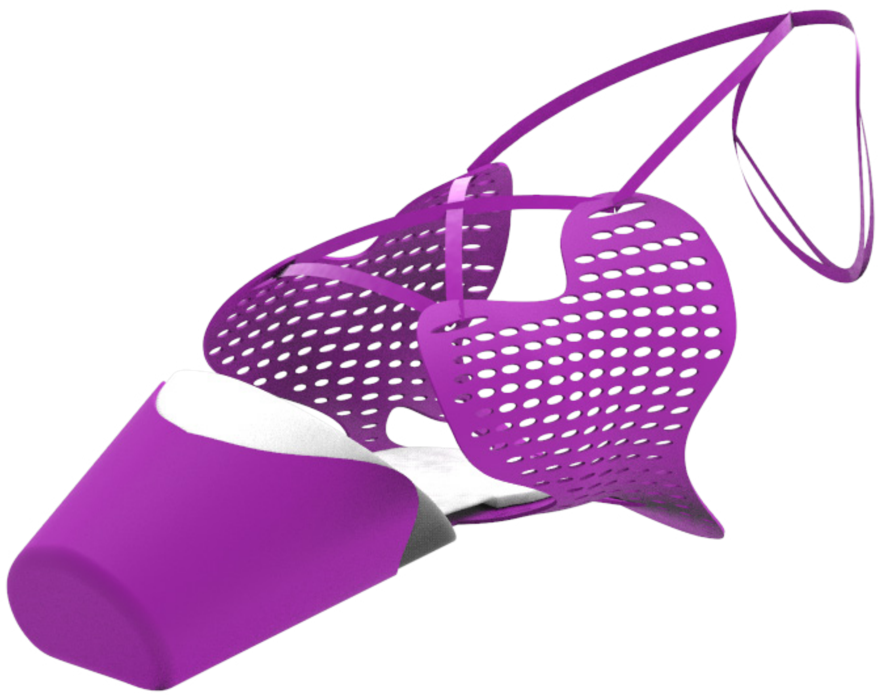
5. The file is sent to the AM machine and then the build up process is automated and done by deposing material layer by layer. The machine can carry on almost without supervision.

6. Once the object is built up and the machine stops working, the object needs to be removed from the build platform and if there is any, from its support structure as well.

7. Finally, there might be required some post-processing such as cleaning, polishing or painting.

As explained above, the advantage of the AM is the automatization of the fabrication process and the fact that the feedback of the prototyping can happen very fast. For this reason, AM is undoubtedly the most appropriate technique to use for the pointe shoes prototypes.

Chapter Six: Results



6. Chapter 6: Results

The results of the investigation are explained and divided into three stages:

- The first part of the investigation is concentrated on the geometrical aspect of the problem. Using 3d scanning technology and the theoretical background related to foot and dancing anatomy, were defined the geometrical variables that need to be taken in account while designing a pointe shoe and its specific parts. A 3d scanner can give us an exact 3d model of any object, that's why scanning different types of feet was very helpful in order to have a more complete topological analysis. This analysis was needed in order to define better the variables for developing the parametric system. The 3d models of the scanning were also used for the development of the parametric system. For the 3D scanning we used a Structure Sensor connected to a computer along with the software SKANECT. Five women's feet were scanned. Scans were done with a naked foot, pointed as much as possible. In order for the scan to be done, the structure sensor had to be rotated 360 degrees around the foot to accomplishing the best result possible.The defined variables, only concerning the geometrical approach of the study were translated into measurable data in order to be introduced to the graphical algorithm editor (Grasshopper 3D). These variables were fundamental for building the topological diagram of each foot. After defining these variables, it was crucial to map points of the foot so that they could be considered for drawing the diagram and thus be able to take the measurements. These points, corresponded to a specific anatomical part of the foot.
- The designing of a shoe using a graphical algorithm editor was made in parts because each part of the shoe has different requirements as per performance and needs to support a different part of the foot.

Figure 6.1 (left) A render of the proposed pointe shoe.

- **The fabrication of the shoe that was done using digital fabrication tools. Pointe shoe making process is an artisanal craftsmanship working with the same materials for at least two centuries. In this project, it was very crucial to study and understand the performance of the traditional materials with the purpose of understanding their properties and be able to propose new materials. One of the advantages of the digital era is that you can link human data to the design and manufacturing. 3D printing as an addictive manufacturing process, allows us to transform digitally developed 3D models into physical objects. For that reason most of the parts of the shoe, 3D printing was proposed as a fabricating process. The different requirements of the different parts of the shoe need different material properties. For that reason for some parts (for example the box) was used PLA filament because the box is the part of the shoe that needs to be strong for supporting the whole body. In other parts of the shoe (for example the inside cushioning) TPU filament was used which is a much more flexible material.**

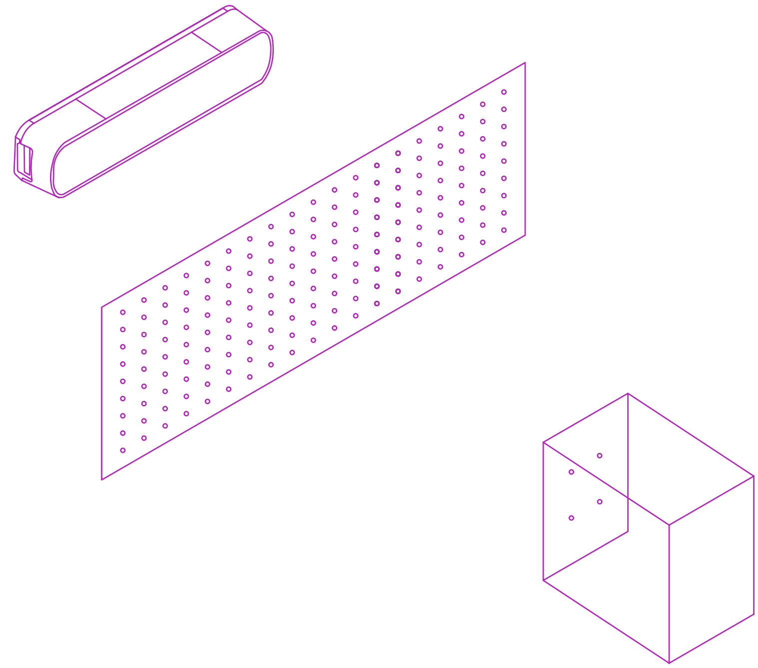


Figure 6.2 Structure Sensor is a mobile device that was developed by Occipital Inc. in 2014. One of its advantages is that can be attached on a mobile device (an ipad or a phone) and that it's fully controlled by a software (it doesn't have any buttons on its surface).

6.1 Scanning process:

As already mentioned, the design process that is being investigating, begins with the geometric analyzation of the foot and the definition of the geometric variables that will be taken in account for designing each part of the shoe. More specifically, the design process begins with the 3D scanning of the foot.

6.1.1.Detailed methodology of the scanning process:

For the 3D scanning, a Structure Light[1] Sensor (SLS) has been used which, like many others 3D scanners, consists of a light source and a camera that are separated. The first one projects a beam of light and the second one captures the points on the surfaces. More precisely, a laser passes through a diffraction grid, in order to project a speckle pattern onto the environment *(Fig. 6.2)*. Then the sensor (camera) gathers the reflected light and generates depth data. This point data-set that is the output of the Structure Sensor, is processed through image and triangulation algorithms in order to be converted into 3D information (Kalantari and Nechifor, 2016).

The scans were made connecting the scanner directly to a computer and using the SKANECT software to process them. SKANECT[2] is a software or a 3D reconstruction system that uses a Structure Sensor, Microsoft Kinect or Asus Cam-

1 Structured light is the process of projecting an accurate pattern (often a grid) onto a target, for measuring the displacement or distortion of it.

2 The recording feedback were executed by a CPU acceleration even though a GPU can also be used, specially if you are willing to render the scanned object.

era for scanning an object and it can create a 3D polygon mesh allowing us to manipulate or render a geometry.

For scanning each foot, the person was placed sat on a chair with one foot touching the ground and the other one (the one that was going to be scanned) supported horizontally on a stool in such a way that the back of the calf touches the stool and the foot, including the ankle is hanging *(Fig. 6.3)*. This position is considered to be quite comfortable for the models, as they had to remain in this position for some time.

Beginning with SKANECT software, there is a list of settings that need to be set in order to get the best possible result of the scanning process. In the first window (Prepare – New), one of the most important setting is the size of the bounding box. The bounding box defines the peripheral area of the object of space we want to scan. In this case, the bounding box needs to include the foot and a small part of the leg (from the ankle until one third of the calf). The vertical dimension from the ground until the foot is also important for defining the size of the bounding box, which it was set at 0.6m X 0.6m X 0.6m *(Fig. 6.4)*.

At the window "Prepare-Settings", it was set the feedback quality of the result to high and the option "All Frames" was chosen for saving all depth and color frames to the machine, so that it would be allowed to reconstruct the scan.

The next tab is called "Record" and this is when the scanning of the object-foot starts. The workspace shows a grid as an x/y plane and the bounding box in the middle. On the right of the screen appears a video and an infrared view of what's

Figure 6.3 The first model prepared for the beginning of the scanning process.

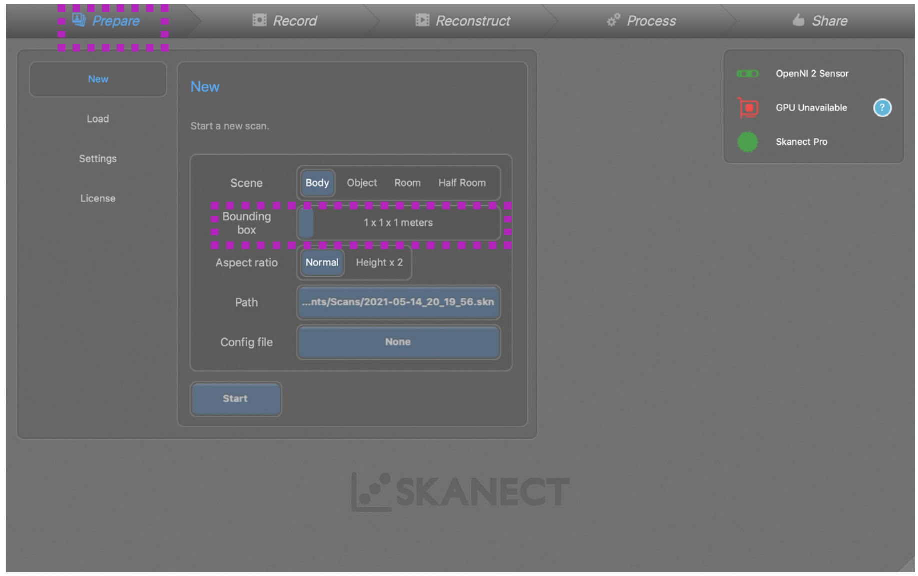


Figure 6.4 Defining the settings of the scanner before starting.

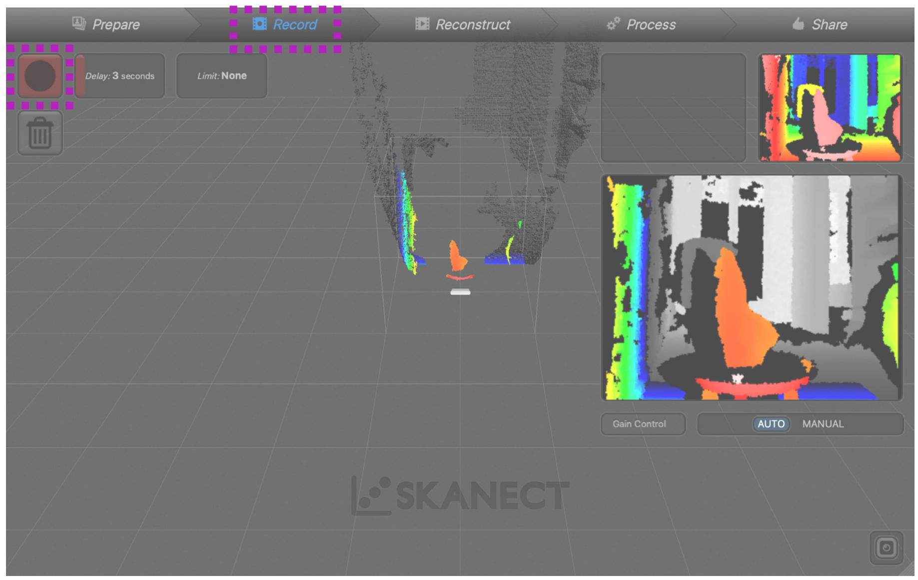


Figure 6.5 On the upper left corner, when a GPU acceleration is availiable, it can be seen also a normal video apart from the infrared view which record in real time, textures and colours that can be used later for rendering.

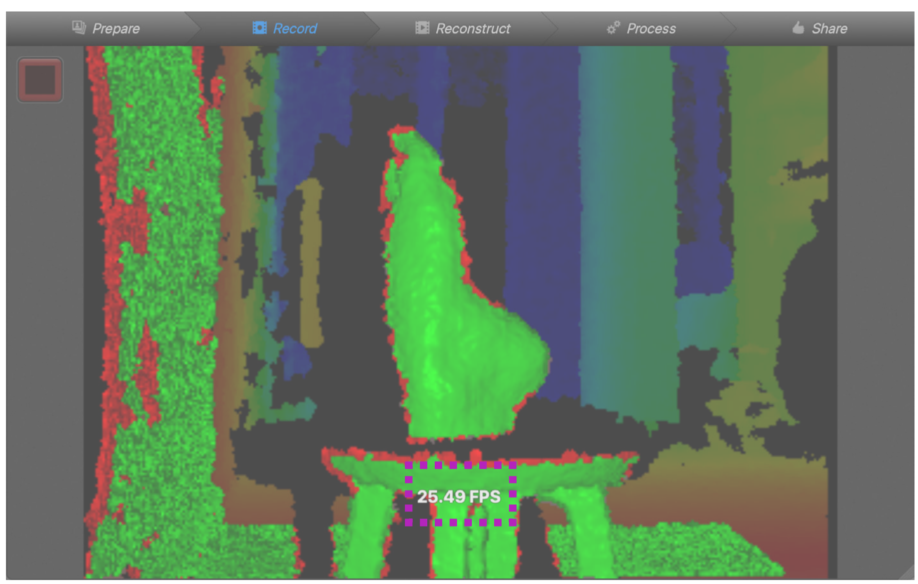


Figure 6.6 Apart from the giving the feedback of how many frames it captures, when moving too fast or getting far from the defined area of the bounding box, the geometries in the screen become red, meaning that there will be errors or that it cannot go on.

included in the bounding box *(Fig. 6.5)*. In the window below these two views it's going to appear the scanned geometry.

When starting the scanning (press "Record"), the scanner needs to capture the foot covering all 360 degrees of the view *(Fig. 6.6)*. The first scans were made with the models having the foot in a relaxed position and the second ones were done with the model performing a complete plantar flexion. One of the reasons that it wa s decided that the foot should be hanging, was for avoiding any distortions of the dimensions of the foot. For example, the width of the foot changed slightly when we put pressure for stepping. Also, because of its structure and depending on the individual flexibility of the joints and muscles, the foot width changes when we are in relaxed position or performing a full plantar flexion and the toes tend to come closer to each other. It was interesting to have both positions of the foot, in order to be able to compare the measurements.

As already told, the scanner should capture a 360 degrees of a view of the foot, including the toes. The sensor should move fast enough to get high frame rate between 18-20 frames but when moving very fast it may mess up the result.

Once the scanning is completed, the "Stop" button can be pressed. Then the software starts processing the mesh, until it appears in the bounding box. In the reconstruct tab we can try and fix the created mesh. Sometimes there might be holes or the mesh may need to become a bit smoother. The "Fidelity" option may add some detail to the textures. In the process tab, we can go on with the reconstruction of the mesh, fill in any holes or make the mesh smooth.

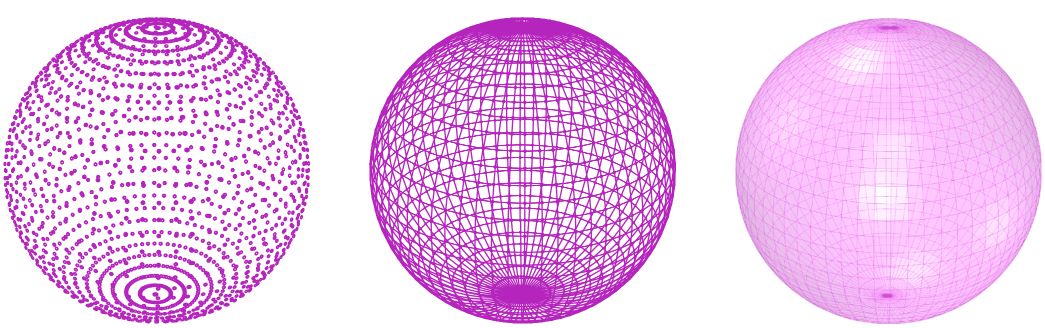


Figure 6.7 A mesh is a representation of a 3D model that consists of a collection of vertices, edges and faces and it's created through the triangulation of 3D points.

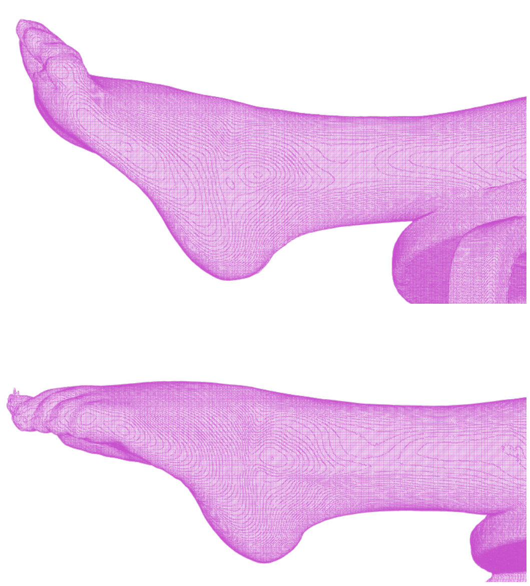



Figure 6.8 (left) Reconstructed meshes from a left foot, above in relaxed position and below performing a full plantar flexion (screenshots from Rhino).
Figure 6.9 (right) A rendered mesh from a right foot.

The next step is the export of the model/mesh *(Fig. 6.7)*. SKANECT gives us four options of exporting type files[3]. The next steps of the design process requires the manipulation of the model in Rhinoceros 3D software. After confirming that all the options can be imported to Rhino, it was decided to go on with the "PLY" file format.

PLY or Polygon File Format, or Stanford Triangle Format, represents a 3D file format, that defines an object as a collection of polygons. More precisely, it defines it as a collection of vertices, faces, edges but also the color and normal direction (vectors) of the faces.

The process of the scanning includes the export of the mesh and then its introduction to Rhino. Once in Rhino, the meshes need to be checked for any discontinuities, reconstruct them and start measuring them *(Fig. 6.8 & Fig. 6.9)*.

6.1.2.3D Scanning results:

Five women's feet were scanned. Three of them were ballerinas, one of them had danced ballet in the past and another one had never danced in her life. Below are reported the examples of one ballerina and the last two models. Besides the variation of the width of the foot, the length, the type of foot, it was also interesting to see the variation of the arch flexibility.

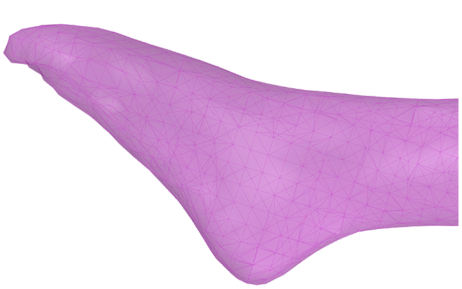
The first scans were made with a low resolution but it was a variable that it

3 Three of the options are PLY, STL or OBJ. There is a big debate which one of the three file formats is better. Even though STL is wide known, is used for the most 3D printing machines, while the other two formats were developed for completing that lack of properties of the STL. The file format one will use, it really depends on the needs, the situation and the software in which it will be used.

was changed because a lot of important information was missing, like have the best possible representation of the toes. As already mentioned, the length of the toes is a crucial parameter for defining the shape and length of the vamp and the box of the shoe. That's the reason why the scans should be done with the best possible resolution *(Fig. 6.10 & 6.11)*.

The next step was to open the PLY archives with Rhinoceros 3D software and convert them to a 3D Rhino file. It was then important to recognize on the 3D model, points that would help to define the geometric variables. As already explained, these variables were needed for the definition of a topological diagram of a foot. For this reason, the points recognized on the model, had to correspond to a specific anatomical part of the foot. This procedure, firstly required the study and recognition of the principal axis (Bähler, 1986) of the foot in order to get an orientation of the 3D models that would allow us to mark the needed points (Mochimaru, Kouchi and Dohi, 2000). The first axis that was needed to define, corresponds to the longitudinal axis of the foot that runs through the center of the head of the second metatarsal and through the center of the calcaneal tuberosity *(Fig. 6.12)*. This axis corresponds to the sagittal plane of the foot, that separates the foot into medial and lateral halves *(Fig. 6.13)*. Parallel to this plane, dorsiflexion and plantar flexion refer to the relationship between the surface of the foot and the anterior surface of the leg. This means that dorsiflexion is when the dorsum[4] of the foot moves toward the leg, and plantar flexion is defined when the dorsum surface of the foot, moves away from the leg. This is the axis

4 Dorsum and planum refer to both mid foot and front foot. Dorsum is the area of the foot facing upwards while standing and planum is the area of the foot facing downwards while standing.



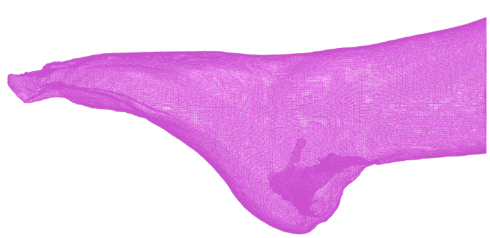


Figure 6.10 (left) The faces of the mesh are bigger and as it can be seen, it lacks of important information.
Figure 6.11 (right) The faces of the mesh are smaller and this is the quality of the scans that it was needed.

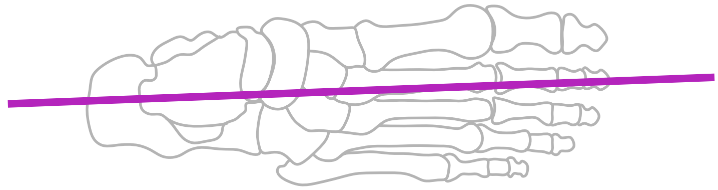


Figure 6.12 The cardinal longitudinal axis of the foot is along the sagittal plane.

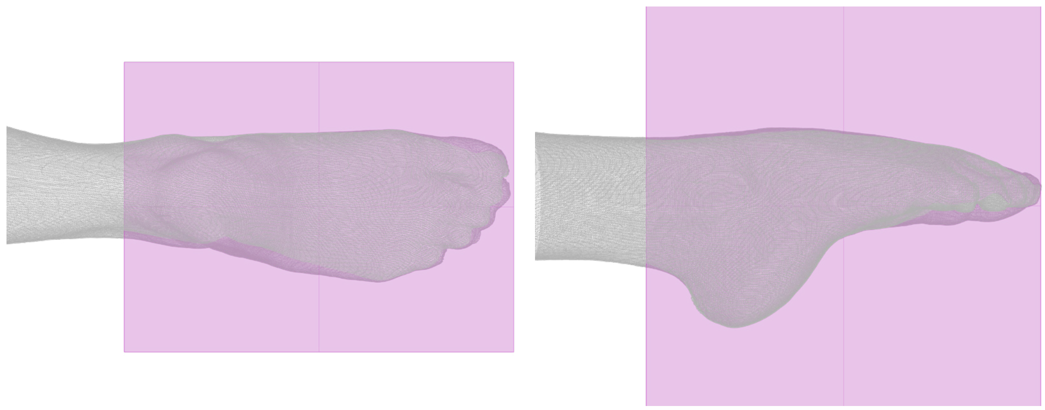


Figure 6.13 The sagittal and transverse plane along of which the foot can move.

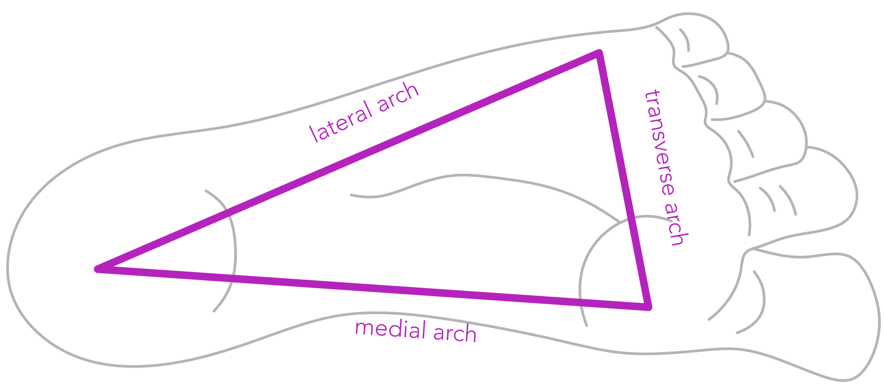


Figure 6.14 Even though the idea of defining the foot as a vault is quite critiz-able, its construction, allows to the fore-foot to take a great amount of weight and also it allows to the foot to adapt to uneven surfaces.

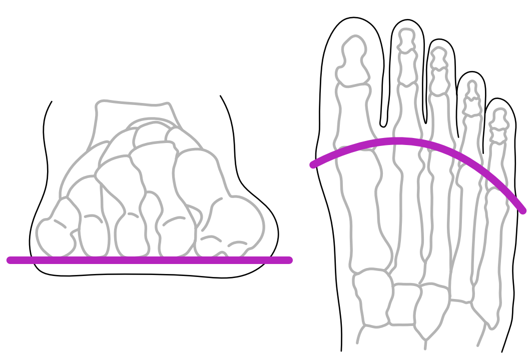


Figure 6.15 From metatarsal I to metatarsal V, the metatarsal bones form an oblique arch.

which traditional pointe shoe makers use for building the shoe last of the traditional point shoe. Some doctors, compare the foot architectonically to a vault (Bähler, 1986) *(Fig. 6.14)*. The second axis that we need, doesn't correspond to a mechanical plane as the first one but it corresponds to the arc of the Transversal Anterior Vault of the foot *(Fig. 6.15)*. This arc is formed by the metatarsal bones, starting from the first metatarsal to the fifth metatarsal and while walking it tends to drop due to excessive pressure and at the same time it can partly be attributed to walking on level ground. While being on pointe shoes though, this arc reaches its highest angle. The imaginary line that is formed when this arch is "dropped" is the axis we need for the orientation of the 3D model (Hill et al., 2017).

Once the foot is oriented as mentioned above *(Fig. 6.16)*, it was needed to define the points that are important for drawing a topological diagram. The chosen points (parts of the foot) had to be the ones that can be seen with a naked eye and the ones that help for building a measurable diagram for the needed variables *(Fig. 6.17)*.

- The first two points correspond to the calcaneus bone and it can be seen on the lateral and medial view of the foot. It is important to recognize the calcaneus bone for it is needed for calculating the heel width and also the foot length.
- The third point corresponds to the Lateral Malleolus that forms part of the fibula bone and it can be seen on the lateral view of the foot, whereas the forth point corresponds to the Medial Malleolus that forms part of the tibia bone (Grivas, 2002).

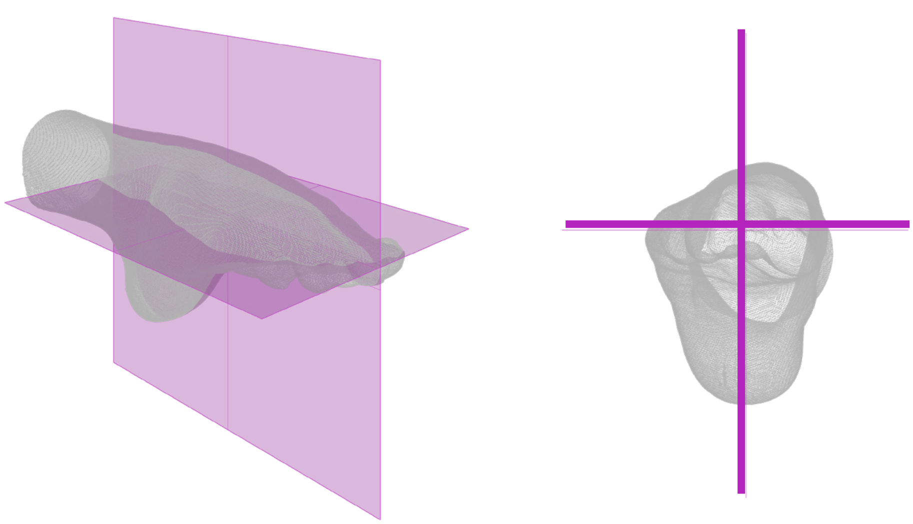


Figure 6.16 Orientation of the scanned 3D models according to the sagittal and transverse plane.

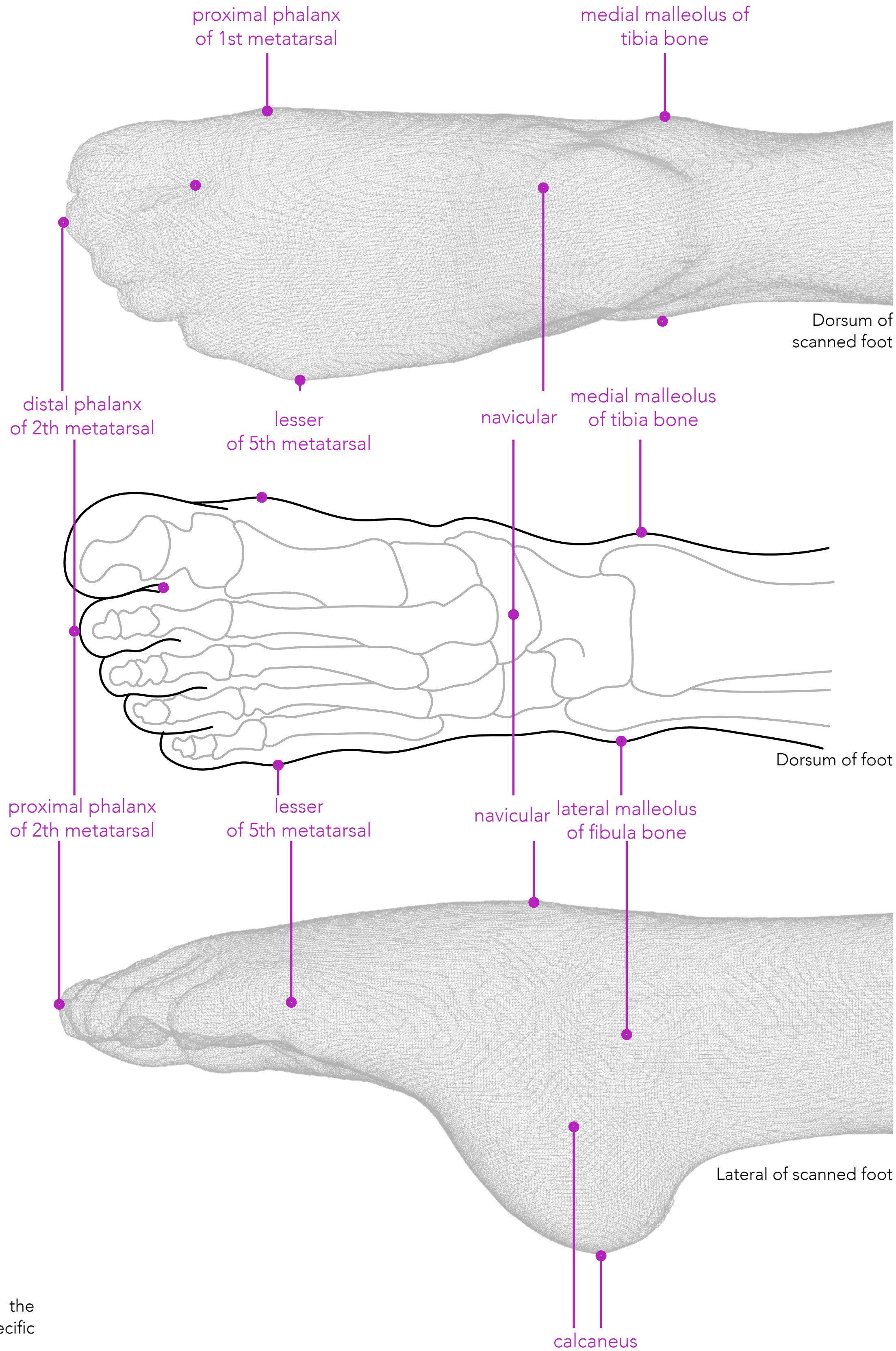


Figure 6.17 Mapping points on the scanned foot that correspond to specific anatomical part of the foot.

- Another point that can be better seen when the foot is performing a complete plantar flexion, corresponds to the navicular bone.
- The outer point on the joint between the Proximal Phalanx and Lesser of the fifth metatarsal can be seen on the lateral view of the foot and along with the Proximal Phalanx of the first metatarsal that can be seen on the medial view of the foot, are needed for defining the width of the foot.
- Another point that is important to mark, is the end of the distal phalanx of the first metatarsal that will help for calculating the length of the foot. It is already mentioned, that some people have the second toe longer than the first one. For those cases, it should be marked the distal phalanx of the second metatarsal.

Even though while designing the shoe, the whole geometry has been taken into account *(Fig. 6.19-22)*, defining some important measurable variables, it's been very helpful for defining each part of the shoe. These variables are:

- Foot width
- Foot type
- Toe Length
- Arch Type & Angle
- Foot Length
- Heel width

	Model 1	Model 2	Model 3
Foot width	83mm	89,5mm	83mm
Foot type	Greek	Roman	Egyptian
Toe length	44mm	49mm	47mm
Arch	Angle: 90° R:53mm	Angle: 69° R:67mm	Angle: 56° R:90mm
Foot Length	197mm	226mm	203mm
Heel width	48,5mm	54mm	57mm

Table 5.2 Measurements of the variables of three of the models.

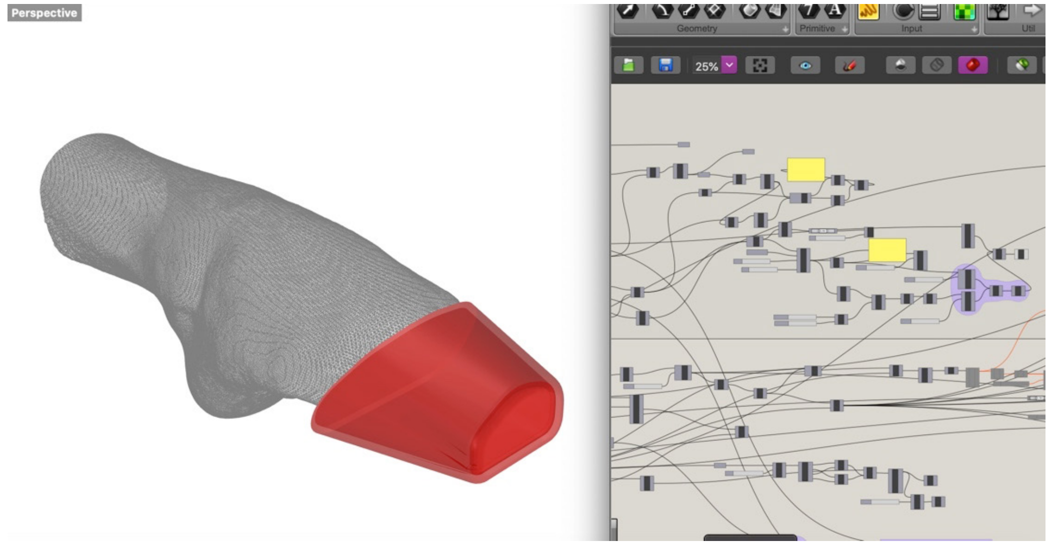


Figure 5.26 Rhino and Grasshopper 3D, parametrization of the box based on the scanned foot.

As it can be seen from the table and diagrams of the feet below, there have been three people with three different types of feet *(Table. 5.2)*. Both No1 and No3 models, have almost the same width and length of foot but the width of the heel and the foot type are very different. The No2 model, has the bigger foot. The angles of the arch of the feet, correspond to the relationship each one of the models has with ballet. The biggest angle corresponds to the feet of the ballerina, the second bigger angle corresponds to the one that had done ballet in the past and the smaller angle corresponds to the person who had never done ballet in her life. Even though this is quite logic, it is also a coincidence. It cannot be taken as granted that people who dance ballet have an arch with a big angle and off course it doesn't mean that people who never danced ballet have am arch with a small angle.

Conclusion:

As a result from the scanning process, can be reported the successful scans of different kind of feet. The detailed 3D mesh exported from the 3D scanning software, provided the required high resolution structure that was needed for continuing with the next step of the process that was the design and parametrization of the shoe. The results are considered to be done successfully as the detection of the characteristics of the foot that can be done effortless. With the information gathered from the scanning, combined with the theoretical background that was

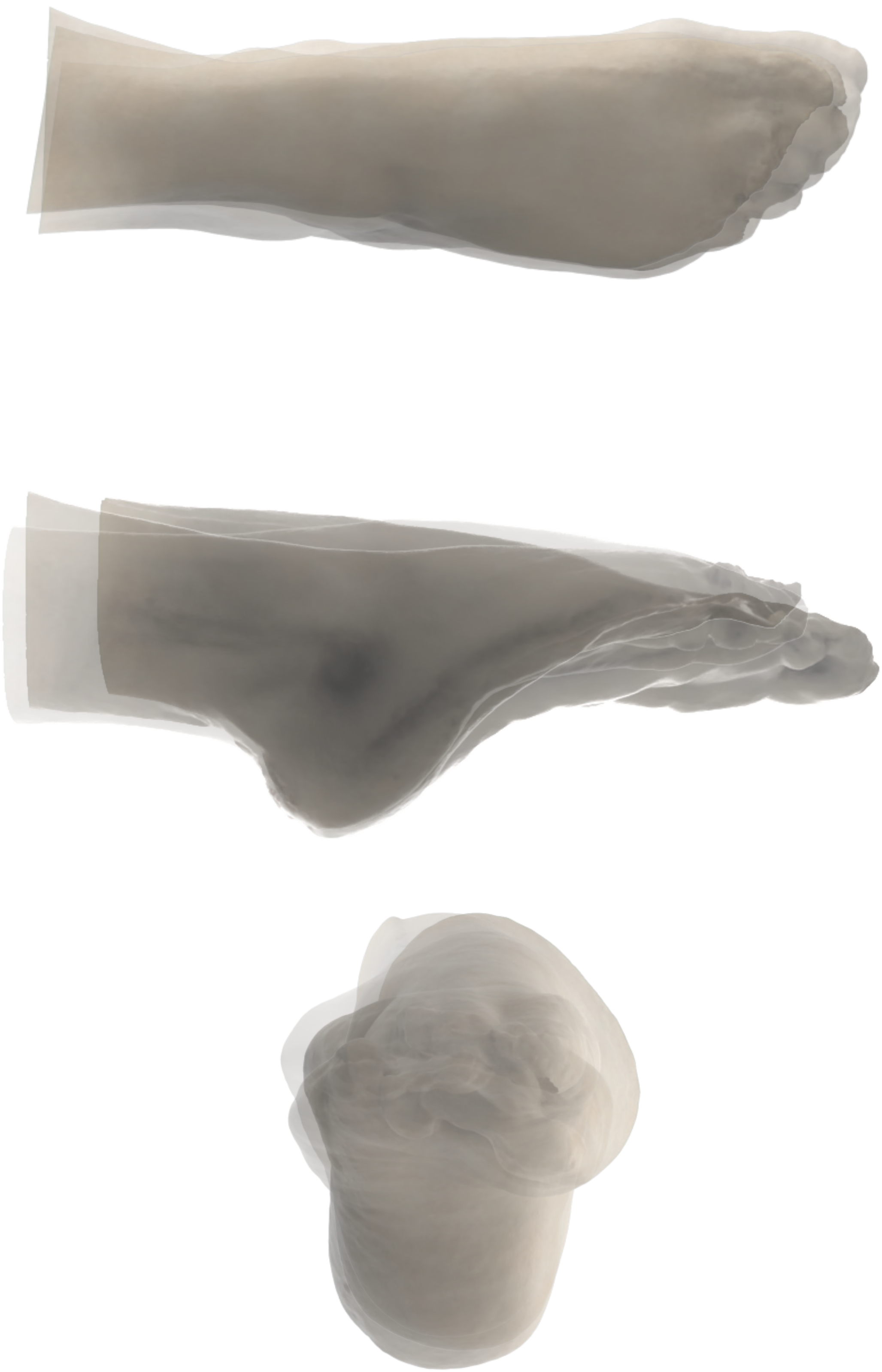


Figure 6.18 Model No 3 - bottom view of the right foot. It is quite notable that even that is smaller that the foot No 2, the heel is wider.

Figure 6.19 Top view of a left foot. The length of the toes is defined by the head of the longer toe until the end of the longer toe-separation line.

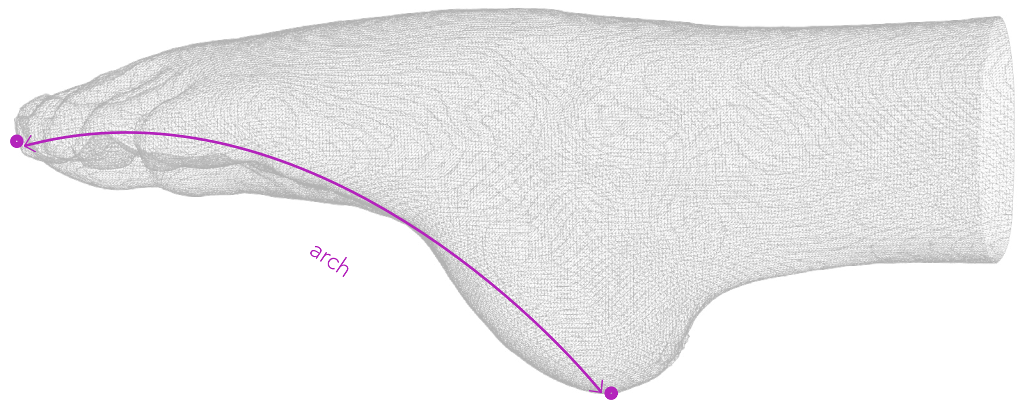


Figure 6.20 Lateral view of a left foot - defining arch of the foot. The angle of this arch is very important for ballerinas for obtaining at least 90° that gives a better support while dancing on pointe.

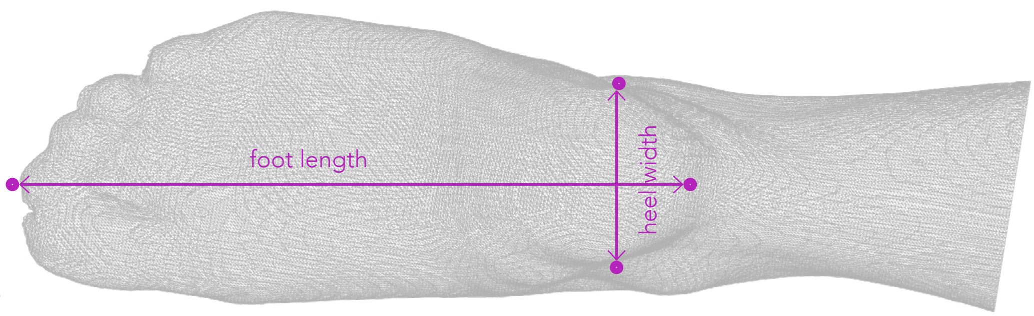


Figure 6.21 Bottom view of a left foot - defining length of the foot and the heel width. One of the injuries that dancers suffer while being on pointe, it's because of the tightness of the heel of the shoe.

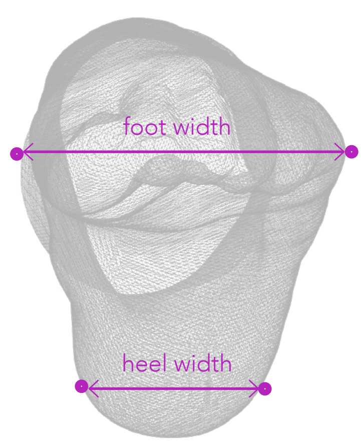


Figure 6.22 Front view of a left foot.

Figure 6.23 Model No 1 - top view of the right foot. It obvious that the second toe is longer than the hallux.

Figure 6.24 Model No 2 - top view of the right foot. Here, the three first toes are quite equal between them, with the hallux being the longest toe.

Figure 6.25 Model No 3 - top view of the right foot. Her first metatarsal is the longest and the rest of them are gradually smaller than the first one.

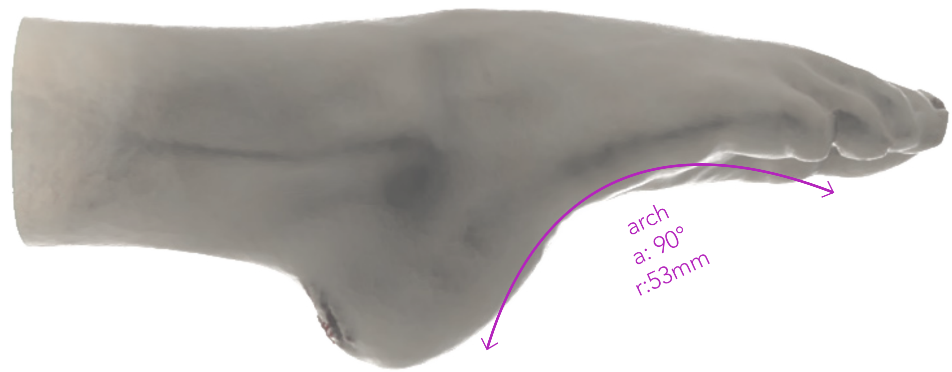


Figure 6.26 Model No 1 - lateral view of the right foot with the bigger angle of the arch.

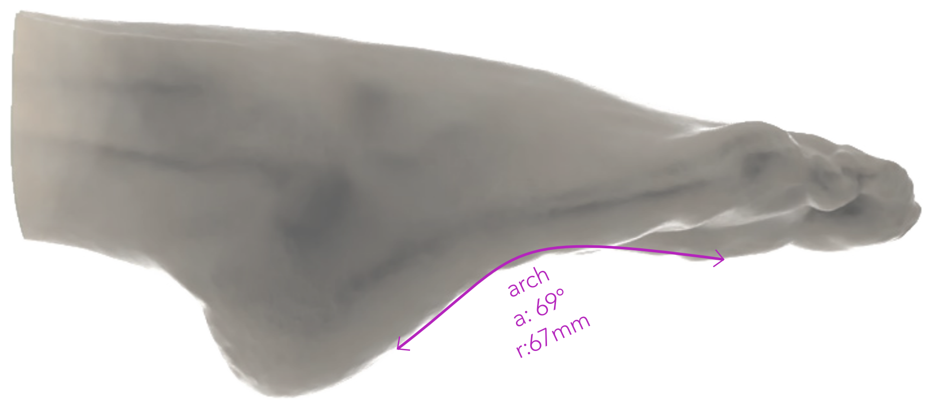


Figure 6.27 Model No 2 - lateral view of the right foot, also with a quite flexible arch.

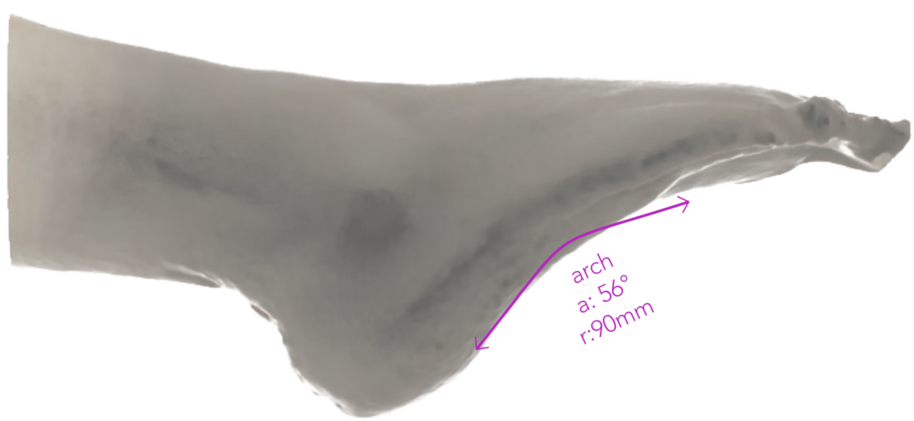


Figure 6.28 Model No 3 - lateral view of the right foot with the smaller angle of all .

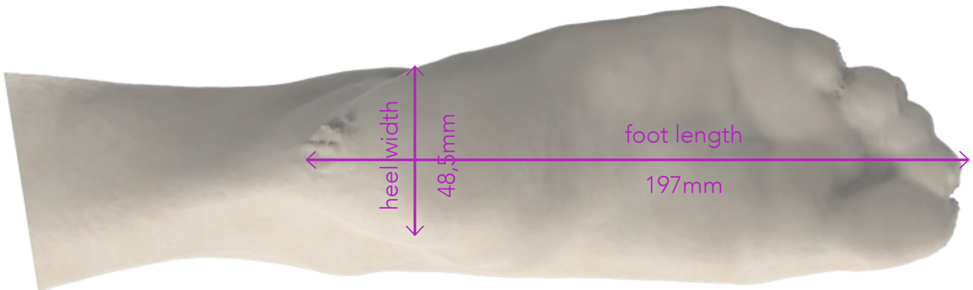


Figure 6.29 Model No 1 - bottom view of the right foot. This is the smaller foot of all three.

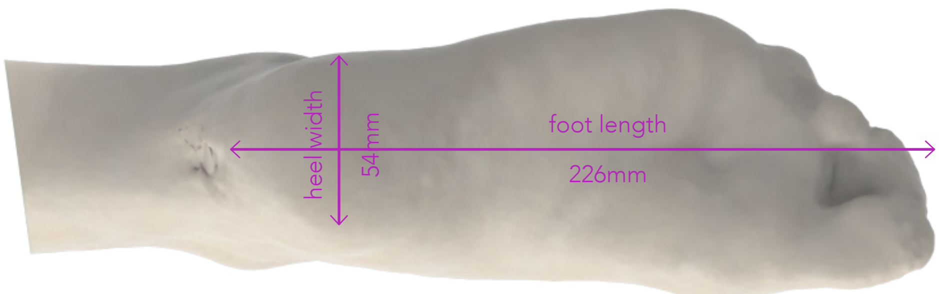


Figure 6.30 Model No 2 - bottom view of the right foot. The biggest foot of all.

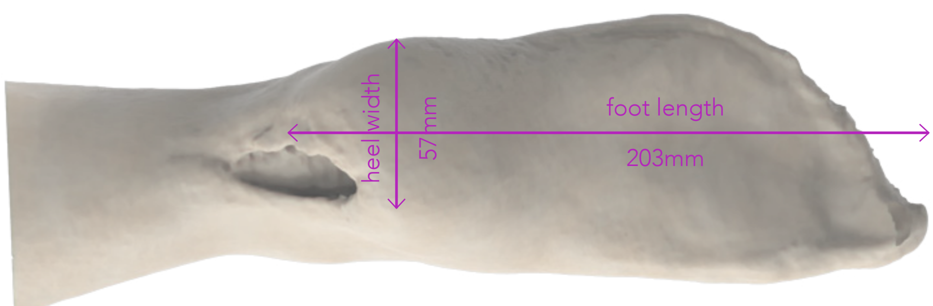


Figure 6.31 Model No 3 - bottom view of the right foot. It is quite notable that even that is smaller that the foot No 2, the heel is wider.

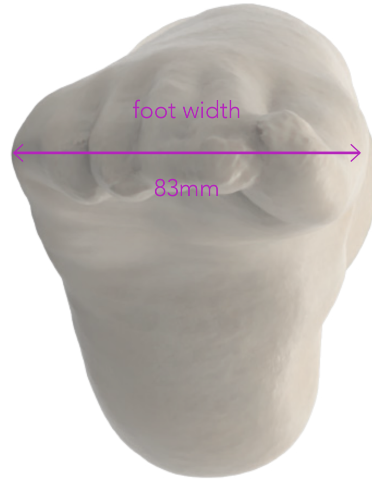


Figure 6.32 Model No 1 - front view of the right foot.

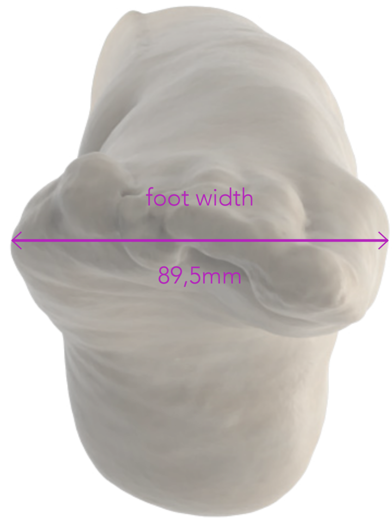


Figure 6.33 Model No 2 - front view of the right foot.

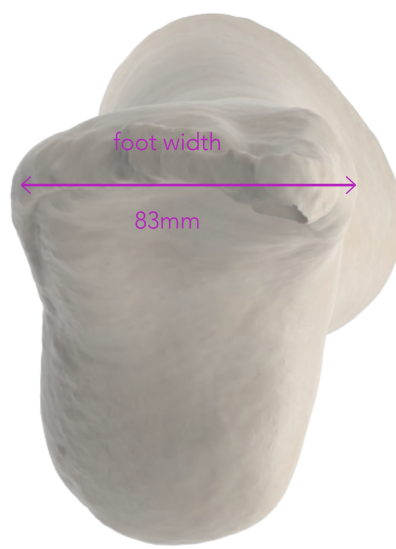


Figure 6.34 Model No 3 - front view of the right foot.

studied in the previous chapters regarding the anatomical characteristics of the feet and the required performance of the pointe shoes, it was easy to define the geometrical variables that need to be taken in account for the parametrization of the pointe shoes.

6.2 Parametrization of the model

The design of the shoe and its parametrization has been done using Grasshopper[5], which is a plug-in of Rhinoceros 3D CAD software and it's a graphical algorithm editor *(Fig. 6.35)*. Basically it's a visual programming language that allows to the user to reference a geometry (surface, mesh, solid, point, curve, etc) from Rhino. Whatever is created in grasshopper you can see it in Rhino but it doesn't really exist as a geometry, it's like designing a "ghost" of a geometry which in order to be able to make it exist in rhino, you have to "bake" it. This allows to the user to manipulate a lot of parameters and data at the same time. The advantage of this, is that you can change the variables/parameters of a geometry very fast and sometimes just by moving a numeric slider. So, you can have many different options at the same time without having to spend a lot of time designing the geometry over and over again. In grasshopper you can perform all the commands of rhino but you can not use the mouse like almost all CAD softwares, instead, everything needs to be defined as a variable, the vectors, the points, the rotation, the movement, the scale etc.

5 Grasshopper was created by David Rutten around 2007 at Robert McNeel & Associates.

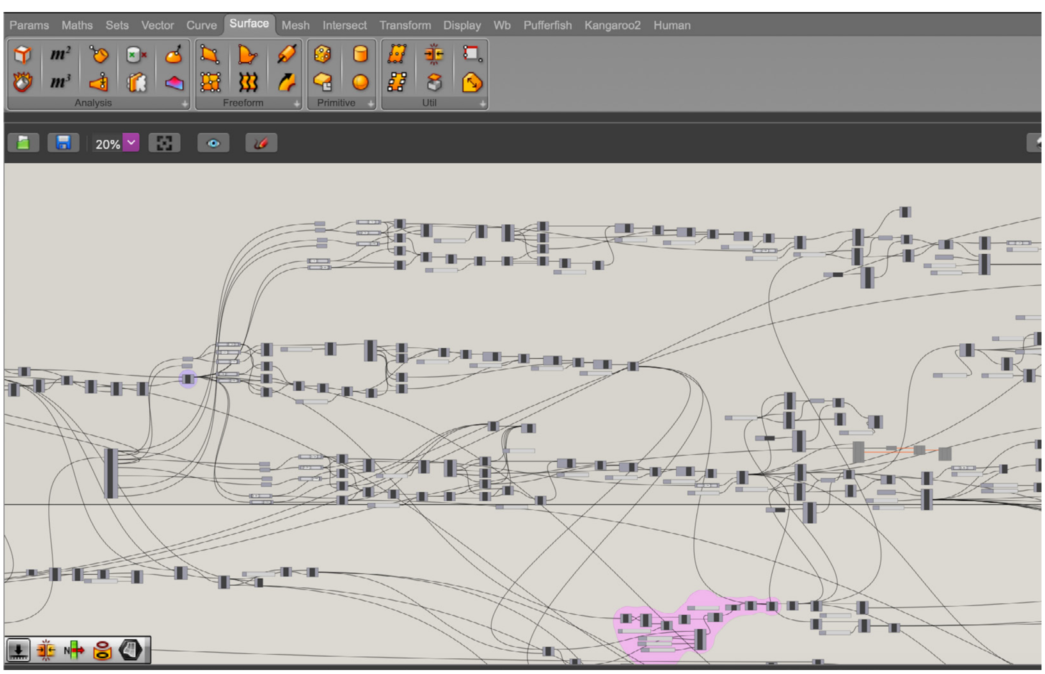


Figure 6.35 The interface of grasshopper: components that represent commands, which need an input data to be activated and they give an output data that can connect with another component to do another command.

	Box & Vamp	Sole & Shank	Outer shoe	Padding
Foot width	√	√	√	√
Foot type	√		√	√
Toe length	√		√	√
Arch		√	√	
Foot Length		√	√	
Heel width		√	√	

Table 5.3 Variables that correspond to specific parts of the shoe.

The parametrization of the design starts by importing information from rhino to grasshopper in order to start to modify and manipulate this information. The most important data that exists up to this stage, is the mesh that we got from the scanning process. Additionally, there were defined some points on the geometry of the foot which are related to the variables that are needed to be taken in account for designing each part of the shoe. Also, there were defined the two axis that helped with the orientation of the mesh geometry in rhino.

Apart of the design of the shoe that needs to answer to many geometrical and performance problems, the complication of the process, consists of the design of the parametric system. The whole design needed to be based on the common information that was extracted for all feet from the scanning process. Meaning that the whole design needed to be based on the mesh, the points and the axis.

The design, as well as the grasshopper definition, are divided into four general parts. These parts are:

1. The box and the vamp of the shoe.
2. The sole and the shank of the shoe.
3. The protective padding.
4. The outer shoe.

All these parts are obviously interconnected. The division was done considering the different mechanical properties that each part requires. At the same time, the separation of the design into parts, facilitated the manipulation of the code and, later on, the fabrication.

6.2.1.Parametrization of the box and the vamp of the shoe:

The first part of the shoe that was defined, was the box and the vamp. For these parts, as already mentioned, the variables that are related to them are the width of the foot, the length of the toes and the type of foot *(Table. 6.2)*. The box is the part that holds the most weight of the body and also holds all the toes together. It needs to be rigid and resistant to the jumps, turns and the difficult steps that the dancer performs and also to the conditions and properties of the dance floor. The platform, as the surface that holds almost the whole body, needs to be completely flat. This surface is the only area of support that someone can have while standing on pointe. The bigger this surface is, the more support would have and the easier would be to stand on pointe. On the other hand, if the box, vamp and platform are too wide, the toes are not well pressed together. The size of the platform really depends on the width of the foot and the type of the foot. Another important consideration is the size of the vamp, that also needs to be proportioned to the width of the foot and its shape but also to the length of the toes.

It was proposed to resolve the design of the box with three "layers" *(Fig. 6.36)*. The outer shoe layer, the main structure of the box, and the inside padding. In this section will be described the main structure of the box. The structure of the box is based on the widest section of the foot, that is an average section that passes through the sections of the lesser of the 5th metatarsal and the proximal phalanx of the 1st metatarsal . This section corresponds to the part of the foot

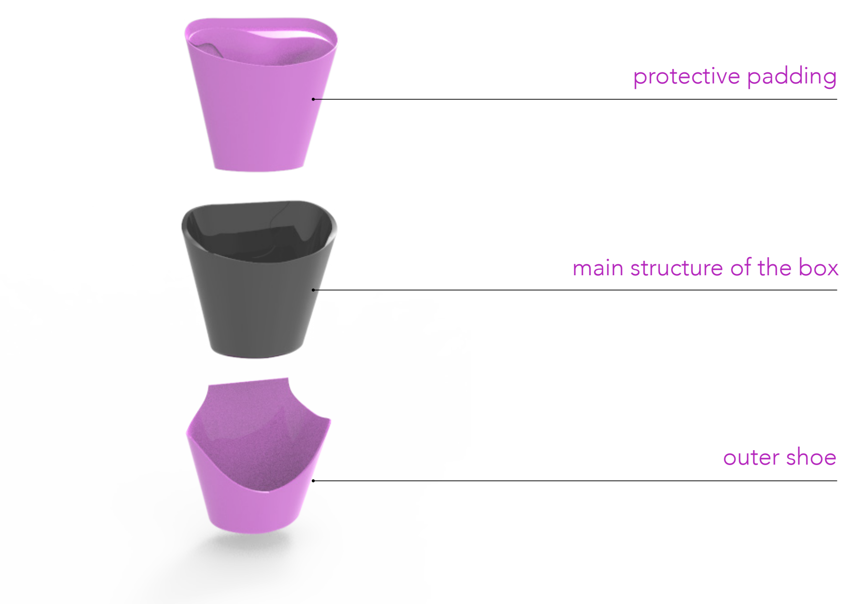


Figure 6.36 The proposal for the box of the shoe consists of three layers. The outer shoe, the main structure of the box and the protective padding.

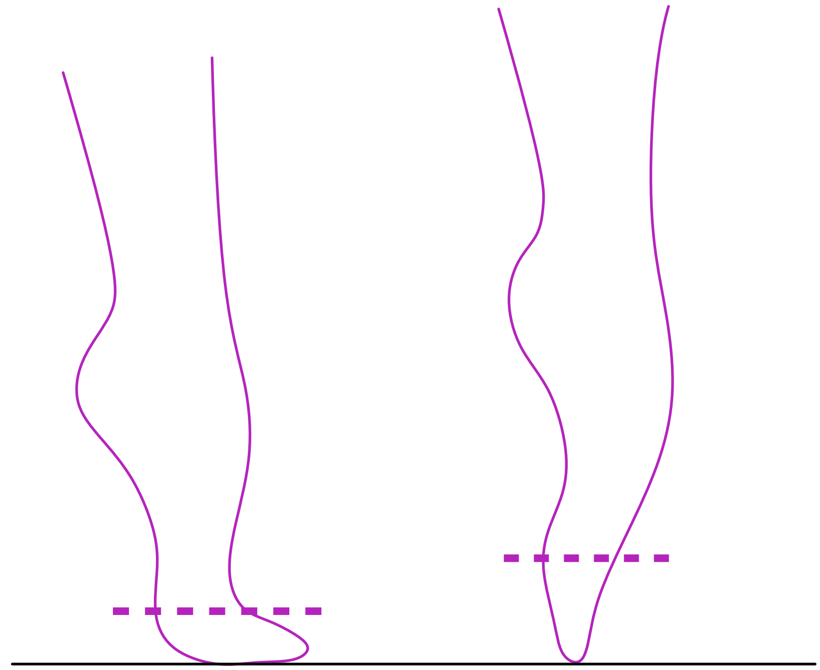


Figure 6.37 This diagram intigates the section of the foot that corresponds to the bending axis of the toes.

that folds when the foot is on demi-pointe position and stretches when on full-pointe position *(Fig. 6.37)*. For having a better support while standing on pointe, the toes need to be very well supported from behind, that's also the reason why this section is so important. The surface of the platform is based on the diameter of the same elliptic section that is proportioned and scaled down in such a way that it covers the tips of the toes *(Fig. 6.40)*. This ellipse is placed in the center of the axis that was defined in the scan process. This is because, as we have already explained, this axis is also the axis of gravity and center of weight of the dancer, so it is very important that the platform corresponds to the center of weight.

The box results from the unification of the two "ellipses" with a surface, creating something like an elliptical cone *(Fig. 6.43)*. The two ellipses on the side that the shoe touches the floor needs to be flat so that the dancer can balance when in flat or demi-pointe position. On the top side of the box, what we call a vamp, the ellipse needs to be modified in such a way that it will cover up until the separation of the toes. Not less and not more than that. As explained in the 5th chapter the center of the front part of the vamp should always reach as far as, or just beyond the third phalange of the first and second metatarsal. Another issue that was quite important, it was the thickness of the box that is also related to the material. The thickness it was proposed to be 3mm.

Many trials have been made for this part of the shoe. The first ones were made in a straight section but it didn't correspond to the requirements of the vamp and when putting it on and folding the toes like in demi-pointe position, it was really uncomfortable *(Fig. 6.46)*. The second trials were made, designing some sort of

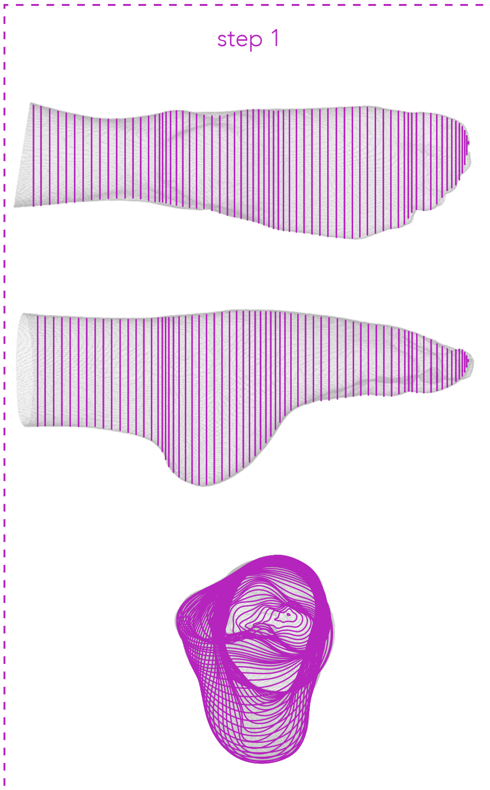


Figure 6.38 Step 1: Dividing into sections the mesh perpendicular to the defined axis for extraxting accurately the dimensions of the foot.

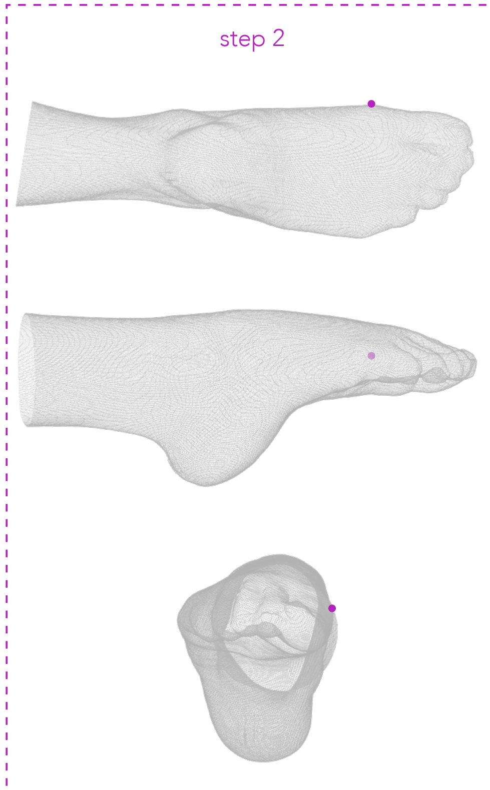


Figure 6.39 Step 2: Inticating the point the corresponds to proximal phalanx of the 1st metatarsal and introducing it as a parameter in grasshopper.

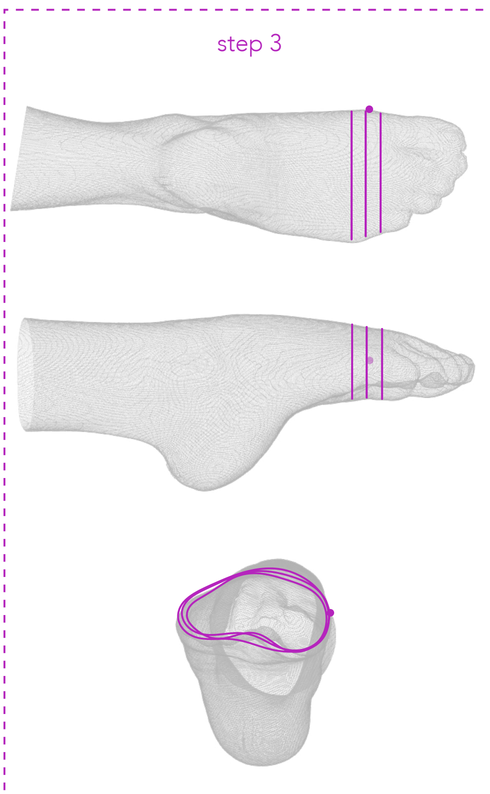


Figure 6.40 Step 3: Inticating the the section of the foot that is closer to the point.

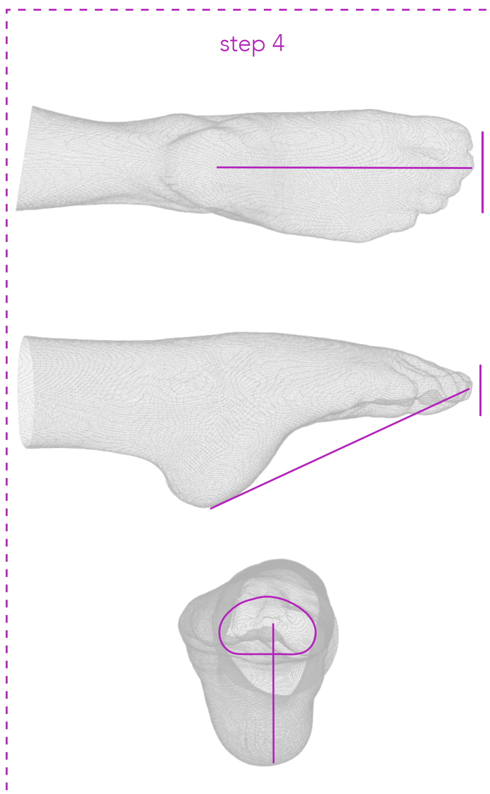


Figure 6.41 Step 4: Scaling down and offsetting the elliptic section fot creating the surface of the platform.

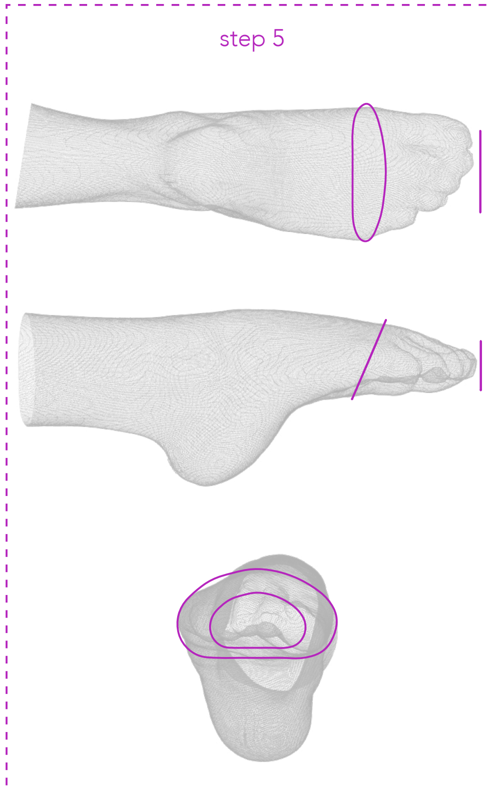


Figure 6.42 Step 5: Getting an average inclined section for fulfilling the requirements of the vamp.

Figure 6.43 Step 6: Unifying the two "ellipses" with a surface, creating the box that looks like a sectioned cone.

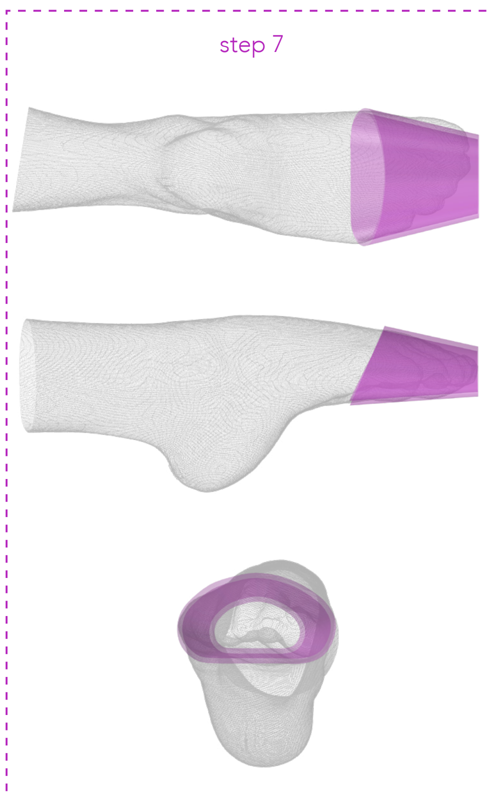


Figure 6.44 Step 7: Giving a thickness of 3mm to the box.

Figure 6.45 Step 8: Creating the surface of the platform and giving a thickness of 4mm.

a recession on the edge of the top side of the box *(Fig. 6.47)*. But this was not enough to avoid the discomfort. Also, there was a lot of unnecessary material that was making the box heavier. That´s why it was resolved by designing an even bigger recession based on the sections of the foot. Up to this stage, the thickness of the box was equal all over the box. After trying out the prototypes, it was realized that on the top side of the box, it could be reduced for aesthetic reasons and for avoiding using unnecessary material *(Fig. 6.49)*.

Figure 6.46 The first designs of the box were done with a straight section on the vamp, making it very unconfortable and difficult to bend the toes.

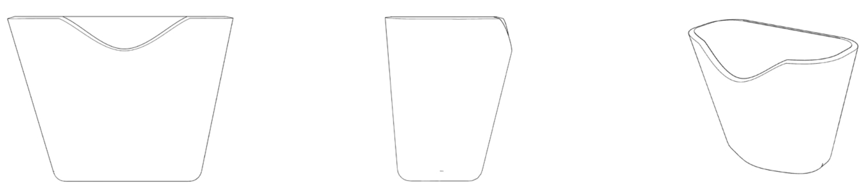


Figure 6.47 Second trial with a small recession on the edge but not big enough for allowing a free movements of the toes.

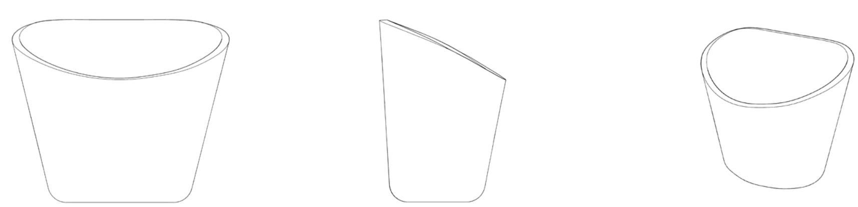


Figure 6.48 An inclination of the section would resolve the vamp problem, but in this case the vamp was very small, leaving a part of the toes un protected.

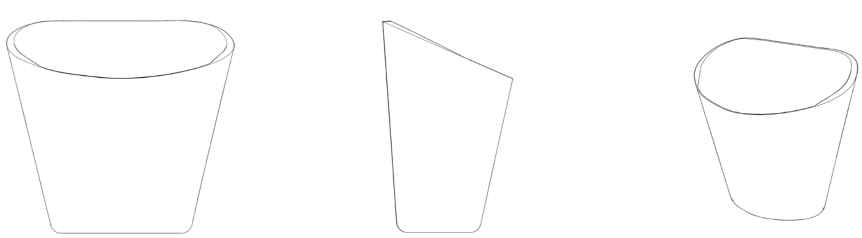


Figure 6.49 An inclination of the section, covering the toes and making thinner the edge of the top was much more functionable and comfortable.

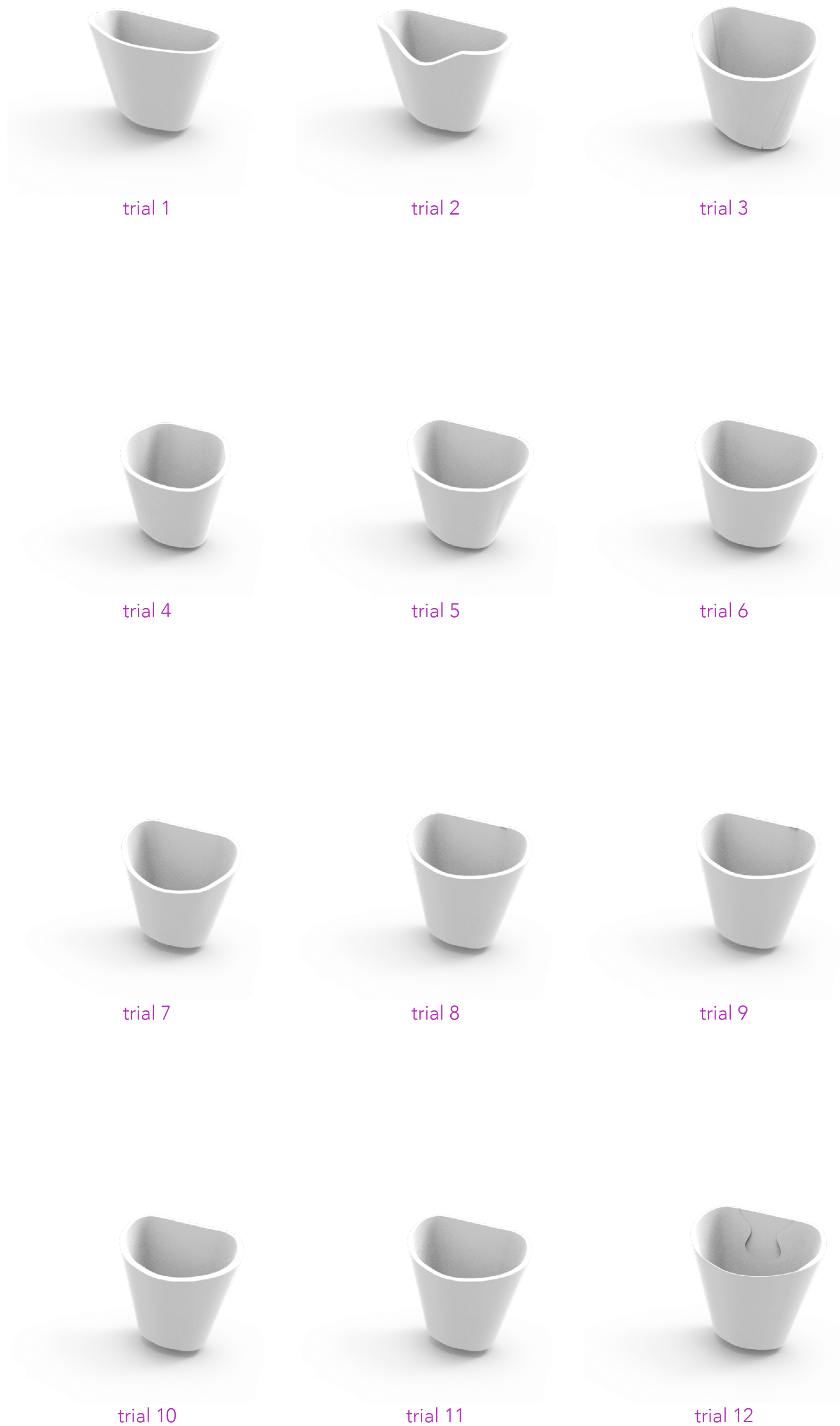


Figure 6.50 Renders of a series of trials. Each trial has a slight change in the creation of the ellipse. In some cases the vamp is shorter, in others the vamp is longer. In some cases the design of the ellipse is different, trying different widths on the back side of the box.

6.2.2.Parametrization of the sole and the shank of the shoe:

The same as the traditional pointe shoe, the shank will be formed by an inner rigid sole and will be covered by the outer sole. For the inner sole, the variables that need to be taken in account are the arch, length and width of the foot and the width of the heel. The shank needs to be supple but also rigid for providing support to the arch and holding the dancer's body weight. After studying well the dancers' needs and movements, it was decided that the shank could be resolved separating it into a rigid and a more flexible part. The sturdy part would be an element that starts from the heel and reaches up until the beginning of the ball of the foot and the supple would be another element from the ball until where the box of the shoe starts. This was a very complicated part of the design because on one hand it needs to be flexible enough so that the dancer cal fold the toes to perform on demi-pointe and on the other hand it needs to provide support.

As a first step, the "hard" part of the shank, was resolved based on the curve that was created from the average points of the sections on the lowest part of the foot. This curve indicates the arch of the foot and the purpose of this design process is to create a shank that will be completely adapted on the arch of the foot. The rest of the geometry of the rigid part, was done following the outline of the foot while trying not to use material where is not necessary *(Fig. 6.52-58).*

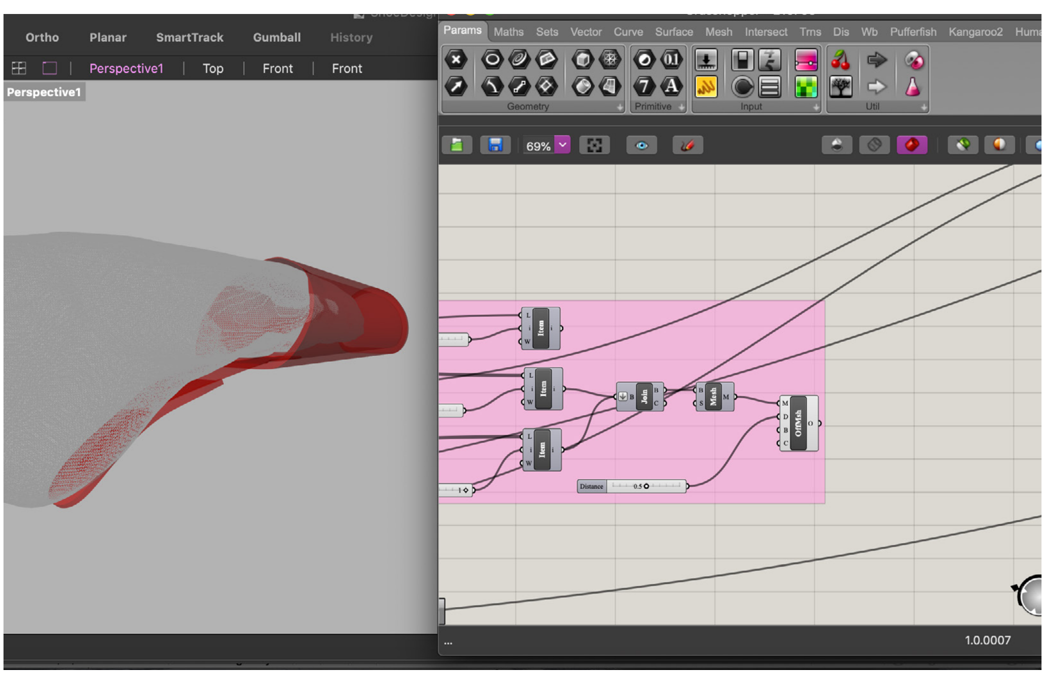


Figure 6.51 Rhino and Grasshopper 3D, parametrization of the shank based on the box.

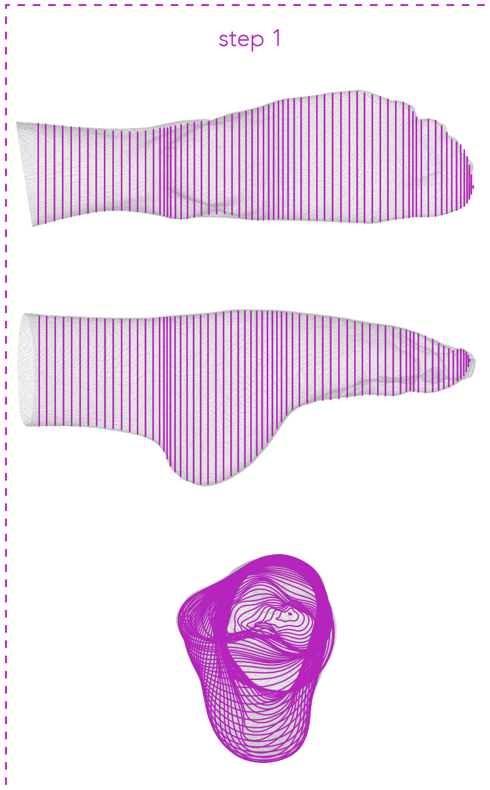


Figure 6.52 Step 1: Step 1: Dividing into sections the mesh perpendicular to the defined axis for extraxting accurately the dimensions of the foot.

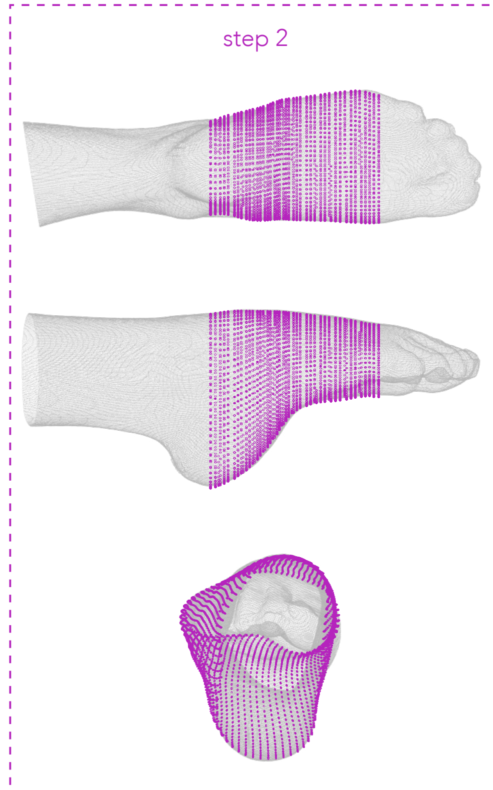


Figure 6.53 Step 2: Selecting the sections that correspond to the part of the shank.

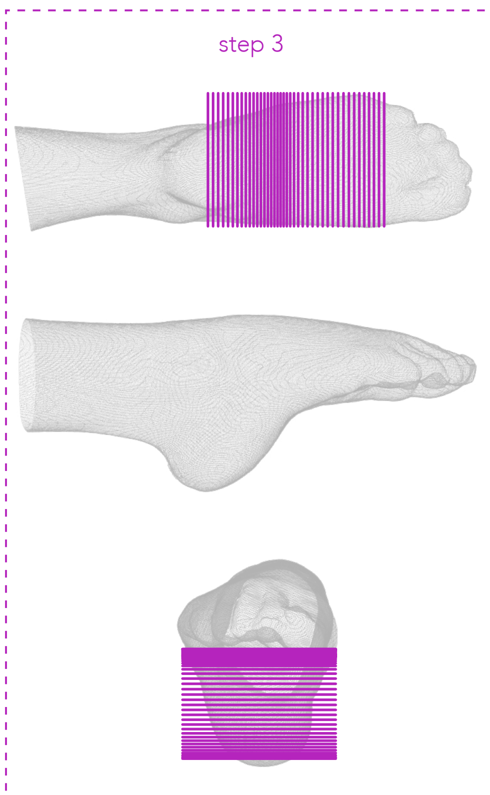


Figure 6.54 Step 3: Extracting straight lines that are tangent on the lower point of the sections.

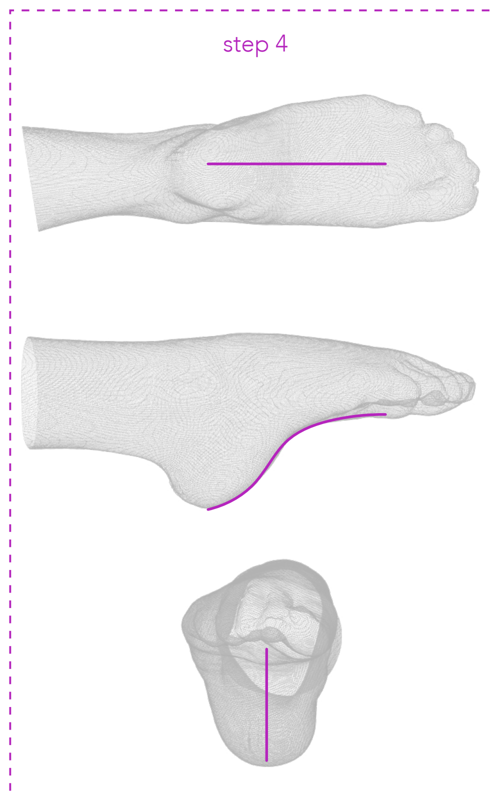


Figure 6.55 Step 4: Getting the middle point of every straight line for creating the curve of the shank.

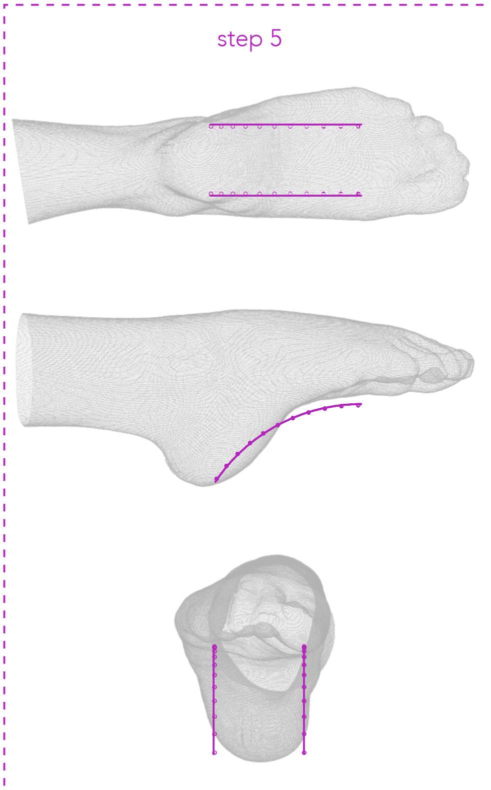


Figure 6.56 Step 5: Defining the perimeter of the inner sole

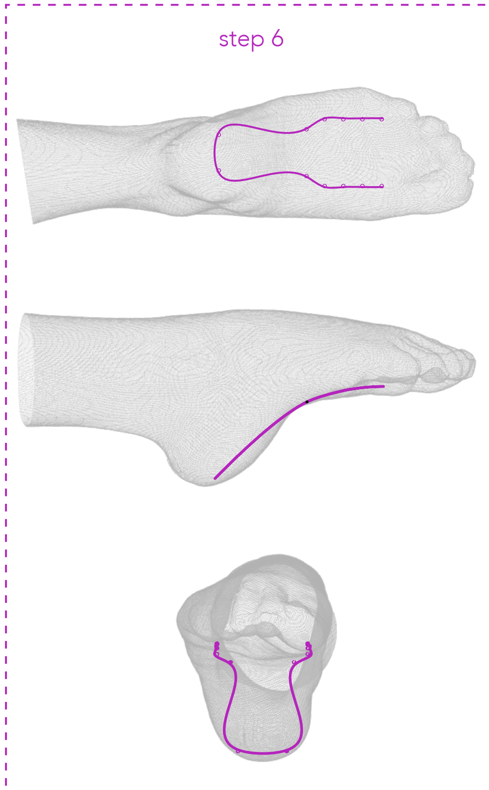


Figure 6.57 Step 6: Defining the outline of the inner sole.

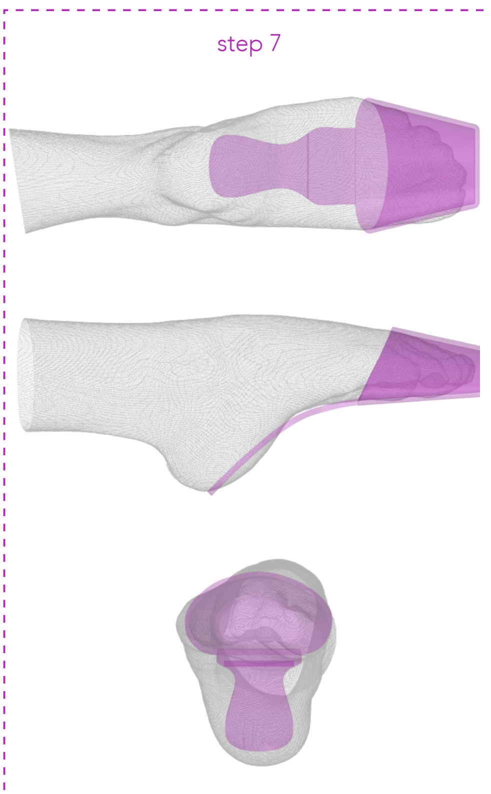


Figure 6.58 Step 7: Defining the surface with a specific thickness for the creation of the outer sole.

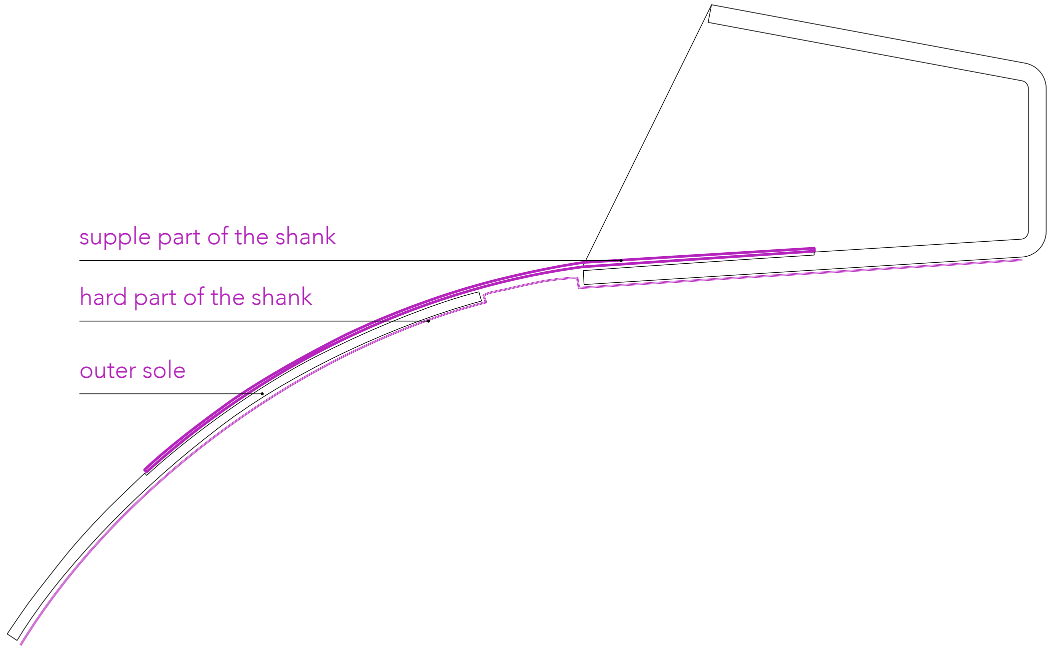


Figure 6.59 A section of the proposal of the shank.

The supple part of the shank is the most complicated part of the shoe. It's the part where the traditional pointe shoe lacks effectiveness, functionality and ergonomics. This happens because it needs to bend and work in two directions and above all it needs to support the foot in both positions (demi- and full- pointe). Most of the shoes that already exist, have a very sturdy shank that only provides support while being on pointe and it's almost impossible to bend it when being on demi-pointe[1]. This part was resolved progressively. The initial idea was for it to be a continuation of the rigid part and try to give flexibility by marking cuts in the direction that it needs to be bent. After trying many types and sizes of cuts, it was realized that it kept breaking because of the rigidity of the material. The second idea was for it to be a continuation of the rigid part but with less thickness at the folding part. This option didn't work either because of the material and the printing direction. The third idea was to have an extra element for this part of the shank, that could be made from a different material and which would even allow to add as a parameter also the strength of the individual and in this way be able to have different materials or thicknesses for providing different levels of rigidness *(Fig. 6.59)*. This element will be attached on the other part of the shank and on the box. The remaining hollow below the shank will be filled in automatically with the outer sole.

1 Even though dancers do not perform many steps in demi-pointe while wearing pointe shoes, demi-pointe position is very important specially when rising on pointe and when land on the ground from full-pointe position or jumping.

top view side view perspective view

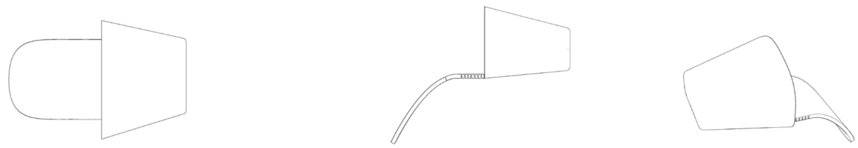


Figure 6.60 The first designs of the shank were done with as a continuation of the box.

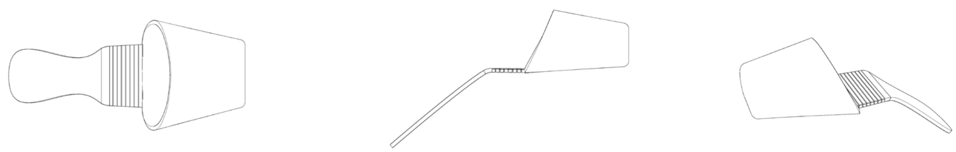


Figure 6.61 A trial of the shank in which the shank and box they come together with an angle and in which they are some cuts on part where it needs to bend.

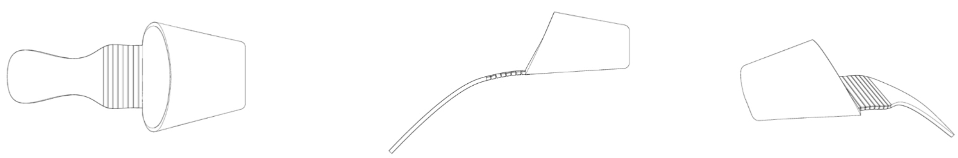


Figure 6.62 The shank is made with an arch and here as well there are some cuts on part where it needs to bend.

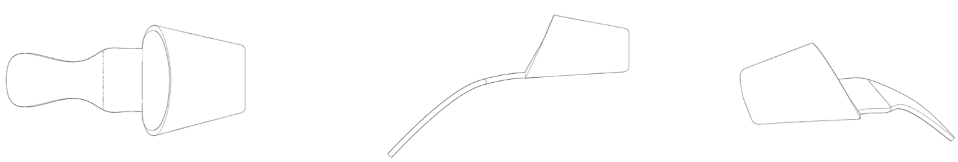


Figure 6.63 The shank is made with an arch and as a continuation of the box without any cuts.

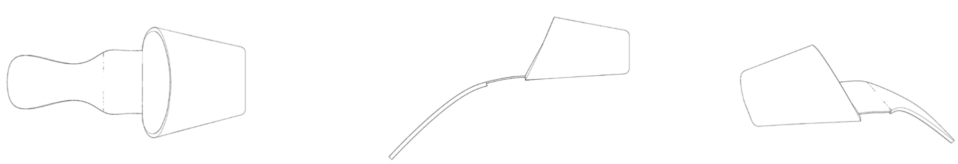


Figure 6.64 Instead of cuts, the supple part is done by a reduction of the material.

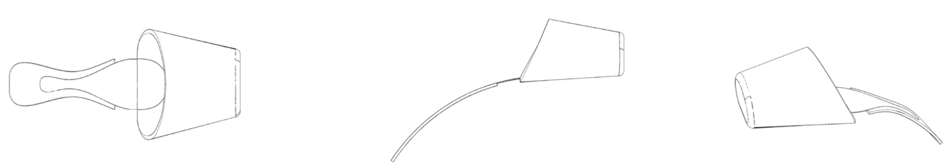


Figure 6.65 The supple part is added as a new element and maybe a new material, which gives the opportunity to add as a new parameter the strength of the dancer.

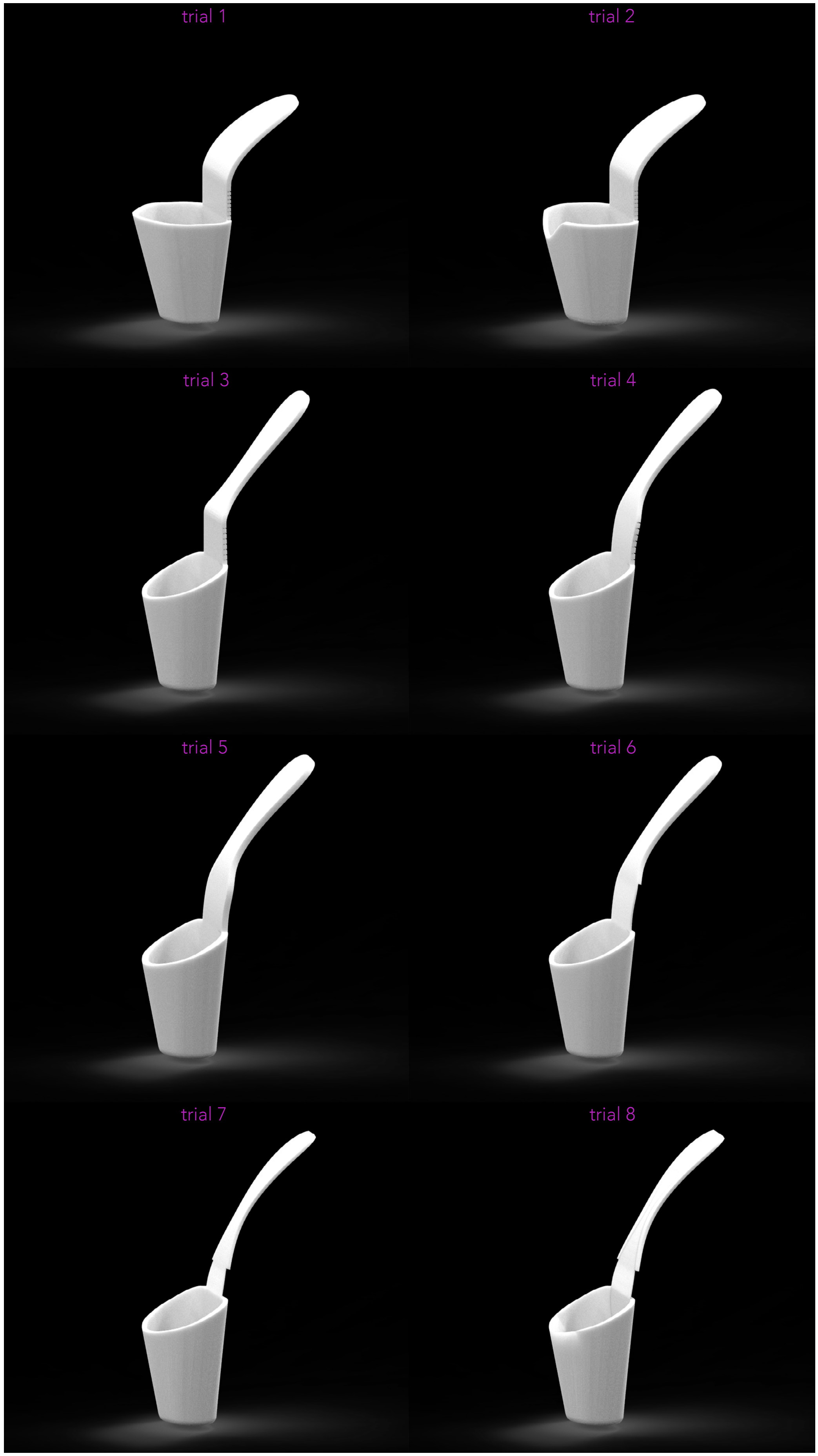


Figure 6.66 Renders of a series of trials. Each trial has a change in the supple part of the shank.

6.2.3.Parametrization of the protective padding:

Up until now, the protective padding it's been an additional accessory for dancers. Although it doesn't form part of the shoe, all ballerinas use it for preventing them from pain, ingrown toe-nails and blisters. Usually they are made of foam or silicone or lamb's wool and they look like a cover for the toes. These kind of paddings are quite protective but in some parts there is a waste of material and in some others they are too thin for providing protection. Also, in many cases, dancers need to combine accessories, like toe pads between the toes or on the tip of the toes. The idea here was not only to integrate it as a part of the shoe but also to create a padding that would completely adapt to the individual's type of foot and toes. This could help for example the dancers who have the second toe longer that hallux, giving them more support by filling in the "empty" space from the hallux. In general, a padding adapting perfectly to the shape of toes would prevent from pain and wounds and at the same time offer much more comfort.

The protective padding here, basically is created as a double mold of the foot and the pre-designed box *(Fig. 6.67)*. The idea was to have a padding that would take exactly the shape of the foot, marking all the details of the toes and gaps between the toes. This would help the dancers not only to feel more comfortable but also it would help them to feel better supported as they would feel a support below every toe.

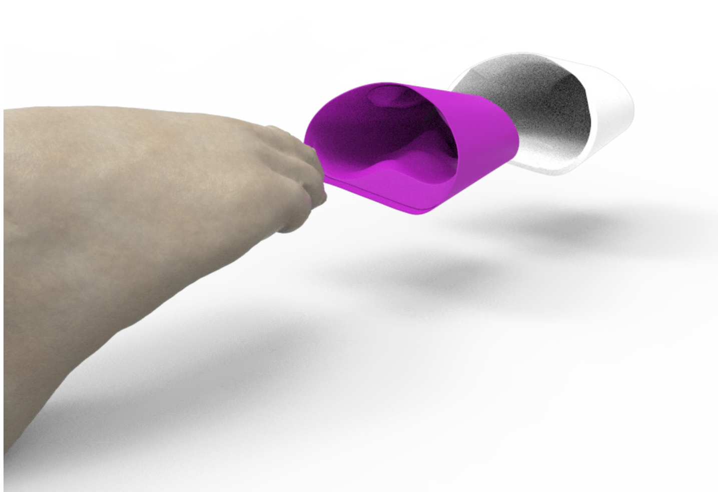


Figure 6.67 The protective padding is created by a double mold.

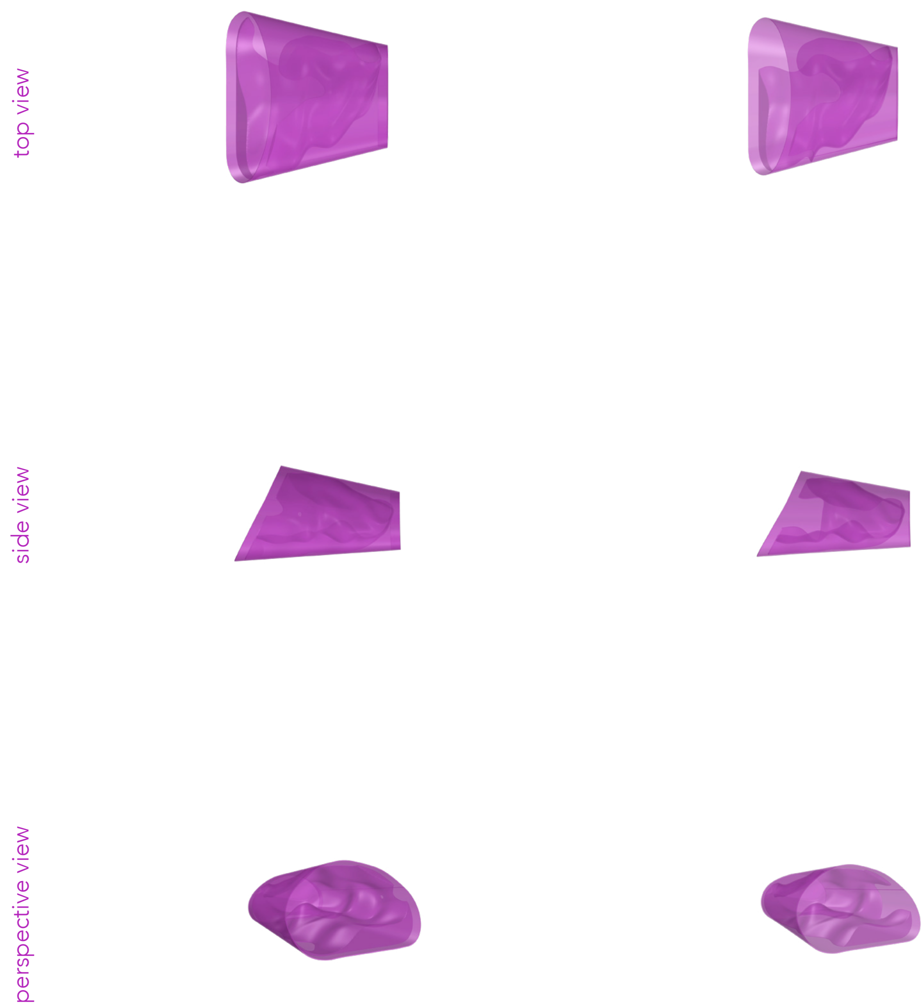


Figure 6.68 The protective padding depends not only on the geometry of the foot but also on the size and shape of the box of the shoe.

6.2.4. Parametrization of the outer shoe:

The role of the outer shoe is to keep all the other parts of the shoe together and to keep the shoe tight on the foot. The idea here was to create a covering layer for the box and sole and a folding part on the sides (wings) that would surround the foot and with the help of the ribbons to adapt perfectly on the foot *(Fig. 6.69)*. This part was also progressively designed because it had to adapt to the changes of the other parts. Every change on the box or shank, required a change on the outer shoe.

Overall, this covering element needs to clothe the dancer's foot but at the same time, the dancer should be able to adjust the tightness of the shoe with the ribbons. In order to satisfy this requirement, besides of using a flexible material, the idea was also to increase the adaptability with the geometry of the design. The idea was to lighten the folding wings with some holes that would have the shape of an ellipse and that their size would vary parametrically from smaller holes to bigger ones. As closer the holes are getting to the edges, the bigger size they have.

The ribbons would also pass through some holes that would be positioned nearby the edges of the wings. The outer sole and the outer box were nothing more than an offset of the inner sole and box. The dimensions of the side folding parts, were extracted from the sections of the foot.

The base for starting the parametrization of the outer shoe was the already designed shank that had to be flattened on a 2D plane for facilitating the param-

Figure 6.69 The outer sole is important for holding all the parts of the shoe together.

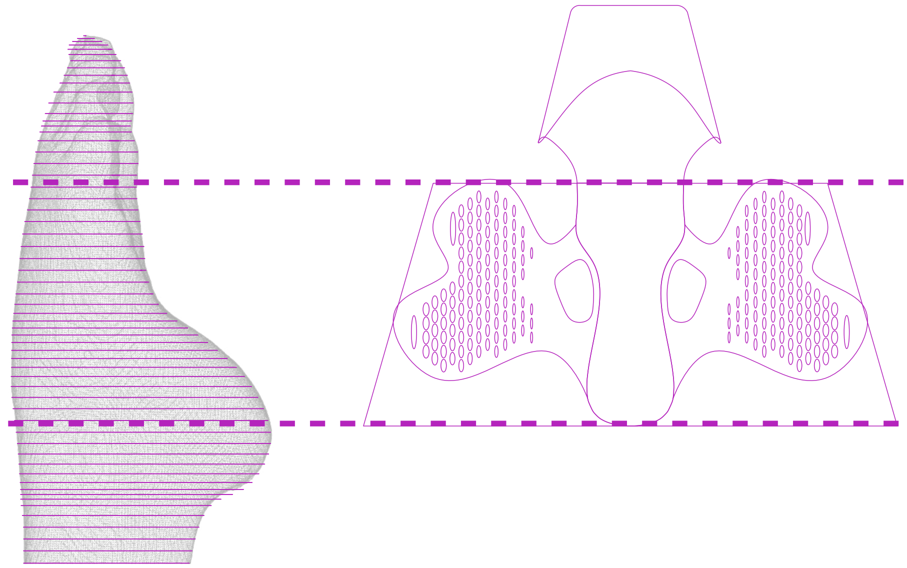


Figure 6.70 The dimensions of the "wings" of the outer shoe are based on the dimensions of the sections of the foot.

etrization but more than anything for facilitating the fabrication. Based on the 2D outer edges of the sole and on the dimensions from the sections of the foot, it was created an unfolded covering of the foot *(Fig. 6.70)*. The sides of the shoe were then designed, progressively with the idea of using the less possible material but also aiming to provide stability and confidence while wearing the shoe. Initially, the two wings were designed as a continuation of the box and just with one hole for passing through the ribbons. This solution though, did not provide the wanted stability and there was too much unused material that was forcing the material to crinkle. After many trials it was decided to separate the folding parts from the box for avoiding the wrinkles. This modification was helpful but not enough as the material kept crinkling right next to the arch of the foot. For this reason it was decided to mark another hole next to the arch, following the outline of the sole to avoid this effect. For better adaptation on the foot and for providing more security there was also added another hole on each side for the ribbons *(Fig. 6.71-76)*.

Conclusion:

From the parametrization process, it can be deduced that using Grasshopper, a parametric definition can be developed for designing a pointe shoe and its individual parts. Based on the 3D geometry of the foot and using as measurable parameters the width of the foot, the type, the toe length, the arch, the foot length and the heel width, a point shoe is designed that can be adapted to every different 3D geometry of a foot and thus to every different foot. The shoe can be adapted to the characteristics and the needs of the foot of every individual. The

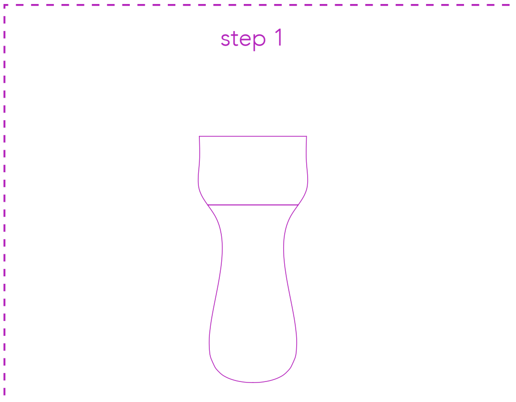


Figure 6.71 Step 1: The design of the outer shoe is based on the outline of the already created inner sole that is flatened on a plane.

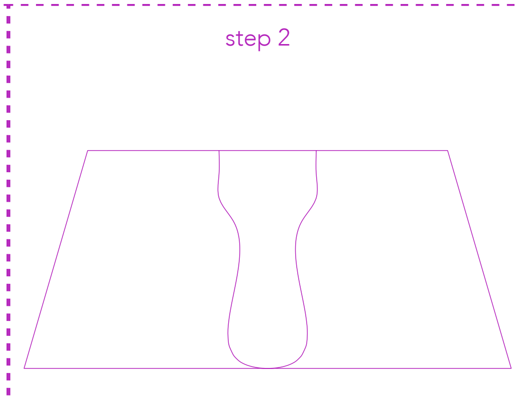


Figure 6.72 Step 2: A parallelogram is defined by the dimensions of the sections of the foot.

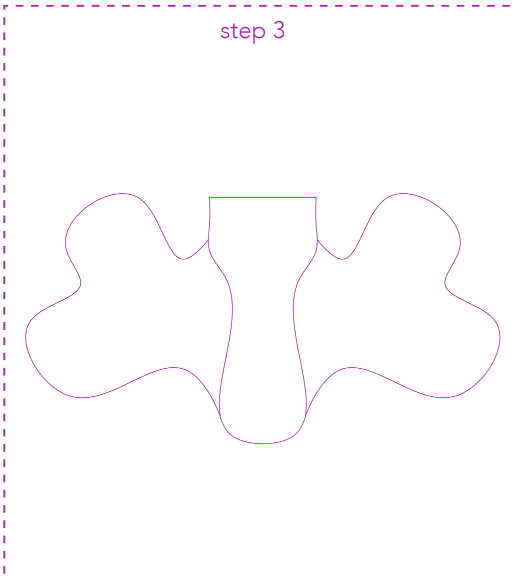


Figure 6.73 Step 3: The sides of the outer shoe are design so that they would "hug" the foot.

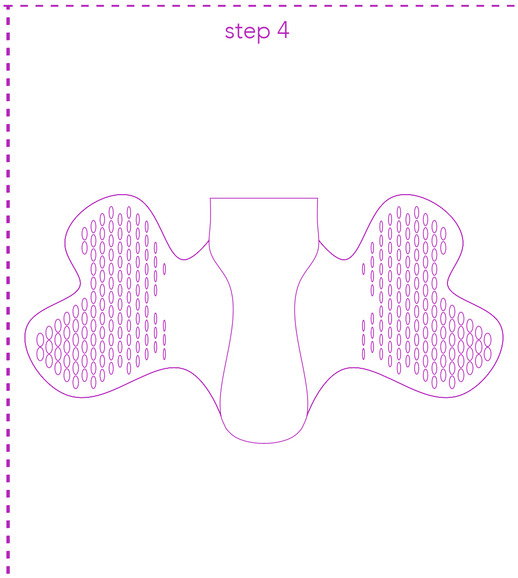


Figure 6.74 Step 4: The elliptic holes vary parametrically from smaller holes to bigger ones for increasing the adaptability and flexibility of the wings.

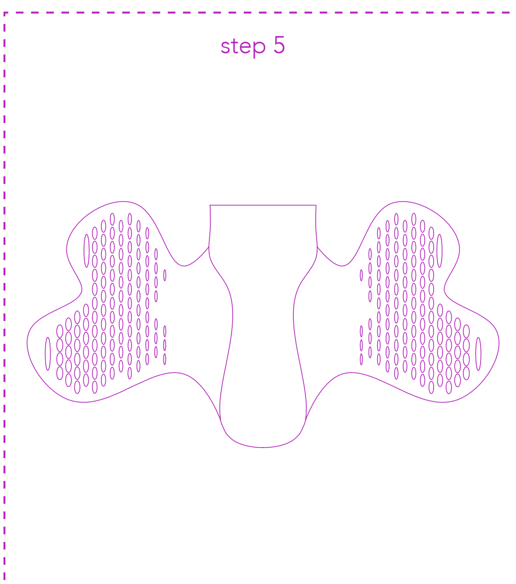


Figure 6.75 Step 5: Holes are marked also on the edges of the wings for the ribbons.

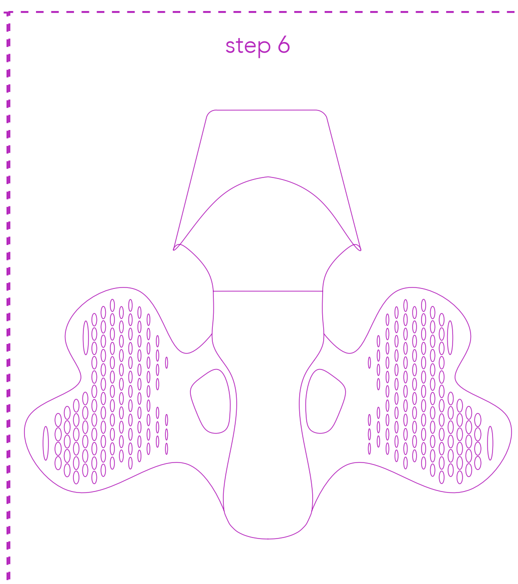


Figure 6.76 Step 6: Another hole was marked next to the arch of the foot for avoiding the wrinkles on the sides of the sole.

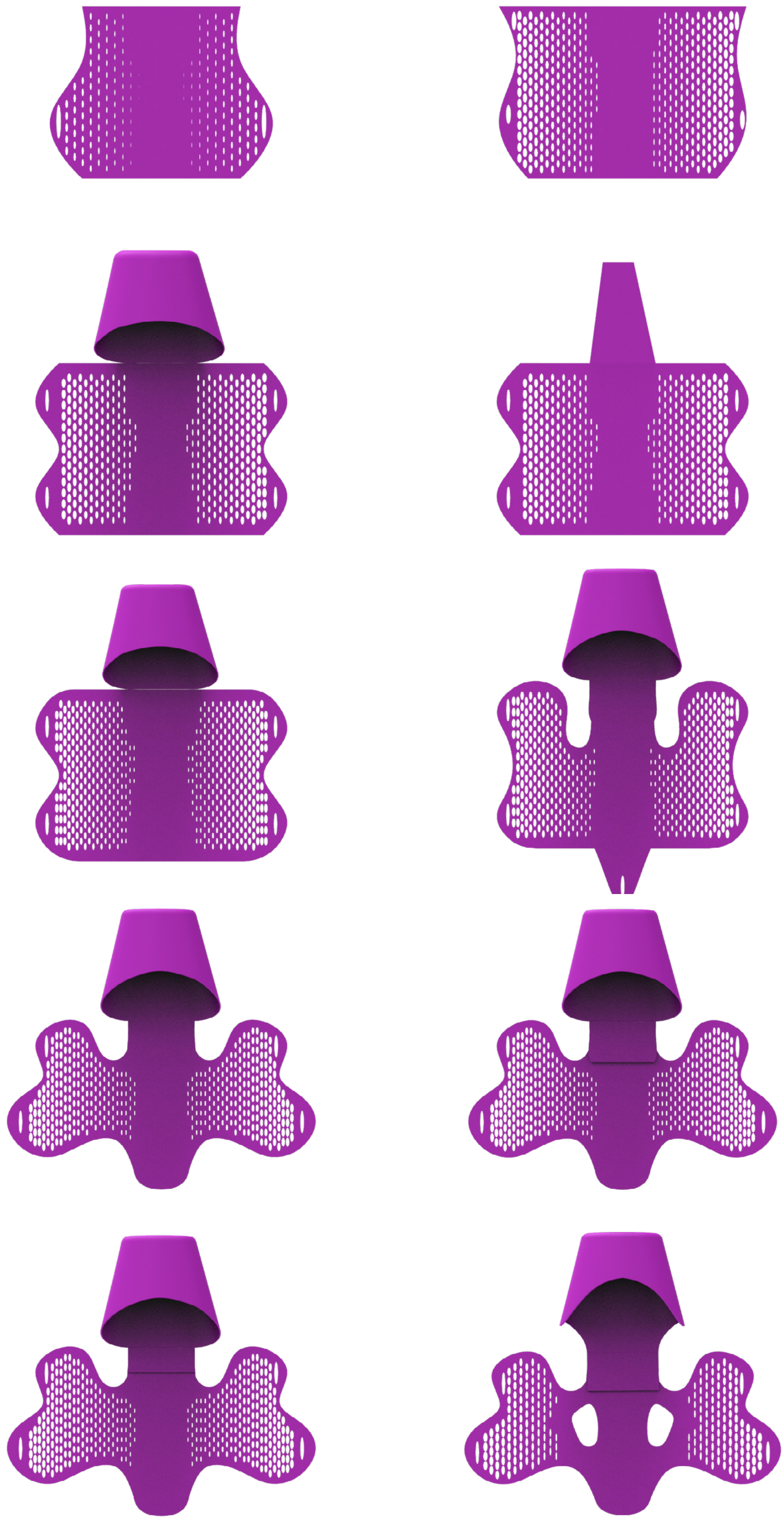
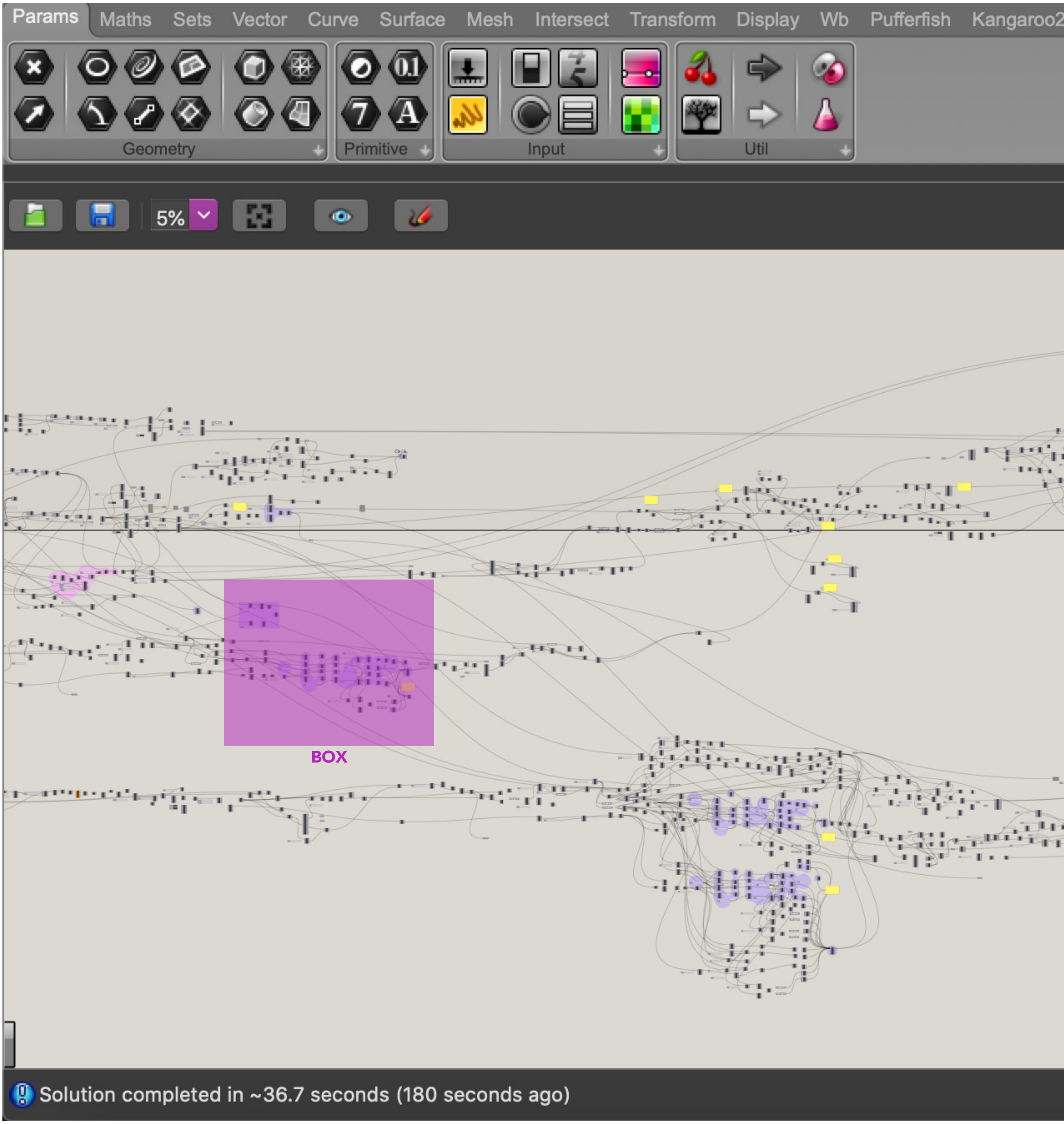
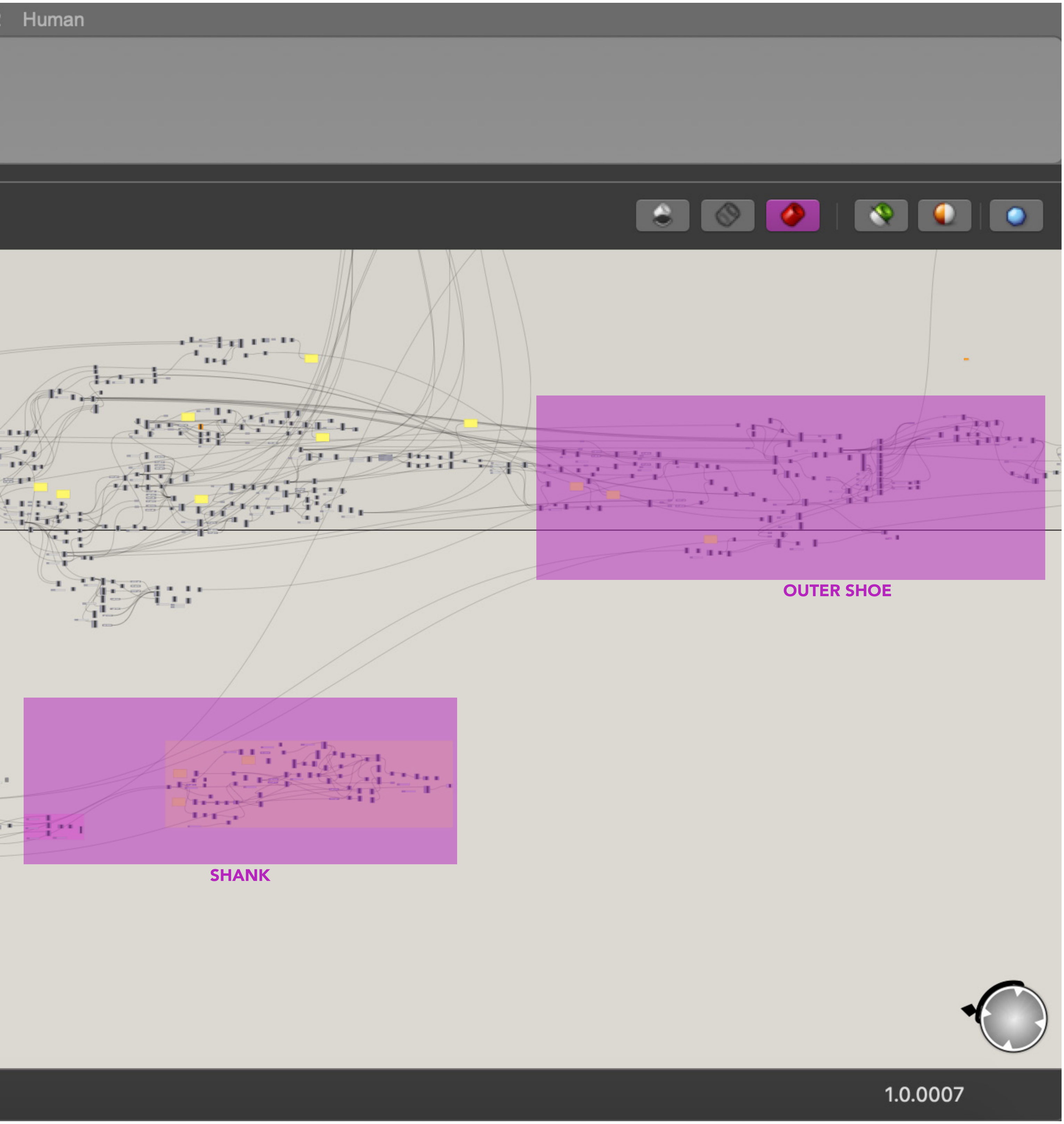


Figure 6.77 Renders of a series of trials. for arriving progressively to the final design.


Params
Maths
Sets
Vector
Curve
Surface
Mesh
Intersect
Transform
Display
Wb
Pufferfish
Kangaroo2
Geometry
Primitive
Input
Util
5%
BOX
Solution completed in ~36.7 seconds (180 seconds ago)


Human
OUTER SHOE
SHANK
1.0.0007

design can be modified by adding parameters for more precision or for fulfilling even more requirements but, the most important thing is that the design is 100% based on the 3D scanning result, allowing us in this way to have a repetition of the same shoe designed exactly in the same way for every individual.

6.3 Fabrication process:

Additive manufacturing was the fabrication technique that was followed for creating. This technique was chosen because allows the fabrication/print of the prototypes directly from the computer, giving the opportunity to correct any kind of errors or omissions. All pieces were fabricated by the printer 3D Creality Ender 3 Pro. Even though it's an open source 3D printer that allows any kind of modifications for upgrading and changing parts for printing a greater variety of materials, there is still a limitation of materials that can be used.

For printing a model, the geometry needs to be constructed as a mesh. From Rhino, it needs to be exported in an STL[1] file format. The STL file then, needs to be imported into a slicing application for preparing a different kind of a file format and sending it to the 3D printer. The slicing software, in this case Cura[2], slices the 3D model into layers and it creates a g-code[3] for printing. With Cura, you can

1 STL comes from Stereolithograophy or "Standard Triangle Language" or "Standard Tessellation Language" and it's a file format that describes the surface geometry of a three-dimensional object without any representation of color, texture or other common CAD model attributes. These files are usually created by CAD softwares and they are widely used for 3D printing. These files encode the information using the concept of tessellation. Tessellation, is the process of tiling a surface with one or more geometric shapes such that there are no overlaps or gaps.

2 Cura was developed by David Braam for the company Ultimaker.

3 G-code stands for Geometric Code and is a computer numerical control (CNC) programming language.

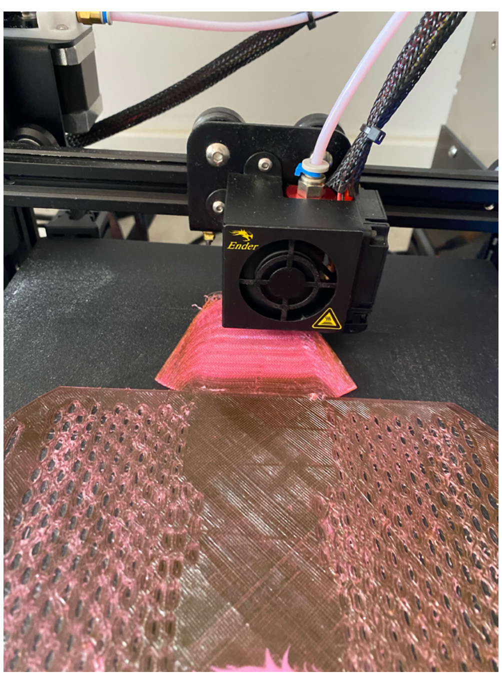


Figure 6.78 3D Creality Ender 3 Pro printing machine. Printinting the outer shoe.

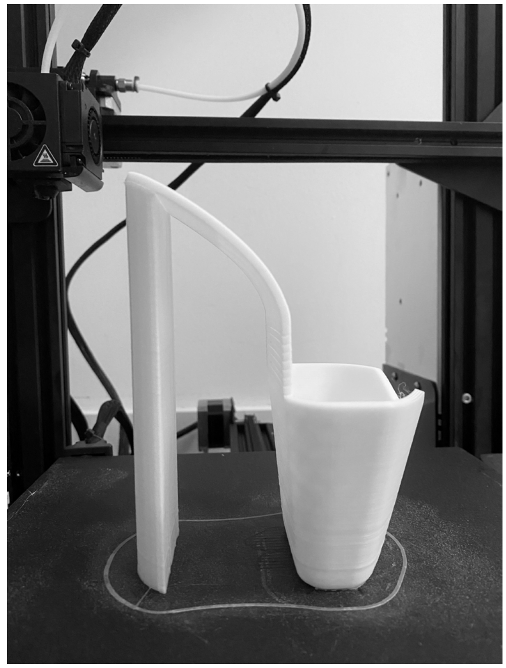


Figure 6.79 3D Creality Ender 3 Pro printing machine.

control the parameters of the printing process, meaning it can be controlled the temperature of the bed or the print head, the size of the layer in which the model can be printed and many other parameters. These parameters vary from material to material.

The fabrication process followed the sequence of the parametrization process and it was divided in four parts:

1. The box and the vamp of the shoe.
2. The sole and the shank of the shoe.
3. The protective padding.
4. The outer shoe.

As already explained, each part of the shoe needs to perform in a different way and so the material properties of each part have to be distinct. For the printing there were used two materials which are known as PLA and TPU.

PLA plastic or polylactic acid is a vegetable-based, fully biodegradable thermoplastic polymer that is usually produced by cornstarch or sugarcane (Farah et al., 2016). It's mainly used in the FDM (fused deposition modeling) technology. As a thermoplastic material, can be melted and reshaped without changing its mechanical properties. In general, it has very good material properties and it's quite resistant when it comes to compression, elongation or tension. It's not consider to be a flexible material although the printing parameters can influence its mechanical properties.

In rapid prototyping in general, there are various parameters than can affect the mechanical properties of the PLA, in these are included the speed, the temperature, the height of the layer, the thickness or width of the extruded filament or even the direction of layer.

This material was used for the parts of the shoe that needed to be rigid and resistant to breaking stress. TPU on the contrary, was used for the parts of the shoe that needed to be elastic and flexible.

TPU or Thermoplastic Polyurethane is a thermoplastic elastomer and unlike PLA it's not biodegradable. It's a rubber-like plastic that can be very flexible, transparent, strong and at the same time smooth to touch. Same as other filaments that are used in additive manufacturing, its mechanical properties can also change depending on the defined printing parameters.

6.3.1.Fabrication of the box and the vamp of the shoe:

For the fabrication of the inside structure of the box it was used PLA material. The box needs to be sturdy and very resistant for it's the part of the shoe that not only holds the toes together and the hole body of the dancer but it also needs to put up with the landing on the ground from jumping and with steps that require "hitting" on the floor. This way of fabrication and material allowed the printing of many trials that were essential for the completion of the design *(Fig. 6.80)*.

As already explained previously, the box was initially designed with a straight section on its upper edge (vamp). Because of the rigidity of the material, that cannot be folded, it was necessary to change the section of the vamp for provid-

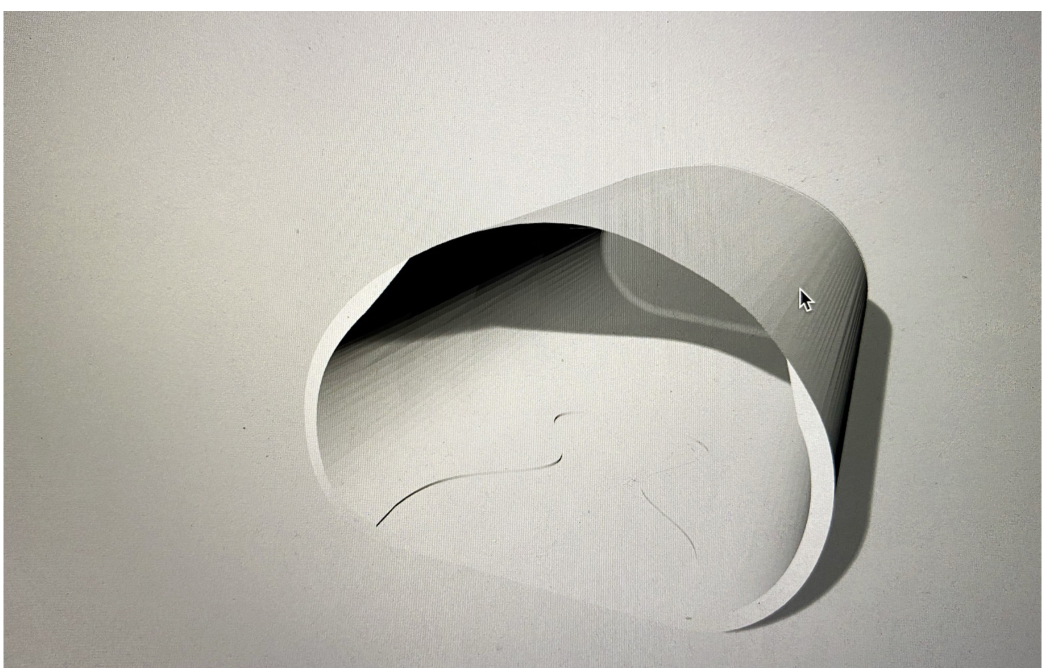
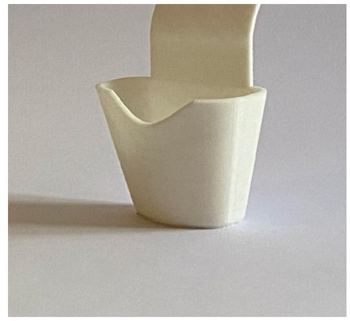


Figure 6.80 Rhino 3D - Detail of the box.


prototype 1


prototype 2


prototype 3


prototype 4

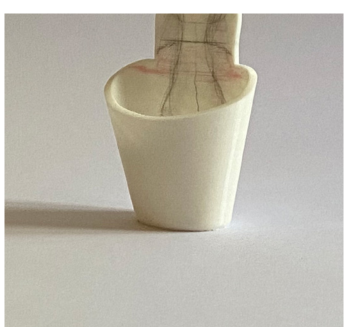

prototype 5


prototype 6


prototype 7


prototype 8


prototype 9


prototype 10


prototype 11


prototype 12

Figure 6.81 A series of prototypes. Each trial has a slight change in the creation of the ellipse. In some cases the vamp is shorter, in others the vamp is longer. In some cases the design of the ellipse is different, trying different widths on the back side of the box.

ing more comfort while folding the toes.

6.3.2. Fabrication of the sole and the shank of the shoe:

The inside sole and shank are the most complicated parts of the shoe because although they need to perform as one piece, there is one part that needs to be very sturdy and resistant and another one that needs to be flexible and resistant at the same time. In the beginning they were fabricated as one piece and as a continuation of the box using the same material (PLA) . On these first prototypes, there was an intention of providing the required flexibility just by marking cuts on the part of the shoe that needs to fold for performing on demi-point. These trials didn't work because when the cuts were too small it wasn't providing flexibility at all and when the cuts were bigger, the shank would break. Another idea was to fabricate it as one piece, again as a continuation of the box, giving a thickness of 3mm for the box and the rigid part and where the flexibility is needed, reducing the thickness of the material to 0,5mm and fill in the remaining gap with the flexible material of the outer shoe. This idea didn't work either because it kept breaking. The last idea was to design and fabricate the supple part as an extra piece that would be printed aside and that it would be attached on a recess on the box and the sturdy part of the sole *(Fig. 6.82)*. Here it was noted that when this extra piece was printed with a direction of the material layers perpendicular to the axis of the folding, the piece was very flexible and resistant *(Fig. 6.83)*:

When the piece was printed with a direction of the material layers parallel to the axis of the folding, the piece was breaking. Ideally, there was the idea of printing this piece using another material, like fiberglass or carbon fiber but this

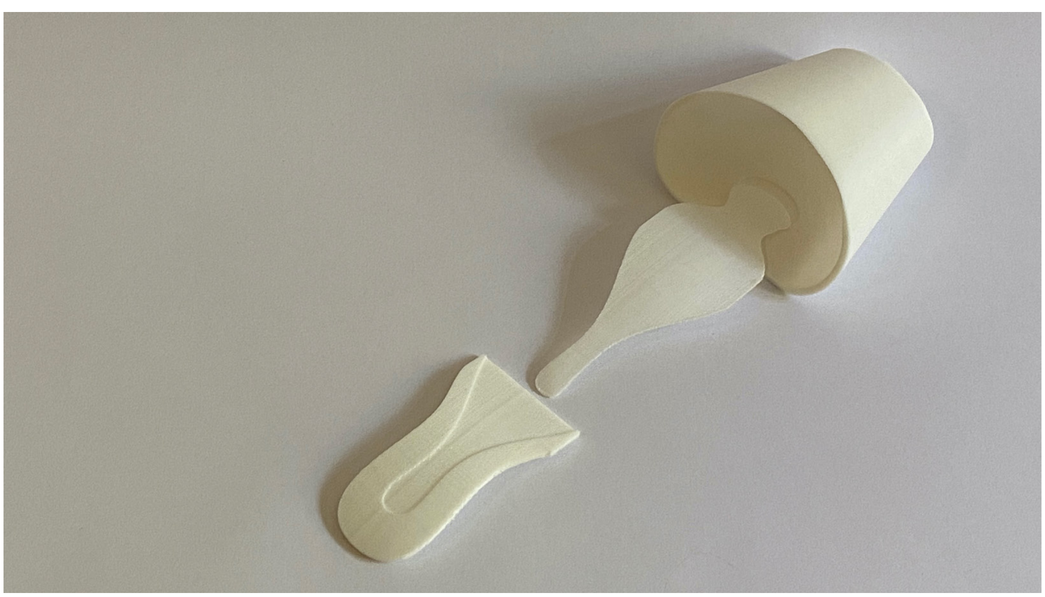


Figure 6.82 The flexible part is designed as an extra piece that would be printed aside and that it would be attached on a recess on the box and the rigid part of the sole.

Figure 6.83 On the left can be seen the prototype printed with the layers in parallel with the axis of the folding and as it can be seen, it kept breaking even when trying to take off the support structure. On the right can be seen the prototype printed with the layers perpendicular to the axis of the folding which made it much more resistant..

wasn't possible due to the limitations of the available printer. In this case as well, the remaining gap would be filled with the flexible material of the outer shoe. The advantage of this piece being a separate element, is that it offers more possibilities of different materials, **that can form a parameter related to the strength of each dancer**.

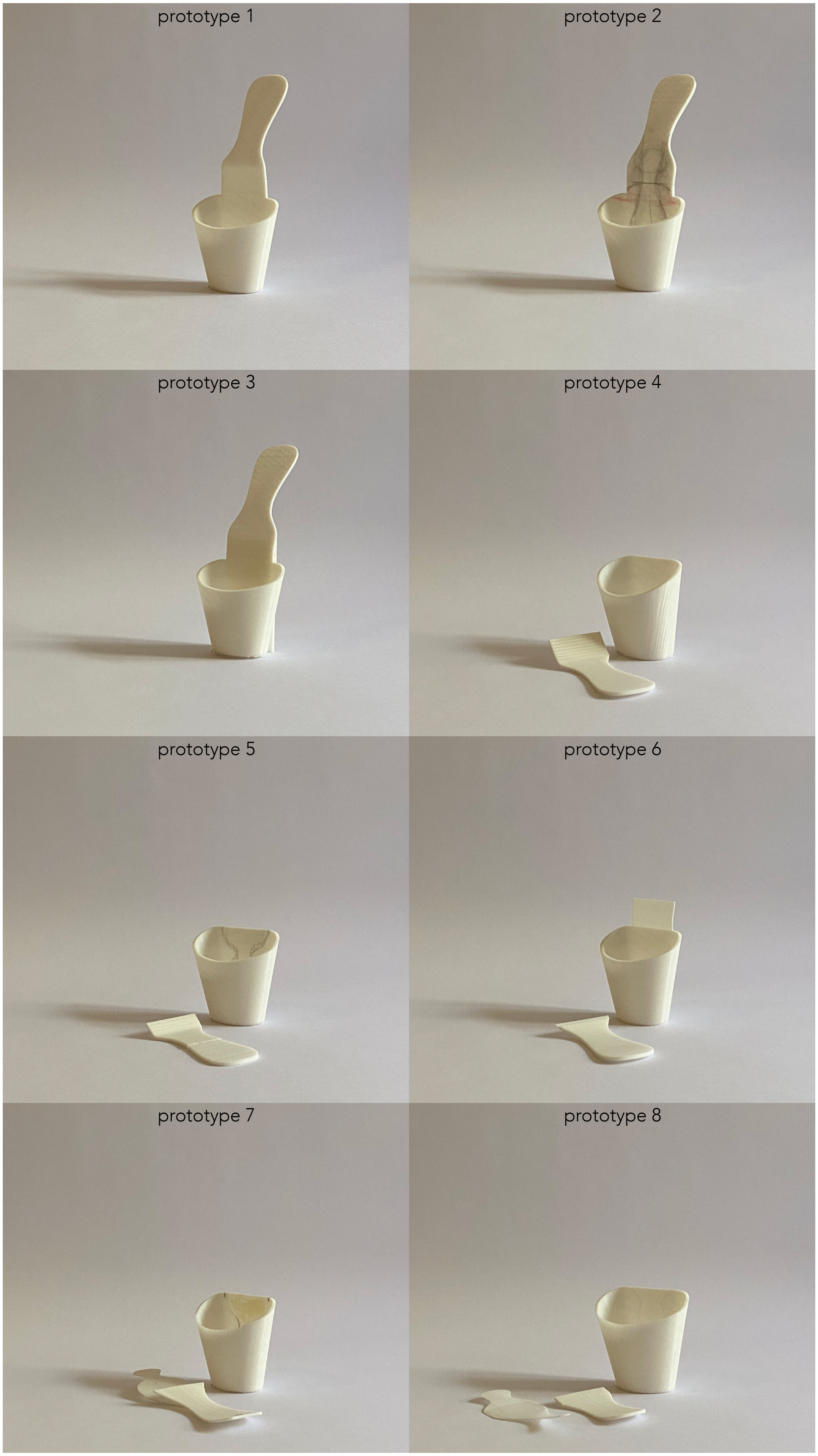


Figure 6.84 Series of prototypes of the inner sole. Each trial has a change in the supple part of the shank.

Figure 6.85 The first trial of the protective padding was made of a mold filled with liquid silicone.

6.3.3.Fabrication of the protective padding:

The protective padding needs to be made of a very comfortable and flexible material for it's the part of the shoe that provides comfort and it's designed for avoiding discomfort, blisters and wounds on the toes. At the beginning it was proposed to fabricate this that using silicone. For that, it was fabricated a double mold that on the exterior there was a layer of the box and on the interior a layer of the mesh of the foot, leaving a gap between the two molds that needed to be filled with liquid silicone *(Fig. 6.85)*. The fill of the silicone was done using a syringe. This material is believed to be ideal for this part of the shoe. The disadvantage was that it's a very expensive process and that the human factor is very crucial, as the fill in with the liquid silicone has to be done with extra attention for avoiding air bubbles. The other idea was to fabricate this part of the shoe using the 3D printer and the TPU material. Depending on the printing parameters the printed protective padding can provide protection but above all it resolves the problem that many dancers have, that some toes are longer than the hallux, or the fifth metatarsal is very short and as a result reduces the stability and balance of the dancer. The protective padding fabricated in this way takes the exact shape of the foot.

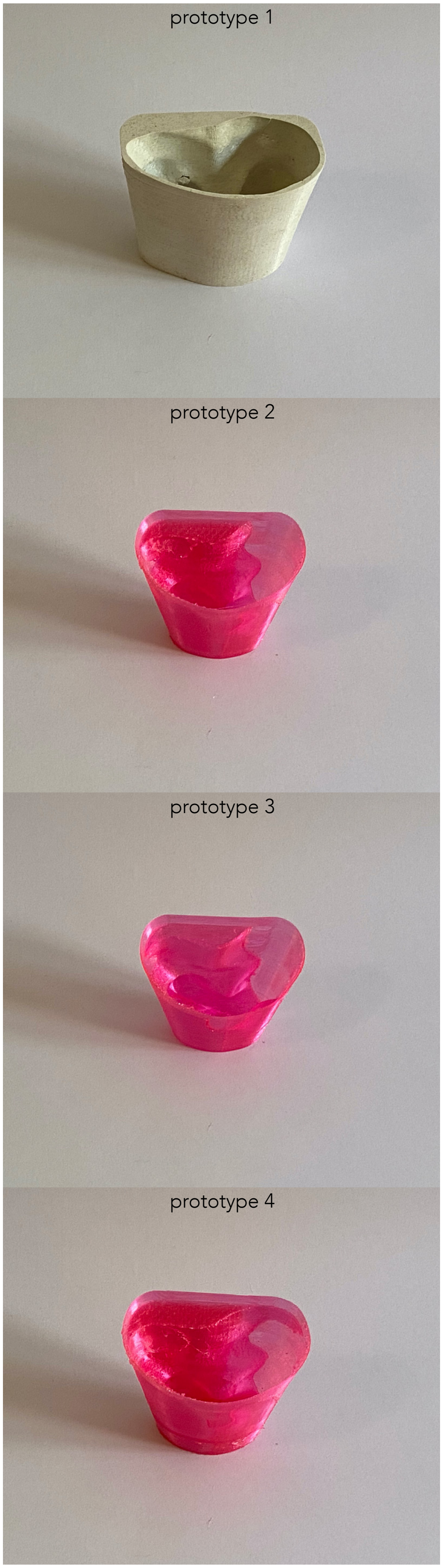


Figure 6.86 Prototypes of the protective padding - Silicone and 3D printed with TPU material.

Figure 6.87 The outer shoe needs to hold together all the part of the shoe and the ribbons are needed for adjusting it on the foot and holding it tight.

6.3.4.Fabrication of the outer shoe:

The outer shoe as the part that holds together the other parts of the shoe needed to be fabricated substituting the role of the fabric or leather of the traditional shoe *(Fig. 6.87)*. In the traditional pointe shoe, this part is fabricated by a satin fabric on the upper and side part, and the outer sole is made of leather. Here, it was proposed to fabricate the whole outer shoe using TPU material for having a material continuity and for tiding together the rest of the parts. The way that this part was designed was very important and affects the behavior of it. The more thickness this part has, the more resistant it is. The holes that are drawn on the sides are for providing flexibility to the outer sole for allowing it to adapt perfectly on the foot. There have be done various trials for the thickness in order to have a quite flexible but at the same time very resistant cover of the shoe.

Conclusions:

As a result, for the fabrication part, it can be reported the successful fabrication of all the parts of the shoe, based on digital fabrication. The shoe was fabricated by 3D printing all the parts of it using PLA and TPU material, depending on the requirements of each part. The most important fact here is that an object was fabricated by simply linking the digital representation of it, directly to the 3D printer, allowing us in this way the repetition of exactly the same process for fabricating a shoe for every individual according to his/her own characteristics and needs.

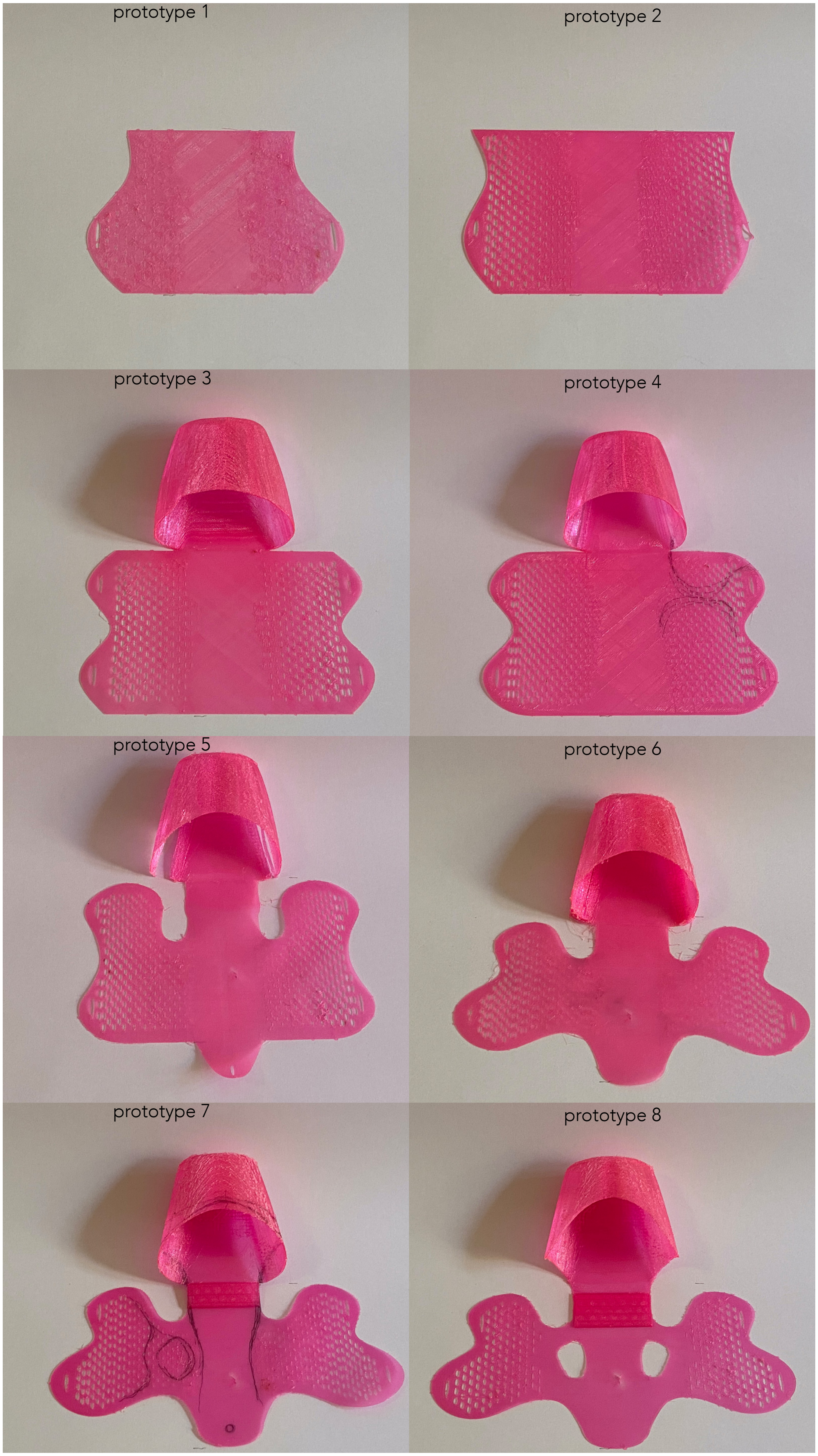


Figure 6.88 A series of prototypes of the outer shoe 3D printed with TPU.


ribbons
outer shoe
shank
box

Chapter Seven: Conclusions

7. Chapter 7: Conclusions

Accomplishments:

The main objective of this project, as defined in the first chapter, was to study well the geometrical and structural parameters that need to be taken into account while designing a pointe shoe and to develop a parametric system using a graphical algorithmic editor, for designing and making pointe shoes that will be adaptable to all feet was successfully accomplished.

In order to achieve this objective, as already explained, the study was divided into five individual subsections:

- With the use of 3D scanning technology for getting many different 3D foot samples, they were defined the geometrical parameters that need to be considered while designing a pointe shoe. For achieving this, a very deep study of a theoretical background which included foot and dance anatomy, as well as the way that the conventional pointe shoe is designed and fabricated was done. The 3D meshed that were extracted from the 3D scanning process were then imported into a 3D software allowing the extraction of measurable information about the geometry of the feet, helping to define better these geometrical parameters.
- Deep research and understanding of the applied forces that act on the foot and shoe while dancing and dancing on pointe were done for the

consideration of the impact that these forces have are very important for designing the shoe.

- An investigation of the materials that could be used for fabricating the shoe was done, having a great consideration of the applied forces while dancing on pointe. The chosen materials had to respond to the requirements of a pointe shoe in order to help the dancer to reach the top of her performance.
- After getting the 3D geometries of the scanning process, a parametric system was developed using Grasshopper 3D, depending on the geometry of each different foot. This parametric system can be used for designing pointe shoes that can adapt to every individual foot.
- Once a parametric system was developed, using digital fabrication and more specifically, 3D printing technology and two specific materials, PLA material for the hard parts of the shoe and TPU material for the less rigid and flexible parts of the shoe, several prototypes were made for each different part of the shoe forming a well-structured pointe shoe that can be used for performing on pointe.

Discussion:

Using 3D scanning technology and the theoretical background related to foot and dancing anatomy, a 3D mesh was provided, which was then imported into a

3d software allowing the extraction of important measurable information about the geometry of the feet. After that, using the same 3D model, a parametric system was developed depending on the geometry of each individual foot. Even though this part of the project is considered to be accomplished successfully, the samples provided from the scanning were only of a very few people, extracting in this way information for only a very few foot typologies. Future work could be done scanning more feet, maybe up to 100, from different ages and maybe even from male dancers. In this way, it can be confirmed that the parametric system works and has taken into account all the necessary parameters that are needed for designing a shoe for any type of foot.

On the other hand, even though a thoughtful investigation about the applied forces while dancing on pointe shoes was done and they were taken into account while designing the shoe, they were not calculated. A future study should be done on how the system could be further developed, adding the applied forces while the shoe is being also used as a measurable parameter, as it has been done with the geometrical approach. The flexibility of the arc of the foot, for example, has been taken into account as well as the strength of the dancer, but as for the last, it should be studied further in order to be introduced as a measurable parameter. For instance, a comparison measure could be the foot pressure that is performed by a dancer while being on demi-pointe per his/her weight. Another parameter that could be added, is the foot strength of the dancer, related to the thickness of the box, of even the material rigidity of the box. The lifespan of a box of conventional pointe shoes usually depends a lot on the individual's strength.

After the parametrization of the design, a prototype was successfully developed, using a 3D printer and a small range of materials. A future investigation should be done for studying not only for trying out more materials but also for trying out more ways for developing a 3D mesh structure which could also affect the material properties and behavior.

The prototype was tried out by a ballerina and can be used for dancing. It lacks of providing comfort and security. In order to reassure its functionality and comfortableness, the inside of the shoe should be better resolved. For example, the material of the padding should be further studied in order to be more flexible and adaptable. It is also very important that the shoe will be tried out by many more dancers.

Future work:

The innovation of this project lays in the integration of digital technologies in the designing process, as well as in the integration of the digital fabrication in the manufacturing process for customizing pointe shoes. In order to succeed and to arrive at a final object (pointe shoe), a process was defined that included a deep investigation, 3D scanning, the definition of variables that needed to be considered for the parametrization, the parametrization of the design using generative algorithms and at last the fabrication of the object using 3D printing technology. In the same way, this process could be applied for designing shoes that require an exceptional performance similar to the pointe shoes. For example, this process could be used for designing shoes for football players, rock climbers, skiers or runners. Additionally, this process could be used for designing equipment for different parts of the body, gloves for the hands of boxers and motorcyclists, bicycle cushion seats for cyclists, helmets for many different sports (motorcycling, cycling, roller skating, boxing, etc.), even for gaming controllers that can be customized-made for every individual game player. In the future, when digital fabrication will be cheaper and more accessible, this process could be used for customizing wheelchairs for people that have disabilities.

Eventually, this project, combining parametric design and digital fabrication, opens the doors and gets a bit closer to the concept of mass customization, allowing in this way, every person to be provided with garments and equipment that adjusts to their own needs and taste.

8. References

- Au, S. (2012) ***Ballet and modern dance***. 3rd Edition. London: Thames & Hudson Ltd. doi: 10.5860/choice.40-1453.
- Bähler, A. (1986) *'The Biomechanics of the Foot CHARACTERISTICS OF THE FOOT', Clinical Prosthetics and Orthotics,* pp. 8–14. Available at: http://www.oandplibrary.org/cpo/pdf/1986_01_008.pdf.
- Barber, R. P. et al. (2007) *'Newton's 2nd Law and the Physics of Dance'*, p. 12. Available at: http://arxiv.org/abs/0706.2717.
- Barber, R. and Popalisky, D. (2008) '*Dancing with physics'*, Physics World, 21(1), pp. 29–32. doi: 10.1088/2058-7058/21/01/30.
- Barringer, J. and Schlesinger, S. (2004) *The pointe book*. 3rd Edition. New Jersey: Princeton Book Company.
- Boër, C. R. and Dulio, S. (2007) *Mass Customization and Footwear: Myth, Salvation or Reality?* London: Springer. Available at: file:///C:/Users/youhe/Downloads/kdoc_o_00042_01.pdf.
- Bossan, M.-J. (2012) *The art of the shoe*. New York: Parkstone International. Available at: http://books.google.com/books?id=bkOMDgwFA28C&pg=PA168&lpg=PA168&dq=200+watt+piezoelectric+transducer&source=bl&ots=F39hTL71Po&sig=jJ2QHIS0GSZMBIgX0ujrnYmFnII&hl=en&ei=7wc7TvXyLInbgQfNmKHPBg&sa=X&oi=book_result&ct=result&resnum=1&sqi=2&ved=0CFYQ6AEwAA#v=o.
- Burry, J. and Burry, M. (2012) *'The new mathematics of architecture',* London: Thames & Hudson, pp. 254–269. doi: 10.1126/science.128.3328.807.
- Carlo, B. (1847) *Notes Upon Dancing, Historical and Practical*. Edited by M. Delaporte. London.
- Chatfield, S. J. (1993) *'Kinesiology and Medicine for Dance'*, (January 1993).
- Clifton, G. (2009) *'The coefficient of friction of the pointe shoe and implications for current manufacturing processes'*.
- Colucci, L. A. and Klein, D. E. (2008) '*Development of an Innovative Pointe Shoe', Ergonomics in Design*, 16(3), pp. 6–12. Available at: https://doi.org/10.1518/106480408X333091.
- Cox, R. and Herzog, V. W. (2013) *'The effect of pointe shoe toe box shape on proprioception in novice ballet dancers'*, Internet Journal of Allied Health Sciences and Practice, 11(2), pp. 1–5.
- Cunningham, B. W. et al. (1998) *'A comparative mechanical analysis of the pointe shoe toe box. An in vitro study'*, American Journal of Sports Medicine, 26(4), pp. 555–561. doi: 10.1177/03635465980260041501.

- Doubrovski, Z. and Verlinden, J. C. (2018) *'Fabricating the Foliage Dress: Computational Design in Couture'*.
- Ebrahim, M. (2011) *'3D Laser Scanners: History, Applications and Future'*, LAP LAMBERT Academic Publishing, (October), p. 104. doi: 10.13140/2.1.3331.3284.
- Farah, S., Anderson, D. G. and Langer, R. (2016) *'Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review'*, Advanced Drug Delivery Reviews, 107, pp. 367–392. doi: 10.1016/j.addr.2016.06.012.
- Fisher, J. (2012) *'The swan brand: Reframing the legacy of Anna Pavlova*', Dance Research Journal, 44(1), pp. 51–67. doi: 10.1017/S0149767711000374.
- Ford, S., Mortara, L. and Minshall, T. (2016) *'The Emergence of Additive Manufacturing: Introduction to the Special Issue'*, Technological Forecasting and Social Change, 102, pp. 156–159. doi: 10.1016/j.techfore.2015.09.023.
- Gibson, Ian, Rosen, David, Stucker, B. (2015) ' *"Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing"*, 2nd Edition', Johnson Matthey Technology Review, 59(3), pp. 193–198. doi: 10.1595/205651315x688406.
- Gibson, I., Rosen, D. and Stucker, B. (2015) *Directed Energy Deposition Processes. In: Additive Manufacturing Technologies*. New York.
- Gibson, L. J., Ashby, M. F. and Harley, B. A. (2005) *'Cellular materials in nature and medicine'*, British Dental Journal. Cambridge: Cambridge University Press, p. 627. Available at: https://books.google.com.sg/books?hl=en&lr=&id=AKxiS4AKpyEC&oi=fnd&pg=PR9&ots=JlVO0Ax-6qW&sig=CvvXz9Ui4MzGrUbJ_IdOUyU8BBs#v=onepage&q&f=-false%0Ahttps://books.google.com.sg/books?
- Grivas, T. (2002) *Foot and Ankle*. Athens: Chr. Vasiliades.
- Haas, J. G. (2010) *Dance anatomy,* Choice Reviews Online. IL, USA: Human Kinetics. doi: 10.5860/choice.48-1383.
- Hammond, S. N. (1987) *'Searching for the Sylph: Documentation of Early Developments in Pointe Techninque'*, Dance Research Journal, 19(2), p. 27.
- Hill, M. et al. (2017) *'The relationship between arch height and foot length: Implications for size grading'*, Applied Ergonomics, 59, pp. 243–250. doi: 10.1016/j.apergo.2016.08.012.
- Imura, A. and Yeadon, M. R. (2010) *'Mechanics of the Fouetté turn'*, Human Movement Science, 29(6), pp. 947–955. doi: 10.1016/j.humov.2010.08.002.
- Jowitt, D. (1988) *Time and the dancing image, Choice Reviews Online*.

Berkeley and Los Angeles: University of California Press. doi: 10.5860/choice.26-2046.

- Kalantari, M. and Nechifor, M. (2016) *'Accuracy and utility of the Structure Sensor for collecting 3D indoor information'*, Geo-Spatial Information Science, 19(3), pp. 202–209. doi: 10.1080/10095020.2016.1235817.
- Klenerman, L. and Wood, B. (2006) *The Human Foot: A companion to Clinical Studies*, Journal of Chemical Information and Modeling. London: Springer. doi: 10.1017/CBO9781107415324.004.
- Krasnow, D. H. et al. (1997) *'Imagery and Conditioning Practices for Dancers'*, Dance Research Journal, 29(1), p. 43. doi: 10.2307/1478236.
- Laws, K. (2002) *Physics and the Art of Dance: Understanding Movement*, The Physics Teacher. Oxford: OXFORD UNIVERSITY PRESS. doi: 10.1119/1.1737979.
- Lee, Y. (2015) *'The Parametric Design Genealogy of Zaha Hadid'*, Asian Architecture and Building Engineering.
- Lee, Y. C., Lin, G. and Wang, M. J. J. (2014) *'Comparing 3D foot scanning with conventional measurement methods'*, Journal of Foot and Ankle Research, 7(1), pp. 1–10. doi: 10.1186/s13047-014-0044-7.
- Lepidi, M. and Bacigalupo, A. (2018) *'Parametric design of the band structure for lattice materials*', Meccanica, 53(3), pp. 613–628. doi: 10.1007/s11012-017-0644-y.
- McDowell, C. (1989) *Shoes-fashion and fantasy*. New York: Rizzoli.
- Mochimaru, M., Kouchi, M. and Dohi, M. (2000) *'Analysis of 3-d human foot forms using the free form deformation method and its application in grading shoe lasts'*, Ergonomics, pp. 1301–1313. doi: 10.1080/001401300421752.
- Novak, B., Možina, J. and Jezeršek, M. (2014) *'3D laser measurements of bare and shod feet during walking'*, Gait and Posture, 40(1), pp. 87–93. doi: 10.1016/j.gaitpost.2014.02.015.
- Oztekin, H. H. et al. (2007) *'Second-toe length and forefoot disorders in ballet and folk dancers'*, Journal of the American Podiatric Medical Association, 97(5), pp. 385–388. doi: 10.7547/0970385.
- Pearson, S. J. and Whitaker, A. F. (2012) *'Footwear in classical ballet: a study of pressure distribution and related foot injury in the adolescent dancer.'*, Journal of dance medicine & science : official publication of the International Association for Dance Medicine & Science, 16(2), pp. 51–56.
- Perrier, A. et al. (2017) *'Biomechanical Modeling of the Foot'*, Biomechanics of Living Organs: Hyperelastic Constitutive Laws for Finite Element Modeling, (December), pp. 545–563. doi: 10.1016/B978-0-12-804009-6.00025-0.

- Peteinarelis, A. (2016) *'Parametric Design: from code to fabrication'*.
- Piperi, E., Spahiu, T. and Galantucci, L. M. (2014) *'From 3D foot scans to footwear designing & production'*, in. Tirana, pp. 1–24. doi: 10.13140/2.1.3172.6404.
- Piroozfar, P. and Piller, F. (2013) '*Mass Customisation and Personalisation in Architecture and Construction'*, New York: Routledge, pp. 114–126. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84925813765&partnerID=tZOtx3y1.
- Russell, J. A. et al. (2010) *'Magnetic resonance imaging of the ankle in female ballet dancers en pointe'*, Acta Radiologica, 51(6), pp. 655–661. doi: 10.3109/02841851.2010.482565.
- Schumacher, P. (2008) *'Parametricism as Style - Parametricist Manifesto'*, Darkside club, 11th Venice Architecture Biennale, pp. 1–5. Available at: http://www.patrikschumacher.com/Texts/Parametricism as Style.htm.
- Schumacher, P. (2009) *'Parametricism: A new global style for architecture and urban design*', Architectural Design, 79(4), pp. 14–23. doi: 10.1002/ad.912.
- Shahrubudin, N., Lee, T. C. and Ramlan, R. (2019) '*An overview on 3D printing technology: Technological, materials, and applications'*, Procedia Manufacturing, 35, pp. 1286–1296. doi: 10.1016/j.promfg.2019.06.089.
- Simmel, L. (2014) *Dance Medicine in Practice*. New York: Routledge.
- Smelik, A. (2019) *'Cybercouture: The Fashionable Technology of Pauline van Dongen, Iris van Herpen and Bart Hess*', Delft Blue to Denim Blue, (October). doi: 10.5040/9781350986039.ch-014.
- Spahiu, T. et al. (2016) *'On the possible use of 3D printing for clothing and shoe manufacture'*, Proceedings of the 7th International Conference of Textile, 10-11 November, (10-11 November), pp. 1–7.
- Sun, L. (2015) *'Accessing Axis (3D Printed Fashion)'*, (October), pp. 1–3.
- Tang, Y. M. and Hui, K. C. (2011) *'Human foot modeling towards footwear design*', CAD Computer Aided Design, 43(12), pp. 1841–1848. doi: 10.1016/j.cad.2011.08.005.
- Taylor, M. C. (2003) *'The Moment of Complexity Emerging Network Culture'*, Culture. Chicago: The University of Chicago Press.
- Thompson, D. W. (1917) *On Growth and Form*. Cambridge: The University Press.
- Tian, Y. et al. (2019) *'Parametric Design of Grasshopper Based on Moulding Characteristics of Longitudinal Profile of Shoe Last*', Journal of Physics: Conference Series, 1267(1). doi: 10.1088/1742-6596/1267/1/012045.

- Tonkin, L. (2019) *'Re Imagining Embellishment The Conservation of Iris van Herpens Radically Engineered Surfaces'*, (January).
- Wienstock, M. (2010) *The Architecture of Emergence: The Evolution of Form in Nature and Civilisation*. Chichester: Wiley.
- Zhang, Y.-F. et al. (2010) *'3D foot scan to custom shoe last 3D Foot Scan to Custom Shoe Last 3D Foot Scan to Custom Shoe Last'*, Special Issue of IJCCT, 1(January), pp. 3–5. Available at: https://www.researchgate.net/publication/228879419.

Web references:

https://3dprintingindustry.com/news/adidas-reveals-futurecraft-strung-the-ultimate-3d-printed-running-shoe-177073/

https://www.3dsystems.com/blog/2015/04/re-inventing-shoes-united-nude

https://all3dp.com

https://all3dp.com/1/pla-plastic-material-polylactic-acid/

https://all3dp.com/what-is-stl-file-format-extension-3d-printing/

https://all3dp.com/2/tpu-filament-explained-and-compared/

https://www.britannica.com/biography/Louis-XIV-king-of-France

https://www.britannica.com/biography/Marie-Camargo

https://www.britannica.com/biography/Marie-Taglioni

https://www.britannica.com/biography/Anna-Pavlova

https://dancer.com

http://www.irisvanherpen.com

https://www.freedoflondon.com/in-the-making/

https://n-e-r-v-o-u-s.com/projects/albums/new-balance-midsoles/

https://www.operadeparis.fr/en/artists/ballet-school/history

https://www.patrikschumacher.com/index.htm

https://pointemagazine.com/history-of-pointe-shoes/?rebelltitem=4#rebelltitem4 https://radiologykey.com/footi/

https://skanect.occipital.com

https://theshoeman647325124.wordpress.com/2020/01/12/charles-didelot-and-pointe-shoes/

https://www.wolfram.com/mathematica/new-in-10/data-and-mesh-regions/meshes-in-3d.html