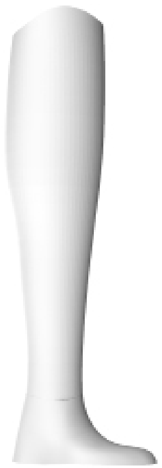
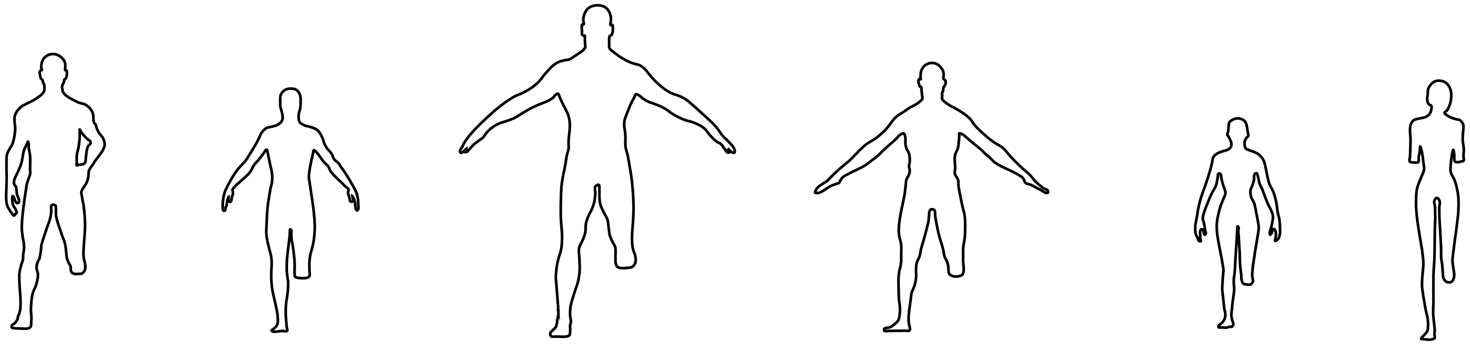


# PARAMETRIC PROSTHETICS

Creating a digital workflow for individualised design

Tinofara Mutambu



*A 90-point thesis submitted to the Victoria University of Wellington in fulfilment of the requirements for the degree of Master of Design Innovation.*

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*School of Design Innovation*
*Victoria University of Wellington*
*2021*

*Figure 1. Cover: Parametric Prosthetics*

# ABSTRACT

Digital design technologies and data collection methods are increasingly being used to cater for personal specification of products and services.

The current process of fitting and making below-knee prosthetics is labour intensive and time consuming. Whilst artificial limb service providers have begun to implement digital technologies, opportunities for individualised prosthesis using parametric modelling and additive manufacture remain unrealised.

In response this thesis develops a digital workflow which acts as the tailor in the prosthetic design process. Together with additive manufacture the capability of parametric variation is examined as a demonstration of future possibilities.

The research looks at innovative ways to visualise future products in the form of a fully 3D printed prosthesis that challenges existing methods. Using field research, design experiments, parametric software and simulated anthropometric models a range of virtual and physical lower limbs were constructed.

The resulting prototypes were evaluated against current methods of making and workflows and engaged with experts in the industry. The outcome reveals new economic and aesthetic possibilities for the wide diversity of people requiring lower limb prosthesis whilst enhancing the innovation prospect of service providers.

# Acknowledgments

Thank you to my supervisors Bernard Guy and Simon Fraser for guiding me throughout this process with enthusiasm.

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My family for their love and support throughout this journey and for keeping me motivated.

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Student learning, for providing their expert knowledge, guidance and support with my academic writing

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# 01

# INTRODUCTION

## 1.1 **CHAPTER CONTENT** DESCRIPTION

### 01

### INTRODUCTION

Briefly introducing the research to the reader. This section also outlines the project and the issues which are going to be investigated.

### 02

### RESEARCH METHODOLOGIES & METHODS

This section outlines the design methodologies and methods used throughout the research. Research through design and research for design were chosen as the appropriate methodologies to apply in this research.

This section also briefly introduces the research methods applied and the role they play within the overall thesis. This chapter describes procedures within the design process, software and hardware.

### 03

### BACKGROUND REVIEW

This section sets the foundation and puts the research into context. An overview into the history, current manufacturing, and fabrication methods will support the research by identifying gaps to help shape the research. The precedent and literature reviews look at investigating current design precedents, methods and applications which explore and test the boundaries of design. Themes such as the history of prosthetics, the changing role of the designer and current 3D printing in the prosthetics industry.

04

## DESIGN EXPLORATION

This section is the experimentation and design phase. The designer used parametric software to assist in developing the digital workflow. Exploration into dynamic prosthetic feet were experimented and developed in this section.

05

## DISCUSSION & CONCLUSION

This section recaps the research ,evaluates design process and places it in context. Research limitations and future projects were discussed in this section.

## 1.2 TERMINOLOGY

**NZALS**: New Zealand Artificial Limb Service.

**AM**: Additive Manufacturing (3D printing).

**PARAMETRIC**: Relating to or expressed in terms of a parameter.

**PARAMETER**: a numerical or other measurable factor forming a set that defines a system or sets the conditions of its operation.

**3D SCANNING**: the process of analysing a real-world object or environment to collect data.

**CAD**: Computer Aided Design.

**RHINO 3D**: Rhinoceros is a commercial 3D computer graphics and computer aided design application software

**GRASSHOPPER**: Grasshopper is a visual programming language and environment runs within the Rhinoceros 3D computer-aided design application.

**M.A.D.E**: Multi-property Additive Manufacturing Design Experiments.

**XYZ COORDINATES**: A coordinate system that specifies each point uniquely by a pair of numerical coordinates.

**ENDOSKELETAL PROSTHETIC**: gains its structural integrity from a pylon made of metal or carbon fiber

**EXOSKELETAL PROSTHETIC**: a prosthesis which gains its structural integrity from the outer laminated shell.

**FDM**: Fused Deposition Modelling

**ABS**: Acrylonitrile Butadiene Styrene

**BREP**: In computer aided modelling , a boundary representation ( BREP)
is a method for representing shapes using units. The solid is visualised as a set of connected elements.

## 1.3 RESEARCH PROPOSITION

*"Given the capability of data, code and generative design to create additive manufactured 3D form, how might this look like in prosthesis design"*

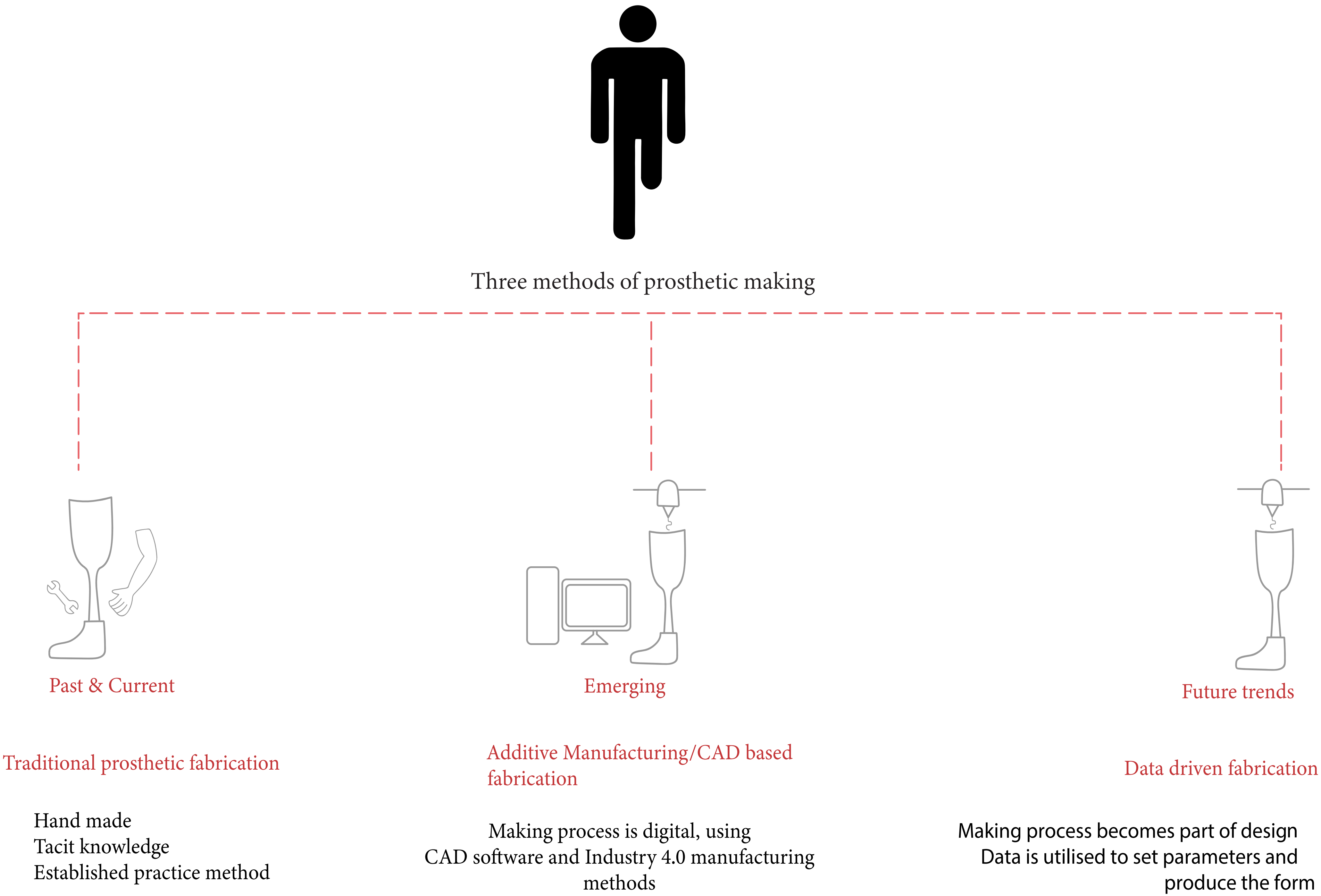


*Figure 1.1 .Methods of prosthetic making*

## 1.4 INTRODUCTION

Statistics show that in New Zealand there are around 4,400 amputees with 74% being men and 26% being women (NZALS, 2017). To provide a better service NZALS looks at new technologies and R&D, this investment allows for research to be made which seeks to benefit the manufacturing processes and patients.

Since 2016 the Multi – Property Additive Manufacturing Design Experiments (M.A.D.E) research group at Victoria University has been involved with NZALS. The longstanding research relationship between MADE and NZALS has matured and NZALS continues to adopt new technologies to find innovative design opportunities. This thesis continues the collaboration and proposes to focus on how data might drive the design of limb prosthesis using additive manufacturing.

Fig: 1 shows the developing methods of prosthetic making , which include past and current , emerging and future trends of prosthetic making. Current practice for prosthetic design consists of mould making for plaster casting and fibre glass fabrication. NZALS has and continues to advance their capability with contemporary digital technologies and 3d printing to make limb prosthesis.

However, the NZALS's far-reaching goal is to utilise emerging technologies as a tool in their design process. In essence, digitised physiological data such as body mass, gait, and body asymmetry information will be used as a design input. This is a gap in current research and an opportunity where design innovation may expose new avenues/visualisation of possible products. This thesis suggests the computer and code type procedural programmes can contribute significantly in the context of additive manufacture and asks; what would design through data workflow look like, and can visualisations act as a case study to communicate possibilities?

My initial research question for this portfolio additionally states, "given the capability of data, code and generative design to create additive manufactured 3D form, what might this look like in prosthesis design?". The aim for this research portfolio is to investigate current and potential future methods and tools to enable digital data to assist the design of additive manufactured prosthesis.

## 1.4 RESEARCH AIMS AND OBJECTIVES

**AIM 1: Create a simulated body dataset**

**Objective:**

Digital data collection technologies – utilising a variety of data driven design technologies such as anthropometric software and 3D scanning to create a generic sample anthropometric or body specification dataset from which parametric design experiments can be developed.

**AIM 2: Develop a parametric design workflow**

**Objective:**

Coding-, utilise parametric design in the design process. Develop a digital workflow through parametric experimentation within the parameters of a simulated human body. With the assistance of the NZALS prosthetic measurement chart, this will set parameters that can be changed.

**AIM 3: Apply workflow to prosthetic limb**

**Objective:**

Design- these prototypes will need to be created with limitations in mind as it involves alignment to simulated human body. Prototyping and developing an overall form should be expressed through design processes within the methodologies.

# 02

# RESEARCH METHODOLOGIES & METHODS

### Overview

Downton (2003) describes three overriding methodologies of approaches to design research: these are research about design, research through design and research for design. These research methodologies feed into one another during the design with a number of different outputs that can be identified and utilised to gain more knowledge.

Both research through design and research for design will provide a framework to assist in investigating the research question in this thesis.

### 2.1 Research for Design

Research for design will be the secondary research area. It will provide information, suggestions and data that can be used as a basis to provide parameters for the design research investigation. This method is useful as it contextualises a foundation for the rest of the study. A literature review will examine and evaluate the history, current manufacturing methods and technological aspects as well as appropriate design precedents which guide the scope of the research framework.

### 2.2 Research through Design

Research through design is the discovery stage of the overall design process. This is where ideas are iterated and refined from start to finish using various research methods. Research through design provides a more practise/ iterative based element toward the design research. Design is often interdisciplinary in its nature where it can range from small ideas or concepts to something more complex like a new material or process (Milton & Rodgers, 2013).

## RESEARCH METHODS

### Concept Generation

This initial stage is where ideas are generated based off literature reviews, precedent analysis, product analysis and limb centre tour .

### CAD & Parametric Modelling

A vital part of this research is the relationship between the information obtained through digital data collection technologies and the tangible output of 3D printing. In this research there is an emphasis on parametric modelling where models are built using coordinates, relationships between coordinates and algorithms rather than fixed numbers for greater control and customisation.

Rhinoceros 3D was predominately used to construct the overall forms using both the surface modelling environment and the parametric plug-in Grasshopper. Using this parametric environment allowed for increased control in the design process, making it easier to generate the overall form. Other software programs like Netfabb, Meshmixer and Keyshot are applied for file reduction and preparation, 3D sculpting and digital visualisation.

### 3D Scanning

3D Scanning technology was used to create a sample dataset from which parametric design experiments were performed. The designer's lower limbs were scanned using Artec Eva 3D scanner, to gain an accurate body specification dataset. From this scan data a range of 3D anthropomorphic models were then scaled into appropriate sizes.

The Artec Eva 3D scanner provides speed, capturing frame rates of up to 16 frames per second (FPS), resolution and accuracy, with 3D point accuracy of 0.1 mm and resolution of 0.2mm, the scans produced are very detailed, and colour data capture, taking full colour information from the objects being scanned. This helps with scan accuracy, rendering or 3D printing (digitize design ,2021).

Once the scan is complete, this information was then analysed and taken through post-processing to erase excess detail.

## Software

**Rhinoceros 3D:** *(or 'Rhino') is commercial 3D computer graphic and computer-aided design (CAD) application software.*

This software application creates both structural and freeform geometry within its interface, this is done through manipulating curves, surfaces and solids (Robert McNeel & Associations, 2018). The accuracy that this software offers means designing at different scales and complexities can be achieved for the best design result. Rhino is the main software used throughout the design process (https://en.wikipedia.org/wiki/Rhinoceros_3D).

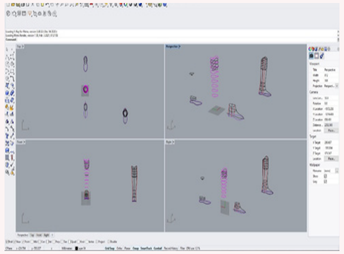

*Figure1.2 Rhino 3D interface*

**Grasshopper:** *a visual programming language and environment that runs within the Rhinoceros 3D computer aided design application.*

Within this application, components of a 3D model made in Rhino can be connected and moved by using sliders or entirely made in Grasshopper. This software displays real time changes to the geometry, showing the result of parametric manipulation. This streamlines the iterative process as multiple variations can be generated without the need to remodel the geometry ((https://en.wikipedia.org/wiki/Rhinoceros_3D).

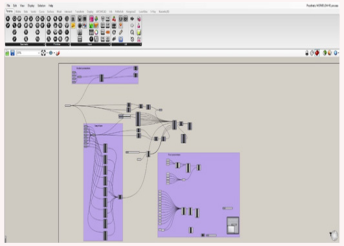

*Figure 1.3 Grasshopper interface*

**Autodesk Netfabb:** *is a connected software for additive manufacturing, design and simulation. It converts 3D printed parts and repairs build errors.*

Netfabb is used to edit and review initial files and finalise files for printing. The advantage of this software is its ability to reduce file size while maintaining accuracy and repair errors in file (https://www.autodesk.co.nz/products/netfabb/).

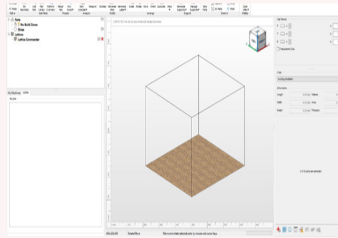

*Figure 1.4 NetFabb interface*

**Autodesk Meshmixer**: *is a free 3D sculpting based CAD programme created by Autodesk* software as a part of their 123D software line.

Meshmixer is similar to Netfabb where it can reduce and repair files for CAD modelling or 3D printing. Features like 3D sculpting, surface mapping and mesh smoothing can be used in Meshmixer (https://www.meshmixer.com).

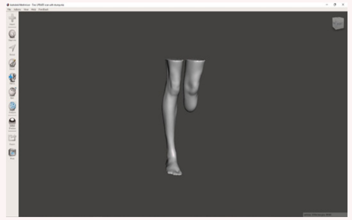

*Figure 1.5. Mixermixer interface*

**Keyshot:** is *designed to make 3D rendering and animations easily through applying materials and lighting.*

Keyshot lets designers validate concepts and ideas through realistic 3D renders and animations. Keyshot puts the model in its contextual setting by applying appropriate materials and lighting to the scene. In some instances, rendering can communicate the overall idea better than the physical product by putting it in various environments(https://www.keyshot.com).

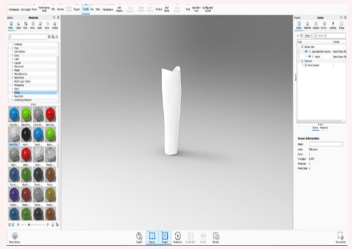

*Figure 1.6 Keyshot interface*

# RESEARCH METHODS

## 3D Printing Process

3D printing provides a quick method of visualising concepts and ideas generated in a digital environment. These can be scaled and printed into physical objects for evaluation. Within this research framework, FDM UP-box printers will be used to better inform design direction and ideas through a range of scale models to validate the concept.

### FDM

Fused deposition modelling (FDM), is a widely used, relatively quick and inexpensive method of 3D printing. These printers operate by extruding thermoplastics filaments like ABS and PLA through a heated nozzle. This heated nozzle melts the plastic and applies the material layer by layer until the part this complete (Formlabs, n.d). Benefits of using FDM printing includes, producing basic proof-of-concept model, simple prototyping and low cost of materials (Formlabs,n.d). Disadvantages of using FDM printing includes the need of support structures and thermal shrinking of filament (What is SLS 3D Printing,n.d).

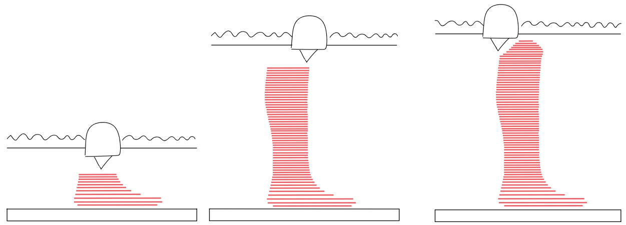

*Figure 1.7 FDM Printing*

### SLA

Stereolithography (SLA), is a 3D printing process where an object is generated by using polymer resin, layer-by-layer using an ultraviolet laser beam. The materials in SLA printers are photosensitive thermoset polymers that are in a liquid form (3D HUBS,n.d). Benefits of using SLA printing includes, ability to produce functional prototypes, patterns, molds and tooling (Formlabs,n.d). Disadvantages of using SLA printing includes small variety of material and high maintenance costs (What is SLS 3D Printing,n.d).

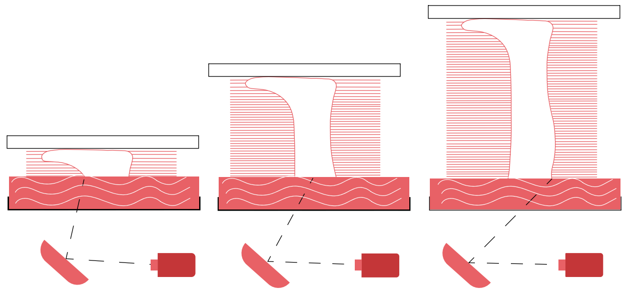

*Figure 1.8 SLA Printing*

### SLS

Selective laser sintering (SLS), is a 3D printing process where a high-powered laser is used to fuse small particles of polymer powder into a physical object, based on a computer-generated 3D mode (Formlabs,n.d). Benefits of using SLS printing includes, producing functional prototypes and end-use production (Formlabs,n.d). Disadvantages of using SLS printing include its long printing time (What is SLS 3D Printing,n.d).

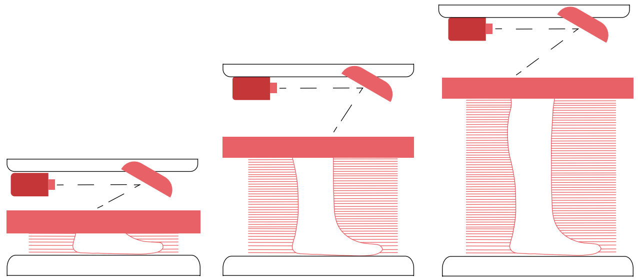

*Figure 1.9 SLS Printing*

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# BACKGROUND REVIEW

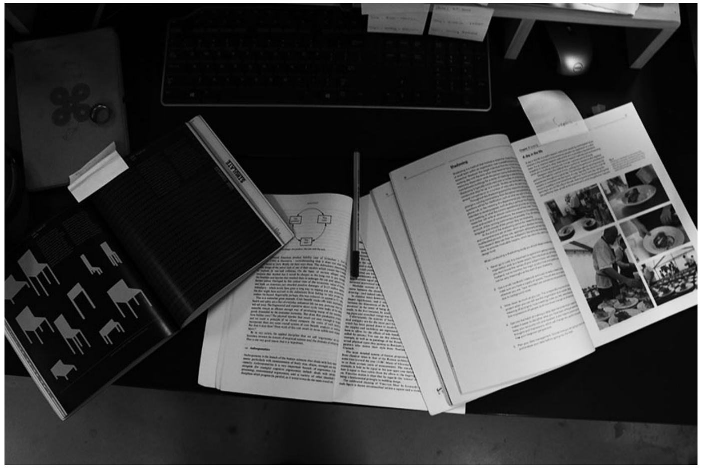

*Figure 2 Researching*

## Parametric Design

The demand for flexibility within Computer Aided Design (CAD) and parametric design has now become mainstream. In comparison to when it was exclusive for manufacturing within the aerospace, shipping, and automobile industries. Parametric design is the process of designing in an environment where variations can be changed by adjusting dimensions , thus replacing singularity with multiplicity in the design process (Barrios, 2004). Designers have demanded this flexibility in mainstream software as it allows for changes to be made without deleting or redrawing while using specific design tools (Barrios, 2004). The relationship between numerous geometries in a model means that parametric design focuses more on the process rather than the end product. This relationship allows for various iterations to be made without the need to rebuild the model when a change is needed (Barrios, 2004).

Parametric models are computational representations of a design that have been made with geometrical objects which consist of points that are fixed and other points that can be modified. In parametric design, parameters are created to define the form. In this process the form will need to be flexible as multiple variations of the model need to be generated (Barrios, 2004). Current parametric software like Grasshopper have become more advanced allowing a better interaction between the computer and the designer. Precise control and rapid feedback from these programmes mean that changes to parameters are in real time.

Parametric design is rapidly being applied within a diverse range of industries giving them flexibility and adaptability when developing products, services or infrastructure. The advantages of parametric design include accommodating modifications, where iterations can be created very quickly and updates from other projects can be integrated seamlessly within the workflow. Automation and optimization are significant aspects where parametric design adds value to the design process, updating changes in the 3D model as the designer goes.

In the case of a below the knee prosthetic, this can be digitally generated by locating variable points on the leg. Variables like height, body weight and foot size are taken into consideration as it influences the overall structure (Summit,2014). In this context parametric design is best described as a digital tailor as all the parameters are closely modified resulting in unique prosthesis for specific body types and the needs of the amputee (Summit,2014).

## Additive Manufacturing

Additive manufacturing is 3D printing in manufacturing context. AM is able to transform specific design files called STL's and produce functional objects. These STL's are initially made digitally using computer-aided-design (CAD) software which then slices the object into thin layers (GE, 2021).

AM is an application that gives the designer "freedom" as it enables users to make unique products which are then manufactured in an economical way. The use of AM technologies and methods are being applied in increasingly more industries and market divisions such as automotive, medical and aerospace. This is anticipated to continue to grow in the years to come (Berman, 2012). Although additive manufacturing has its advantages compared to conventional manufacturing methods, AM is comparatively slower and more expensive technology (Diegel,2019). Therefore, AM should only be used in a situation where traditional manufacturing techniques are unable to perform the task (Diegel,2019).

As AM advances at a rapid pace the market of unique one-off prosthetics and other artificial limbs .An example of a company that has exploited the advantages of AM in the footwear is Under Armour, an American sports equipment company that produces recreational and high-performance footwear. Under Armour partnered with EOS, a German company which provides additive manufacturing solutions and industrial 3D printers.

These companies manufactured the "UA architech futurist" a pair of sneakers made utilising advanced laser sintering technology, an additive manufacturing process where a laser creates objects using a powder-based material (Booton,2017). Under Armour's goal to industrialize and scale 3D printing performance footwear is made possible with the design and manufacturing of this sneaker as an example. The eye-catching precision and detail of the sneaker's midsole shows how AM technologies are able to deliver high level 3D printed lattice structures which distributes support throughout the foot (designboom,2017).

These companies explored current additive manufacturing techniques like laser sintering technology where the output were the sneakers as well as developing new polymer-based materials, also applying the laser sintering technology. Ultimately these AM techniques will be applied into Under Armours diverse range of products (Booton,2017).

### 3D Printing in Prosthetics

The accuracy of 3D printing allows for more customisation, giving the amputee more choice with the shape, form and material. For amputees, prosthetic products are finding their way into the market as technologies advance and manufacturing processes are more accessible and the cost is reducing. The fairing, a prosthetic product that is attached to a metal pylon pole is used as an aesthetic by the amputees thus giving companies the opportunity to provide a service for customisation.

3D printing has been successfully implemented in the design and commercialisation of prosthetic fairings but the execution of a fully 3D printed below the knee prosthetic has only been applied and produced by a small number of companies.

An example of a company that is utilising 3D in the prosthetics sector is UNYQ, this company manufactures innovative mass customized products (UNYQ,2021). UNYQ utilises emerging 3D printing technologies to create tangible products that are aesthetically pleasing, giving the amputee confidence.

UNYQ provides a variety of designs and colours for it is below the knee prosthetic cover. With a specialised app, users able to personalise design, texture, colour and finish. The app also assists in the measurement process by having the user take photos of their remaining limb and measure in increments along the leg (UNYQ,2021).

Instalimb is another example, they provide an affordable full 3D printed limbs and sockets based out of the Philippines. The company's intention is to produce high quality prosthetics, manufactured quicker and cheaper (designboom,2021). 3D scanning technology is used by Instalimb to map out the patient's residual limb (stump).

Biomimicry was applied to assist with the structural integrity of the limb, Instalimb used a hexagonal pattern reference from honeycombs as they are the most efficient sequence of shapes able to support weight and applied that into the negative space which makes up the shape of leg (Cirineo,2020). Instalimb states that "the overall process reduces production cost and production costs and production time by one-tenth compared to traditional methods (designboom,2021).

Autodesk, a multinational software company collaborated with Paralympic athlete Denise Schindler to create fully 3D printed cycling prosthesis (Hobson,2016). The goal for this cycling prosthetic was to create an aerodynamic leg which switches the paradigm for how products can be developed. Traditional cycling specific prosthetics are hand made from carbon fibre, which is a time-consuming process.

Specialised sports prostheses require precision for them to be made, and as the human body is ever changing this requires consist redesigns and refitting very often (Hobson,2016).

Traditional manufacturing methods of plaster casting, socket vaccum forming and carbon fibre moulding as mention earlier in the research now have alternatives such as 3D scanning, digital sculpting and 3D printing, Schindler adds that these digital methods allow for faster processing and changes to the 3D model. These software package enable for surface modelling, animation, simulation and code giving designers and engineers easy accessibility during the design process. (Hobson,2016). The sporting industries application of these emerging technologies and the relative successes of it will hopefully now allow for the average amputee to benefit from this (Hobson, 2016).

A Traditional lower limb prosthesis consists of the following:

Socket
Plate adaptor
Stainless steel adaptor
Titanium pylon
Carbon fiber foot

A more advanced trans-tibial prosthesis may have additional componentry for the foot and ankle such as:

Single axis foot
Multiaxial foot
Dynamic response foot
Variable heel height
Vertical Shock Absorbers
Special use (sports) foot
Computerised feet

This prosthesis type gains its structural integrity from the outer laminated shell, through which the amputee's body weight is transmitted.

The shell is commonly made from a fibreglass resin socket. This socket is durable in comparison to a filler material such as wood or foam. Endoskeletal prosthesis, also called conventional or crustacean is generally constructed with wood or plastic.

The overall prosthesis is shaped to appear like the amputated limb. The opposite remaining limb is used as reference for limb shape and skin colour.

Components in endoskeletal prosthesis are firstly aligned in an alignment device, then briefly connected to each other for trial. Any adjustments if required can be made during this trial fitting stage. After final finish has been done, only slight changes can be made. The resulting lamination then provides extra strength to the prosthesis while producing a striking surface.

The disadvantages of an endoskeletal prosthesis include its weight, these are heavy and cumbersome in comparison to endoskeletal prosthesis. The alignment cannot be changed after its final finish, meaning no further major adjustments can be made to the prosthesis. The last drawback from an endoskeletal prosthesis is the fabrication time. Shaping the exterior of the prosthesis, additional lamination for strength and creating an attractive surface quality adds to the overall fabrication time is contrast to an endoskeletal prosthesis.

The average life span of a prosthesis is around three to five years. Factors which call for replacement are changes in amputee's residual limb from atrophy, weight gain, or weight loss.

*Figure 2.1 endoskeletal prosthetic*

This prosthesis type gains its structural integrity from the outer laminated shell, through which the amputee's body weight is transmitted.

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*Figure 2.2  exoskeletal prosthetic*

## 3.3 Previous VUW & NZALS Design-led research projects

Victoria University of Wellington and the NZALS have been working together since 2016. This collaboration mainly involves design research with emphasis on the potentials that 3D printing has as a method of prototyping.

The outputs from the various theses, summer research scholarships and practicums displayed a range of speculative design ideas for future applications such. These include multi-density feet and information driven prosthetic limbs. Tangible outputs from Victoria University and NZALS's design research included Stuart Baynes' thesis which looked at utilising 3D scanning, parametric design and flexible material to develop a swim limb (Baynes, Guy, Miller,2016).

Fenella Richards "Celebrating the spectacular: Discovering the new enabled through performance art" research looked into extending social inclusion for amputees by developing a prosthesis for performing art. Sports has begun to change how amputees are looked at but the advanced technology only allows for athletes to obtain it. Visibility and acceptance for amputees and their devices plays a vital part in her research (Richards, Miller, Fraser, 2018).

Matt McGowan's "Adding Brand" research portfolio addressed the creation of branded design products for the NZALS. McGowan designed a fully 3D printed below the knee prosthe¬tic to show the importance of creating tangible products that allow NZALS to understand the importance of design, branding, and emerging platforms of manufacturing (McGowan, Guy, Fraser, 2020). Lastly Vincent McQueen's "Additive Alternatives". His research portfolio addressed finding alternative ways to designing traditional carbon fibre feet and the biomechanics behind the movement of the foot allow it to withstand beach and coastline activities (McQueen, Guy, Fraser,2020).

As a service NZALS is willing to look at innovative technologies and their potential outputs in the context of prosthetic fitting and manufacturing process through collaborations with institutions, technology developers and users (NZALS, 2017).

## 3.4 Role of the designer

Before the inception of what is now industrial or product design people would either make the object themselves or find an individual to make it.

Vast improvements in the capabilities of manufacturing tools during the industrial revolution in the 18th and 19th centuries meant a shift to mass producing identical goods. This gives the design profession separation from the act of making. Designers now had the challenge of accommodating for the needs of a larger population, balancing multiple elements which make up the overall product (O'Reilly Media, 2021). Before computers, designers had been using pencils, paper, rulers and other tools to communicate ideas in 2D and 3D, followed by physical prototypes made from paper and cardboard. The early developments of CAD date back to the 1950's where Dr. Patrick J. Hanratty made PRONTO, a commercial numerical- control programming system. It was not until the 1960's when CAD was developed to show the basics of technical drawings, substituting paper and drawing boards. In the 1970's and 80's 3D modelling was created letting designer make 3D objects on screen. In the next few decades, CAD became more precise, sophisticated and multi-faceted with the addition of visualization software packages.

Although surface modelling is still applied in various organizations, designers are now exploring the potentials within parametric design. What used to be sketching, then surface modelling for countless, hours is now applying data into visual programming software like Grasshopper which enables the designer to generate geometries. These geometries have parameters that can be changed as they are transformed using number sliders where these new shapes are simultaneously created (Eltaweel, SU, 2017).

Throughout this research the designer's role will be to first consider the fundamentals within parametric design and surface modelling. Then subsequently, the designer applies it through a range of digital and physical experiments which vary in complexity. Various parameters will then be applied the context of a prosthetic limb to assist in validating research findings. Tangible prototypes will show the power of code and parametric design through a range of scales that display the different considerations developing a below the knee prosthesis.

## 3.5 Technology- Industry 4.0

Callaghan Innovation (2019), states that industry 4.0 provides a variety of digital technologies which advances performance, output, monitoring and the control of the manufacturing processes .Smart factories and smart products are the two distinct areas that are analyzed by businesses to understand where the benefits stand in an organization. Process automation, real-time process monitoring, additive manufacturing (3D printing), virtual and augmented reality visualizations all make up these initiatives make up industry 4.0 (Callaghan Innovation,2019).

Industry 4.0 gives organizations the ability to obtain data which is valuable for gathering information about maintenance, performance and other issues. This data is also able to be converted into physical objects, opening opportunities for manufactures to quickly replace parts and develop geometric structures that are lighter, stronger and cheaper (Callaghan Innovation,2019).

Traditionally humans or old worn-down machines would have performed these tasks, thus taking a significantly longer period of time. As a result, accidents are more prone and productivity fluctuates. However, with Industry 4.0 techniques these services provide a streamline approach, bringing beneficial results to an organization (Callaghan Innovation,2019).

## 3.6
## PRECEDENT REVIEW

This section reviews six design precedents that have been developed using digital design technologies with various outputs.

*Figure 2.3 EasyLimb prosthetic*

## EasyLimb,3D printed prosthesis

Easylimb (2021), by Matt McGowan is a fully 3D printed lower-limb prosthesis which addresses the creation of branded products and emerging platforms of manufacturing for NZALS.

The Easylimb envisions how the future of prosthetic design and manufacture might look like by implementing additive manufacturing and branding elements into an everyday limb. This was done through McGowan engaging with NZALS and extensively researching elements of branding, design and manufacturing. McGowan (2021) and NZALS saw 3D printing as a way of creating a shift in the prosthetics market, providing innovation and a competitive advantage over other companies.

As a service, NZALS is constantly looking at new avenues for prosthetic development, this is shown in integrating smart technologies and AM into the manufacturing of selected 3D printed below-knee sockets. (McGowan,2021). McGowan's research looked at extending how AM can be adopted in NZALS, showing how design and AM production "can lead to the creation of products and product diversity" (McGowan,2021, P.29).

The Easylimb is a fully 3D printed lower limb prosthesis which has an integrated 3D scanned socket, SLS printed construction of the anatomical form and a TPU flex sole (McGowan,2021). This research produced a limb with no external components, using SLS printing which gave the Easylimb structural and comfort benefits (McGowan,2021). This form of 3D printing is beneficial in producing high-quality functional prototypes (Formlabs,2021).

This project showed the potentials of creating tangible products using smart technologies and AM to show the importance of branding. This precedent was used as a template to guide the form and aesthetics for the overall prosthesis.

*Figure 2.4 Cortex 3D printed cast*

## Cortex 3D Printed Cast

Cortex (2013), by Jake Evill is a 3D printed cast for fractured bones that could replace the way traditional casts are made by utilising AM and data.

Usually casts are cumbersome, irritating on the skin and the plaster becomes smelly. This concept by Evill utilises 3D scanning technologies, AM and physiological data sets to create a product that is lightweight, ventilated, washable and thin. This allows for the user to wear it under a shirt sleeve (Etherington,2013). The Cortex cast is manufactured with the assistance of x-rays, 3D scanning and computer software.

The individual is x-rayed and then 3D scanning takes place on the outside of the limb to create a 3D model which can then be put into a computer software programme to begin the design phase. Generative design is then used to create a form that provides sufficient amount of support around the area or areas that are fractured. Once the cortex has been created in a digital environment the pieces are then printed on-site and clipped into place with fastenings (Etherington, 2013).

3D printing this cast takes around three hours. This is in comparison to traditional cast which only take around 3-9 minutes but the downside is the plaster itself takes 1-3 days for the material to set. Evill states that "with the improvement of 3D printing, we could see a big reduction in the time it takes to print in the future" (Etherington,2013, para.5).

The Cortex Cast explores the idea of utilising emerging digital data tools, computer software and AM to assist in the design process of a functional cast. Cortex cast tests the fundamental traits that are required for a traditional cast and streamlines it through the application of digital tools.

*Figure 2.5 XYZ shoes*

## XYZ Shoes

XYZ shoe (2013), by Earl Stewart is a pair of shoes manufactured by using rapid manufacturing techniques as a way of creating an individualized product.

The XYZ shoe investigates, how rapid manufacturing techniques can be utilised as a means of adapting and adjusting for the individuals need, and in this case, what is on their feet. Stewart uses high precision 3D scanning technology to create a 3D model of his feet which then can be used to make the personalised shoes (Stewart,2013).

Expert engagement with a podiatrist allowed Stewart to get a better biomechanical understanding of the foot, thus assisting him in the design process to consider maximum comfort, stability and foot alignment. The shoes are designed from 3D scans of the individual's foot to ensure a perfect fit (Stewart, 2013). The digital design of the shoes is then sent to a multi-material 3D printer. The printer then interprets the 3D scans and designs into an all-in-one shoe that is constructed from a range of different materials which offer the wearer flexibility and support based off the data collect from the 3D scans (Stewart, 2013).

Biomimicry principles were used as a way of influencing the overall form and aesthetic for the XYZ shoe. The aesthetic of the XYZ shoes are based on the exploration of biological systems and how this can be interpreted to represent the individual (Stewart,2013).

The XYZ shoe explores the application of rapid prototyping and manufacturing techniques to create an individualised tangible object in the form of a shoe. XYZ shoe tests the effectiveness of a material and the accuracy of 3D scanning and 3D printing.

*Figure 2.6 Free swim prosthetic*

FreeSwim Prosthesis, 2016

Free Swim (2016) by Stuart Baynes is a functional 3d printed prosthesis that supports trans-tibial amputees when swimming.

The FreeSwim prosthesis enables the amputee to walk to the pool, get in and swim. This was possible through Baynes' implementing and recreating the anthropometric symmetry that had been lost to give back balance while in the water. NZALS felt the need for a swim limb to be manufactured and Baynes was able to utilise digital technologies and manufacturing methods to address certain aspects.

This design system developed by Baynes prototypes an all in one prosthesis that includes a suction socket and flexible interior fin. The fin is made from flexible Thermoplastic Polyurethane (TPU) that helps with swimming and a removable stiff sleeve over the fin for walking to and from the pool (Baynes,2016).

3D scanning was used to get information from the amputee's residual limb. The scan data is then imported into a CAD file. This file enables Baynes to take the geometries from the scan, and construct a customisable swim limb around the amputee's residual limb utilising parametric software providing the ideal fit (Baynes,2016).

This project showed the potentials of using additive manufacturing through the development and creation of a specialised swimming prosthesis. The combination of multi material 3D printing, scanning technology and parametric design shows how this new method to prosthetic design is quicker and costs significantly less can traditional manufacturing.

*Figure 2.7 Nike zoom superfly elite*

## Nike Zoom Superfly Elite

The Nike Zoom Superfly Elite is a running shoe (track spikes to be specific) developed by the sportswear company Nike to maximise and maintain sprinting pace for athletes using data, rapid prototyping and computational design.

The Superfly Elite collection explores the idea of fabricating individualised products based on athlete- specific data, giving the wearer the ideal fit and maximises performance. The Nike designers in collaboration with engineers, scientist and runners investigated the performance potential of running spikes through using computational design. 3D scanning and motion capture technologies were used to analyse specific athlete data like speed off the blocks and running characteristics. This information gathered from the individual allowed for an algorithm to be made which delivers the ideal spike plate stiffness in relation to the size of the feet and pressure (Howarth, 2016).

In this study Nike designed the geometrical structure based on ocean organisms. This provided a base plate design with both lightweight and stiffness that is needed to withstand the stresses applied on the material. This assists in maximising the overall performance of their athletes. Nike applied computational design which looks at using computer-based strategies in the design. In contrast to traditional design which is based on intuition and understanding to solve problems, computational design seeks to enhance the design process by programming the design decision using a computer language (Kilkelly,2016). This as well as rapid prototyping let the Nike design team quickly 3D print, test and iterate on their results. This gives them a comprehensive understanding of the limits needed to accommodate the particular wearer.

*Figure 2.8 ADAPT prosthetic platform*

## ADAPT Prosthetic Platform

University of Washington students Justin Taylor and Josiah Tullis created a lower limb prosthetic platform which uses sensors and other data collection techniques to gather, monitor and generate custom designs for its users.

The ADAPT platform prosthetic explores a different perspective in prosthetic design. There are a large amount of lower limb prosthetic designs and concepts in design and medical industries, Taylor and Tullis decided to re-evaluate the interaction between patient, prosthetist and technician in their research. Customization was vital when it came to designing prosthesis as the user needs to have the best fit (Taylor, & Tullis ,2018).

Traditional prosthesis fabrication is very trial-and-error based and this method takes a few weeks and regular visits to get the best fit. 41% of trans-tibial amputees are projected to suffer from having an ill-fitting socket and in some cases, patients are unable to notice where discomfort and misalignment comes from. Over time nerve damage occurs (Taylor & Tullis,2018).

The ADAPT prosthesis platform looks into resolving the ill-fitting socket fit by utilising industry 4.0 techniques to assist in collecting patient data, monitoring comfort and generating custom designs (Taylor & Taylor,2018). The pressure points between the residual limb and socket are measured and documented through a selection of sensors and microprocessors fixed in the prosthetic shin (Taylor & Taylor,2018). The input data is then sent to the technician where concepts for the socket and foot are generated based on the information.

Prosthesis platform applies generative design and finite-element analysis to visualise the data collected through running a range of simulations. The designers and technicians take into consideration overall form and alignment to arrive at a result that accommodates the user's needs.

## Summary

The six precedents review during this stage of the research have a number of aspects in common. Applying digital design tools in the design process for customisable outputs. Data collection tools such as 3D scanning, motion capture and sensors were used to gather information . Lastly additive manufacturing, for durable and refined products manufactured faster using less material.

## History and current fabrication

*Figure 2.9 History of lower limb prosthesis*

## 3.7 Historical Overview

The earliest evidence of a designing prosthetic or artificial limb dates back to between 3500 and 1800 BC (Evan,2019). For centuries prosthetic making had not changed with the same processes and materials where leather, wood and to produce the prosthetic limbs. In the beginning of the sixteenth century Doctor Ambroise Pare helped to pioneer prostheses which had a hinging system for the hand as well as a prosthetic leg with a locking knee joint (Evans,2019).

The advancements in prosthetic technology and manufacturing were further developed after WW1 and WW2. A significant number of soldiers were returning home with missing limbs.

As amputation methods, anaesthesia, sanitation and surgical techniques advanced and survival rates from those who went into war improved the development of prosthetic limbs proceeded to do so with the introduction of mass-produced metal limbs (Evans,2019). As the mass production of prosthetics increased due to the aftermath of war, returning soldiers would be able to go back into society and work via limb fitting centres around the country.

The increased mass production of prosthetics for returning soldiers to go back into society and work. The advancements in prosthetic technology which tied into the third industrial revolution meant that mass production of components, new metals and plastics saw researchers rethink the interaction between the prosthesis and the human body.

This was instead of mimicking the motion of normal limb developments which were made to focus on increasing gait and reducing friction (Bender,2015).

The current practice of prosthetic fitting and fabrication processes of mould making, plaster casting and fibre glass fabrication are still very alike to the processes used for post-war limb fitting services.

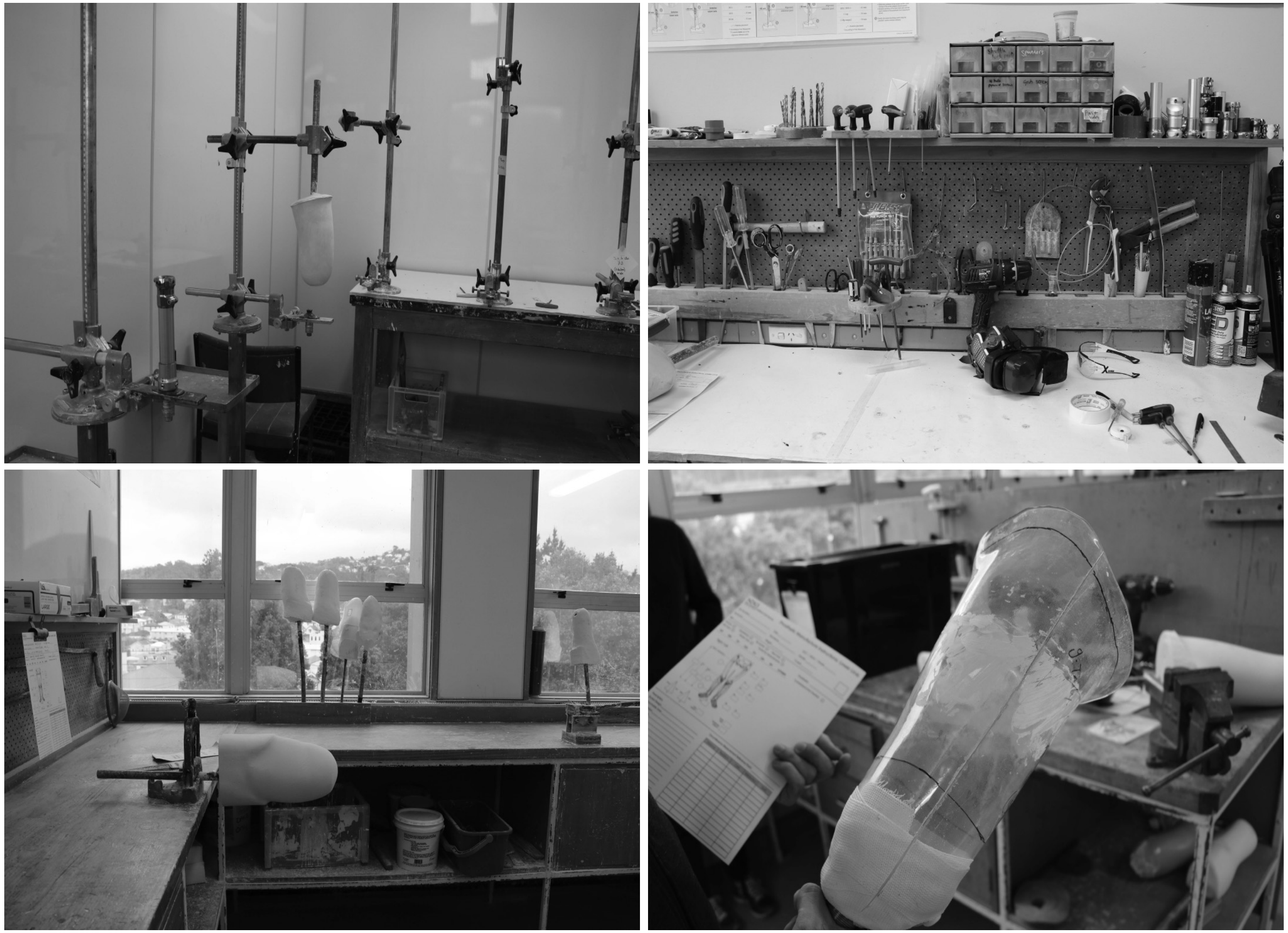


*Figure 3  NZALS workshop*

## 3.8 Current prosthetic Fabrication

The current fabrication and fitting process behind prosthetic sockets and the overall limb requires a lot of time and accuracy. This labour-intensive process requires a skilled technician who has training in both human anatomy and extensive tacit knowledge of residual limbs and limb defects through various limb fittings. In addition, technicians need skills in mould making, plaster casting and fiber glass fabrication methods.

Those are just the tasks required to produce the prosthetic socket alone. In addition, the technician is required to configure and assemble the appropriate components to each section of the prostheses.

The method in which traditional prosthetics are made requires workshop skills. In the NZALS workshop the prosthetic technicians need a grasp of anatomy, torque, pressure and angle as well as workshop skills (Evans,2019). Evans states that prosthetists “use sewing needles, bandsaws and grinding techniques on a daily basis, manipulating leather, silicon, resin and plaster of Paris subtlety and perseverance” (Evans, 2019, para. 23). These skills and techniques require specific knowledge into how the tools and materials react in certain settings to best assist the technician in the fabrication process.

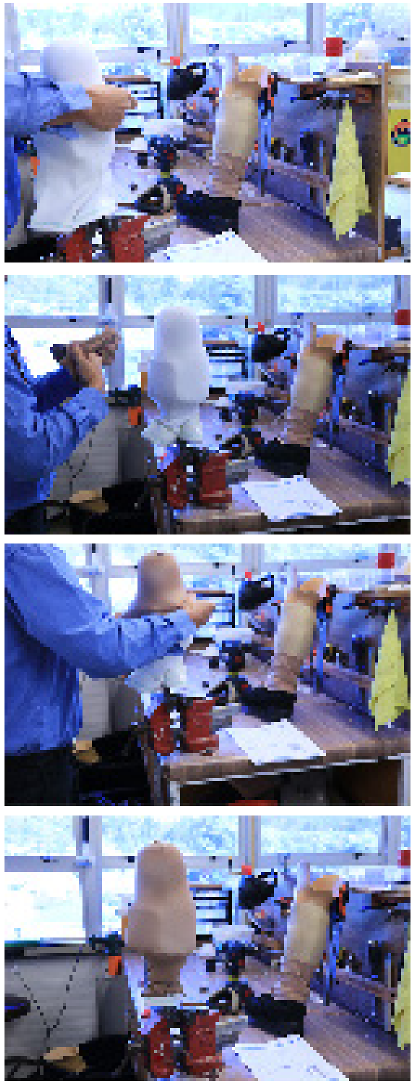
Incorporating additive manufacturing into the design process of prostheses means that significantly less material is used. This is because hospital costs that are associated with these processes waste material, like plaster moulds and excess fabricated materials, are then destroyed in the making process (Jin et al.,2015).

# 04

## DESIGN EXPLORATION

*Figure 3.1 3D printed models*

1



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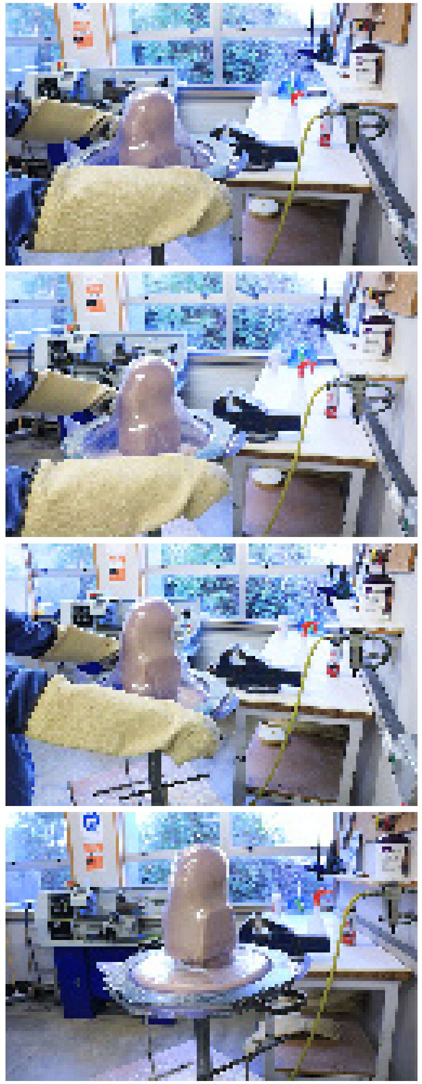


4

5 6 7 8

*Figure 3.2 shadowing*

## 4.1 Shadowing

**1 Plaster cast residual limb with first layer of PVA bag, also pin lock system is put in during casting process.**

The PVA bag- this bag is used to cover the cast before the resin is poured in. Too many wrinkles in PVA bag during the initial application would result in wrinkle appearing on the cast/socket.

**2 Layers of fabric are applied onto the residual limb cast in preparing for vacuum forming**

Multiple layers are applied so that water does not get inside.

**3 Powder being applied to the plaster before being put in the Ottobock heater.**

**4 Heated plastic being applied onto residual limb cast through vacuum forming.**

The process of forming the plastic onto the cast takes a short amount of time. But the time it takes to heat the plastic takes ten to fifteen minutes.

**5 Layers of fabric applied onto residual limb cast, then stuck together using a lighter.**

**6 Combination of fabric and glass sleeve put onto the cast, then tied together in preparation for resin pour.**

The glass sleeve is applied onto the residual limb cast along with a soft fabric like an elastic fabric. This process is further repeated two to three times. To finish off the sleeve is then tied up. A bigger residual limb cast will need to be reinforced with carbon fiber strips. This is for above knee cast only.

**7 Mixture for the resin pour is prepared by the technician.**

The resin in poured into a cup, this is because the resin can solidify faster than if poured straight into glass sleeve. The resin stays in the cup for four minutes.

**8 Resin is slowly poured into cast via a hole at the top of the PVA.**

1.5 litres of the resin mixture is poured into the opening for lamination until it reaches the bottom. For the resin to be distributed evenly during the lamination stage, the mixture is moved around using the technician's hands and a scraper

## Reflection

Before field research was done, the designer had brief knowledge of current prosthetic fabrication and process. Aspects such as having tacit knowledge of human physiology and workshop skills were identified before extensive field research.

The first factor identified by the designer was time. The tasks required to construct a lower limb prosthesis were time-consuming, whether it was waiting for material to set, layering fabrics or physically sculpting things into form. These processes and techniques required a lot of time to complete, adding to the duration it takes to construct the prosthesis.

The second factor identified was accuracy. Many of these processes are trail-and-error based, such as applying PVA plastic for initial lamination or the resin pouring process. There was a continuous back and forth procedure where the technician is making sure imperfections are limited during each process. An example of this was during lamination stage where wrinkles in the PVA plastic were smoothed out. Accuracy from the technician is needed to ensure that no wrinkles appear on the cast, enabling the next steps to proceed efficiently. Second example was during the resin pouring process. Accuracy was needed to ensure no bubbles appeared on the cast, as this helps with overall structure of the socket.

The last factor considered was experience. Experience ties into both time and accuracy. In this profession individuals are highly skilled in various aspects regarding the human body and workshop skills. With many professions, experience allows individuals to perform tasks faster while maintaining a high level of accuracy. Guidance, feedback and demonstrations were shown to less experienced technicians during complex situation during the fabrication process.

NZALS has slowly begun to implement digital technologies alongside traditional fabrication methods. Both 3D scanning and 3D printing technologies are being applied in the construction of below knee sockets. Software's such as meshmixer, rhino 3D and omegawillowood are used to generate, sculpt, refine and then checked for 3D printing. The sockets are then externally 3D printed on Multi Jet Fusion (MJF). MFJ uses fine-grained materials that allows for ultra-thin layers of 80 microns (materialize,2021). The process of generating these 3D printed sockets is more efficient and creates less excess material than traditional fabrication methods.

To conclude, NZALS as a service is willing to integrate these digital designs as an alternative method of generating lower limb prosthesis.

# PRELIMINARY EXPERIMENTS

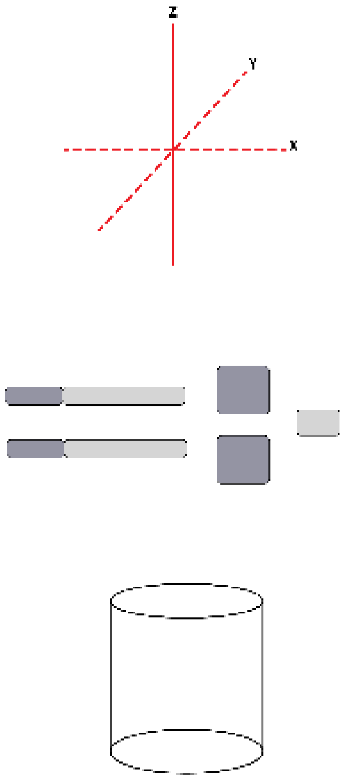



*Figure 3.3 Experiment components*

Grasshopper was used to implementing parametric design experiments on basic geometries. These experiments began with generating a cylinder made up of three ellipse curves that can be adjusted with set parameters. An independent variable was established within this first geometry, meaning that it stands alone and is not changed by the other variables that are attempting to be measured. The three curves which make up the cylinder were altered only by their radiuses using number sliders

**Grasshopper Components:**

XYZ points
Number sliders
Ellipse shape
Point construction
Loft

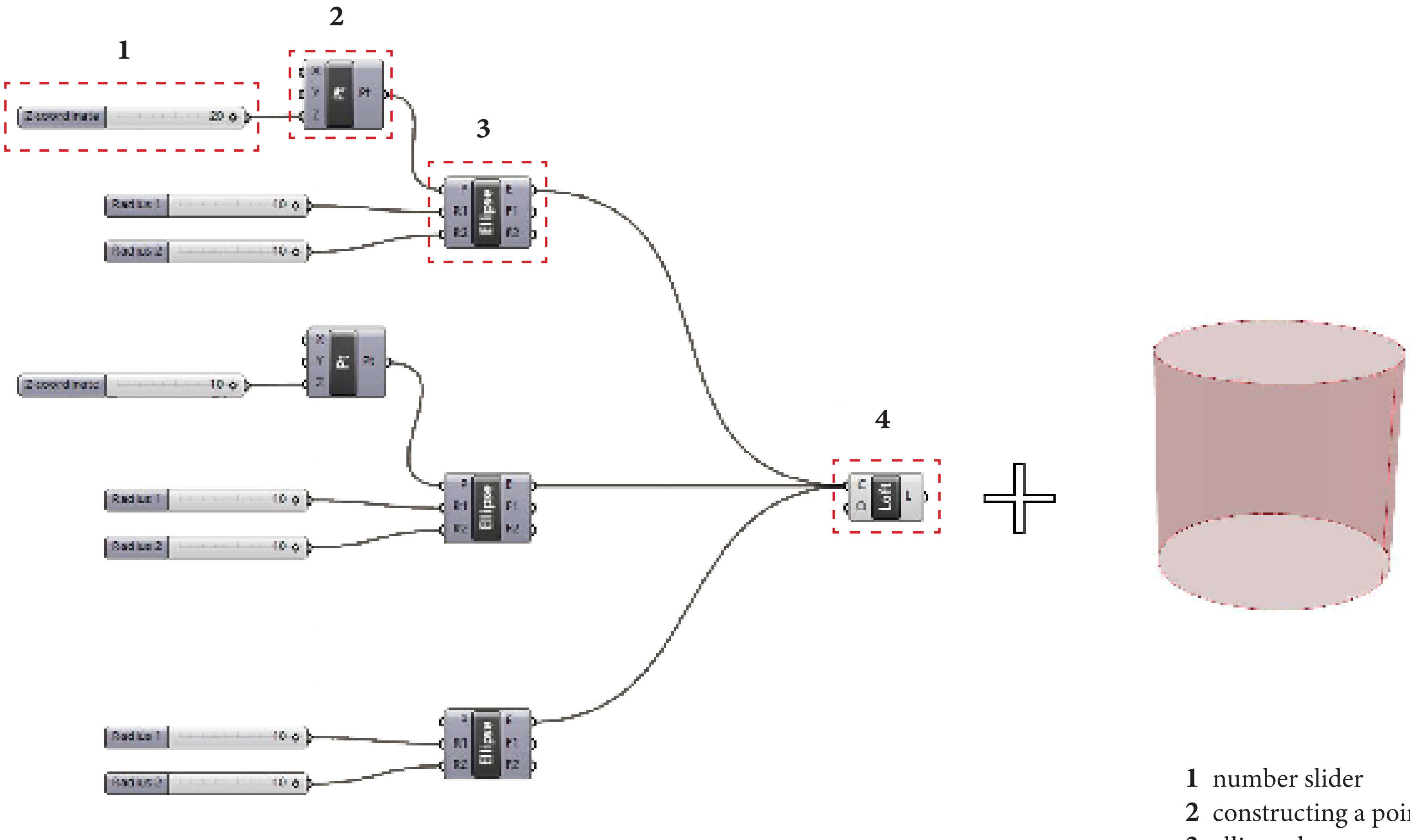



*Figure 3.4 Grasshopper cylinder script*

**1** number slider
**2** constructing a point
**3** ellipse shape
**4** loft

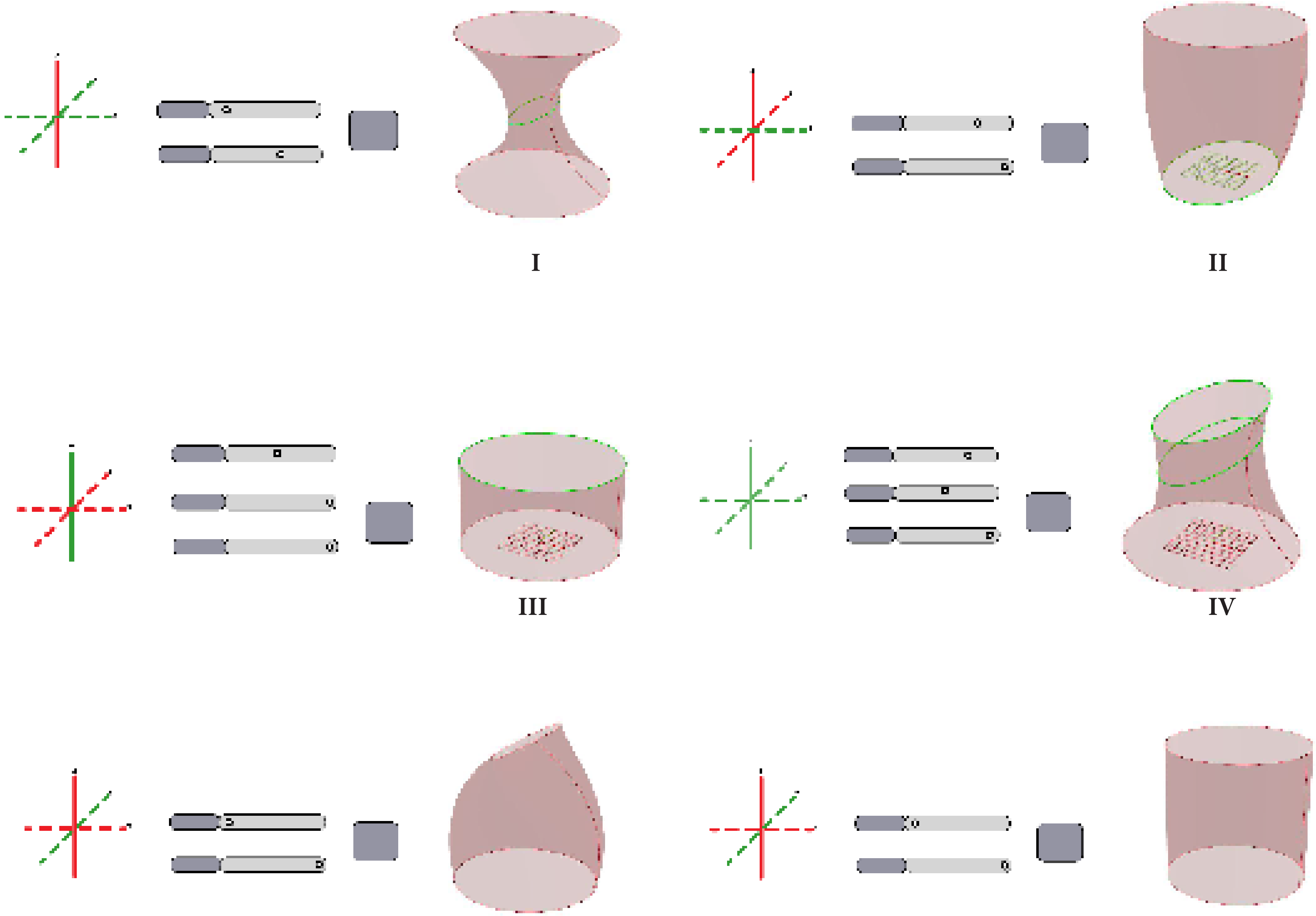



*Figure 3.5 Grasshopper experiments*

## Reflection

This section briefly showed the capabilities that grasshopper has, where  a set of parameters are easily able to the changed and results are presented in real-time. The overall radius of all three ellipse were taken into consideration when altered the parameters. Height was the second parameter that could be changed along the z and negative z axis to determine height. The third parameter was width, where shape could be alter along its x and y axis' , this enabled what was once a liner cyclinder to be sculpted into different forms. This is relative in generating customised lower limb prosthesis as factors such as height and width in certain area will need to considered. The importance of these basic tests was also to understand the limitations of the software.

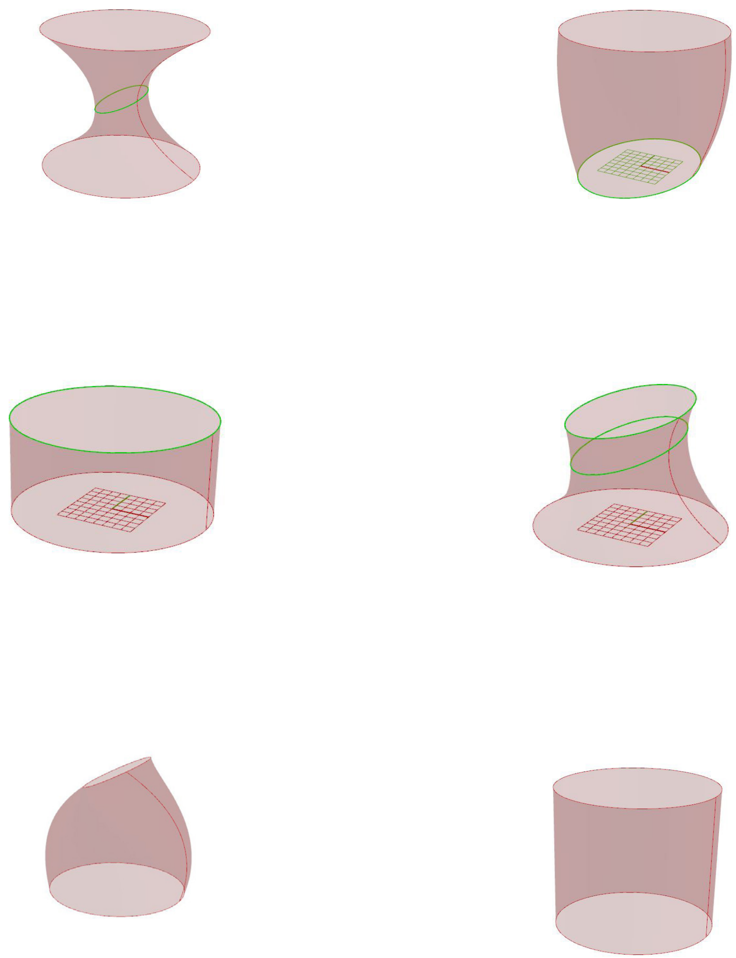


*Figure 3.6 inital experiments*

# PARAMETERS FOR DESIGN

This section introduces the anatomical and measurement references for the experiments. These references were interpreted by the designer to establish parameters for the design process.

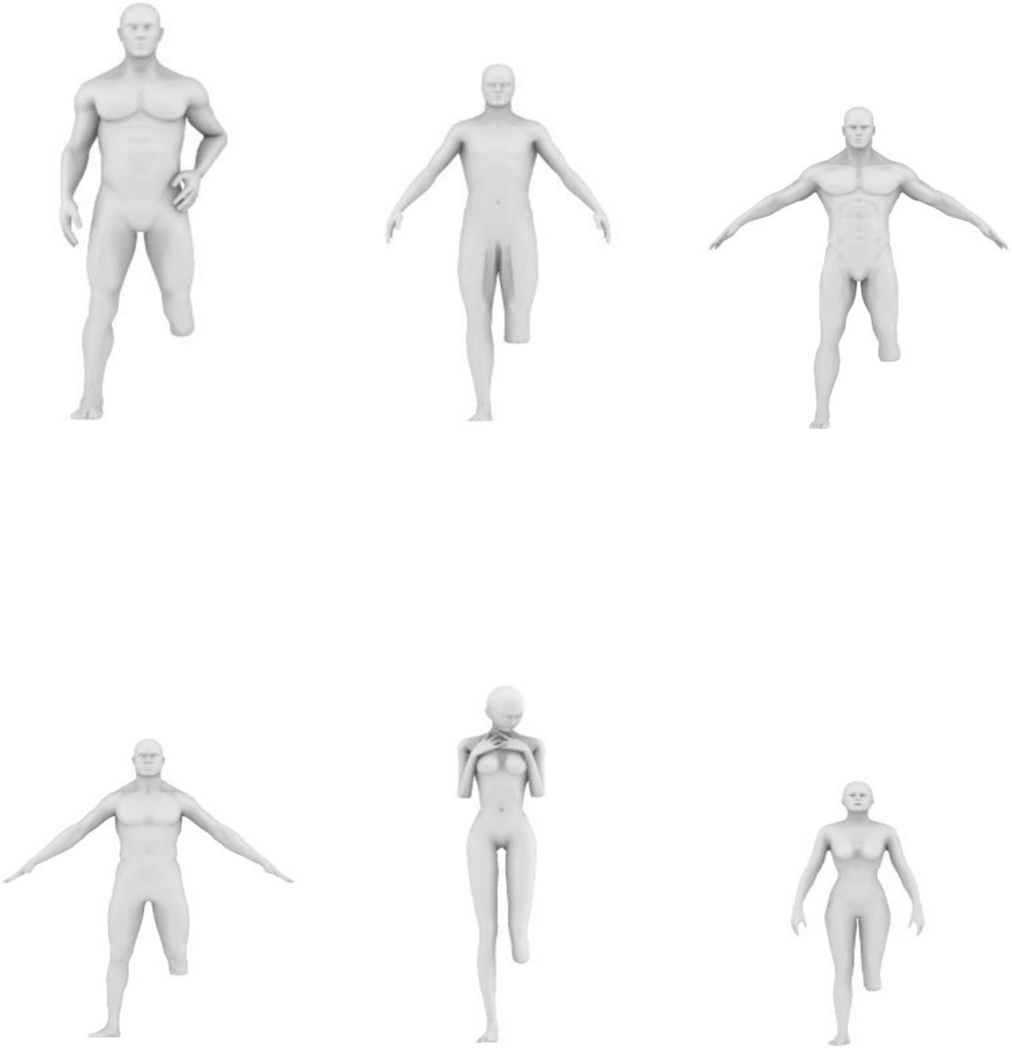
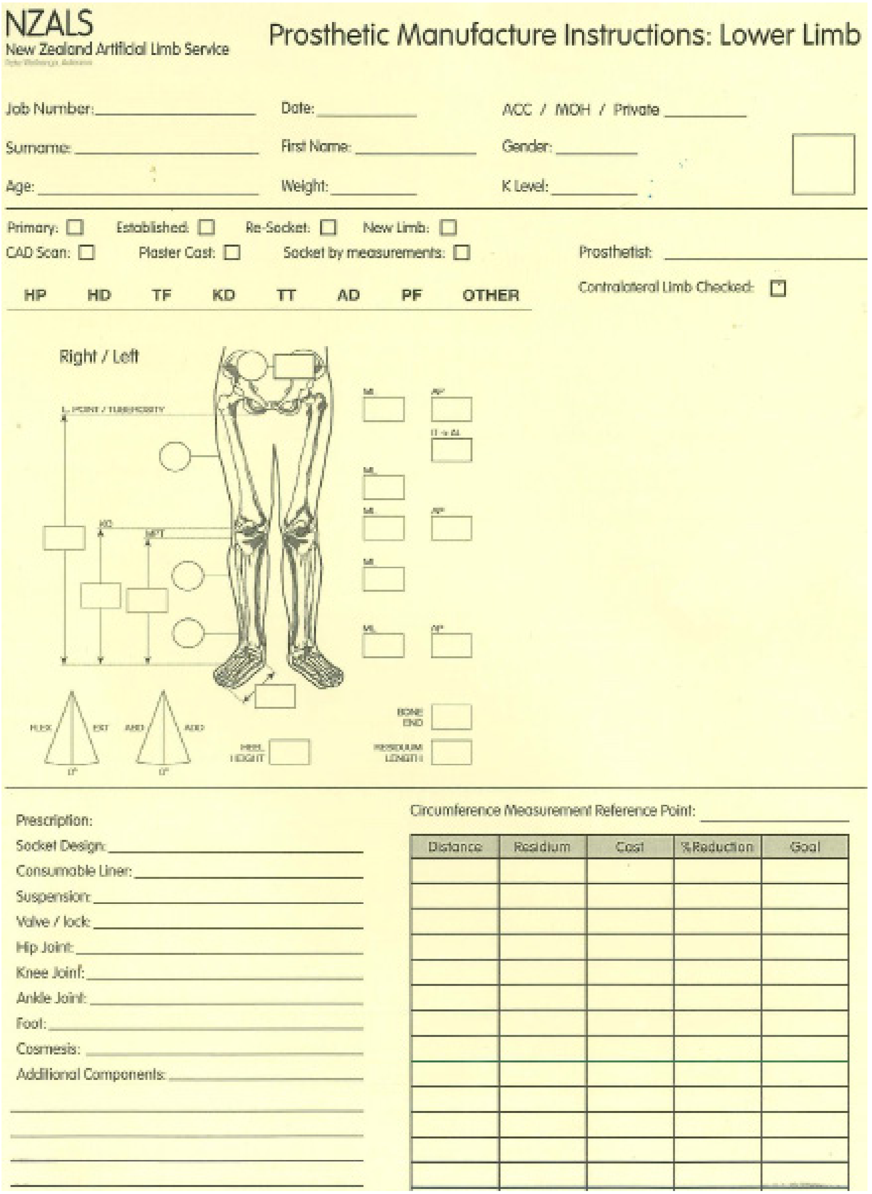


*Figure 3.7 anatomical models*

**Anatomical Reference**

A range of simulated anthropometric 3D models were used as anatomical reference to conduct the parametric experiments in grasshopper.

These models were analysed in meshmixer to see the mesh quality then sculpted to assist in the design process then imported and scaled in rhino 3D. A 1:1 scale digital model of a lower limb prosthesis was used for accurate proportions. The range of anthropometric models assist the designer along with grasshopper to the capabilities of parametric variation.



NZALS
New Zealand Artificial Limb Service

Prosthetic Manufacture Instructions: Lower Limb

Job Number: ____ Date: ____ ACC / MOH / Private ____

Surname: ____ First Name: ____ Gender: ____

Age: ____ Weight: ____ K Level: ____

Primary: ☐ Established: ☐ Re-Socket: ☐ New Limb: ☐

CAD Scan: ☐ Plaster Cast: ☐ Socket by measurements: ☐ Prosthetist: ____

HP HD TF KD TT AD PF OTHER

Contralateral Limb Checked: ☐

Right / Left

Prescription:
Socket Design: ____
Consumable Liner: ____
Suspension: ____
Valve / lock: ____
Hip Joint: ____
Knee Joint: ____
Ankle Joint: ____
Foot: ____
Cosmesis: ____
Additional Components: ____

Circumference Measurement Reference Point: ____

| Distance | Residium | Cast | %Reduction | Goal |
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## NZALS Measurement Sheet

NZALS use the prosthetic manufacture instructions to measure lower limb amputees before their first limb fitting, if adjustments are needed for current limb prosthesis and changes to the amputee's body. The designer used this sheet as reference for accurate measurement points as input data for the digital workflow.

*Figure 3.8 NZALS measurement sheet*

# APPLIED EXPERIMENTS

This chapter showcases how grasshopper was explored through a range of applied experiments to develop an accurate and time efficient parametric method for prosthetic customization. This research has an emphasis on parametric modelling where forms are generated using adjustable coordinates and parametric relationships rather than a set of fixed numbers. This allowed for the designer to have better control over customizable features. A digital workflow was developed and acts as the tailor in the prosthetic design process.

A range of digital and physical prototypes were generated by the designer to assist in communicating ideas throughout the design exploration stage. Rhinoceros 3D and the parametric plug-in Grasshopper provided the designer with greater control. This control allowed for the prosthetic socket, overall shape, thickness and foot sizing to be adjusted.

*" Typically, as you're designing a football boot, we designers gather images and start sketching immediately. In this case with Phantom GT , we didn't do any of that. We actually went straight to the lab and collected data"*

Jeongwoo Lee
Global Football Senior Creative Director

**Areas of focus**

Socket

Anatomical form

Foot

*Figure 3.9 Lower limb prosthesis*

*Figure 4 socket*

*Figure 4.1 foam*

*Figure 4.2 foot*

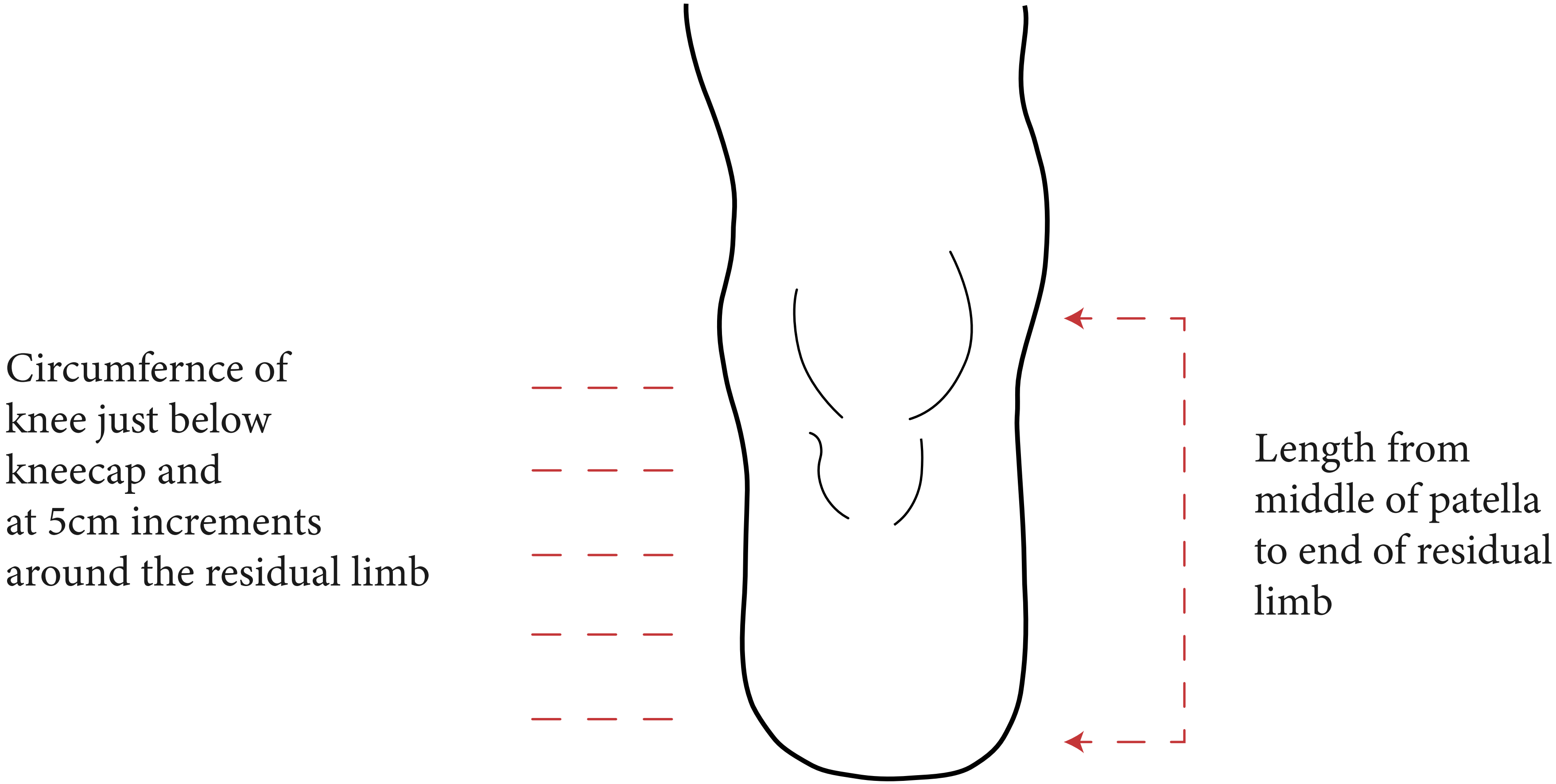



*Figure 4.3 socket measurement considerations*

# Grasshopper script generation

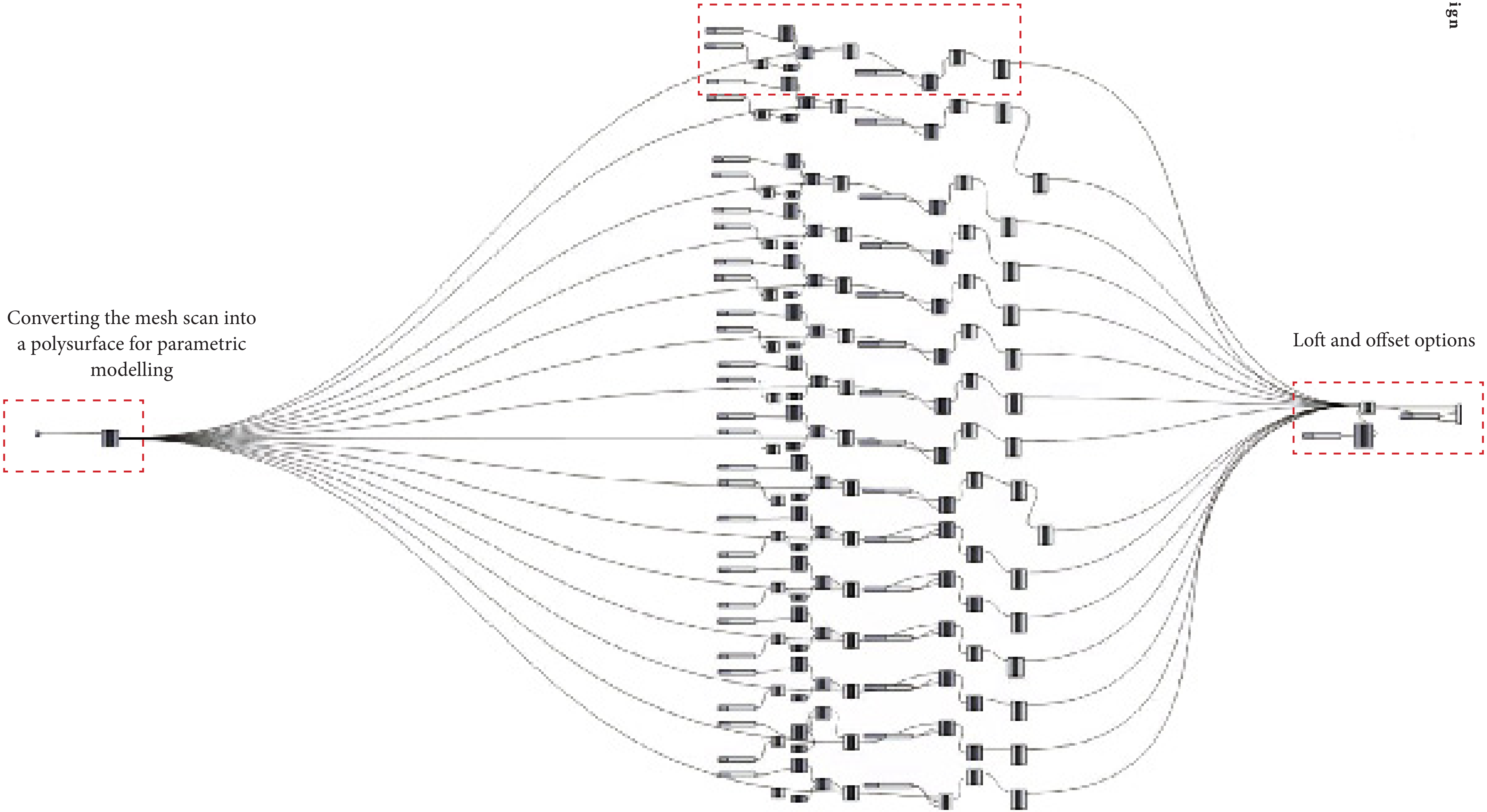



*Figure 4.4 Grasshopper script*

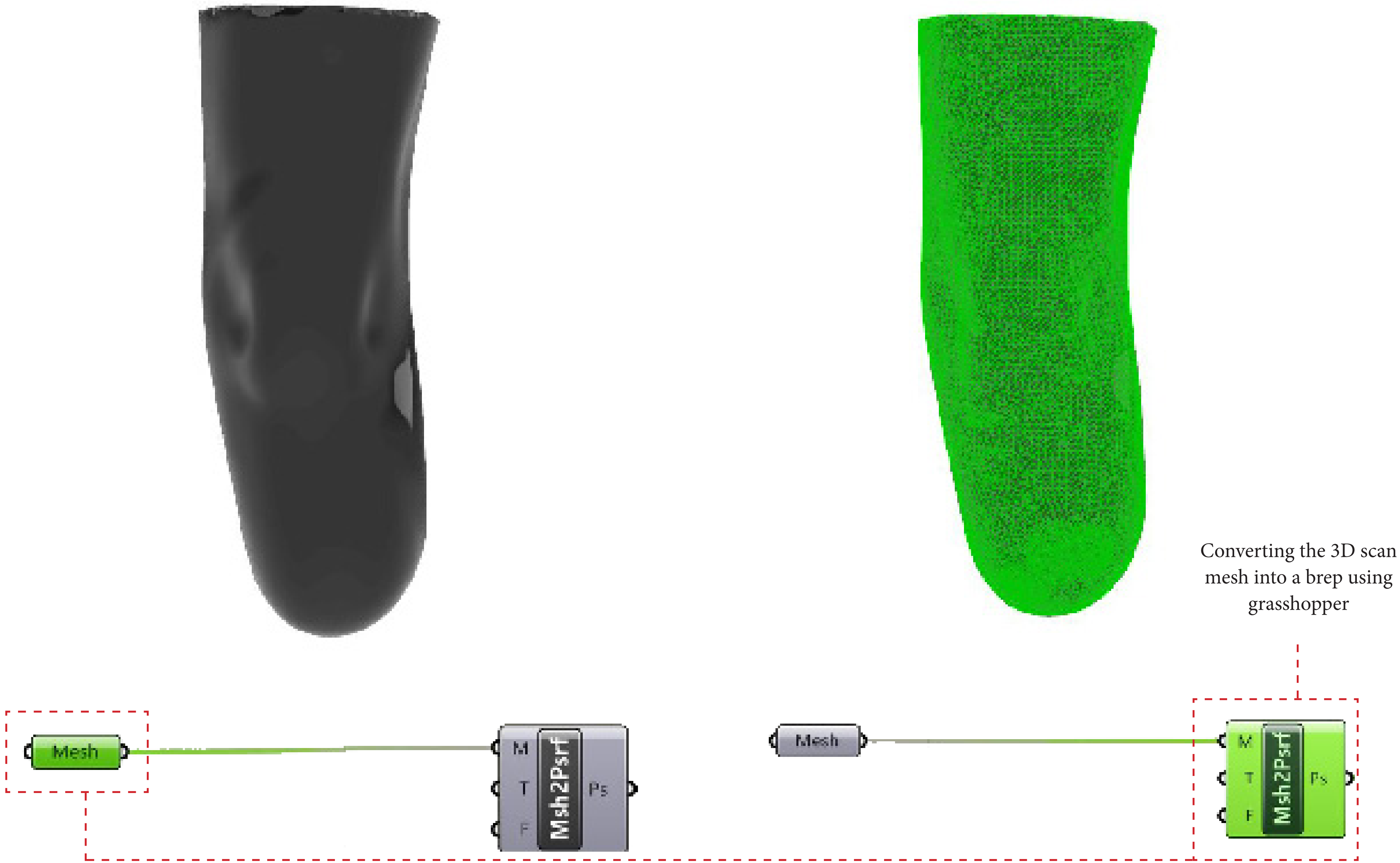



*Figure 4.5  Mesh to polysurface*

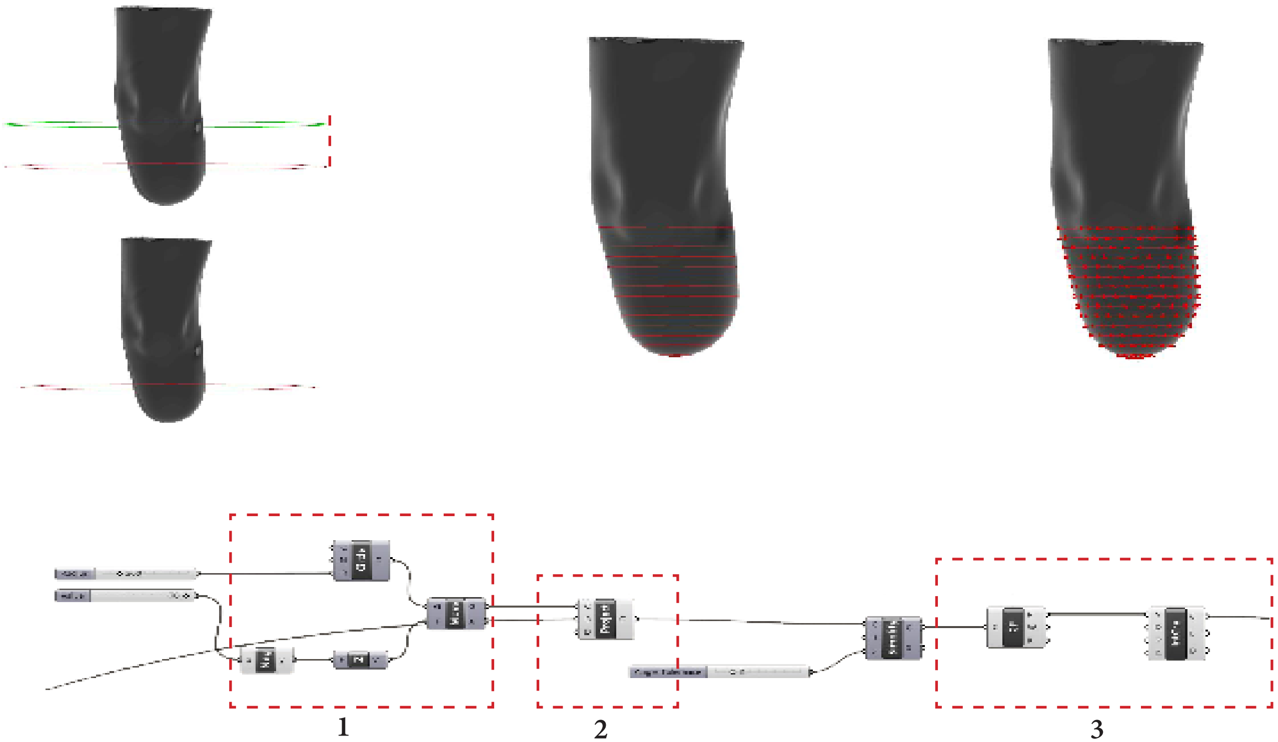



*Fig.4.5 Projecting  control points*

1 Moving curve along z axis.

2 Projecting a series of curves onto the converted scan.

3 Generating control points around residual limb.

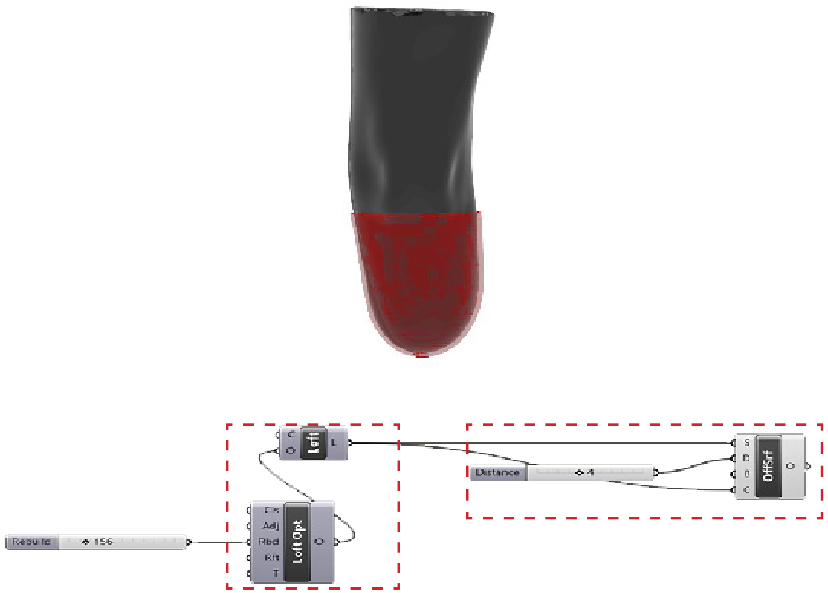



*Figure 4.6 Socket surface*

Lofting the curves made from the projected control points to produce form.

Offsetting the socket 40 mm outwards.

To produce the socket form, a 3D scan of the residual limb was imported into Rhino then Grasshopper. This scan was then converted from a mesh to a brep ( boundary surface ), this step helped as designing with meshes required extensive computer processing power.

Generating the socket shape was develop from creating a set of control points on the XY planes of the model. These points were then projected and fixed onto the 3D model, letting them follow the natural shape of the residual limb. Once the initial shape had been generated, the curves were repeated numerous times at different Z axis values. These curves were then lofted to generate the socket. This was an important part of the workflow , ensuring that if any information is imported into this part of the workflow, a parametric model could be built from it .

In prosthetic making  context , the technician, who has a wealth of tacit knowledge about the human body would manually gather data from the amputee and interpret their findings through plaster cast moulds.

*Figure 4.7 Plaster cast residual limbs*

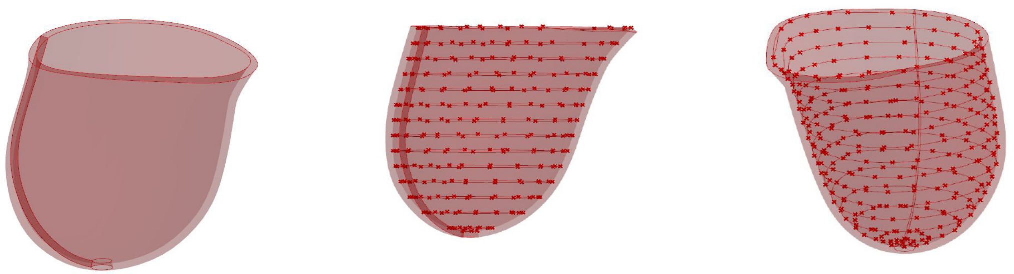


*Figure 4.8 Grasshopper socket form*

**Reflection**

Initial grasshopper script accurately produced a socket form through controlled set of points and set measurements.

Converting the mesh to a polysurface required a lot of computer processing power. This is because of the complexity and shear number of triangles which made up the mesh. Reducing the number of triangles will mean a less accurate mesh, resulting in a final form that is not accurate. Softwares like meshmixer or netfabb could assist in reducing file size while maintaining accuracy. Alternatively, the designer considered cutting-down the script, so processing time is not as long.

# Grasshopper Script Refinement

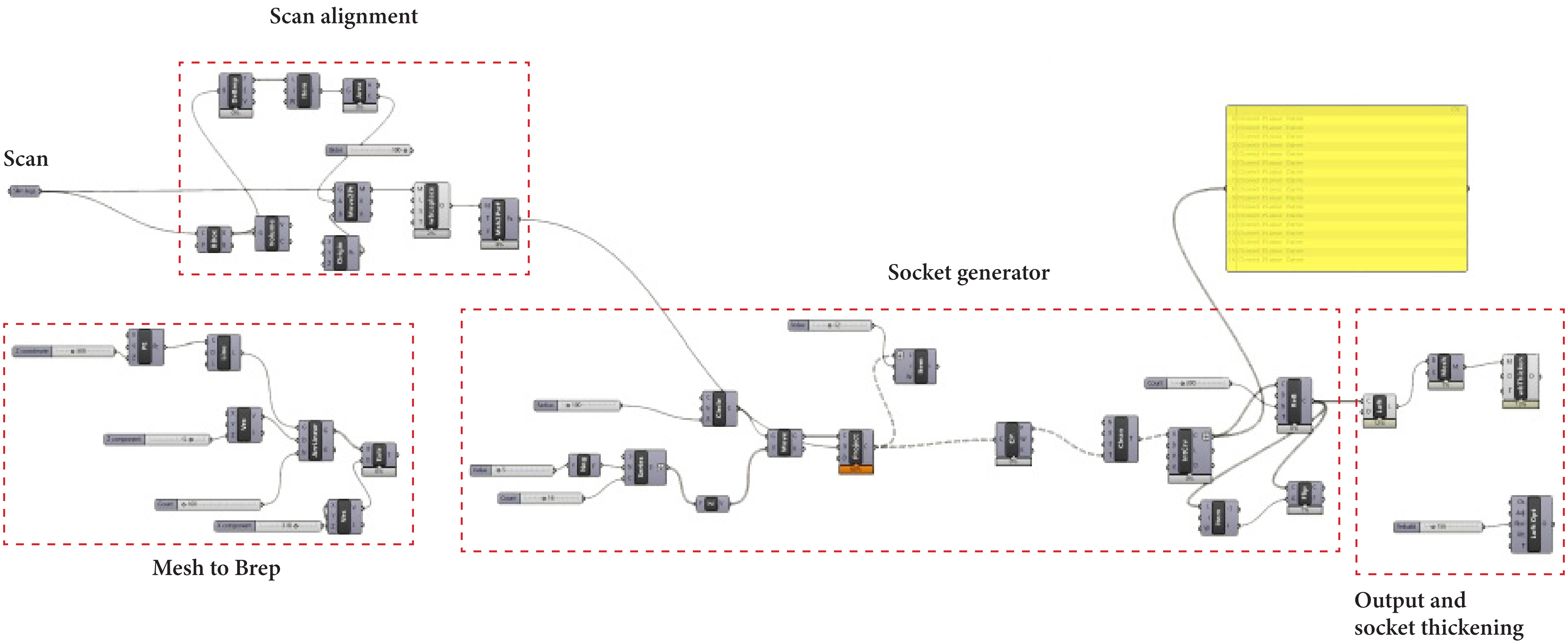



*Figure 4.9 Grasshopper script*

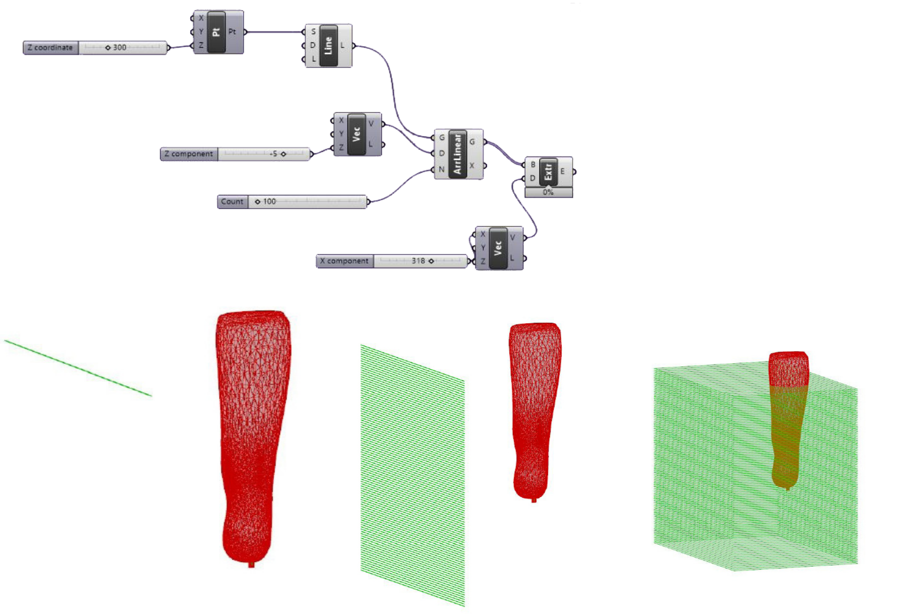



*Figure 5 Refined mesh to brep*

Once the scan is aligned the mesh was sliced with intersecting curves. This was done through created an array of lines down the Z axis of the scan, the lines were then extruded along the X axis, cutting through the mesh. These planes create an outline of the scan , these outline curves were then lofted to produce a 3D form of the scan.

This version required less processing time while achieving same results.

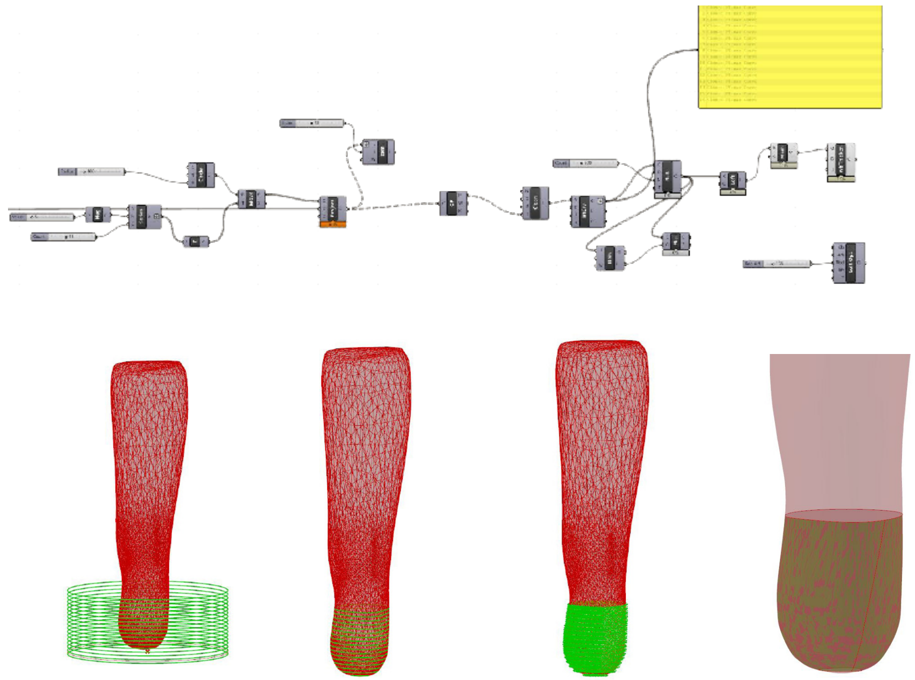


*Figure 5.1 Projecting curves*

This section performs the same actions in generating a socket form based off projecting curves and control points onto the residual limb scan, allowing for the computer to loft a surface which resembles the natural shape. Only refinement is reducing the amount of nodes, which ended up contributing in the long computer processing time.

# RESULTS

Visual representation of digital experiments performed in grasshopper 3D. This visually displays the changes in form from adjustments made within the limits of the simulated human bodies .

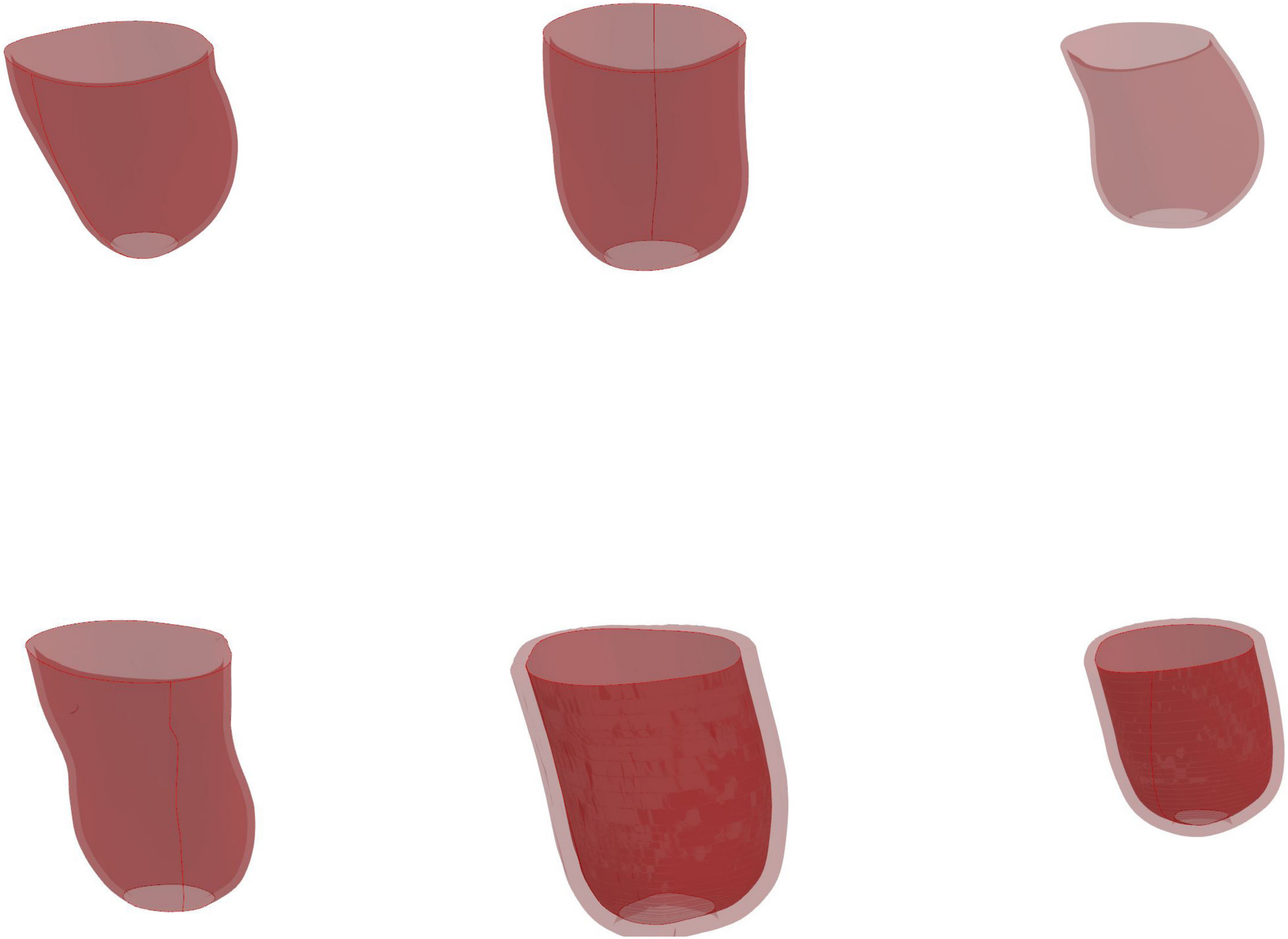


*Figure 5.2 Grasshopper socket forms*

*Figure 5.2 Renders*

## Reflection

The refined grasshopper script was able to be cut down while still producing an accurate socket form based off a set of control points. The addition of curve intersections, projections and lofts to convert the mesh to brep required less processing time, while providing an accurate base to start parametric design experiments.

# ANATOMICAL FORM

# Measurement considerations

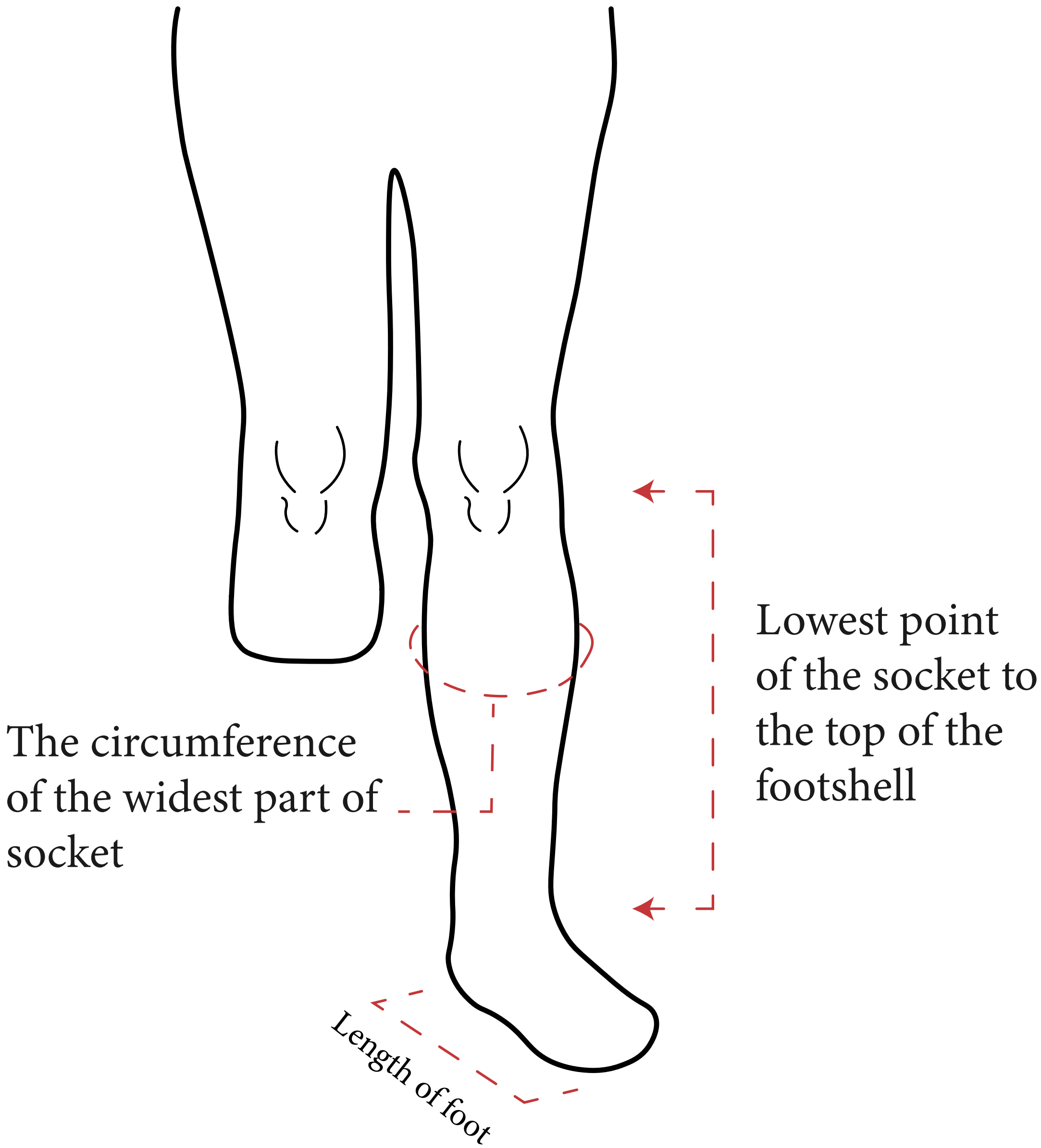



*Figure 5.3 Anatomical measurement considerations*

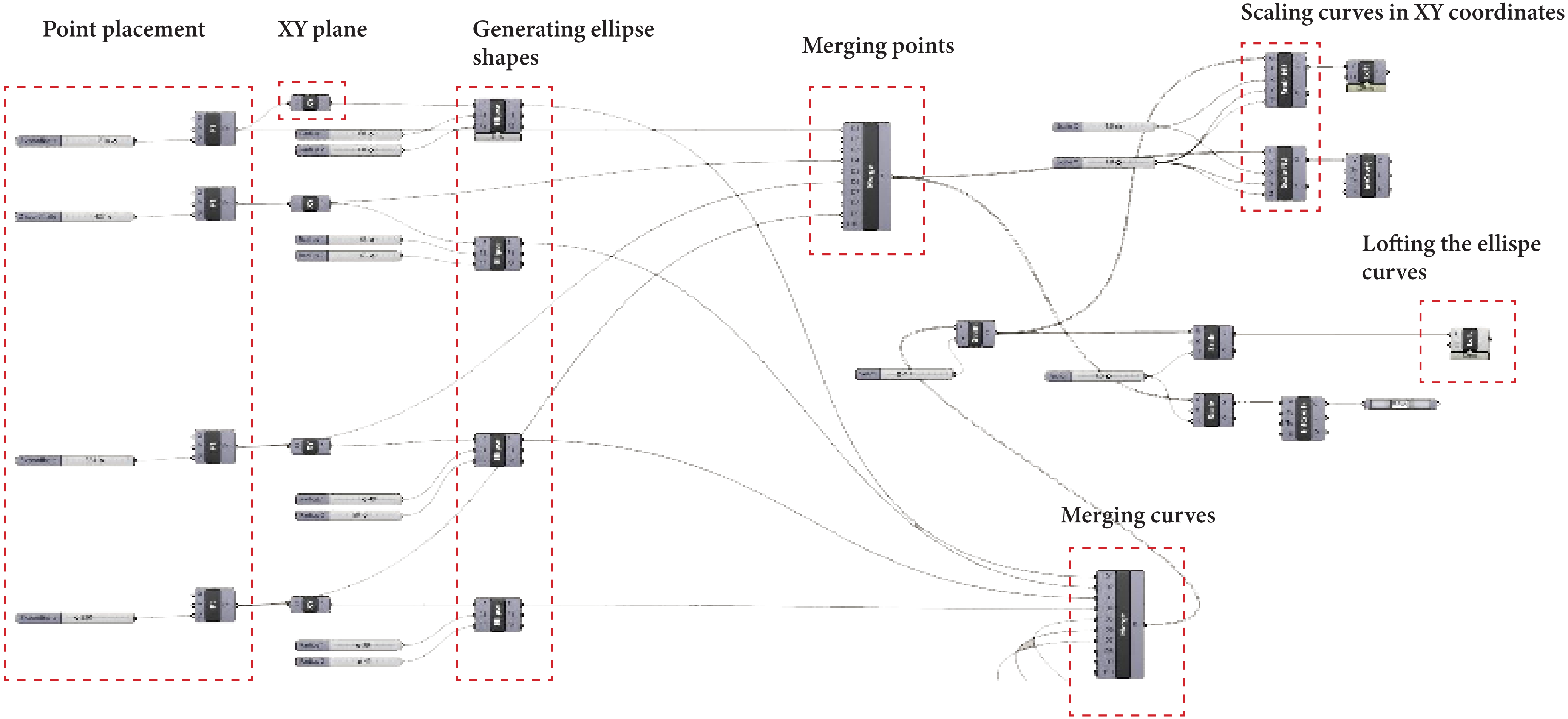
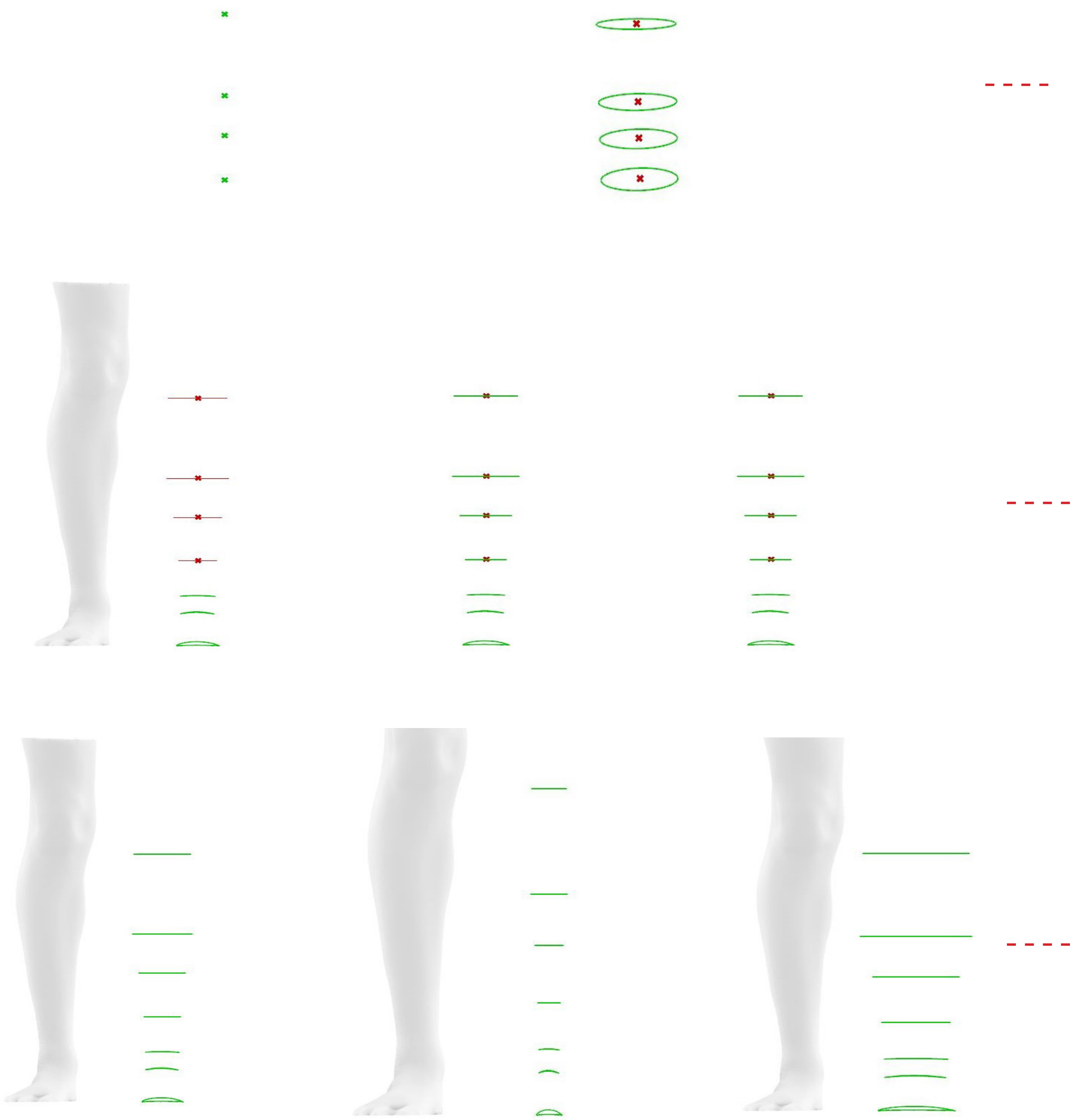



*Figure 5.4 Anatomical form grasshopper script*

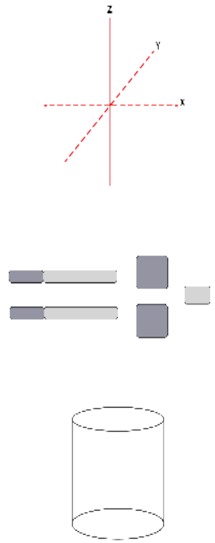


A set of points were placed alongside the limb scan at several Z axis points from the bottom of the patella to the top of the ankle. The ellipse node in grasshopper was placed, where points were assigned X and Z coordinates on the XY plane making up the curves.

The ellipses were then adjusted using number sliders to mimic the anatomical form of the remaining leg. These ellipses were grouped together, allowing for simultaneous adjustments to all ellipses while having the option of individually adjusting the curves for more control. A set of curves which make up the foot were merged with the ellipses for seamless integration with flexibility.

These merged curves are adjusted by scaling up and down with non-uniform factors, meaning that XYZ coordinates, height, width and length, can be adjusted at different values.

*Figure 5.5 demonstrating process of constructing anatomical form parameters.*



The anatomical form was generated without the socket and foot section. These experiments display the capabilities of parametric software by adjusting number sliders and scaling curves to sculpt an anatomical form, resembling the remaining limb.

**Components:**

XYZ coordinates
Number sliders
Ellipseshape
Point construction
Loft

*Figure 5.6 Components for experiments*

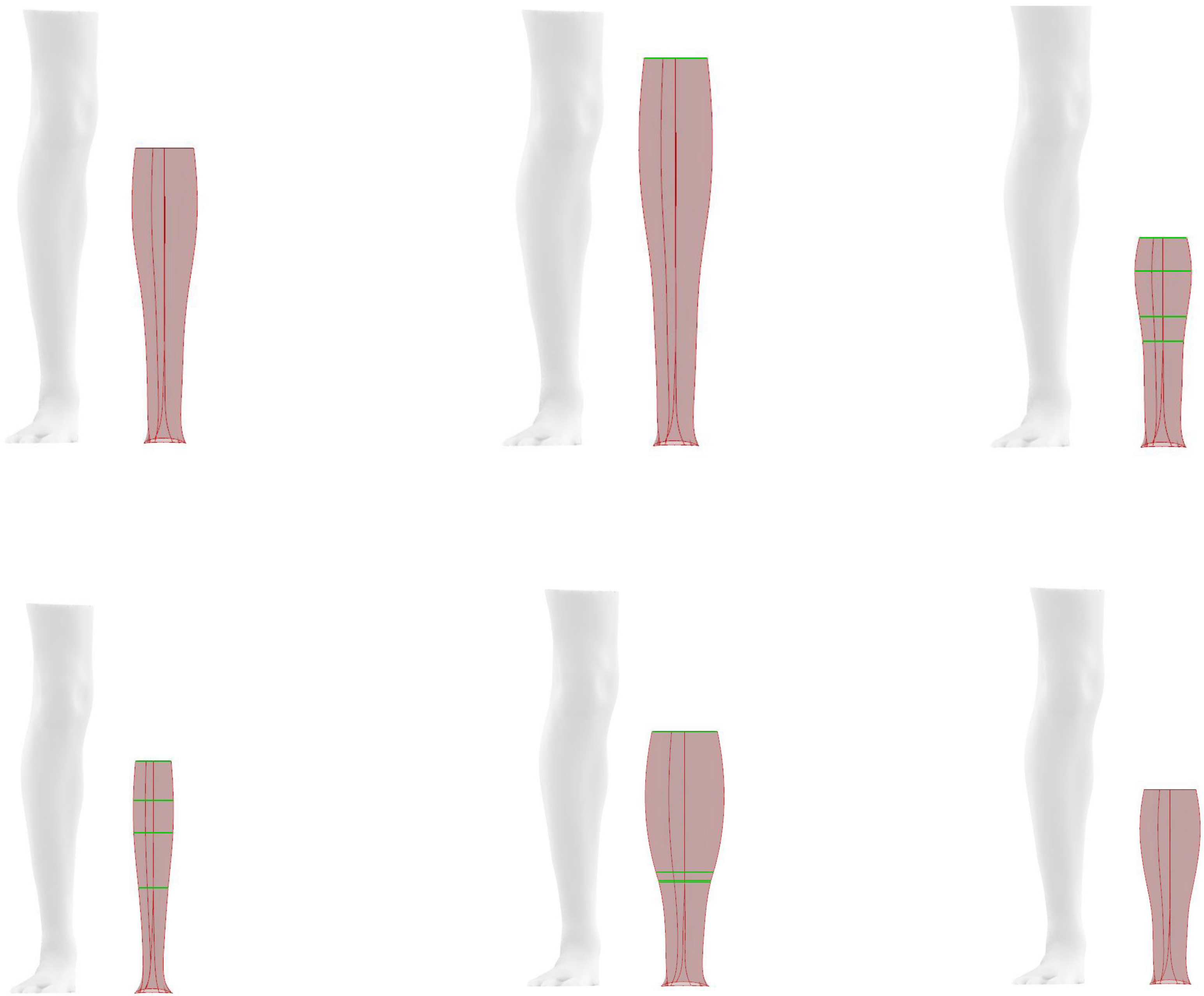


*Figure 5.7 Results from grasshopper experiments*

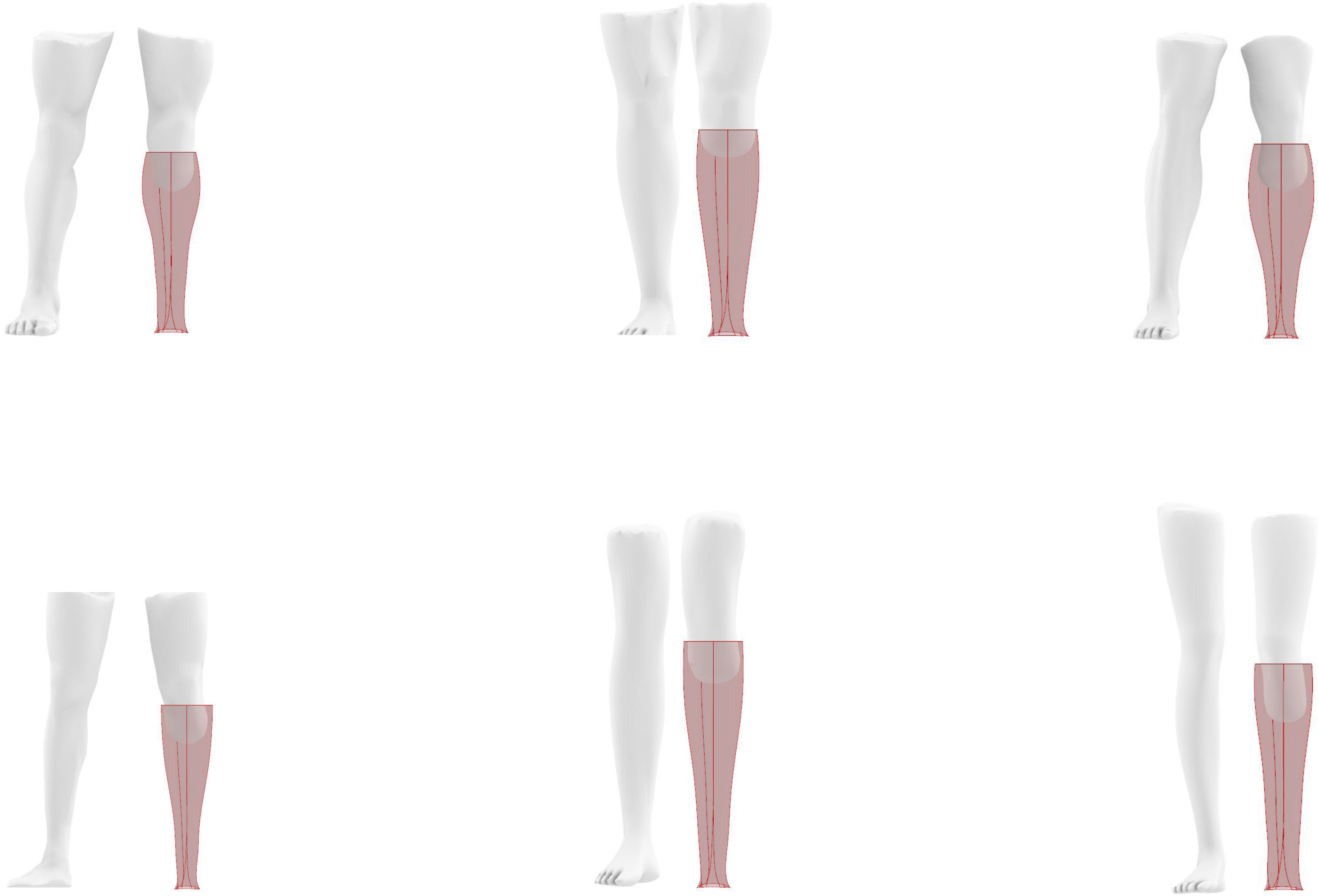


*Figure 5.8 Results from grasshopper experiments*

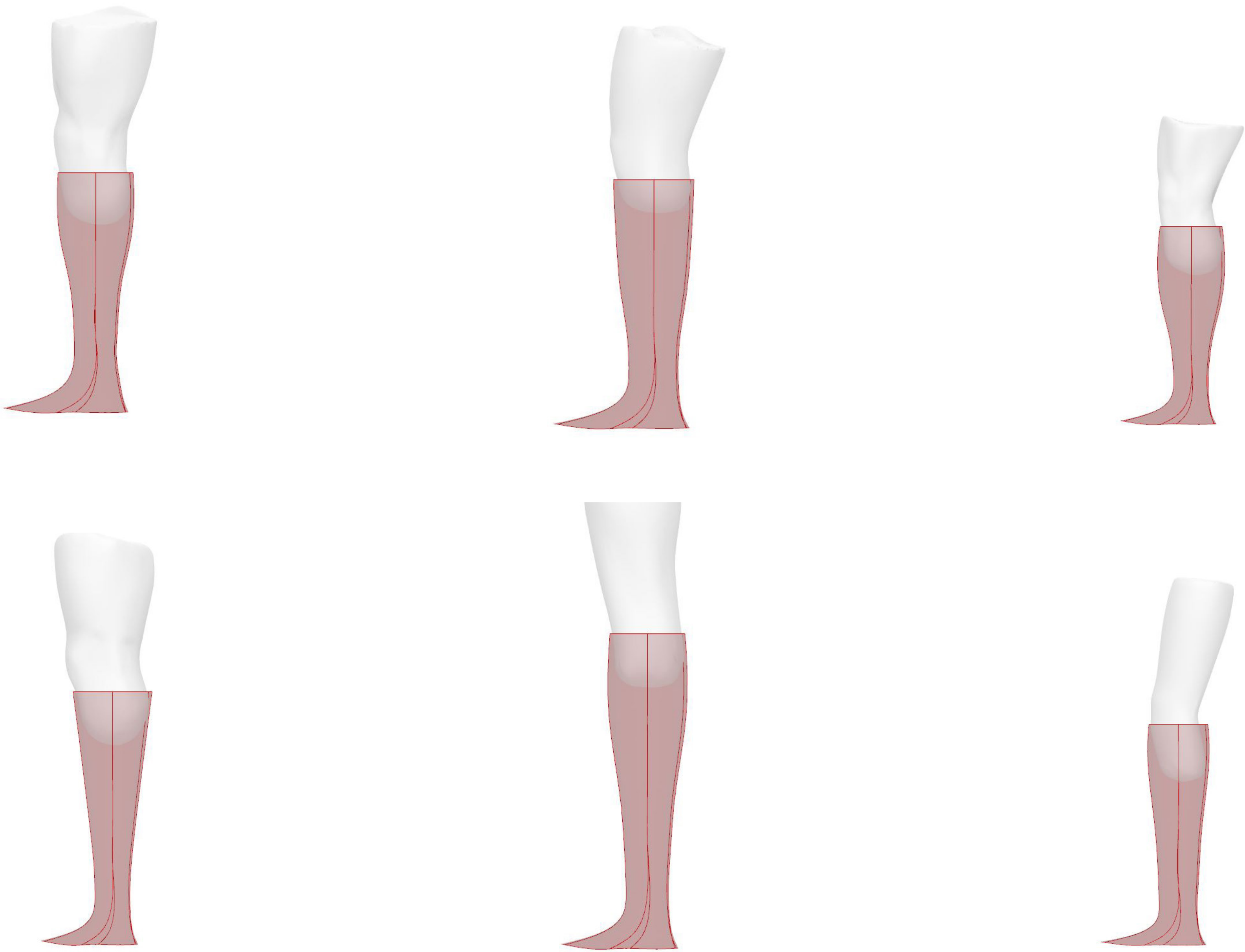
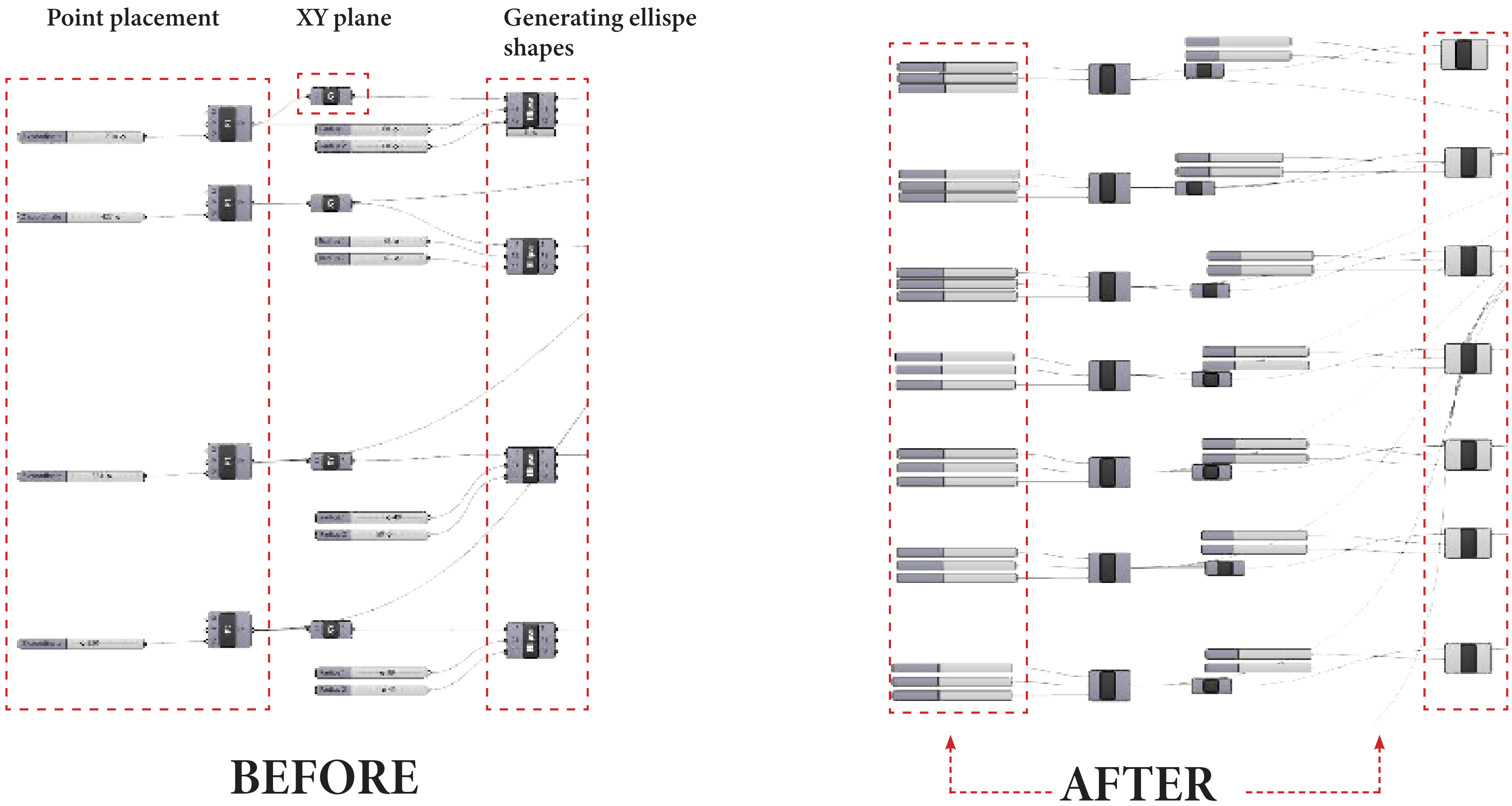


*Figure 5.9 Results from grasshopper experiments*

**Reflection**

The grasshopper script developed to generate the anatomical form provided sufficient results from the digital experiments. The slider system was able to generate a range of anatomical forms from different 3D anthropomorphic models where the existing limb was referenced. The anatomical accuracy was not completely accurate but displayed promising results. Refining this script for the final system will require adding more ellipse nodes into the grasshopper, achieving a more accurate anatomical representation, especially transitioning from lower calf to ankle/foot region.

# Grasshopper Script Refinement



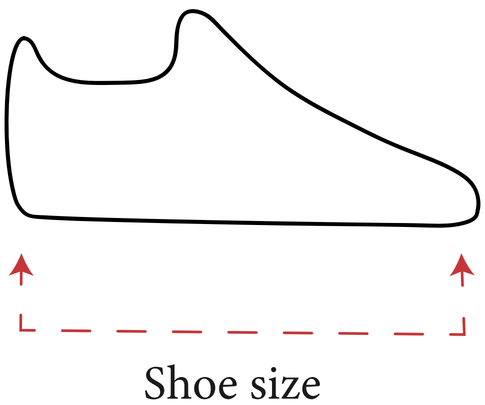

Changes made to the script : additional number sliders at the X,Y point for more accuracy

Changes made to the script : additional ellispe curves for greater control while adjusting anatomical form.

*Figure 6 Refined grasshopper script*

*Figure 6.1 Demonstrating refinement and results from refined script*

# FOOT MODELLING



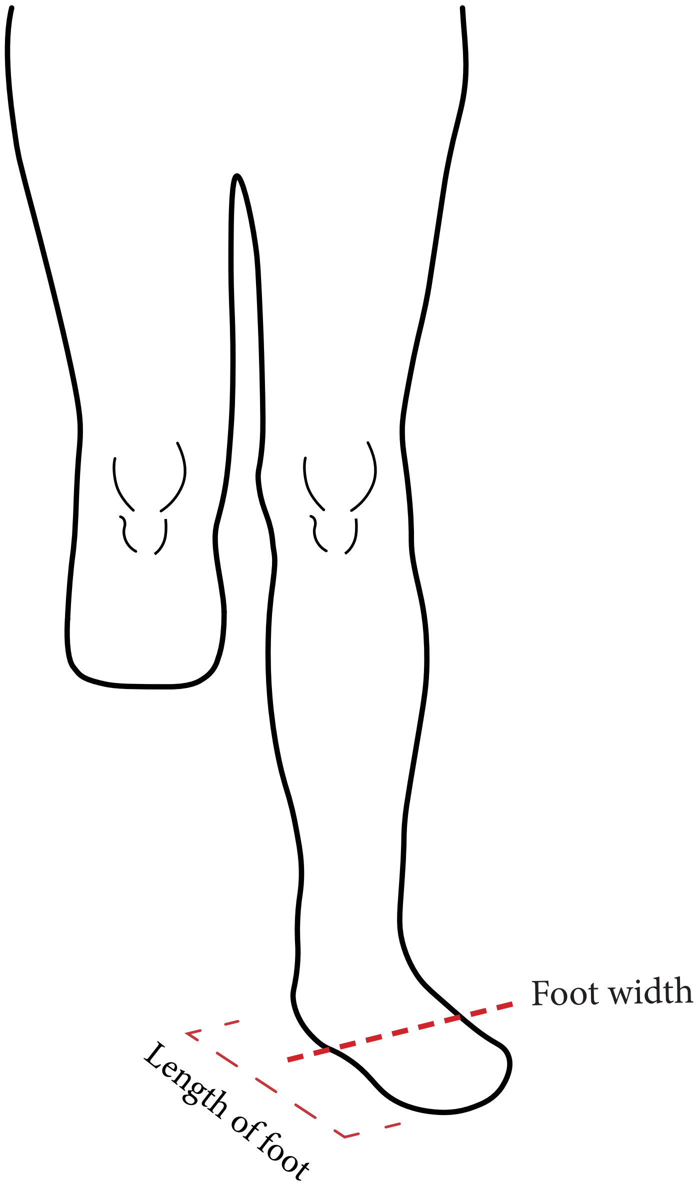




*Figure 6.2 Measurement considerations*

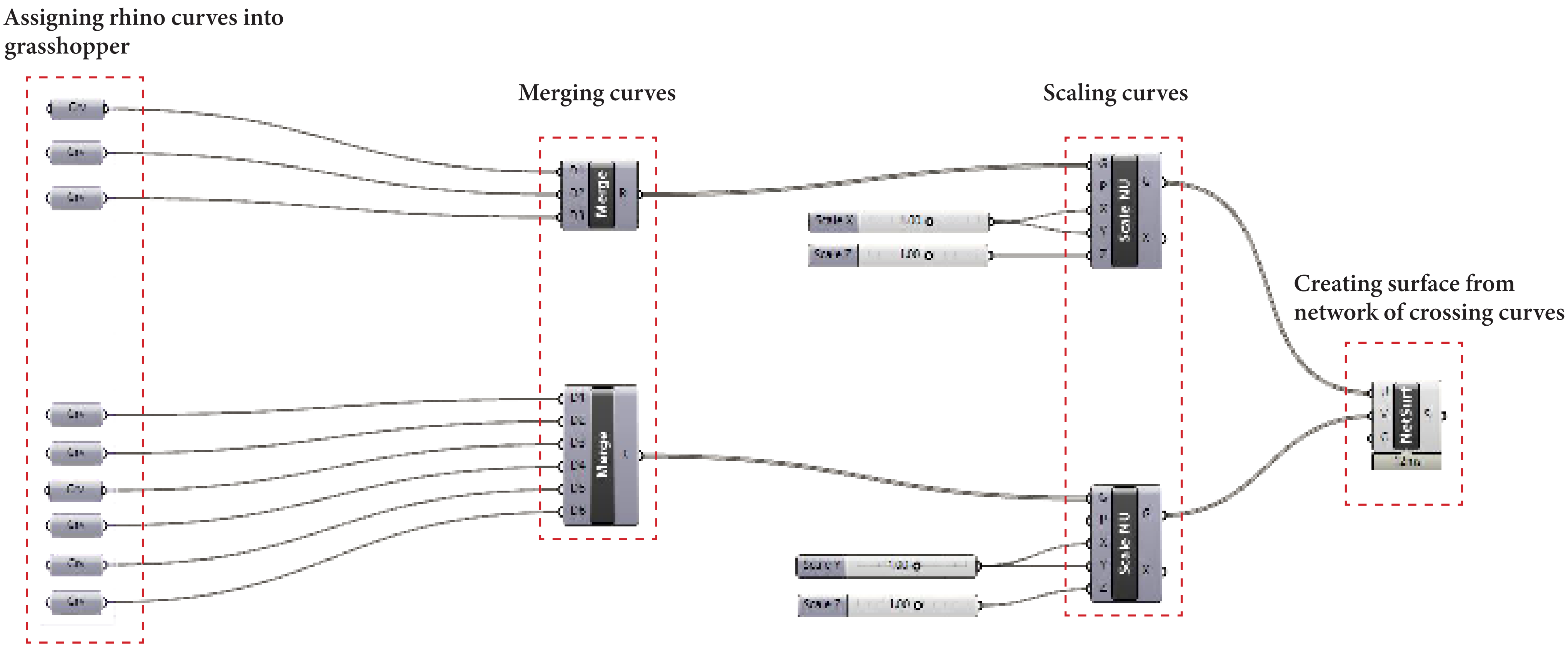
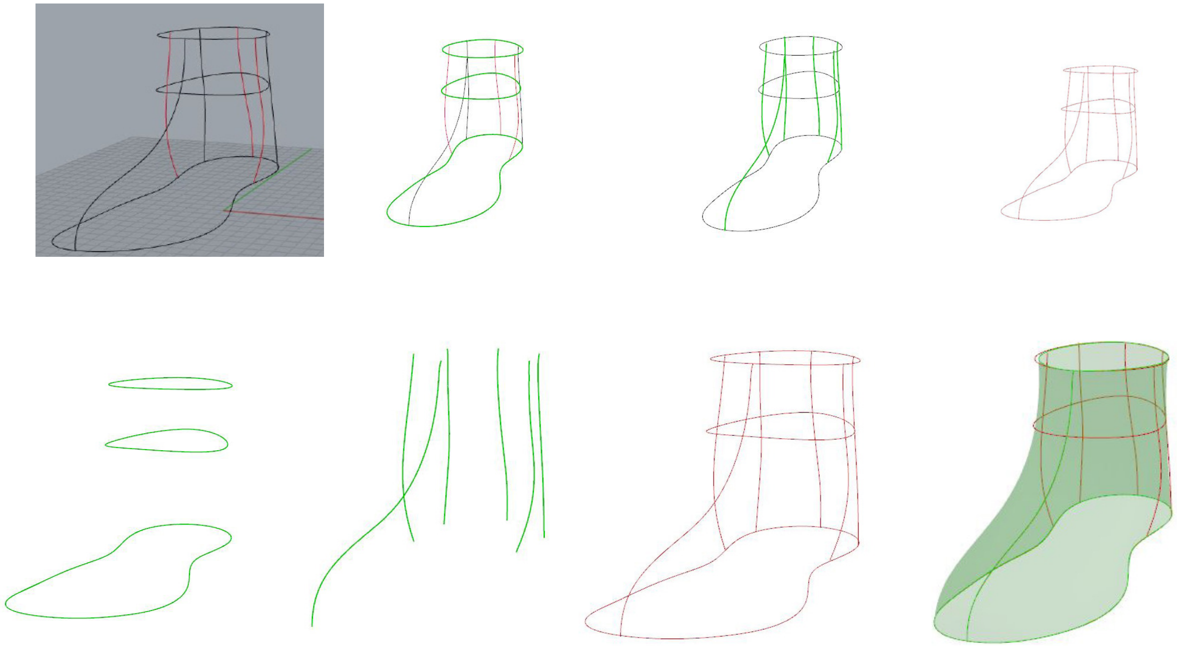



*Figure 6.3 Grasshopper script - foot modelling*

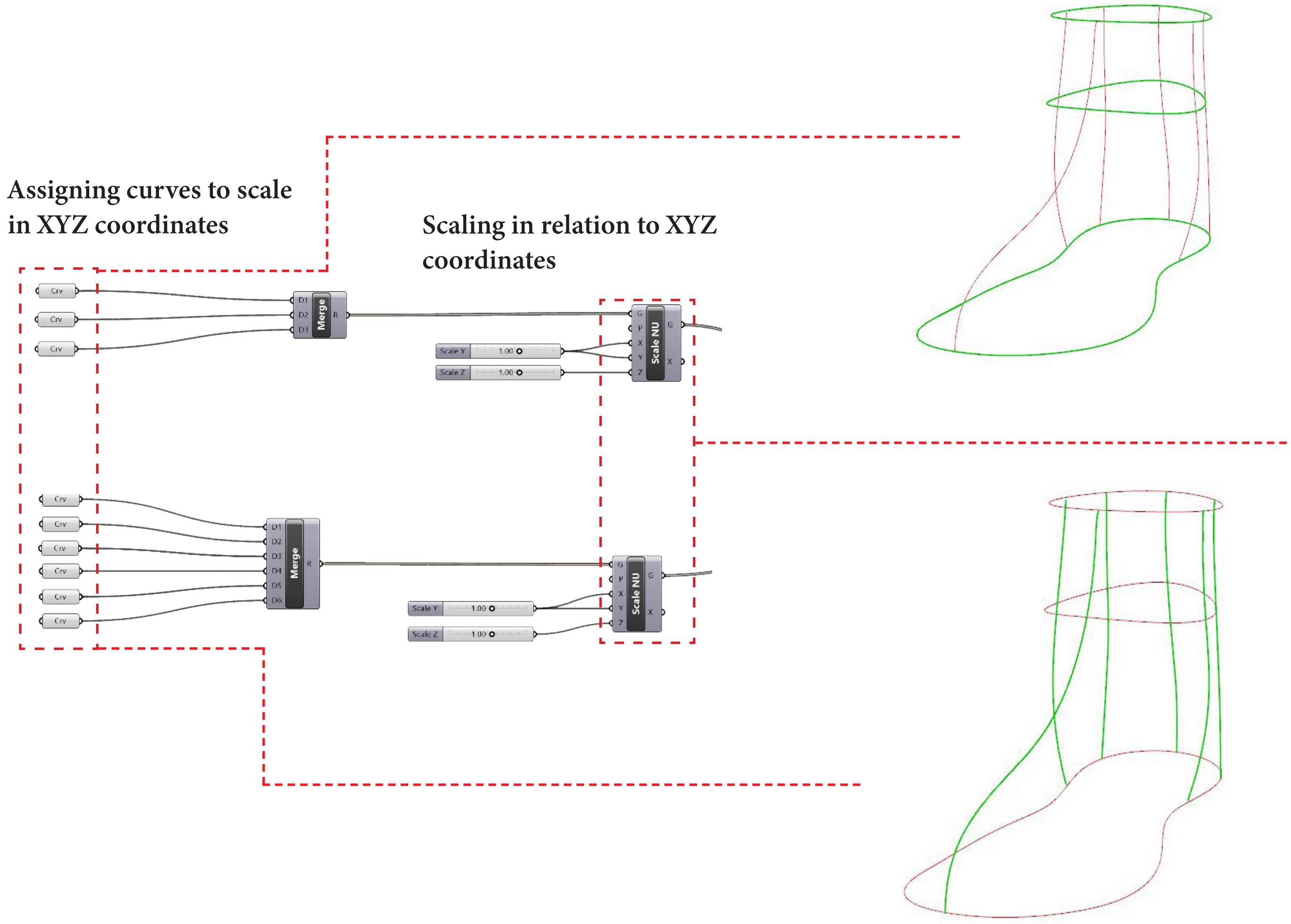


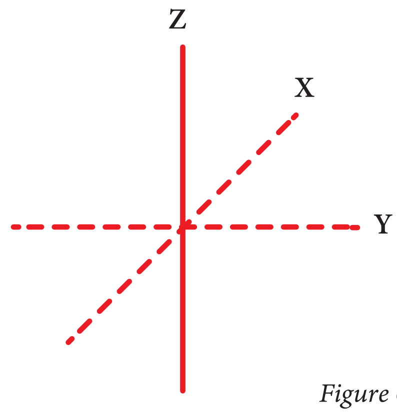
- - - - Building curves in rhino or grasshopper which makes up the overall form.

- - - - Assign curves in approriate U and V directions to create a network surface.

- - - - Network surface

*Figure 6.4 Process of constructing form*

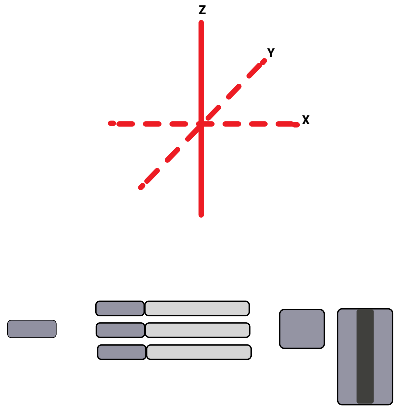


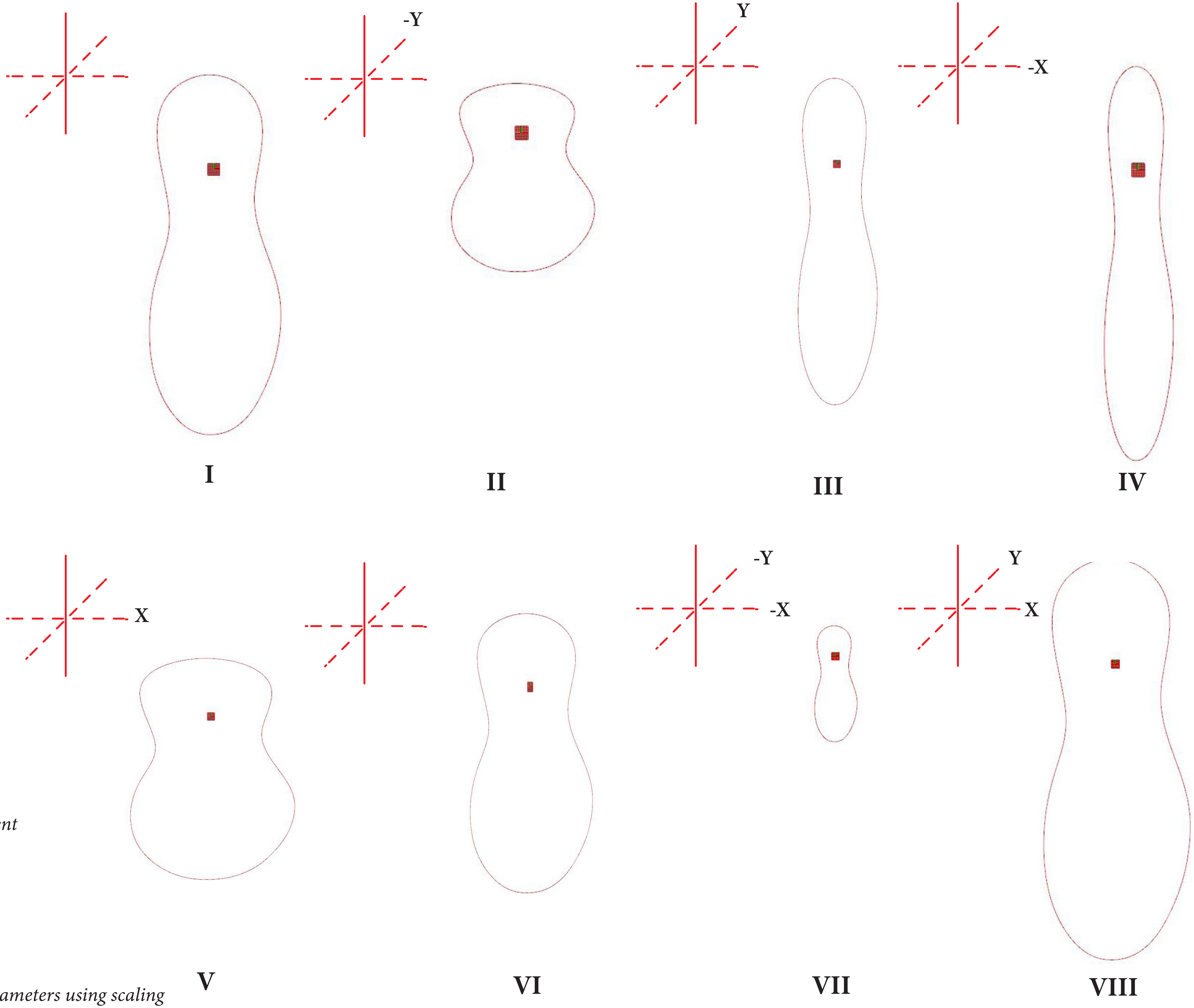




Z = height
X = width
Y= length

*Figure 6.5 Coordinates*

*Figure 6.5 Grasshopper- assigning curves to scale in XYZ directions*




**Components used:**

Curves
XYZ coordinates
Number sliders
Merge
Scale

*Figure 6.6 Components for experiment*

*Fig 6.6 Results from adjusting parameters using scaling*

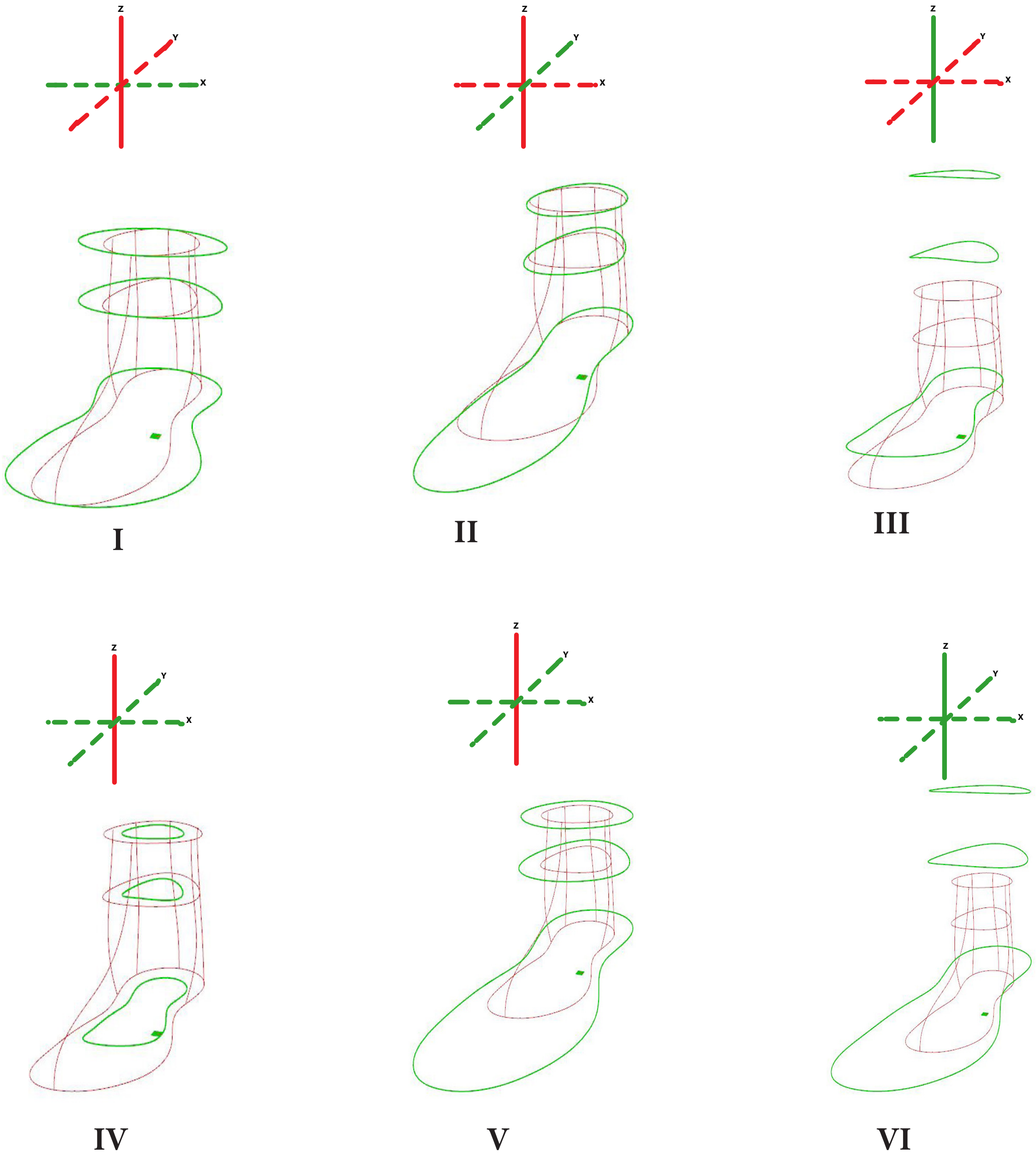



*Figure 6.7 Grasshopper- results from adjusting parameters using scaling*

*Figure 6.8 Grasshopper- results from adjusting parameters using scaling*

## Reflection

The experiments show a variety of ways parametric design exhibits its flexibility. These explored establishing independent variables and dependent variables using grasshopper. Examples on page 99, fig.(I to V) demonstrate the bottom of the foot being adjusted on the X and Y axis, changing the length and width of the bottom curve. Page 100 fig. (I to III) demonstrates the same but applied to three curves.

Next series demonstrates multiple variables working with each other while adjusting parameters. Example of this shown on page 100 fig. (IV to VI). As the width in one axis changes parametrically, second axis width changes, making it equal to the original parameter changed. This flexibility allows for greater control, where the initial foot size can be scaled for the individual along with freedom to adjust to different foot types.

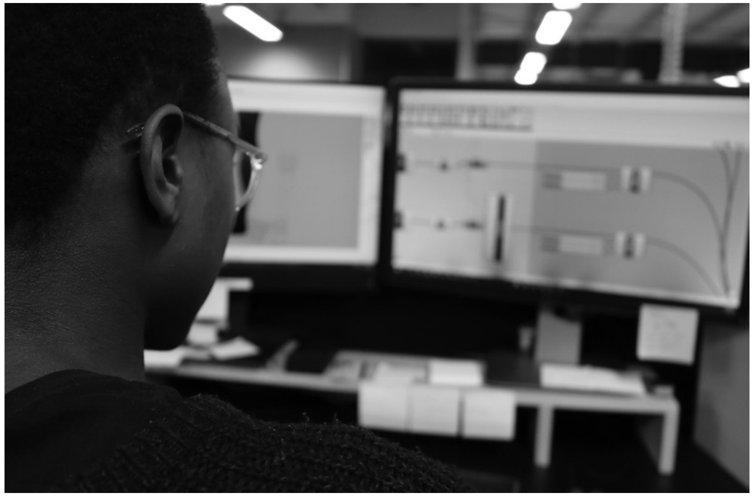


*Figure 6.9 Designer working in Grasshopper*

# Designing for Movement

## Introduction

This section seeks to generate and develop a dynamic foot concept that displays appropriate human gait cycle movements while adhering to a minimal aesthetic. Analysis into the standard prosthetic foot types such as the Ottobock 1C30 Trias (Ottobock,2021) and the solid ankle cushion heel (SACH) foot-passive keel (NZALS ,2021) were used to better understand the movements required in a prosthetic foot.

A template of the foot section was created from a series of curves making up the overall surface. During the initial design exploration, minimal changes were made to the form. While developing the movement, no changes were made to the curves in Rhino. A sequence of Boolean splits and Boolean differences were applied to create negative spaces for the dynamic foot.

## Aims and objectives

**Analyse movements in the human foot**

Research, analyse and annotated the anatomy of the human foot to gain an understanding of dynamic prosthetic foot qualities.

**Conceptualise design ideas physically and digitally**

Generate concepts by sketching, CAD modelling. Visualise ideas through 3D printing and rendering

**Test and evaluate findings from experiments**

Perform test on 3D prints imitating movements in the foot. Evaluate and document findings. Develop further concepts from evaluation

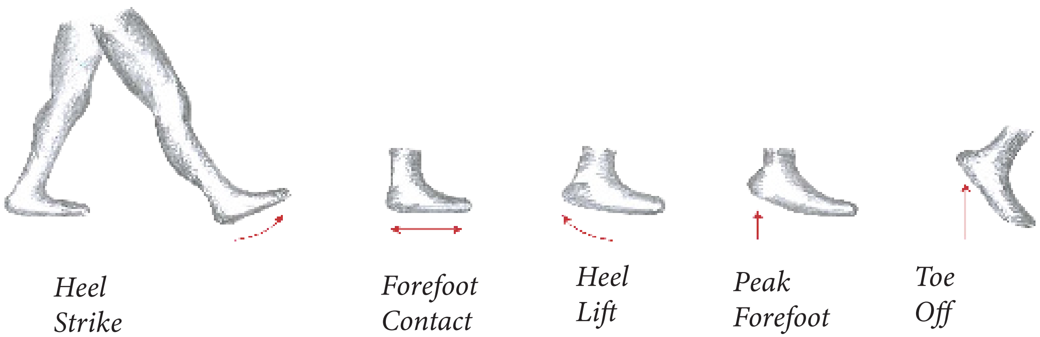



*Figure 7 Gait cycle annotated*

## Gait Cycle

Gait cycle is a series of repetitive movement made up of steps and strides. This cycle is broken down into 5 sections, heel strike, forefoot contact, heel lift, peak forefoot and toe lift off. The first contact between the foot and ground is important, as well as the transfer of load on the foot. This foot contact should carry out through to the heel, making the walking process as natural as possible. Afterwards the sole contacts the ground, transferring the load to the foot. This is followed by the heel lift and forefoot peak where the foot rolls away from the ground and pushes off through the toe (physiopedia,2021).

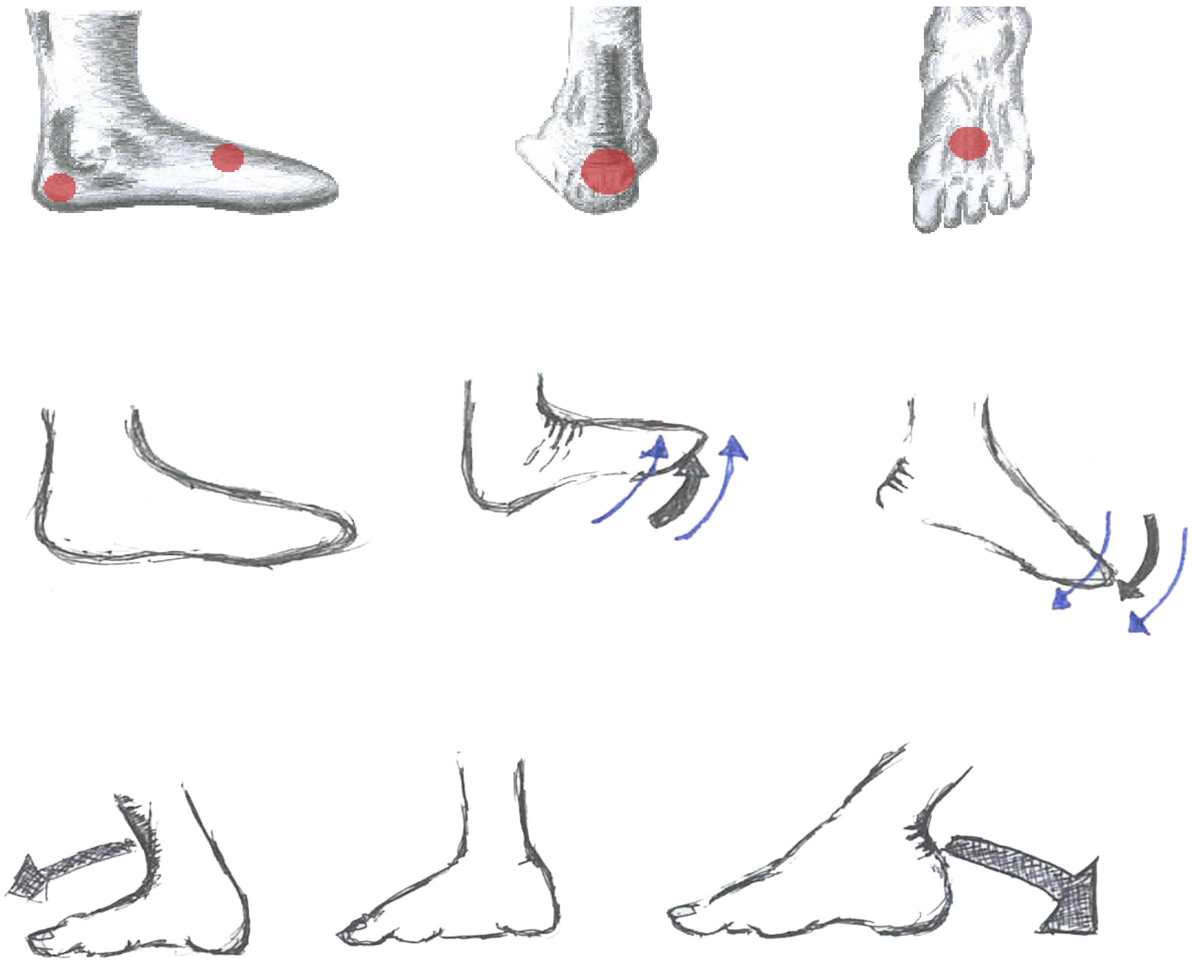
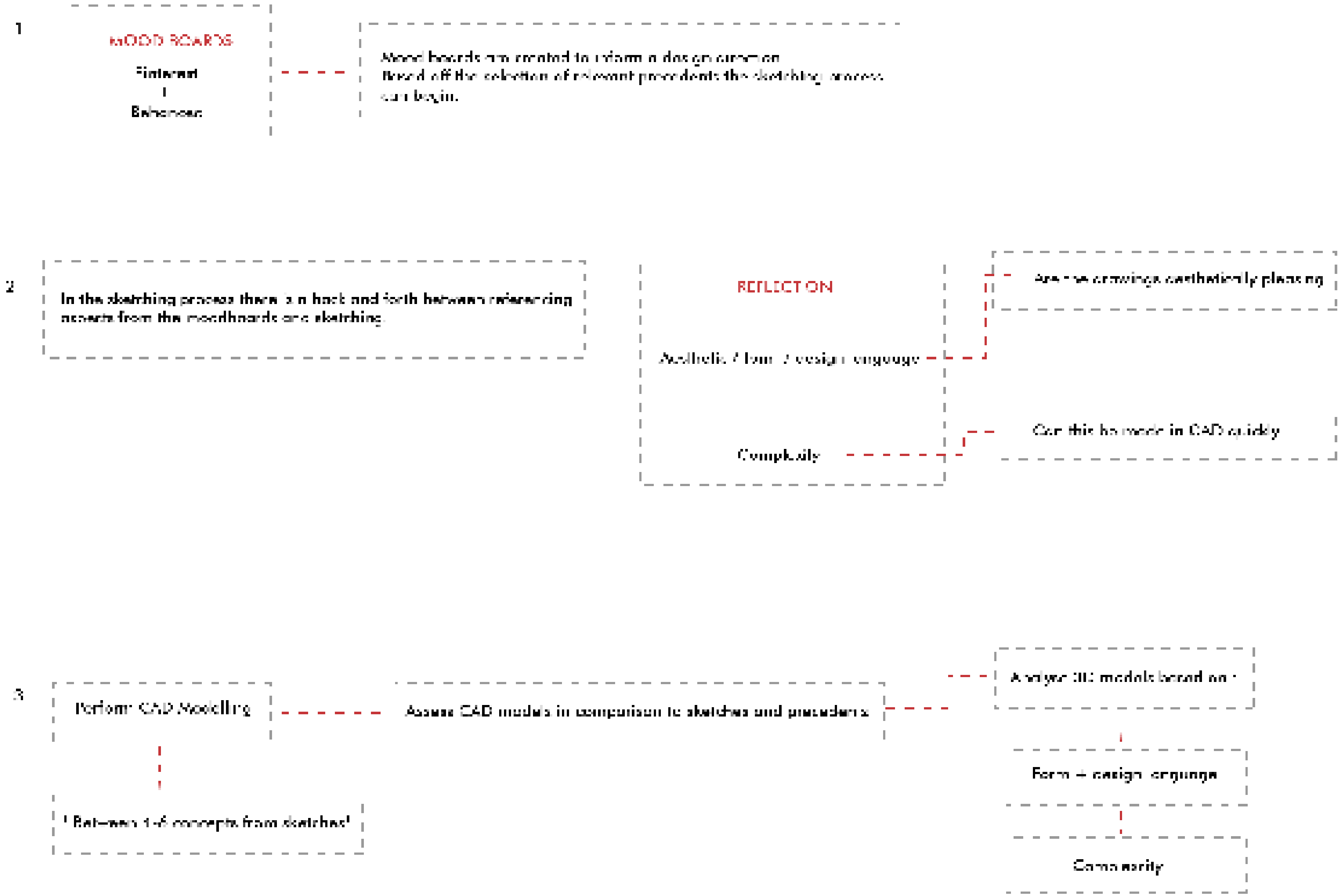


*Figure 7.1 Areas of movement and consideration annotations*

## Areas of Movement

Current prosthetic feet regularly use carbon fiber flex foot, this foot is able to mimic the basic motion of the human foot.

Weight activation is a big factor which determines how the prosthetic foot is designed or redesign. Expert opinion from NZALS technicians identified the forefoot and heel as the main locations for movement.


1
MOOD BOARDS
Pinterest
I
Behance
Mood boards are created to inform a design direction.
Based off the selection of relevant precedents the sketching process can begin.
2
In the sketching process there is a back and forth between referencing aspects from the moodboards and sketching.
REFLECTION
Aesthetic / form / design language
Complexity
Are the drawings aesthetically pleasing
Can this be made in CAD quickly
3
Perform CAD Modelling
( Between 4-6 concepts from sketches)
Assess CAD models in comparison to sketches and precedents
Analyse 3D models based on :
Form + design language
Complexity

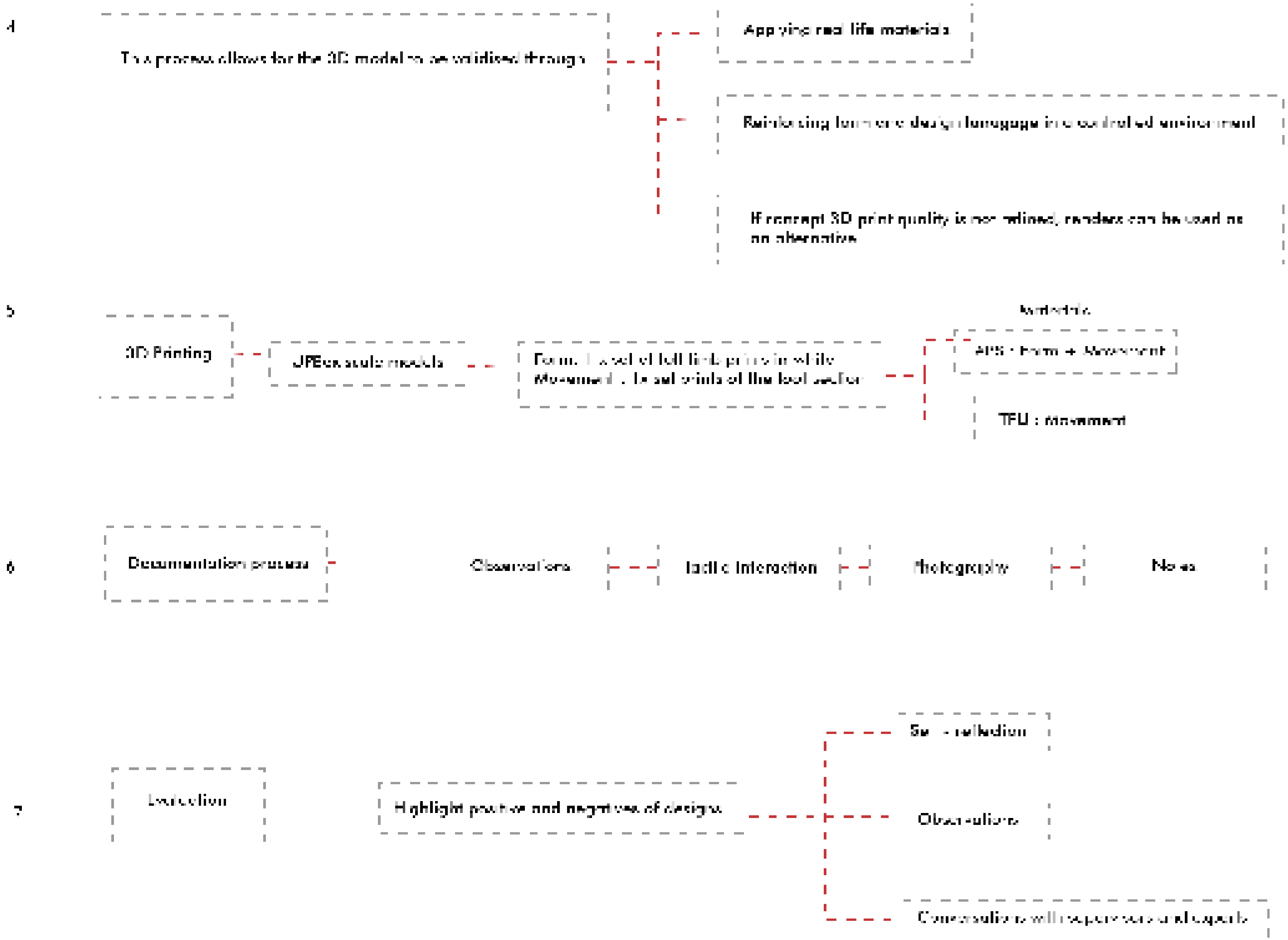



*Figure 7.2 Designer's iterative process*

# SKETCHING


*Figure 7.3 Sketches*

# CAD MODELLING
# &
# RENDERING

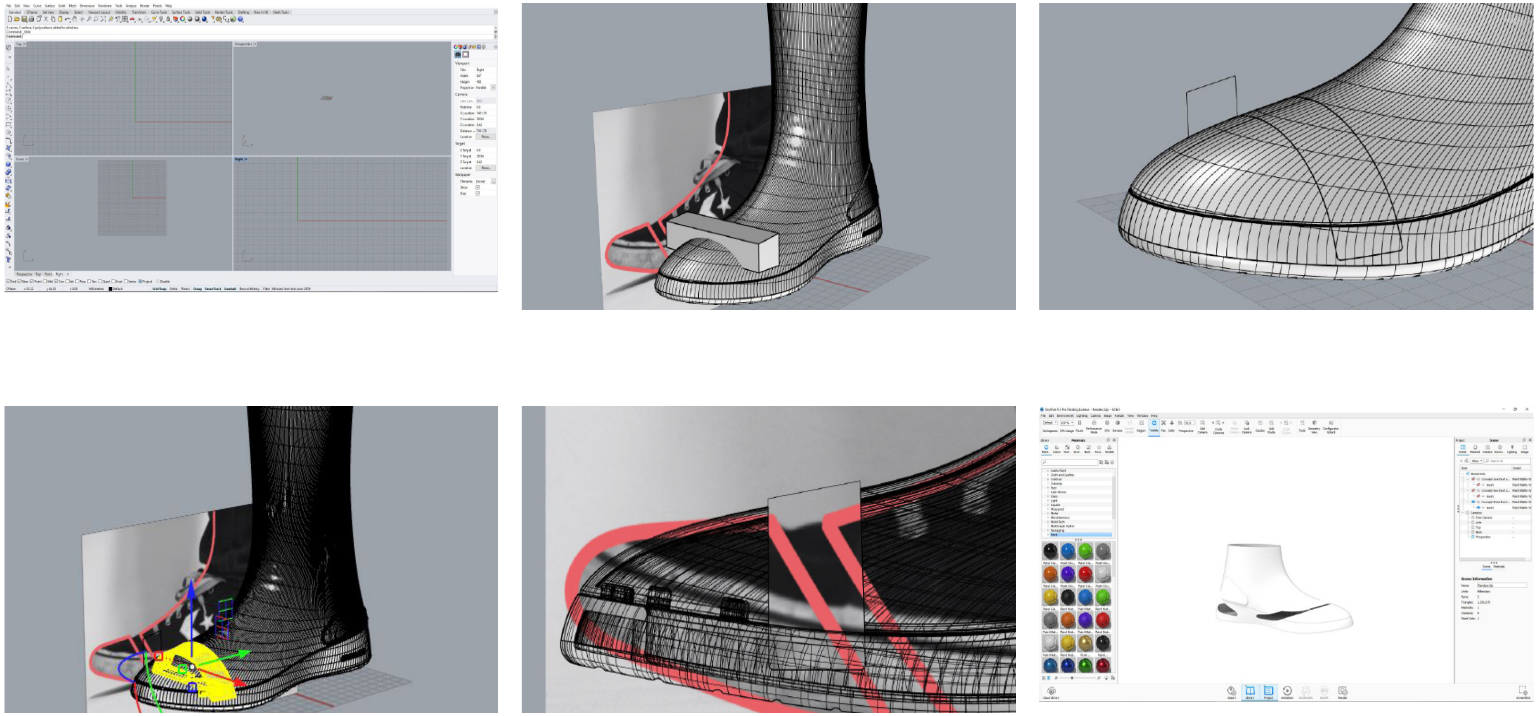


*Figure 7.4 CAD modelling process and rendering*

# 3D PRINTING PROCESS

Once the surface modelling is done in Rhino, the model is then exported as STL's for rendering and 3D printing. UP Studio is the software used when perparing STL files for FDM printing. Once the STL is imported into UP Studio aspects like scale , print orientation, layer thickness, print quality and so on are considered when configuring the settings. These changes can determine how it will take to print the model and also how long it takes to remove the support material and raft.

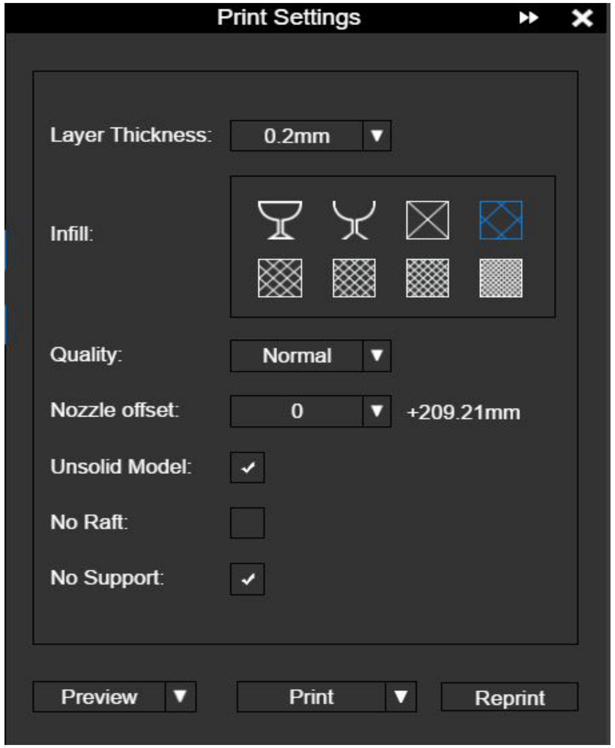



*Figure 7.5 Print settings*

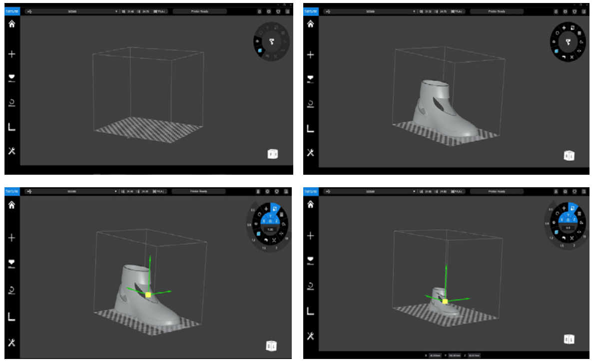


*Figure 7.6 Scaling model*

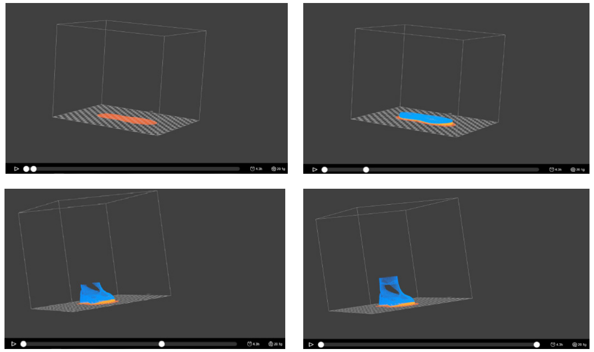


*Figure 7.7 Print preview*

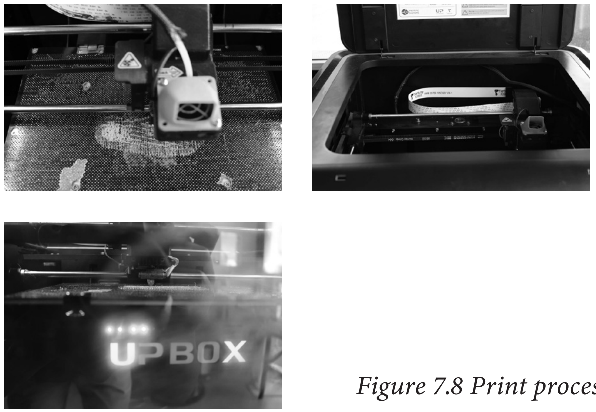



*Figure 7.8 Print process*

# CONCEPTS

The initial concepts focus on exploring movement in the forefoot and heel through a range of scaled down sketch 3D print models

# CONCEPT 1

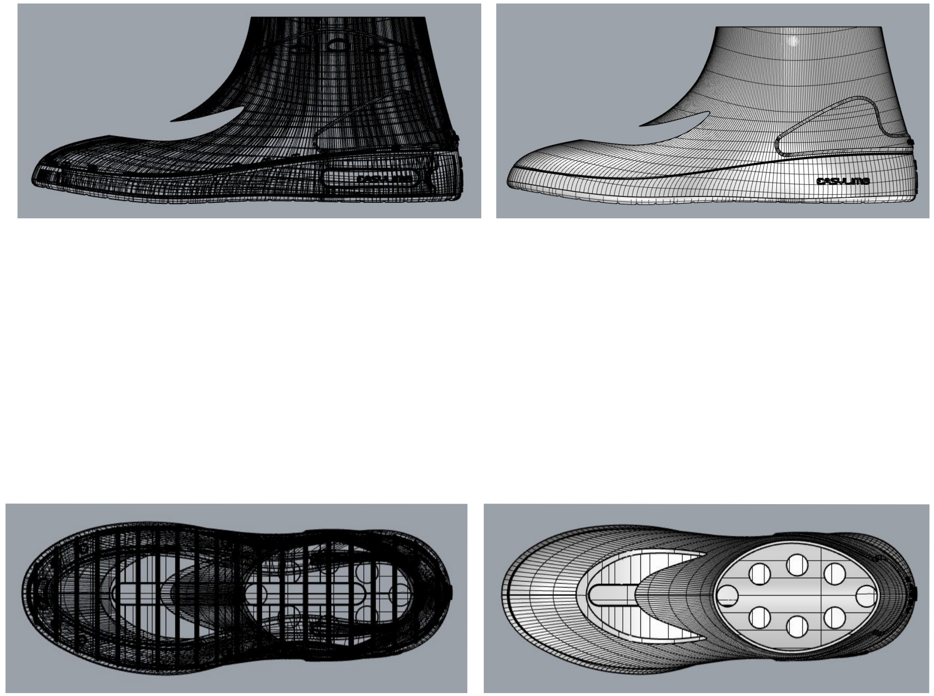
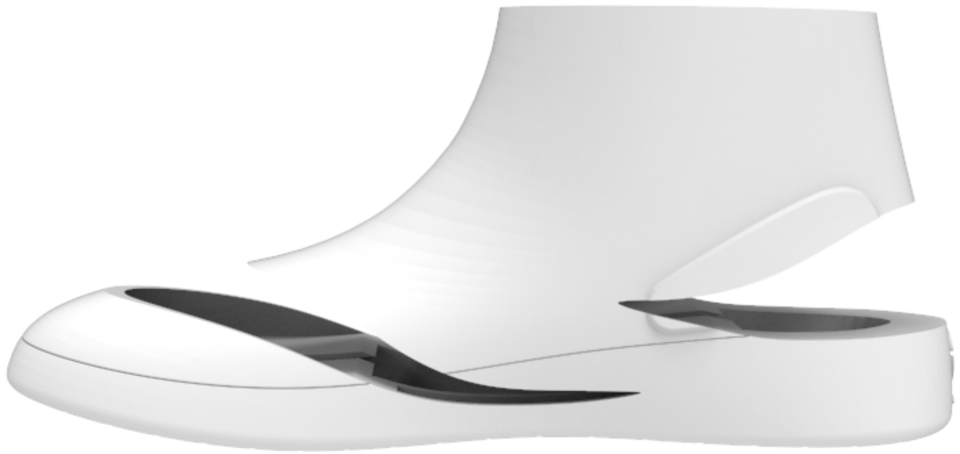


*Figure 7.9 Concept one - CAD and render*

# CONCEPT 2



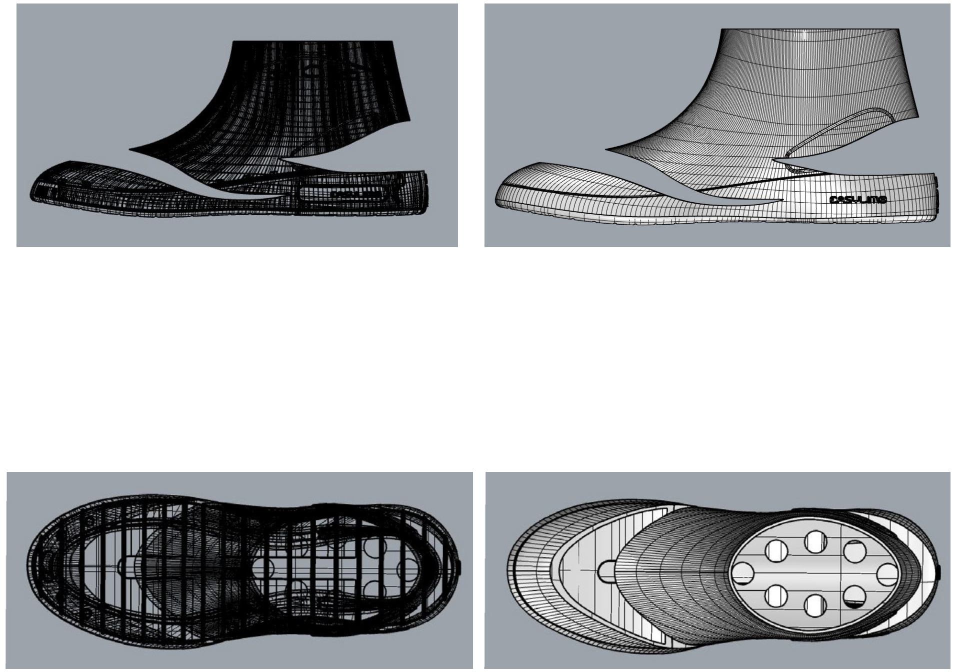
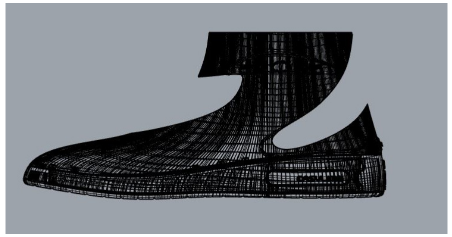
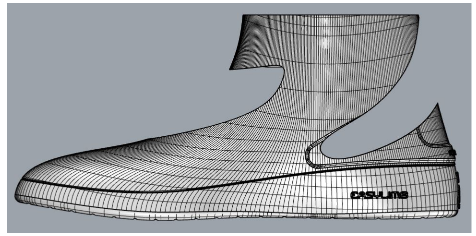
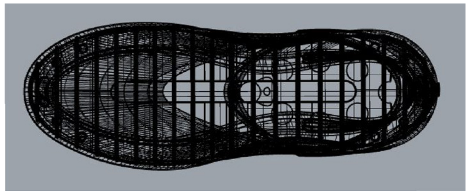


*Figure 8 Concept two - CAD and render*

# CONCEPT 3







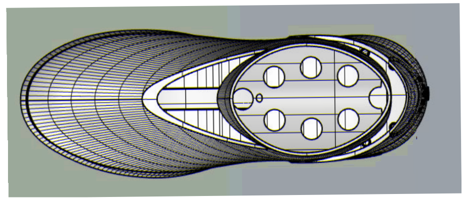
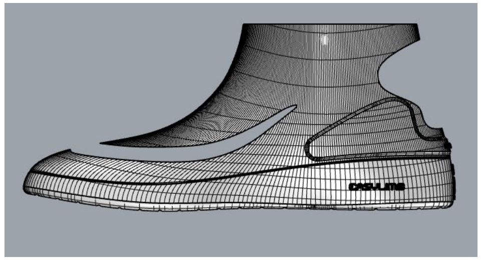
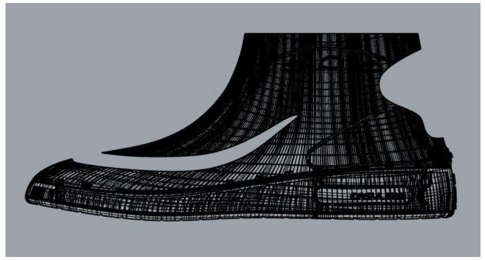
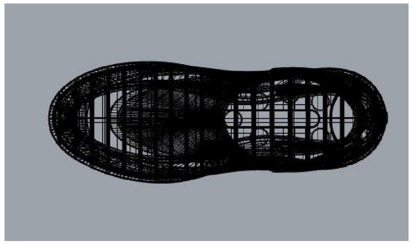


*Figure 8.1 Concept three - CAD and render*

# CONCEPT 4







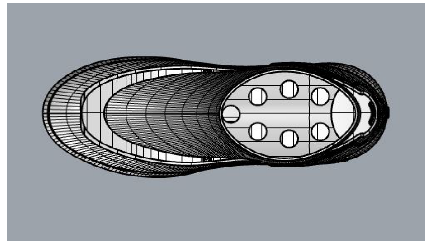
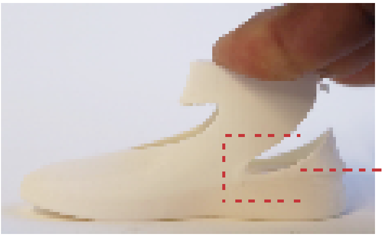


*Figure 8.2 Concept four - CAD and render*

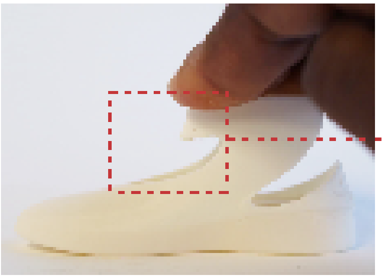
# EVALUATION

# CONCEPT EVALUATION 1









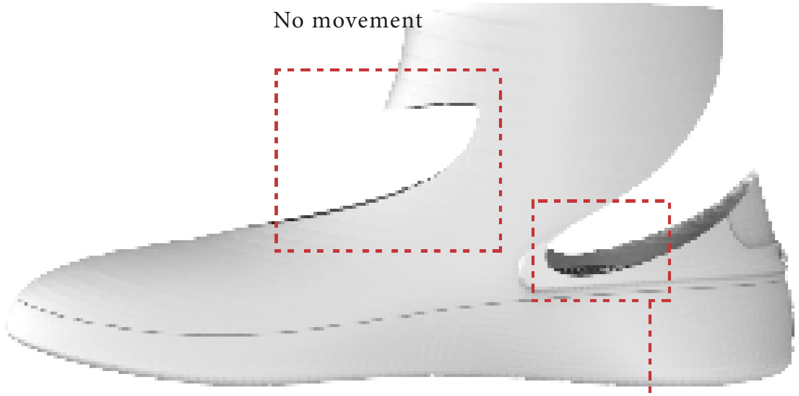
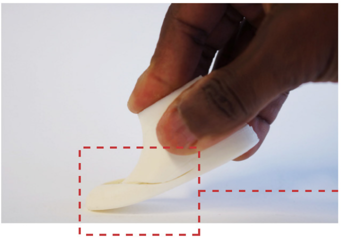



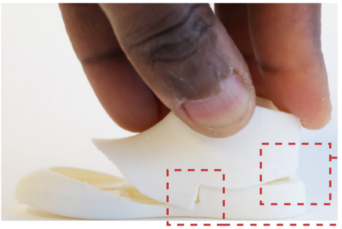

*Figure 8.3 Concept evaluation - one*

# CONCEPT EVALUATION 2



Dorsiflexion motion in the print performed well , plantarflexion motion did not perform as well

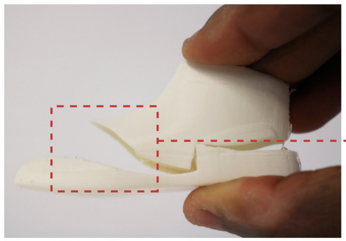
Spring and bounback from the model when dorsiflexion motion was applied was promising



Compression throughout the heel performed significanlty better than concept one.

The boolean split cut will need to be placed lower as it was too high and resulted in the print snapping where the curves intersect.

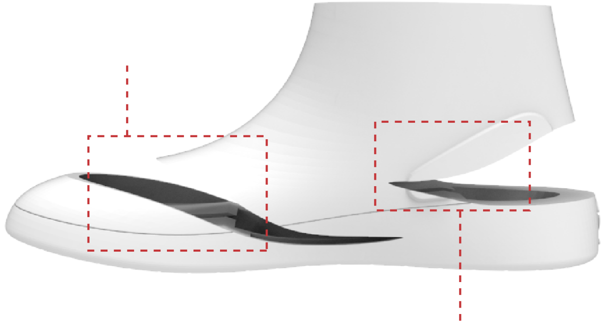
Distance between the curves could add more stability to future 3D prints.



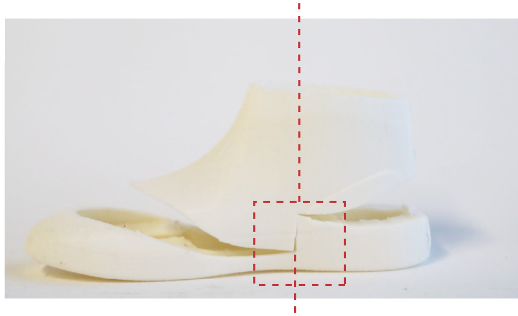
ABS material performs well but extensive tests on dynamic qualities result in model breaking.

Material is fragile

Consideration : increasing wall thickness of the model



Points where model is fragile



Point where model split

*Figure 8.4 Concept evaluation - two*

# CONCEPT EVALUATION 3



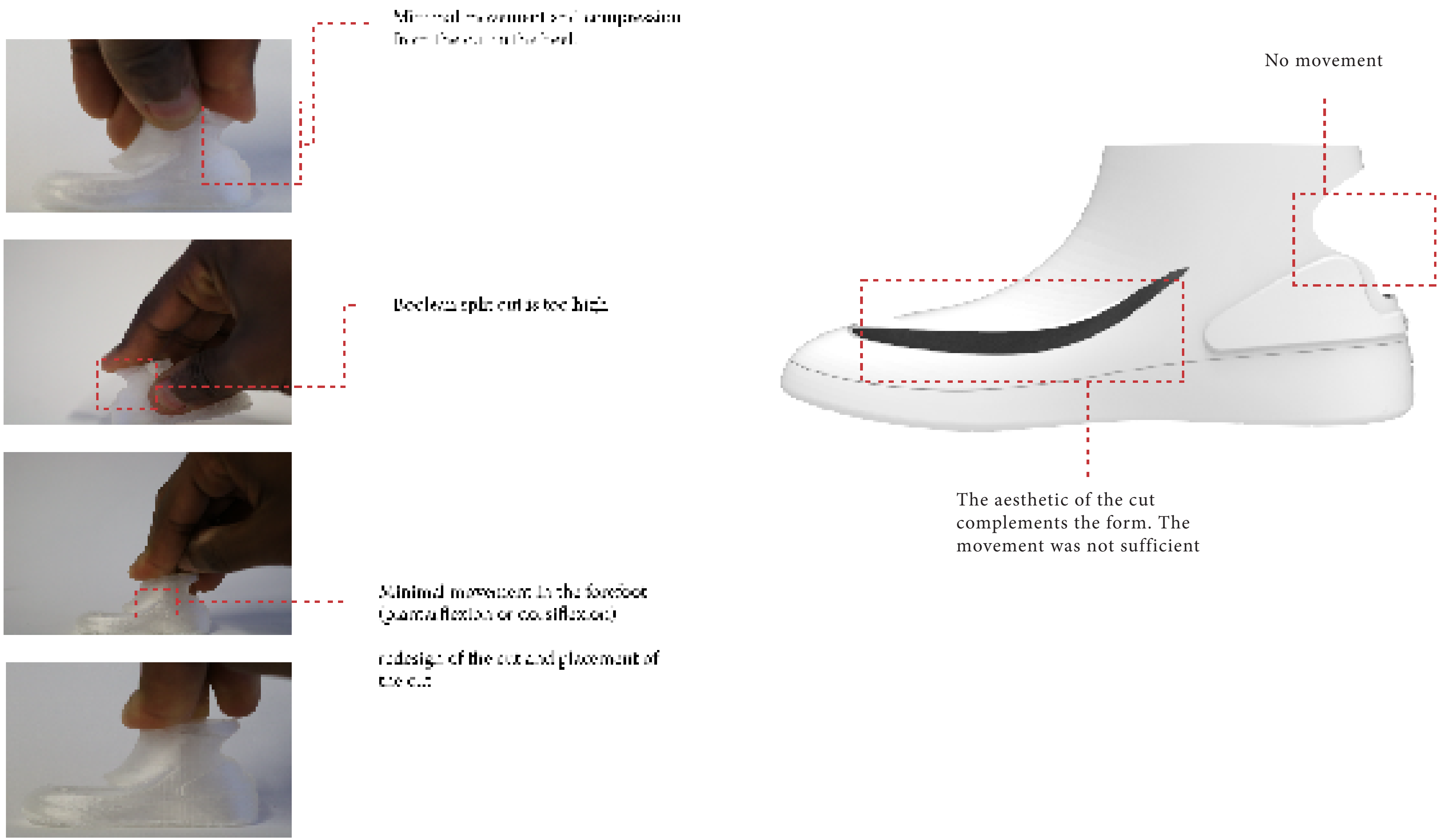
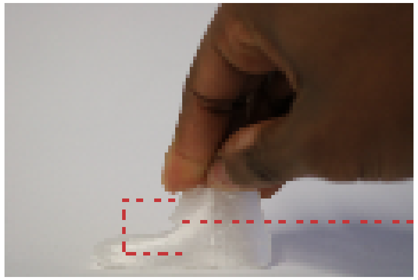


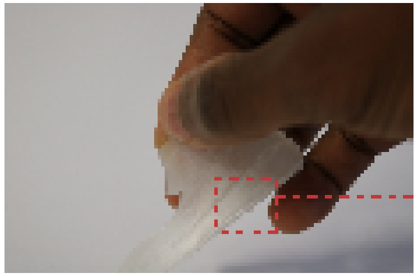

*Figure 8.5 Concept evaluation - three*

# CONCEPT EVALUATION 4

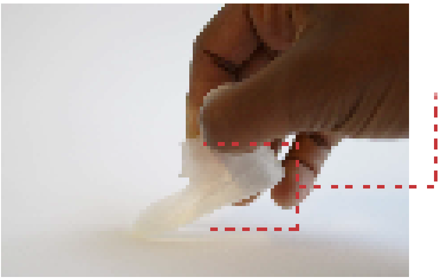




No cut was modelled on the heel. This resulted in no movement.



The cut was placed too high on the model, this resulted in very minimal plantarflexion and dorsiflexion motion.



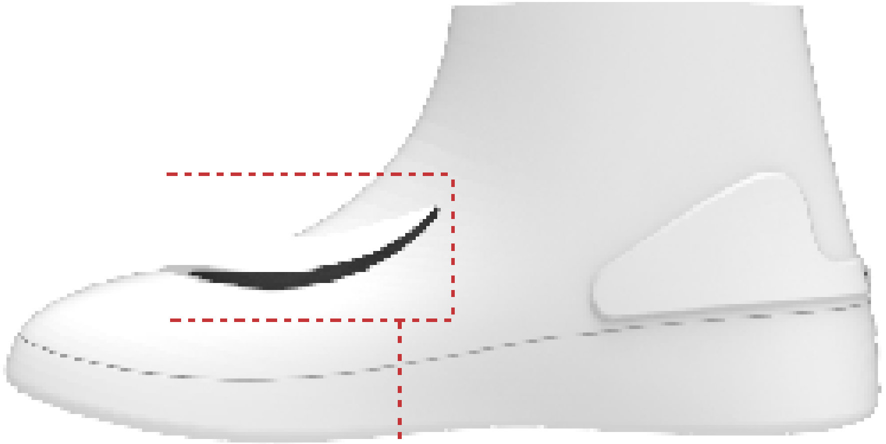



*Figure 8.6 Concept evaluation - four*

# REFLECTION

After evaluating the four initial concepts there were aspects which needed further development. The positioning of the cut on the models was one common observation. In concepts one, three and four the cuts were positioned too high, meaning the areas of movement within the forefoot and heel could not be applied sufficiently. The cuts on concept two showed the most potential with both the heel having sufficient amount of compression and the forefoot showing promising plantarflexion and dorsiflexion movements.

Aesthetically, the cuts will need to be less noticeable, thus taking away from overall form of the limb. Concept one takes away too much from the overall aesthetic. Concept two is less obvious and flows along the silhouette of the foot well. The forefoot cut of concept three follows the form of the foot well but the heel cut does not make sense within the overall aesthetic. Concept four's cut is also too noticeable and takes away from the quiet aesthetic.

Further developments will need to consider having the cuts finish on the base of the foot which is a flat plane. This will allow for more flexibility as only one part of the model is initiating the movement.

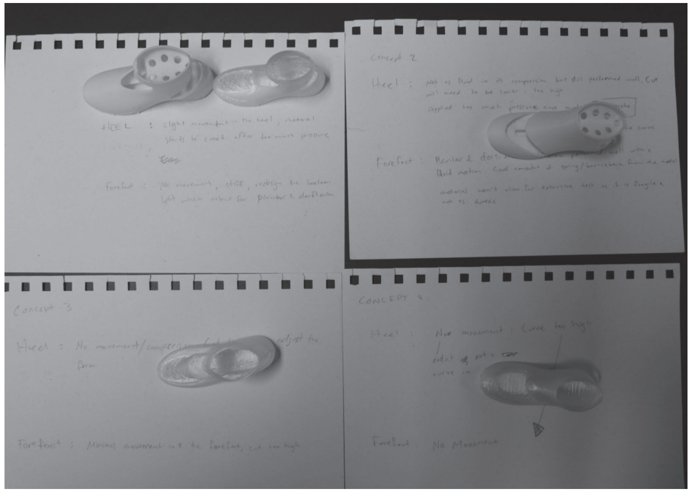


*Figure 8.7 Evaluated results*

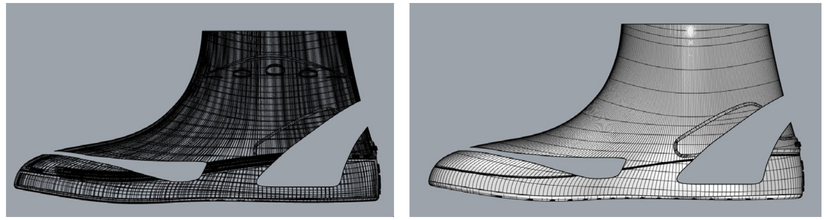
# DEVELOPMENT

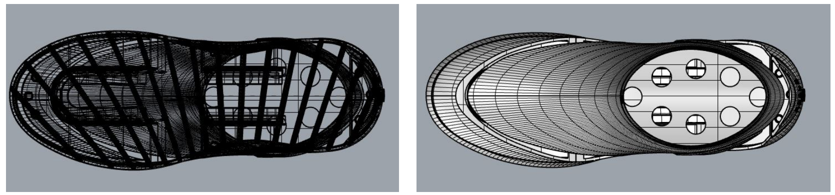

*Figure 8.8 Physical annotations for developments*

Upon reflecting and analysing the initial concepts with the guidance of supervisors, the designer went back a few steps to progress forward within the design process. A 3D printed the foot section with no alterations was treated as a canvas with the use of masking tape and markers. As visual reminders for where movement would occur in the foot, small sketches were made drawn on this model.

# CONCEPT 1







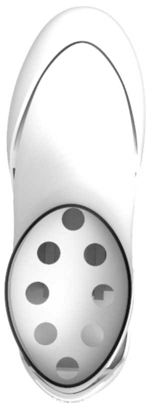
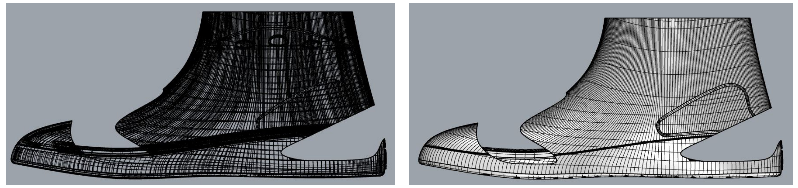


*Figure 8.9 Development Concept one - CAD and render*

# CONCEPT 2



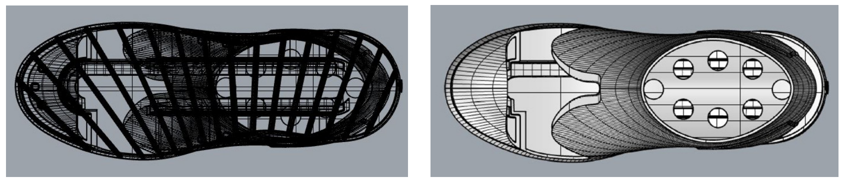
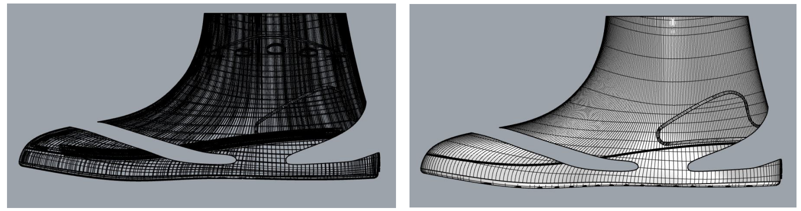


*Figure 9 Development Concept two - CAD and render*

# CONCEPT 3



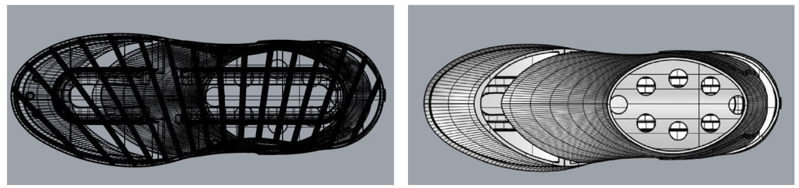
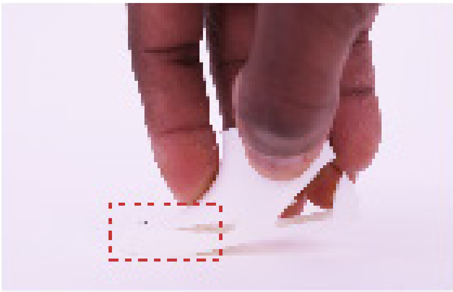


*Figure 9.1 Development Concept three - CAD and render*

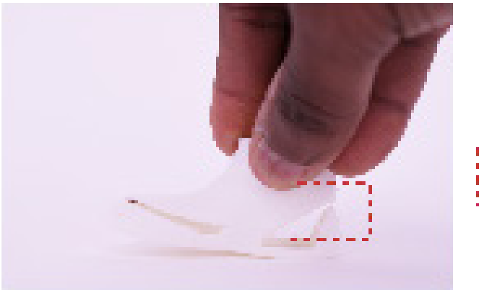
# EVALUATION

# CONCEPT EVALUATION 1



Location where movement occurs is not in the exact spot.

Although movement occured in the incorrect spot dorsiflexion motion performed well in the model.

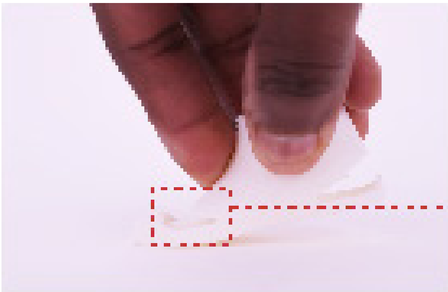


Plantarflexion movement resulted in the model breaking.

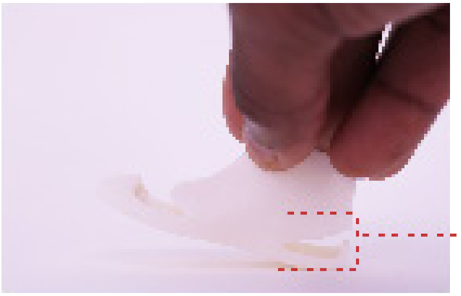
Compression in the heel section provided sufficient movement.

*Figure 9.2 Concept evaluation . Development one*

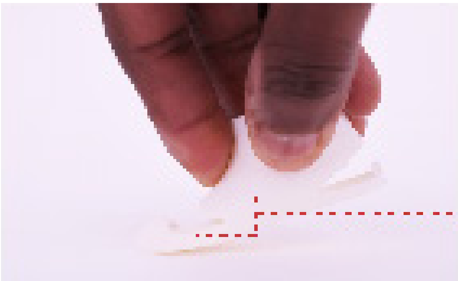
# CONCEPT EVALUATION 2



Minimal dorsiflexion movement.
Cut was not placed low enough.



Heel compression was satisfactory. The cut will need to start lower and finish as close to the bottom as possible.



Similarly, with the plantarflexion, movement was very minimal.

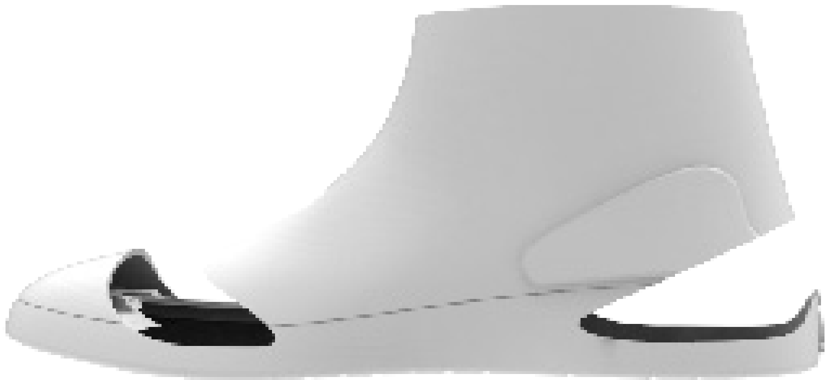
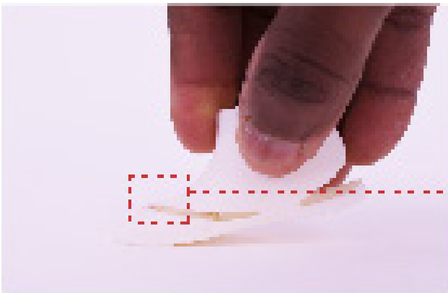


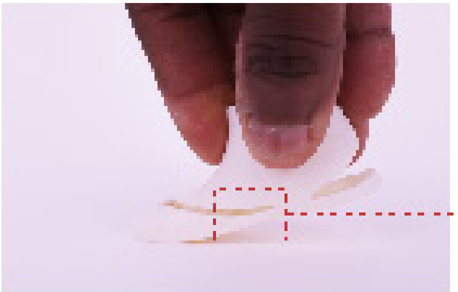
*Figure 9.3 Concept evaluation . Development two*

# CONCEPT EVALUATION 3

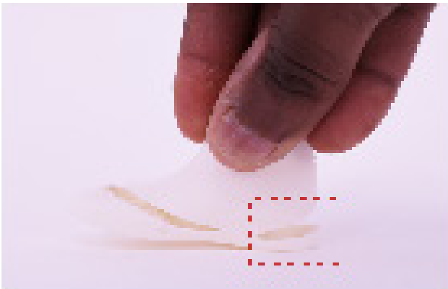




While dorsiflexion movement is being applied the top section intersects with the bottom section. This resulted in insufficient dorsiflexion movement



Plantarflexion movement is restricted due to the distance between the curves at the toe section of the model.



The origin where the cut is needs to be lower.

*Figure 9.4 Concept evaluation . Development three*

# REFLECTION

Upon evaluating these three concepts, what needs to be considered when re-developing the concepts is the location of the cut. The movements in concepts one and three were sufficient but the origin of the cut was not in the right area.

Experimenting with form and function, concept two did not succeed in any of them. The dorsiflexion and plantarflexion movements in the forefoot were very minimal. The cut itself, took away from the minimal aesthetic.

The accuracy of the cut on concept three was not desirable as the top section of the model intersected with the bottom when performing dorsiflexion movement.

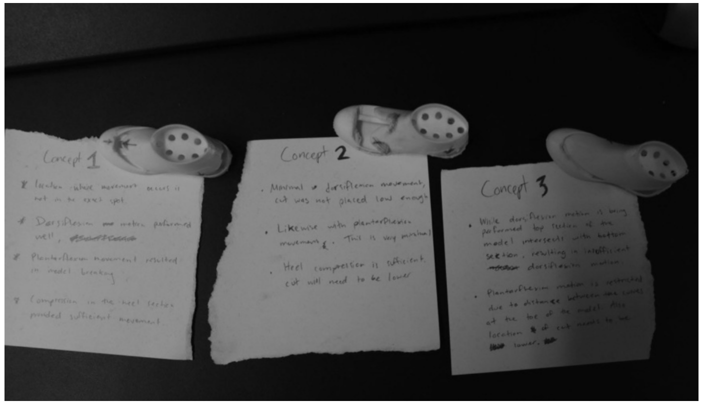
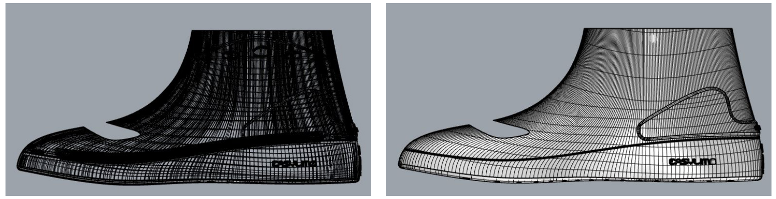


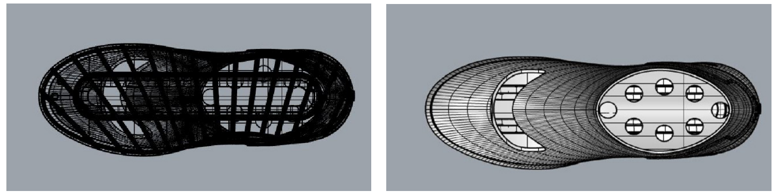

*Figure 9.5 Evaluated concepts*

# DEVELOPMENT 2

Experiments focused on movement in the forefoot.

# CONCEPT 1



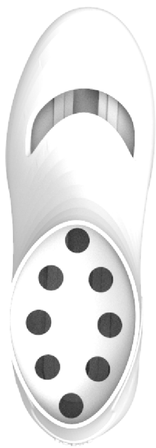
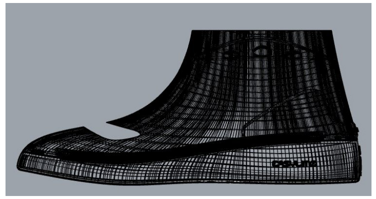
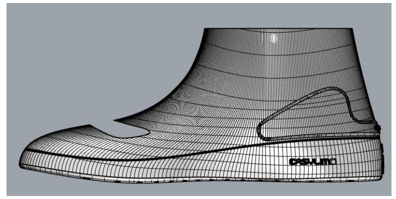
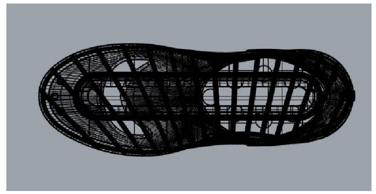


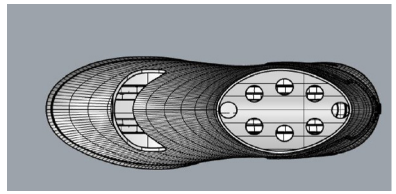
*Figure 9.6 Development 2.0 Concept one - CAD and render*

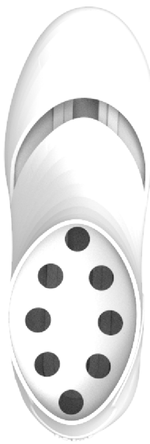
# CONCEPT 2









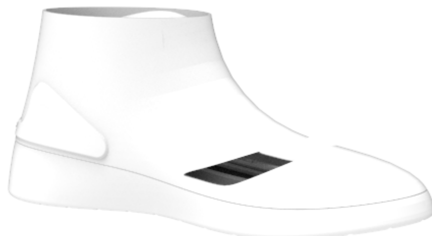
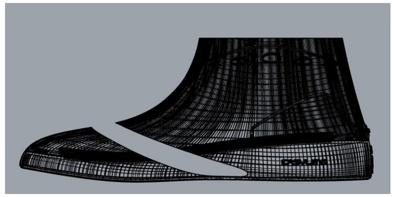
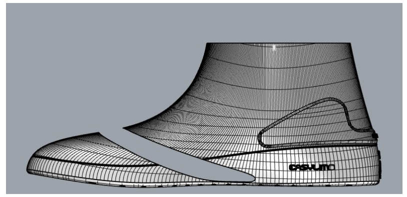
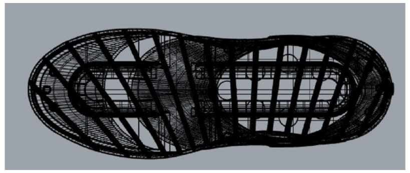


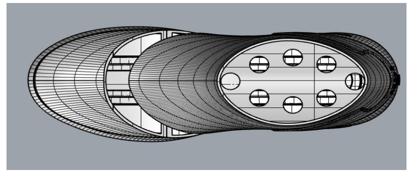
*Figure 9.7 Development 2.0 Concept two - CAD and render*

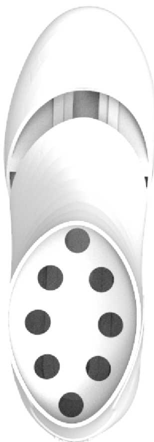
# CONCEPT 2









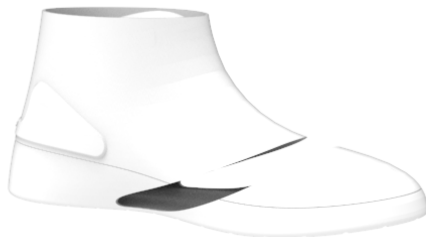
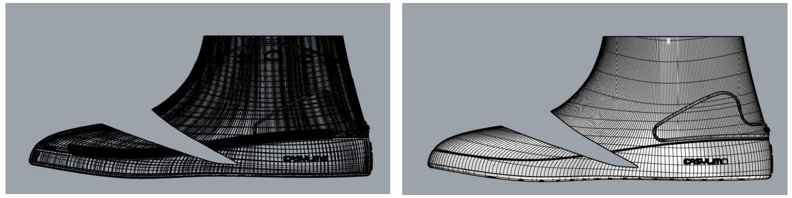
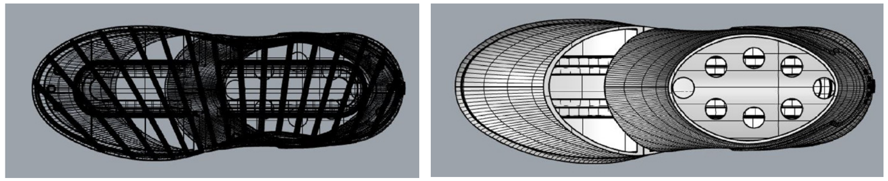
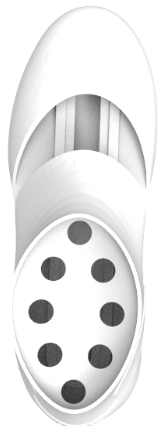


*Figure 9.8 Development 2.0 Concept three- CAD and render*

# CONCEPT 3







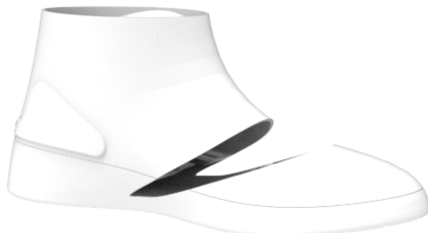


*Figure 9.9 Development 2.0 Concept four - CAD and render*

# EVALUATION

# CONCEPT EVALUATION 1

This initial cut finished high on the model resulting in no movement. This was due to the placement and length of the cut.

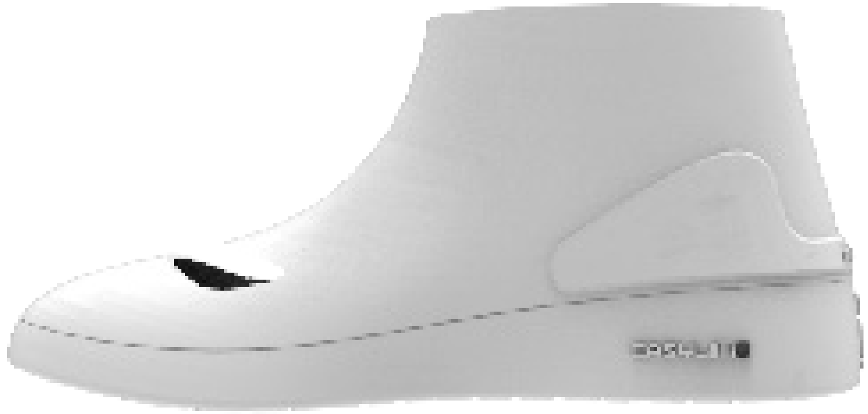
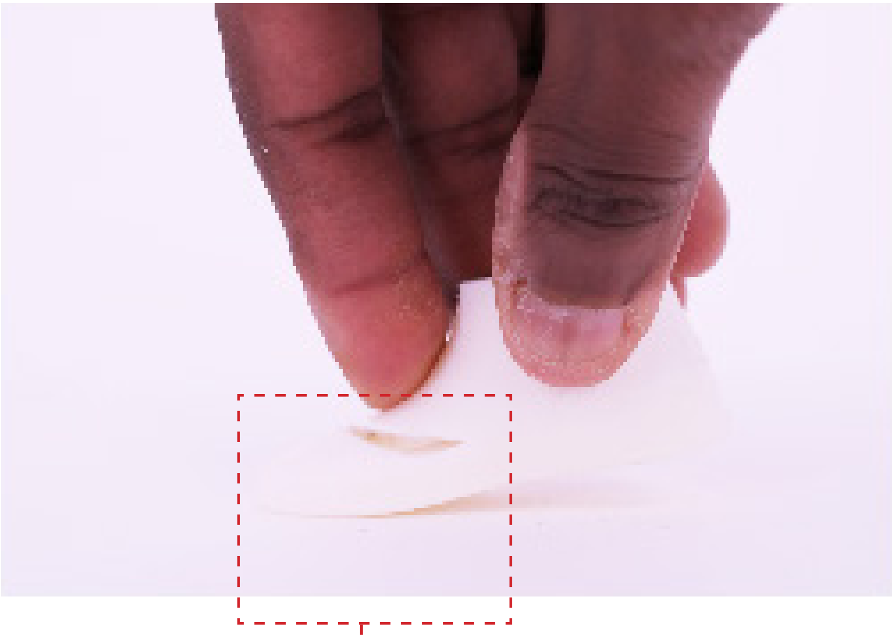


*Figure 10 Concept evaluation . Development 2.0 one*

# CONCEPT EVALUATION 2





Although the cut finishes further down than on concept one, there was still no movement in the forefoot.

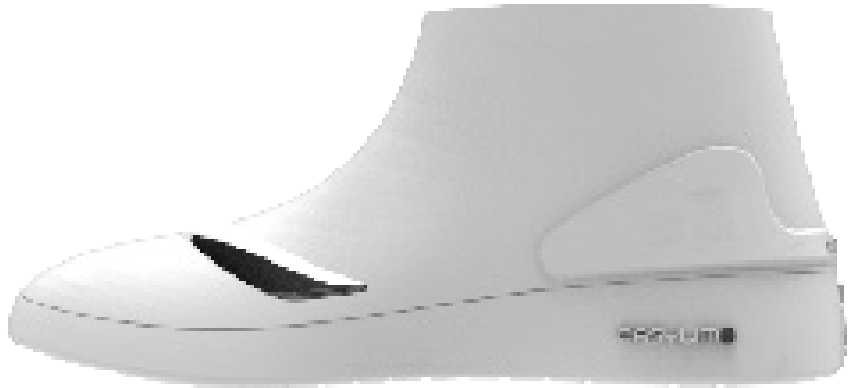
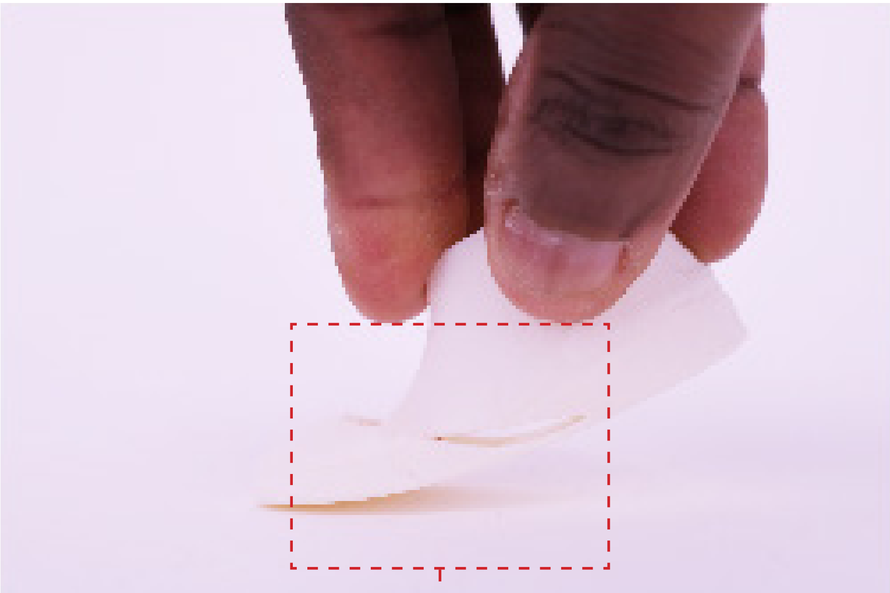


*Figure 10.1 Concept evaluation . Development 2.0 two*

# CONCEPT EVALUATION 3





The length and depth of the cut is sufficient, but it is not positioned in the correct area.

Dorsiflexion and plantarflexion movements perform satisfactorily.

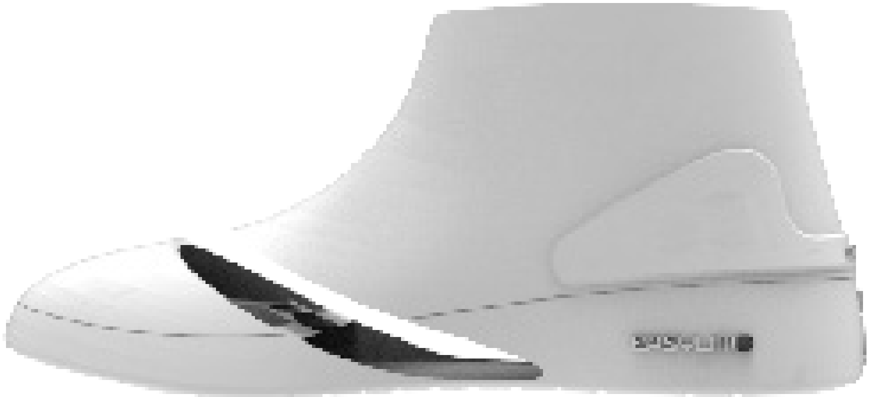


*Figure 10.2 Concept evaluation . Development 2.0 three*

# CONCEPT EVALUATION 4



The gradual widening of the split gave the model more control when applying dorsiflexion and plantarflexion movements.

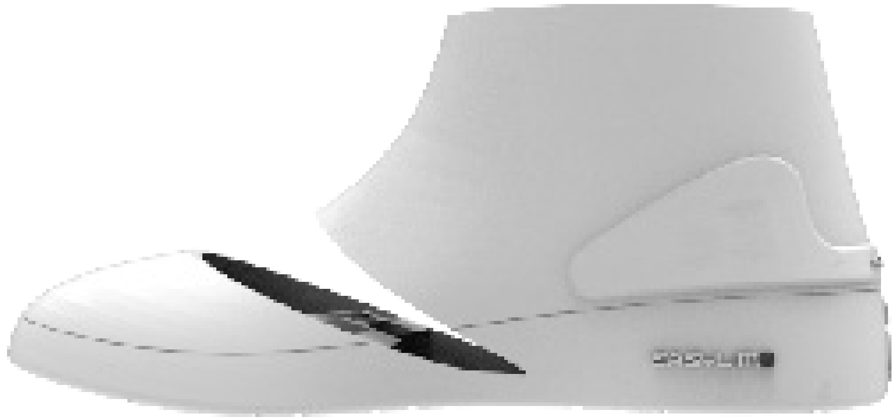


*Figure 10.2 Concept evaluation . Development 2.0 four*

# REFLECTION

Upon evaluating these three concepts, what needs to be considered when re-developing the concepts is the location of the cut. The movements in concepts one and three were sufficient but the origin of the cut was not in the right area.

Experimenting with form and function, concept two did not succeed in any of them. The dorsiflexion and plantarflexion movements in the forefoot were very minimal. The cut itself, took away from the minimal aesthetic.

The accuracy of the cut on concept three was not desirable as the top section of the model intersected with the bottom when performing dorsiflexion movement.

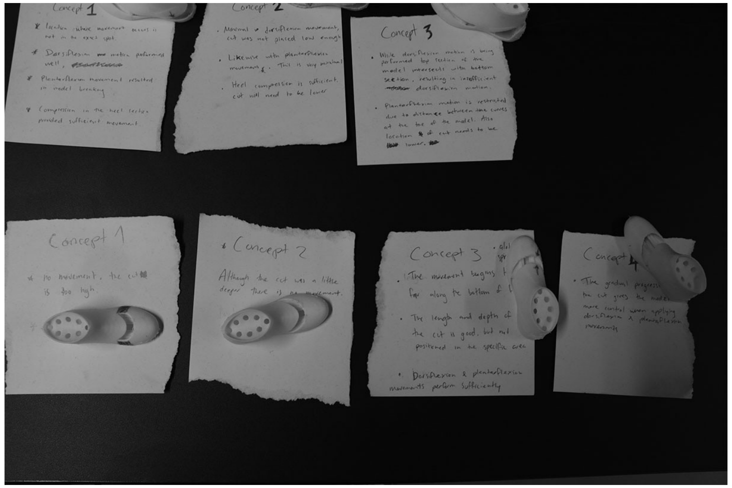


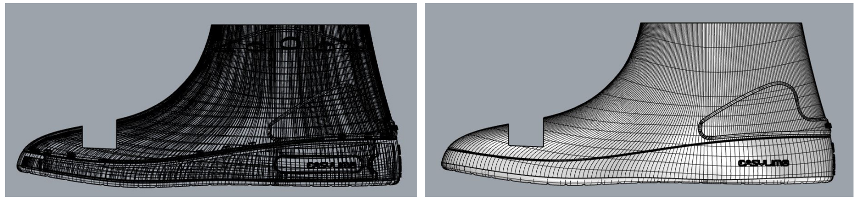

*Figure 10.3 Evaluated concepts*

# DEVELOPMENT 3

Upon reflection and evaluation, a marked sequence of images which shows the human gait cycle was produced. This allowed for a refined decision to be made for where exactly movement occurs this gait cycle.

*Figure 10.4 Refined annotated gait analysis*

# CONCEPT 1

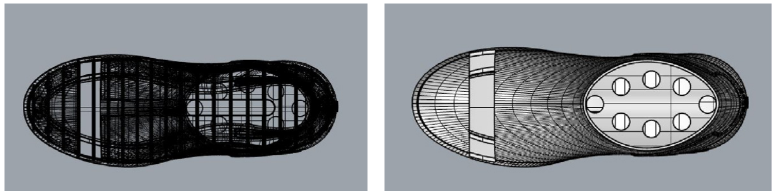
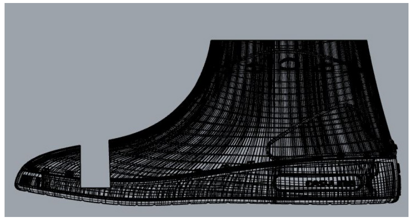
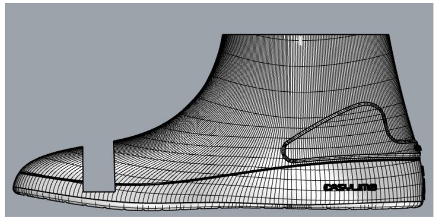
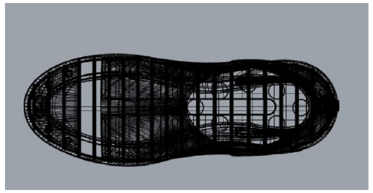


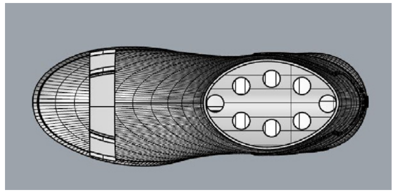
*Figure 10.5 Development 3.0 Concept one- CAD and render*

# CONCEPT 2







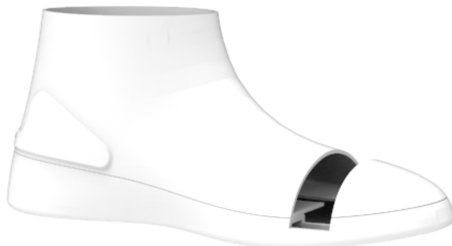
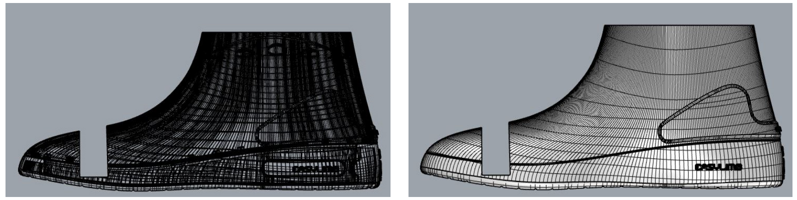
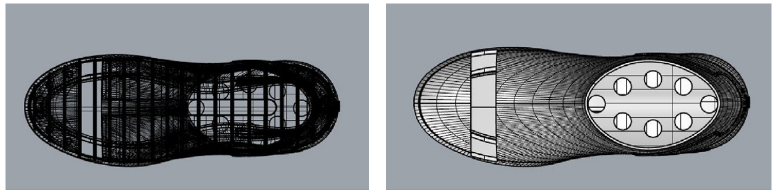


*Figure 10.6 Development 3.0 Concept two - CAD and render*

# CONCEPT 3





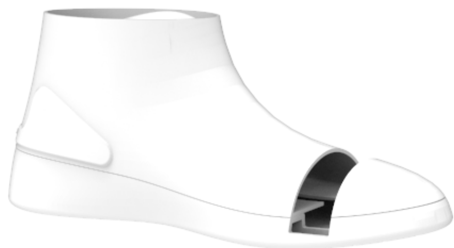


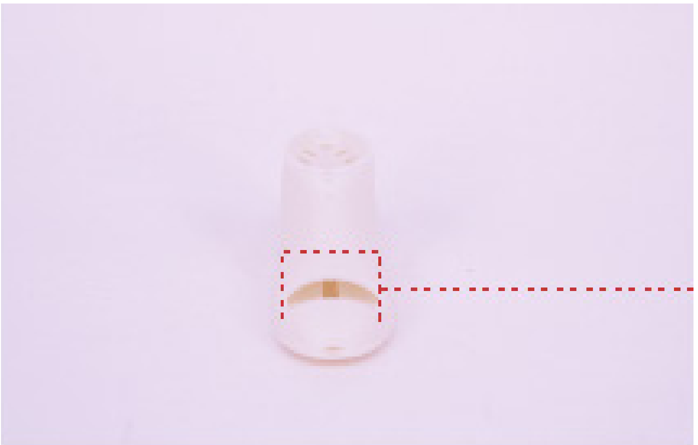
*Figure 10.7 Development 3.0 Concept three - CAD and render*

# EVALUATION

# CONCEPT EVALUATION 1

Too stiff

No desired movement



Although the cut is positioned in the correct area, it is not deep enough so that dorsiflexion and plantarflexion movements can be applied.

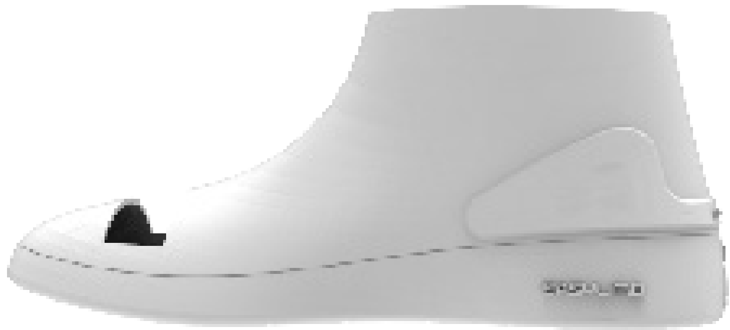
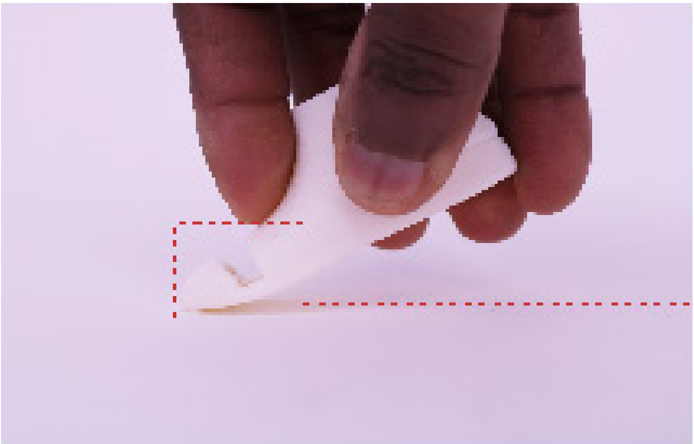


*Figure 10.8 Concept evaluation . Development 3.0 - one*

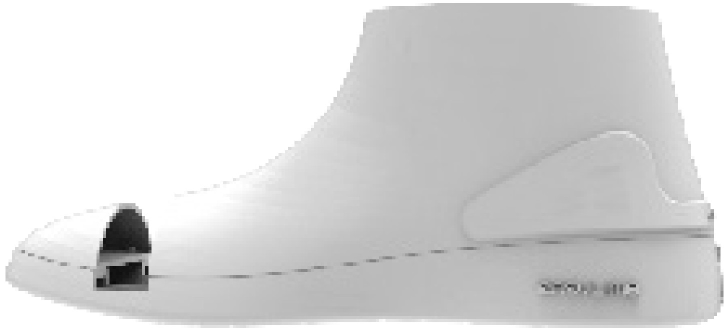
# CONCEPT EVALUATION 2

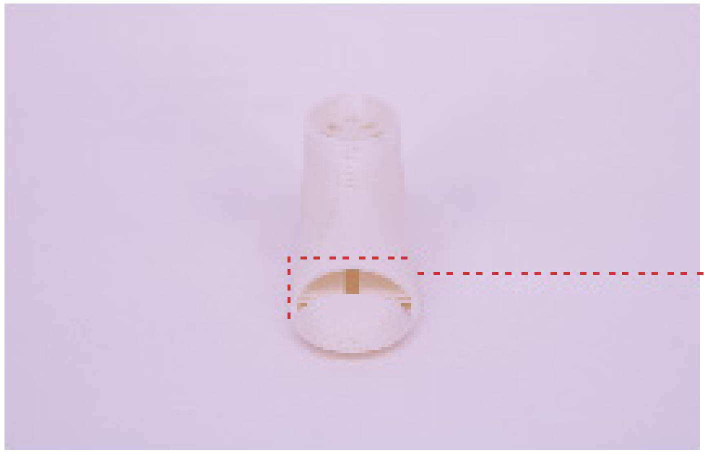




Cut is slightly deeper than in concept one , this gives the model more movement.

Cut will need to be lower for more flexibility.

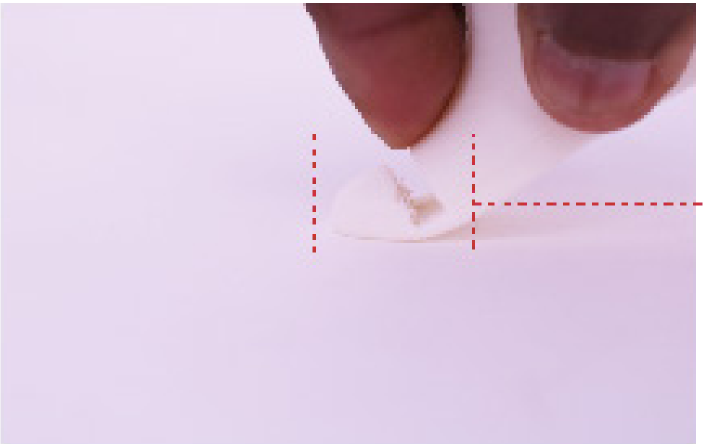




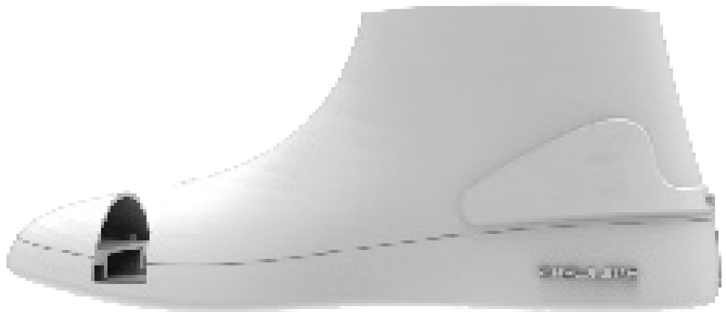
The dynamic movement in the model is being restricted by the internal structure, this will need to be removed for the final model.

*Fig. Concept evaluation . Development 3.0 - two*

# CONCEPT EVALUATION 3



Fillet was applied to concept three. Due to the scale of the model there was no significant difference from concept two.



Both concept two and three have the same cut, only difference is the fillet on concept three.

*Figure 10.9 Concept evaluation . Development 3.0 - three*

# REFLECTION

After referencing the annotated gait cycle diagram, the designer was able to pin point the area where movement occurs.

The cut on concept one was not deep enough, therefore no movement occurred. Both concepts two and three performed dynamic qualities well as cut was near the bottom of the sole.

A fillet was added to concept three but due to the scale of the print and the small radius of the fillet, there was difference in the movement.

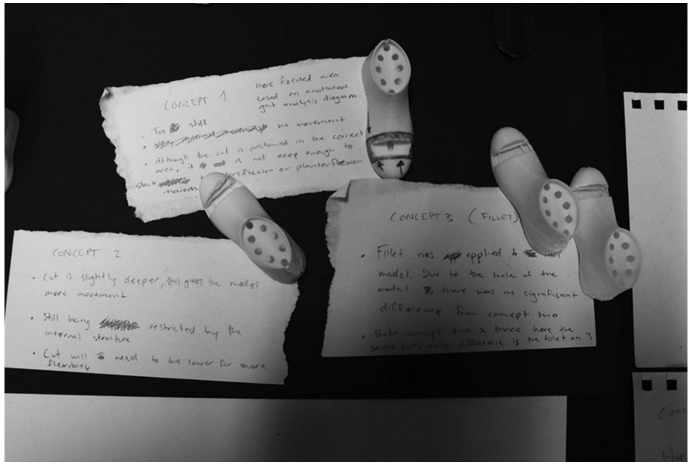



*Figure 11 Evaluated concepts*

# CORRUGATION TESTS

As a design detail, corrugations were analysed as an alternative for applying flexion in the foot. The experiments looked at testing various ridge heights, depths and the spacing between each other. Rhino's surface modelling was decided as the method for building these forms. These models were made by drawing diagonal lines in rhino, a fillet was then applied to the top and bottom of the ridges, creating the curve in the corrugation. The revolve command in Rhino was used to create these corrugated surfaces by revolving these profile curves around an axis to define the surfaces shape. The models were then thickened with an offset surface command to make it a 3D printable shape. FDM printing was used to test the flexibility within these models, using two materials, ABS and TPU.

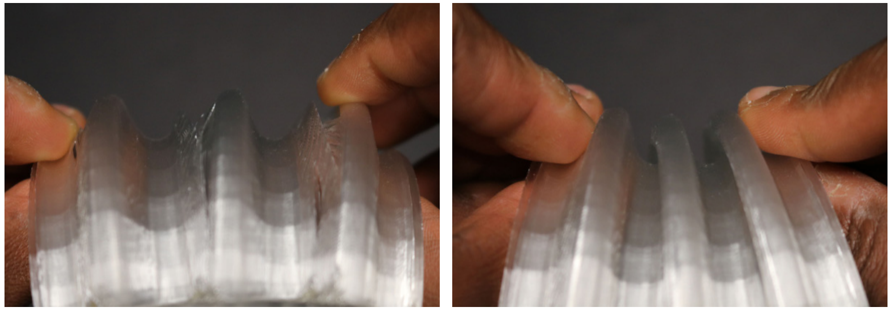
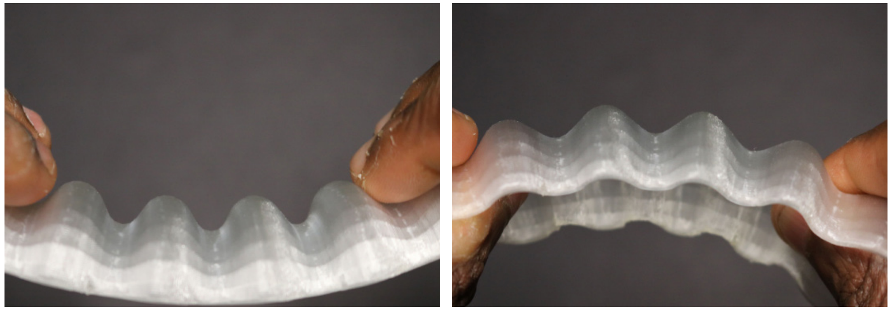
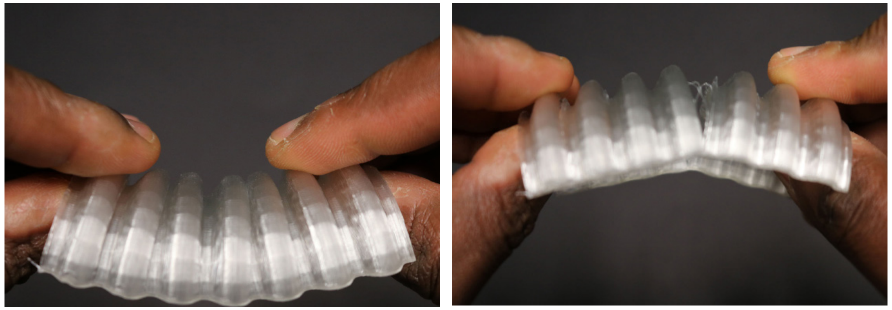
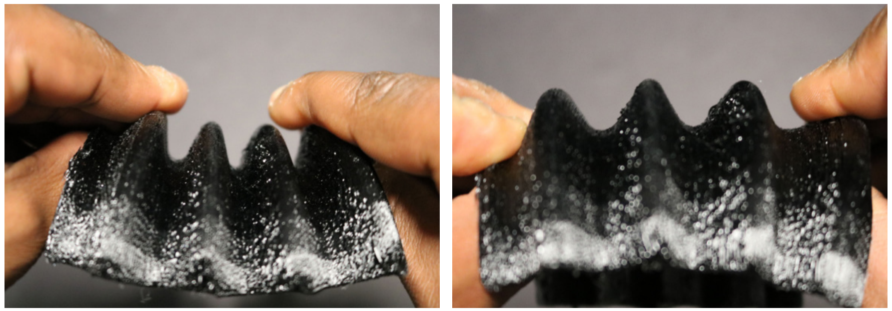
1


*Figure 11.1 corrugation test*

2


3


4


## Reflection

The corrugation experiments performed well, as the ridges were able to compress and flex sufficiently. Models one to three were printed in ABS and model four was printed in flexible TPU. The ABS models were printed in shell setting on UPBOX, meaning that there is no infill, creating a hollow model for maximised flexibility. The TPU model had 13% infill, structurally allowing the model to be printed.

Model two performed the best out of the ABS tests, the width between the ridges and the depth allowed for promising flexibility. The corrugation depth was shallow, giving the model a more controlled motion during the compression and expansion movements. The TPU model performed well as the material is flexible. The corrugation depth was much deeper in this model, giving it more freedom in the range of movement where the trough, bottom of the corrugation would expand and compress more significantly.

Common issues such as support material removal, print orientation and print quality occurred during these experiments. Limitations during these experiments was material. While testing, the models would break due to material not being durable, print settings and amount of force used while testing.

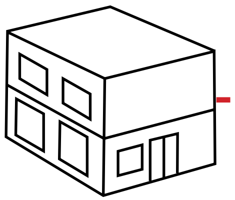
# DIGITAL WORKFLOW PROPOSITION

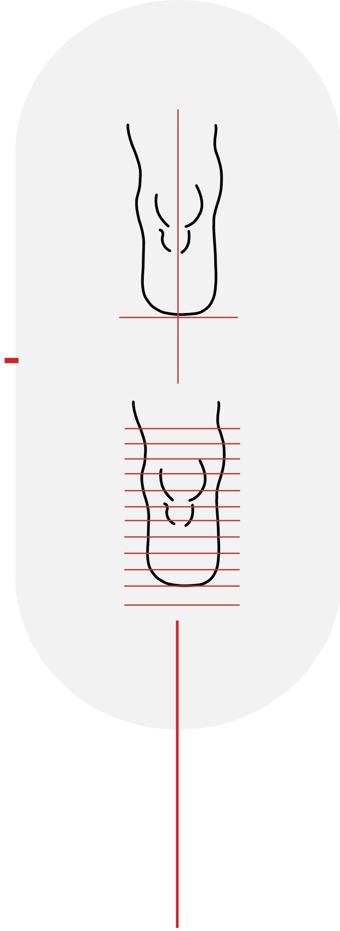
The final design proposition introduced the designer's projected future digital workflow for prosthetic fitting and customisation.

Six simulated anatomical human model were used to show capabilities of parametric design in lower limb customisation based off the different data set of each anatomical model.

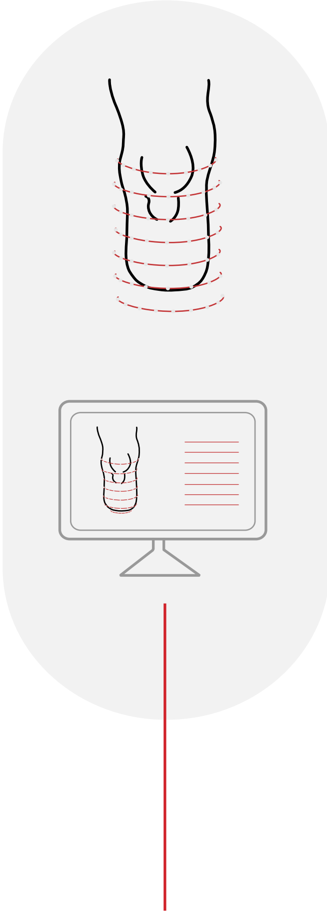
The base parametric prosthetic model developed by the designer was able to be adjusted according to parameters set at each measurement section. The measurement points in the project future workflow continue to reference NZALS's prosthetic manufacture instruction sheet.

These designs were developed for 1:1 scale , tangible objects, but were 3D printed as scale models on the UPBOX 3D printers in white ABS.





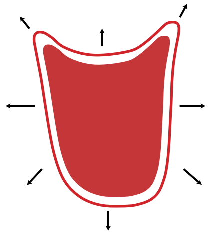
Scanning the leg or knee
using
the Artec Eva 3D scanner.



Import scan into parametric
software , eg
grasshopper.

Grasshopper automatically
assigns control points to
around the residual limb,
creating the socket shape.

Number sliders allow for real
time adjustments.



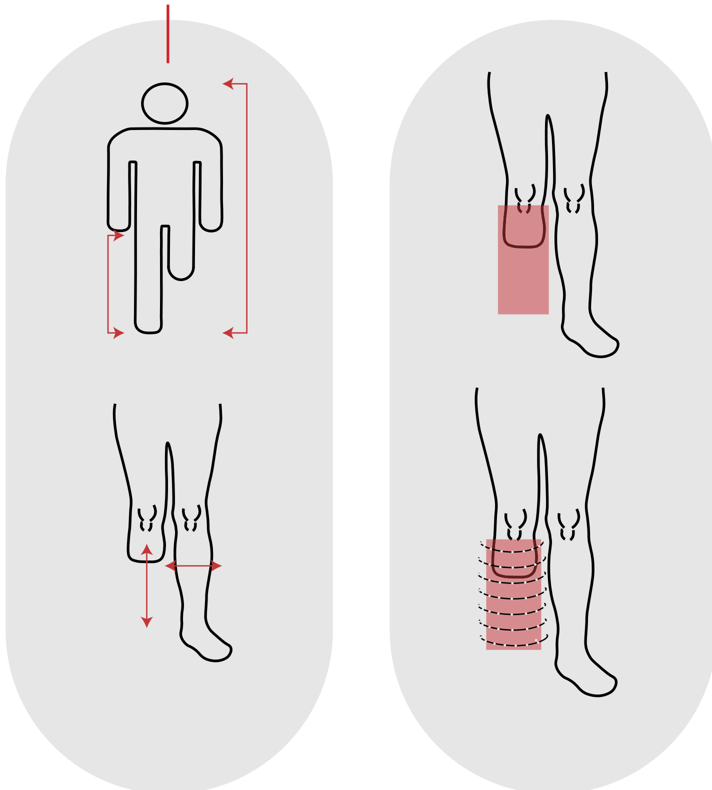
Information from 3D
scan gives accurate model
for parametric system to
measure:

Height, foot length and width

Remaining limb length- from
the bottom of the patella to
ankle

Width: widest part of the calf
or socket.

Patient's weight is taken and
also input into parametric
system.



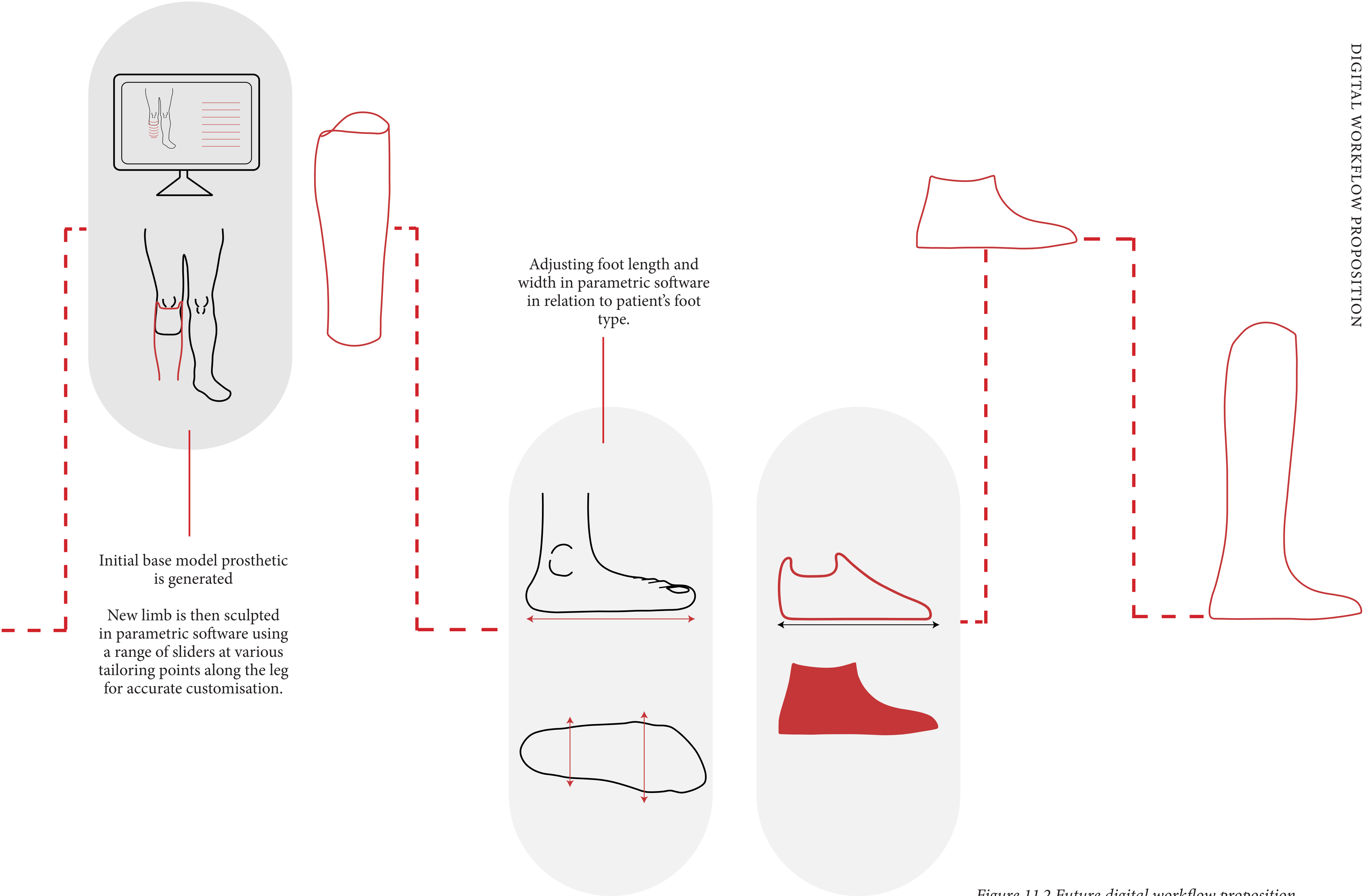
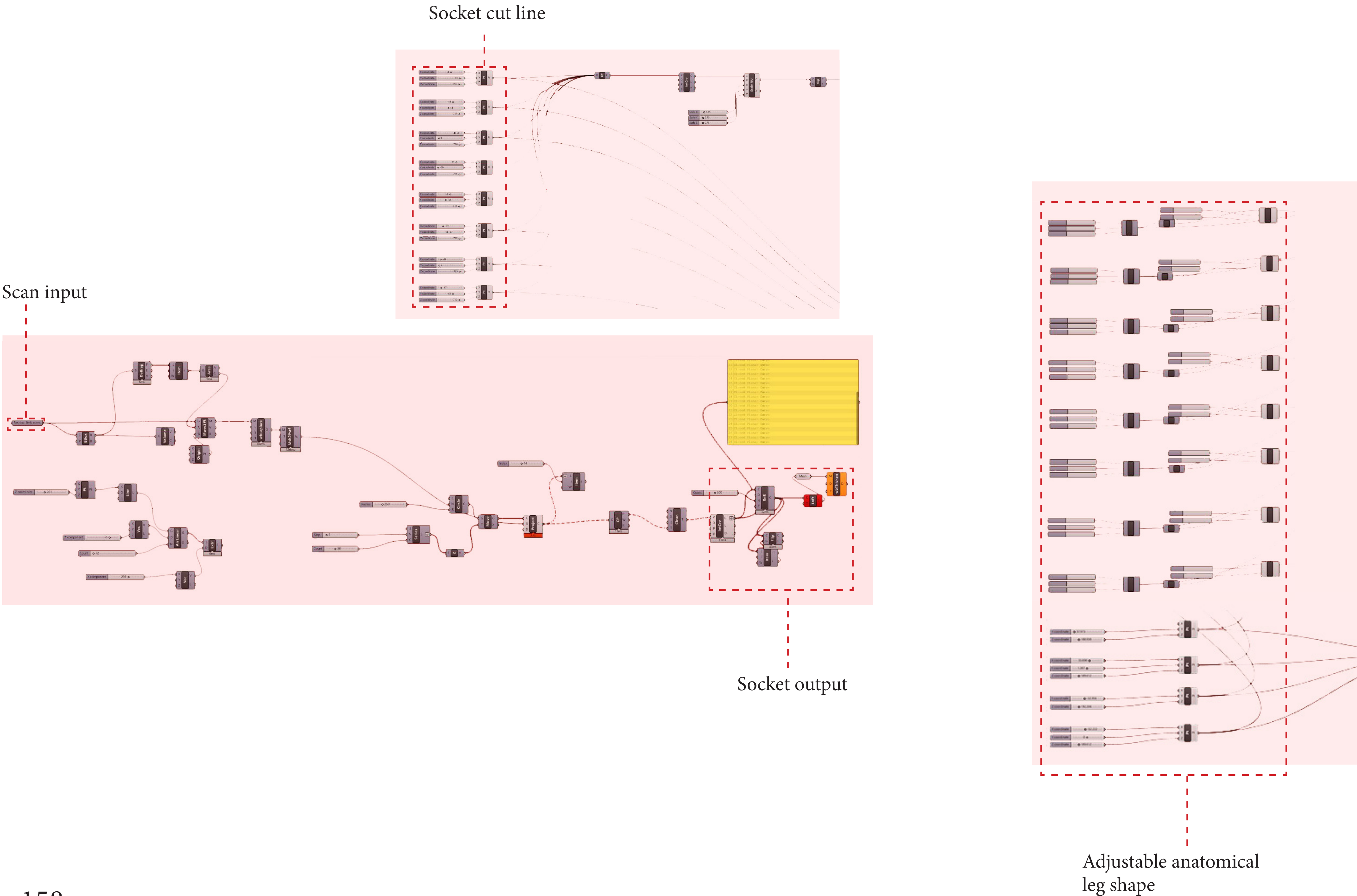



*Figure 11.2 Future digital workflow proposition*


Socket cut line
Scan input
Socket output
Adjustable anatomical leg shape

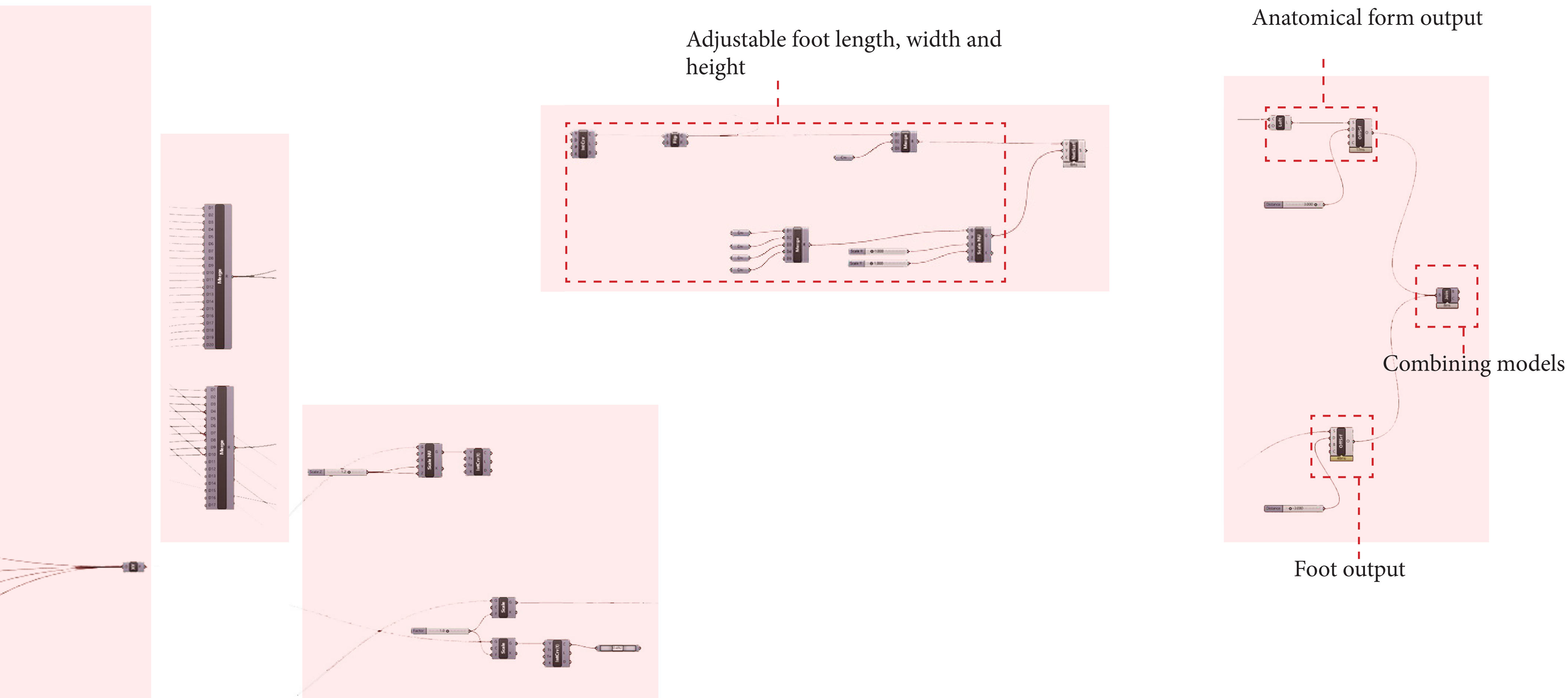



*Figure 11.3 Full workflow grasshopper script*

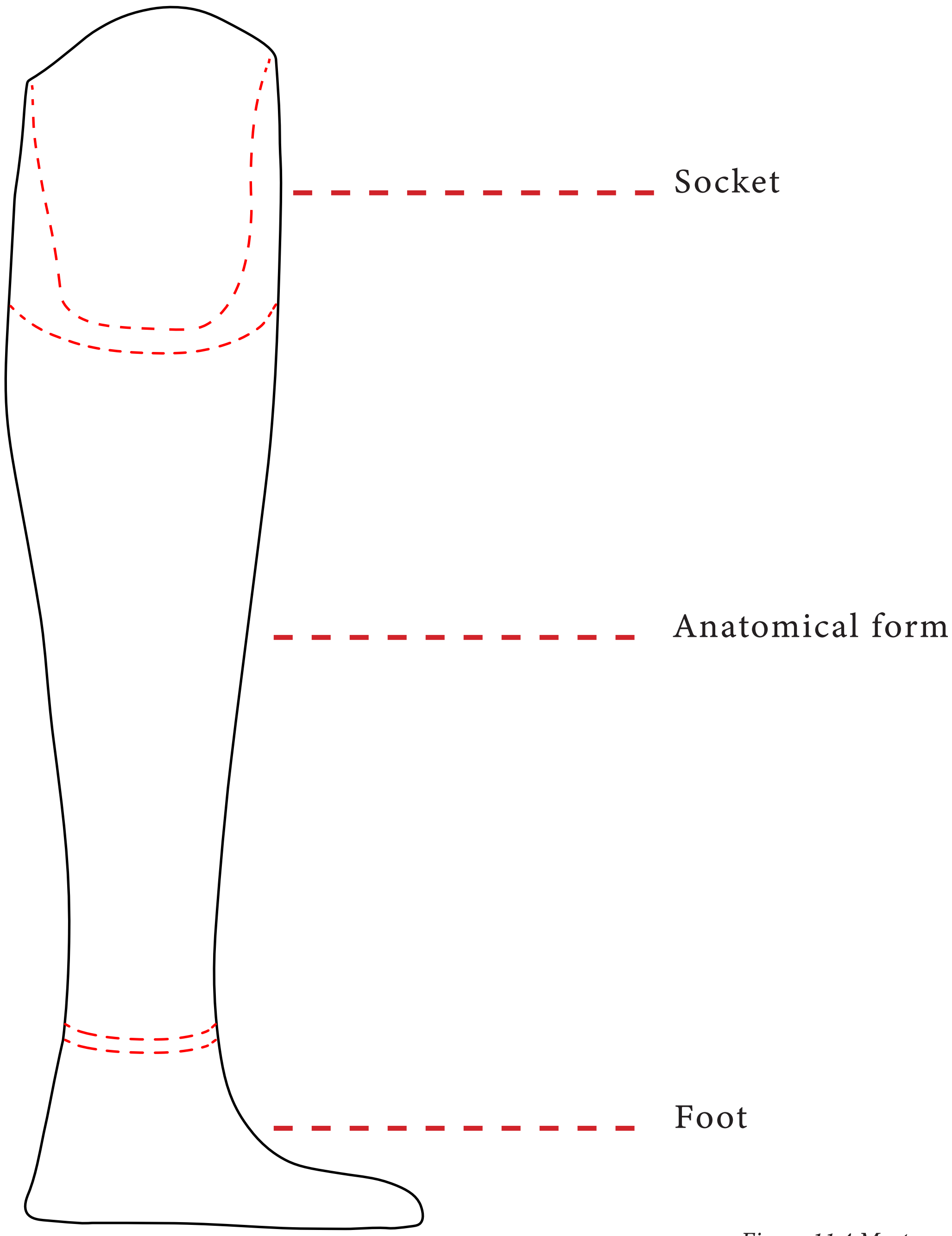



*Figure 11.4 Master model- digital sketch*

# MASTER MODEL

The master model developed in grasshopper can be adjusted and sculpted using various parameters. This provides flexibility as numerous models can be produced and visualised swiftly.

Figure 11.5 master model- render- side

Figure 11.6 master model- render- front

*Figure 11.7 master model- render- perspective*

*Figure 11.8 master model- render- close up*

# MODEL 1

*Figure 11.9 Studio images*

*Figure 12 Context render with anatomical model*

# MODEL 2



*Figure 12.1 Studio images*

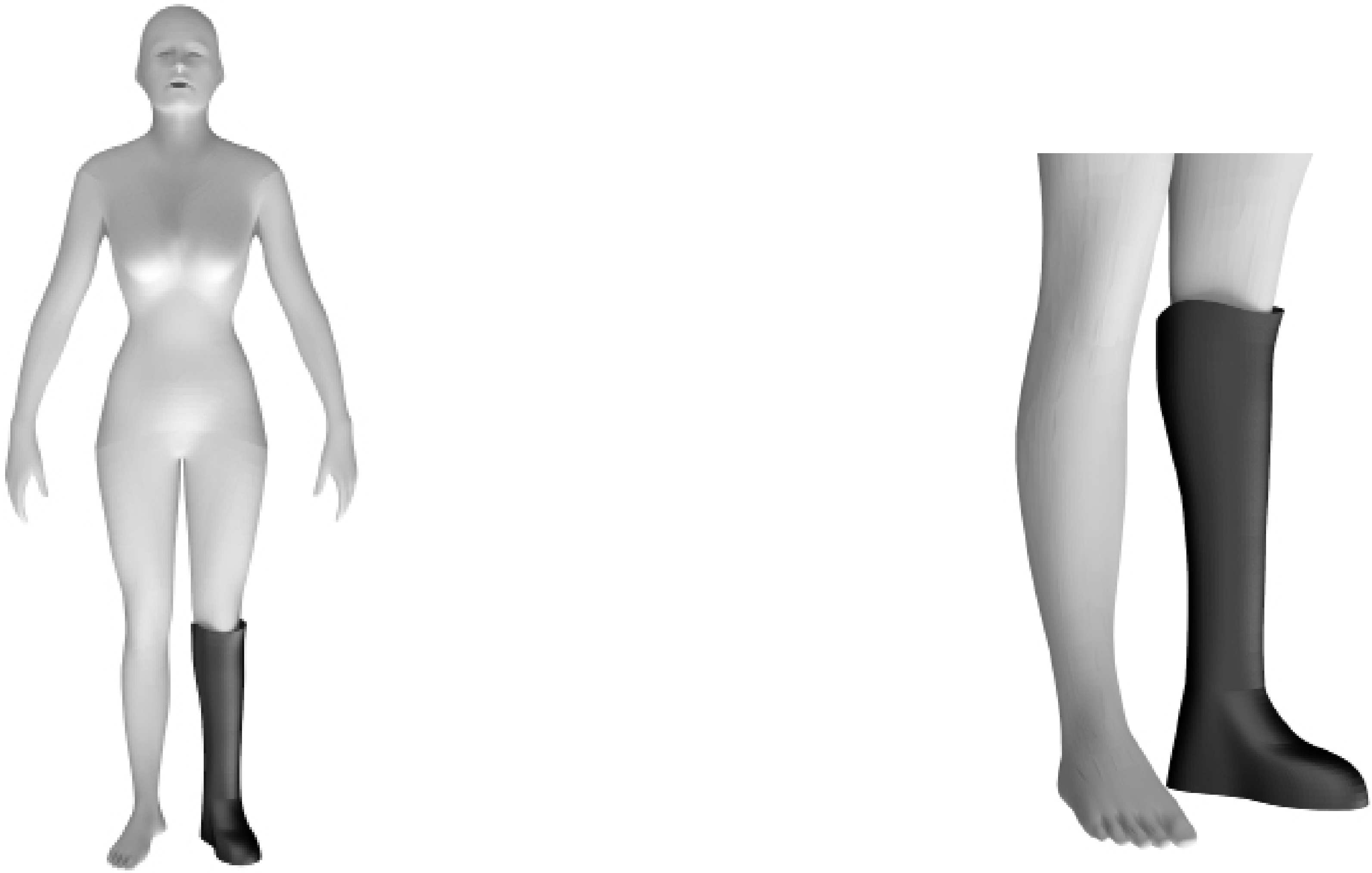


*Figure 12.2 Context render with anatomical model*

# MODEL 3



*Figure 12.3 Studio images*

*Figure 12.4 Context render with anatomical model*

# MODEL 4



*Figure 12.5 Studio images*

*Figure 12.6 Context render with anatomical model*

# MODEL 5



*Figure 12.7 Studio images*

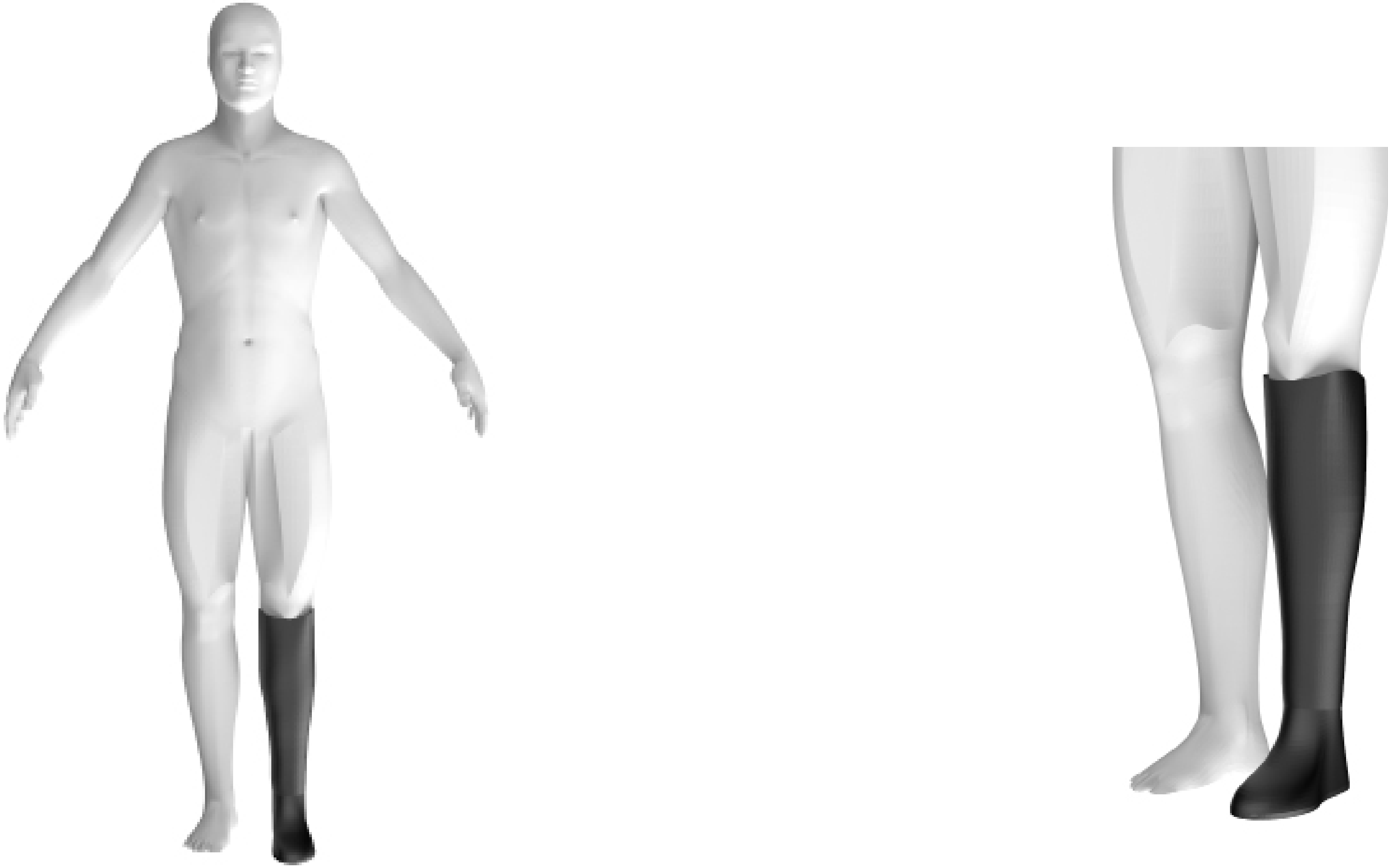


*Figure 12.8 Context render with anatomical model*

# MODEL 6



*Figure 12.9 Studio images*

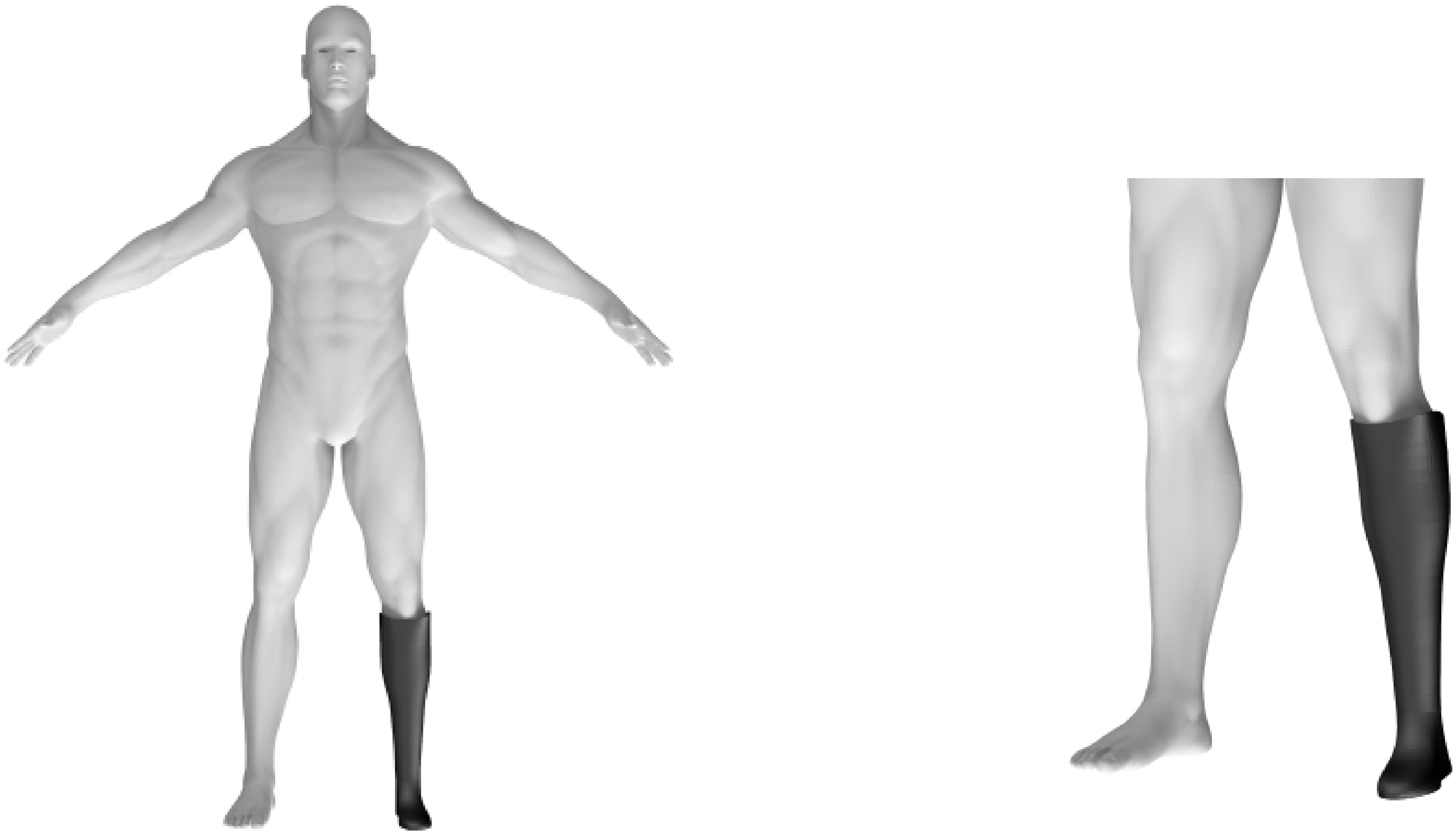


*Figure 13 Context render with anatomical model*

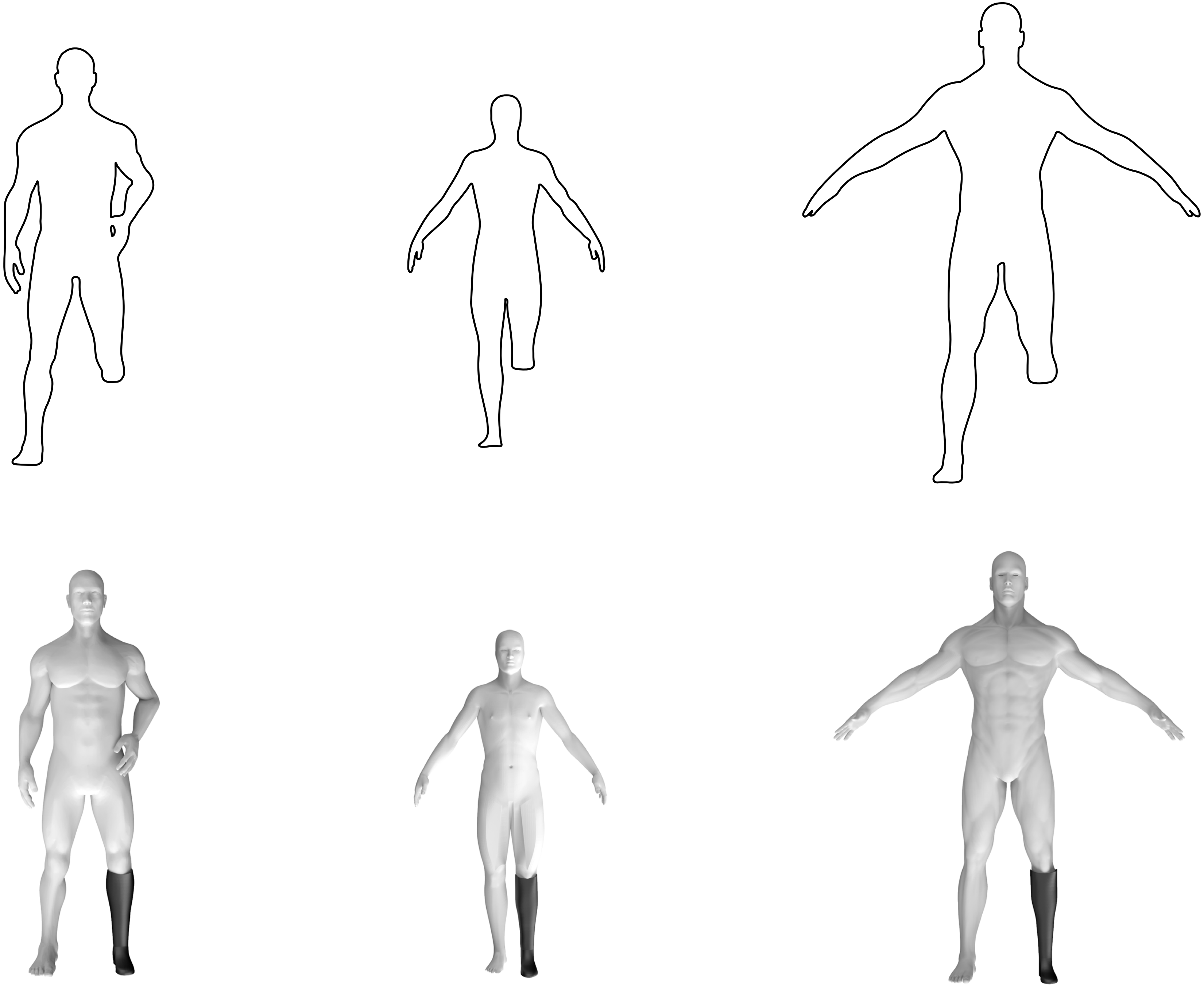
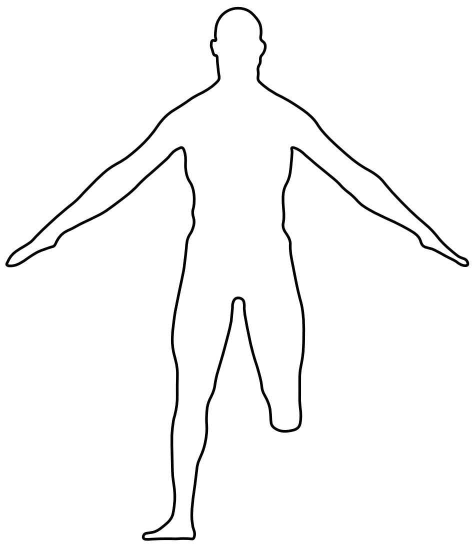


*Figure 13.1 Anatomical model, outline, without prosthetic*



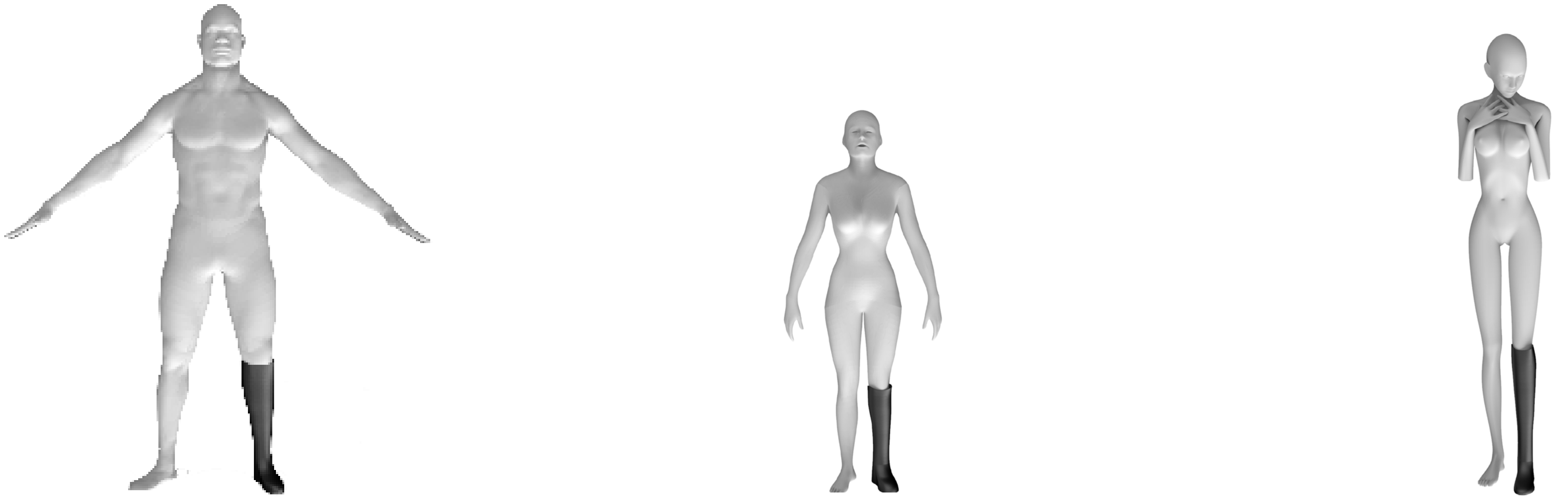


*Figure 13.2 Render- final models in context*

*Figure 13.3 Render- final models*

# 05

# DISCUSSION & CONCLUSION

## Discussion & Conclusion 5.1

This section aims to describe the outcomes, limitations in the research and future opportunities.

### Summarising key findings

This research presents a digital workflow proposition for NZALS to consider the future of prosthetic making and customisation. This research analyses prosthetic making and digital design tools, evaluates findings, and interprets them into the design process. The ultimate goal was to propose a future workflow trend to facilitate NZALS delivering a comprehensive service.

Two research methodologies were used, research for design and research through design, with subsequent research methods applied under these methodologies (Milton & Rodgers,2013). The main focus of these methodologies was to gain new theoretical and technical design knowledge through actively creating a workflow.

The research showed the potential of utilising emerging digital technologies and parametric design for lower limb customisation. The workflow development the potential value of software applications such as rhino and grasshopper in a manufacturing and industrial setting. These tools, provided accuracy, flexibility, and real time model updates. Past and current making methods were hands on and time consuming. Whereas, parametric design allows for forms to be generated efficiently. Both methods attend to the individual amputee's new limb based on anthropomorphic data. However, traditionally making prosthetics, plans or specifications are held with the craftsmen, whereas digital uses a set of coordinated points to design and make from 3D data.

### Research proposition/Aims and Objectives

The research proposition stated; "Given the capability of data, code and generative design to create additive manufactured 3D form, what might this look like in prosthesis design". This statement gave the designer room to explore and experiment with parametric design. Initially, it was projected that parametric design would be vital in the process of designing this workflow, with the ability to construct adjustable forms for customisation based off fixed points.

The aims and objectives assigned in the beginning were successful in meeting the framework. From these, digital and physical models were produced, showcasing new avenues for lower limb customisation through different visualisations. The coded workflow developed using grasshopper was able to parametrically control the socket, anatomical form and foot to the limits of the simulated human body, providing sufficient parametric variation during the experiments. Ultimately, the research addressed the framework through outputs guided heavily on a computer-based design process.

### Methodology-Research for Design

The research project began with identifying appropriate precedents and an extensive literature review. Analysing past and current, emerging and future trends of prosthetic making gave the designer a starting point. It was found that 3D printing and personalisation were utilised to cater for a diverse range of individuals. This emerging method may provide prosthetics that are lighter and durable with the option of personalising the product with different colours and patterns. The manufacturing of the products took less time and produced aesthetically pleasing resolved products, using less material. The designer explored the footwear industry, where examples of data driven design showed speculative experimental forms to commercialised products which displayed the capability of parametric design. These research findings were evaluated and extended, questioning the role of the designer in the overall process. What emerged was an opportunity for situating the research in the digital design space, where the digital or virtual tools act as the tailor in the prosthetic making process. Product analysis and shadowing provided a context where past, current and emerging prosthetic making could be evaluated and reinterpreted by the designer for experiments to begin.

**Research through Design**
**Design process: Parametric Design**

The main objective was to utilise parametric software in the design process. Parametric modelling offers various benefits in the development of lower limb prosthesis.

Applying digital technologies and customisation options provided two effective processes for prosthetic making. A large proportion of time was spent understanding and experimenting with grasshopper. Developing the grasshopper script for each section required the designer to understand the measurement process, this was when the NZALS prosthetic measurement sheet was referenced. Unlike surface modelling, grasshopper required coordinating a fixed set of points, which can be interpolated and lofted to make the 3D adjustable form.

For controlled flexibility at each area of focus, the designer performed trial-and-error based experiments, develop an understanding of the relationship and limitations of the parameters. Earlier experiments in the research saw the designer attempt to parametrise curves made in rhino's surface modelling interface. This attempt provided promising signs as the curve could be altered on a XYZ axis through scaling in non-uniform factors. However, while establishing independent and dependent variables between curves the resulting forms were not satisfactory. The designer evaluated and assigned another option where it provided more control and accuracy. The curves were constructed in grasshopper, assigning a XYZ point for each in space.

The refined grasshopper models were able to have relationships set with both independent and depended variables, giving the designer control to adjust one parameter alone or multiple parameters at the same time, in relation to length and width. Joining the ankle/foot to the remaining model was a challenge for the designer. Usually in rhino, curves can be matched or joined together with ease, but in grasshopper the designer had difficulties performing this. Joining the curves in grasshopper using the match curve component did not work. Joining the curves by matching point coordinates resulted in a sufficient outcome, although technically the model was still separated as examined by the designer. The final model has a line where ankle and rest of the model meets.

**Applications**

Six anatomical 3D models put context into the final outputs, demonstrating changes in form, based on different parameters. A diagram provided a step-by-step process of the digital workflow and tools needed. The workflow proposition section demonstrated knowledge gain and skills learnt throughout the experimentation phase. Final outputs explored different media to communicate design ideas. Contextualised renders displaying each model wearing a customised prosthetic altered from the master model. Product renders display the results from designing with visual programming software. Scale model prints provide another avenue to communicate 3D forms designed from grasshopper. This research, seeks to challenge current making methods, introducing a proposition that provides accuracy, flexibility, efficiency and the possibility to visualise before making

**Limitations**

Throughout this research, a number of limitations became apparent. While testing the dynamic foot qualities, very often the models completely break, snap or crack during experiments. While FDM printing is ideal for rapid prototyping, the strength of the material under excessive stress caused it to give way several times during the testing phase. This issue was also apparent during the corrugation test as models broke due to force placed. The design of the models was intended for thin walls and zero infill, to maximise material flexibility, as ABS filament does not flex. Future research would consider experimenting with Multi Jet-Fusion (MJF), a more durable material for refined decisions.

### Improvements

For a resolved anatomical form, the addition of scan alignment in the grasshopper script, acting as a traditional bench alignment device. Lastly, what could be improved is seamlessly joining the ankle to the remaining anatomical form was one piece while maintaining parametric control.

**Advance simulation software:** Further exploration into simulation software test such as Finite Element Analysis (FEA) is needed to recognize stresses and forces are applied to the model once generated. This information would assist with adding more or less material density between the offset model and support structures.

### Future Research

In this research user input was not considered nor was integrating sensors into the prosthetic. While simulation software testing was briefly considered, research needs to be further explored. Results from these are documented in the appendix. This research proposition sets the foundation for additional research and development.

**User testing**: The next step is to take this workflow and apply in context with, prosthetic technician with the necessary skills and approach.

Overall user testing of the workflow is needed to identify the accuracy and feasibility of the system. This would improve the usability for both the technicians and amputees.

**Implementing sensors:** Inserting sensors in certain areas of the prosthesis. A generic limb (master model for example) is provided, sensors integrated in the socket, ankle and foot where information is gathered. The amputee performs a series of exercise, this is where real-time data can visualise in software. The data is then analysed and optimises the ideal limb for the amputee.

## Conclusion

This research aimed to establish digital workflows as a future method. The workflow is imperative to streamlining a service through increased efficiency, accuracy and quicker production. This research explored these workflow benefits, developing and demonstrating these throughout the design process using digital design tools.

These digital design tools facilitated the development of the workflow. The outputs demonstrate a range of lower limb forms showing the flexibility, accuracy of parametric design in prosthetic making.

Further research into parametric design would build upon the knowledge gained from this research. This would include user input, advance simulation software and implementing sensors, applying the workflow in context necessary industry knowledge.

This research aimed to provide future considerations for NZALS, helping to expand them into an innovative service. Integrating a comprehensive digital workflow into NZALS may cause concern to technicians, as workshop and technical skills deemed unwanted due to automation. Contrary to this, these future methods will assist the technician during the making process. This principles can be applied to multiple prothesis types, and designed for additive manufacturing ,providing a longer product life.

# 06

# APPENDICES

# FIGURE LIST 6.1

Figures listed here were not produced by the author

# REFERENCES 6.2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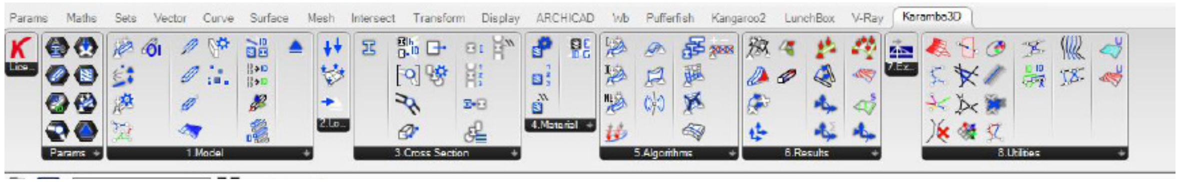
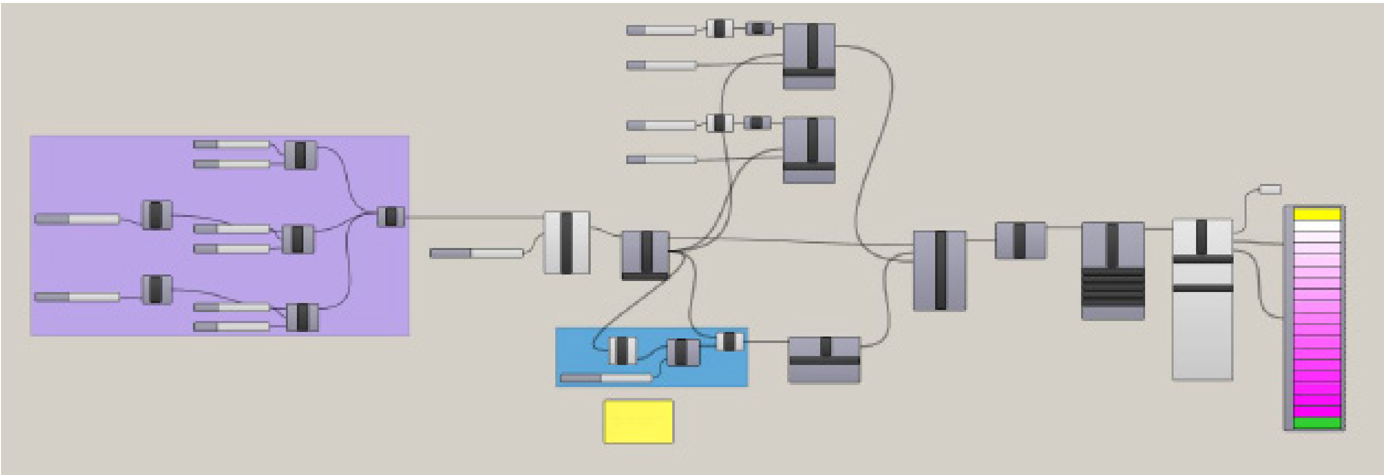
# APPENDIX 6.3

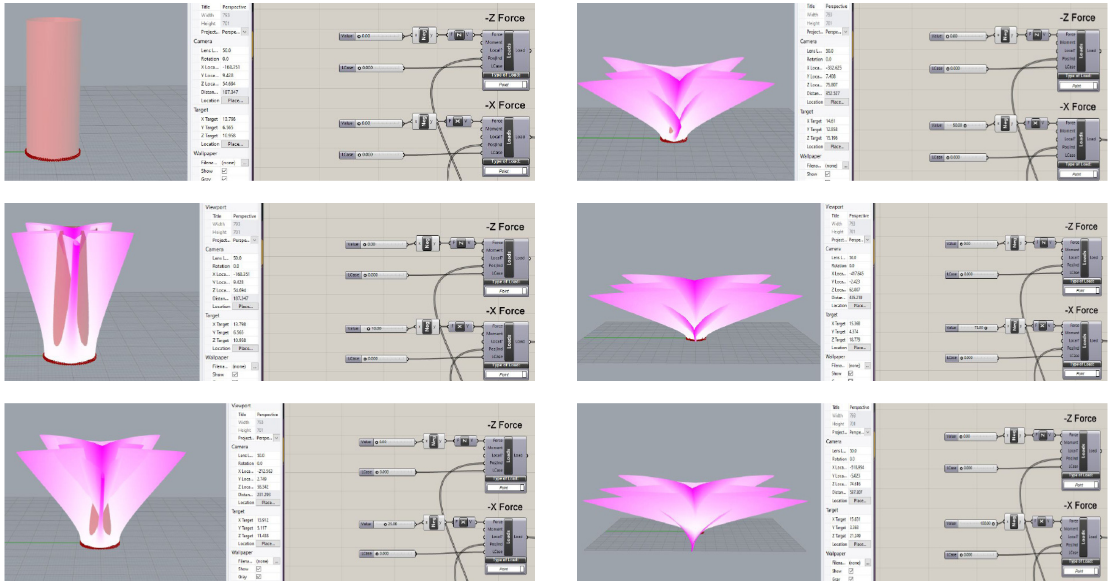
This section shows parts from early in the research where the designer explored simulation software.



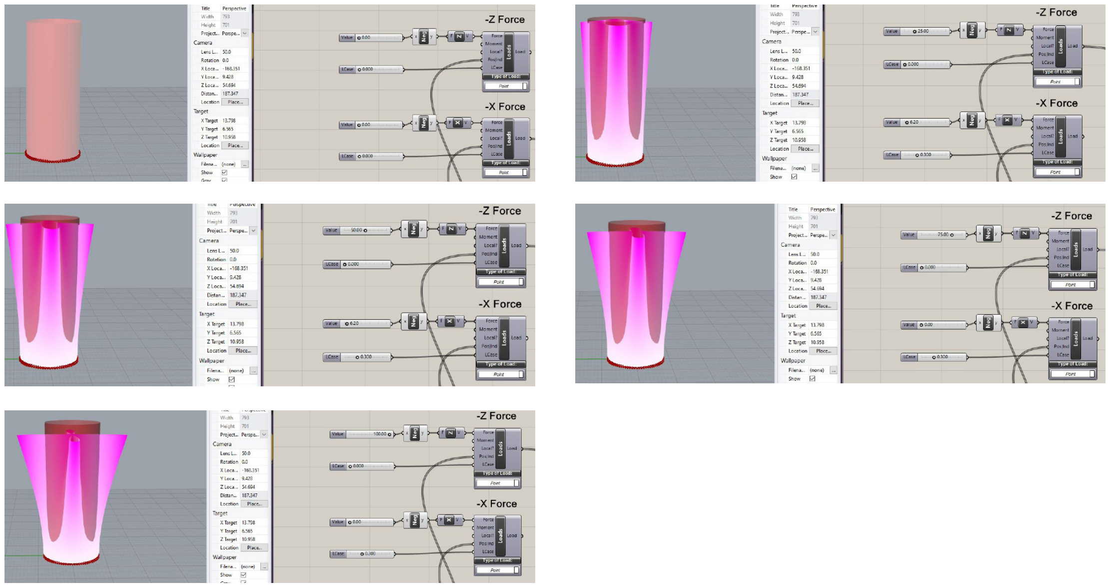

Karamba is a finite element analysis plug-in for grasshopper. This plug-in lets the designer analyse 3D beams and shell structures under various loads.



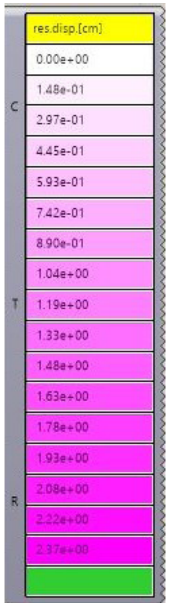
Experiments looked at applying forces to a cylinder in various axis'. This resulted in interesting visualisations , capturing the capability of simulation software.




FORCES IN -X DIRECTION




FORCES IN -Z DIRECTION




DISPLACEMENT NUMBER VALUES (CM)

"Given the capability of data, code and generative design to create additive manufactured 3D form, how might this look like in prosthesis design"

PARAMETRIC PROSTHETICS

by

Tinofara Mutambu