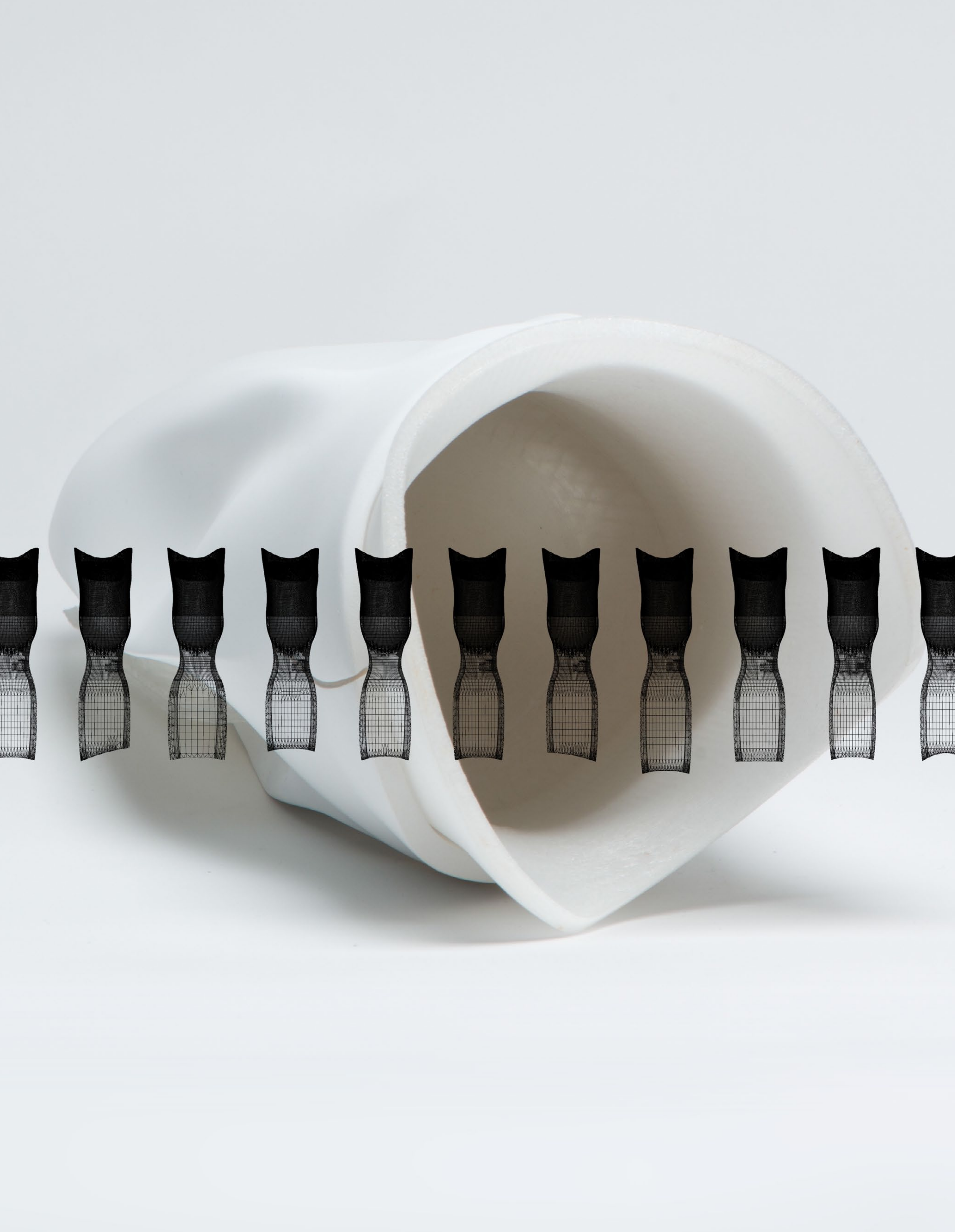

Printable Prosthetics

The design of a 3D printed swimming prosthesis

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The design of a 3D printed swimming prosthesis

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90 Point Thesis Submission for fulfilment of requirements for the Master of Design. Victoria University of Wellington, 2016

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Completed by Stuart Baynes
Supervised by Bernard Guy & Tim Miller

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A thank you to everyone that has supported me and made this possible.

Thank you to the NZALS for this opportunity, to my supervisors for their constant support and wisdom, and to our participant for his enthusiasm and engagement.

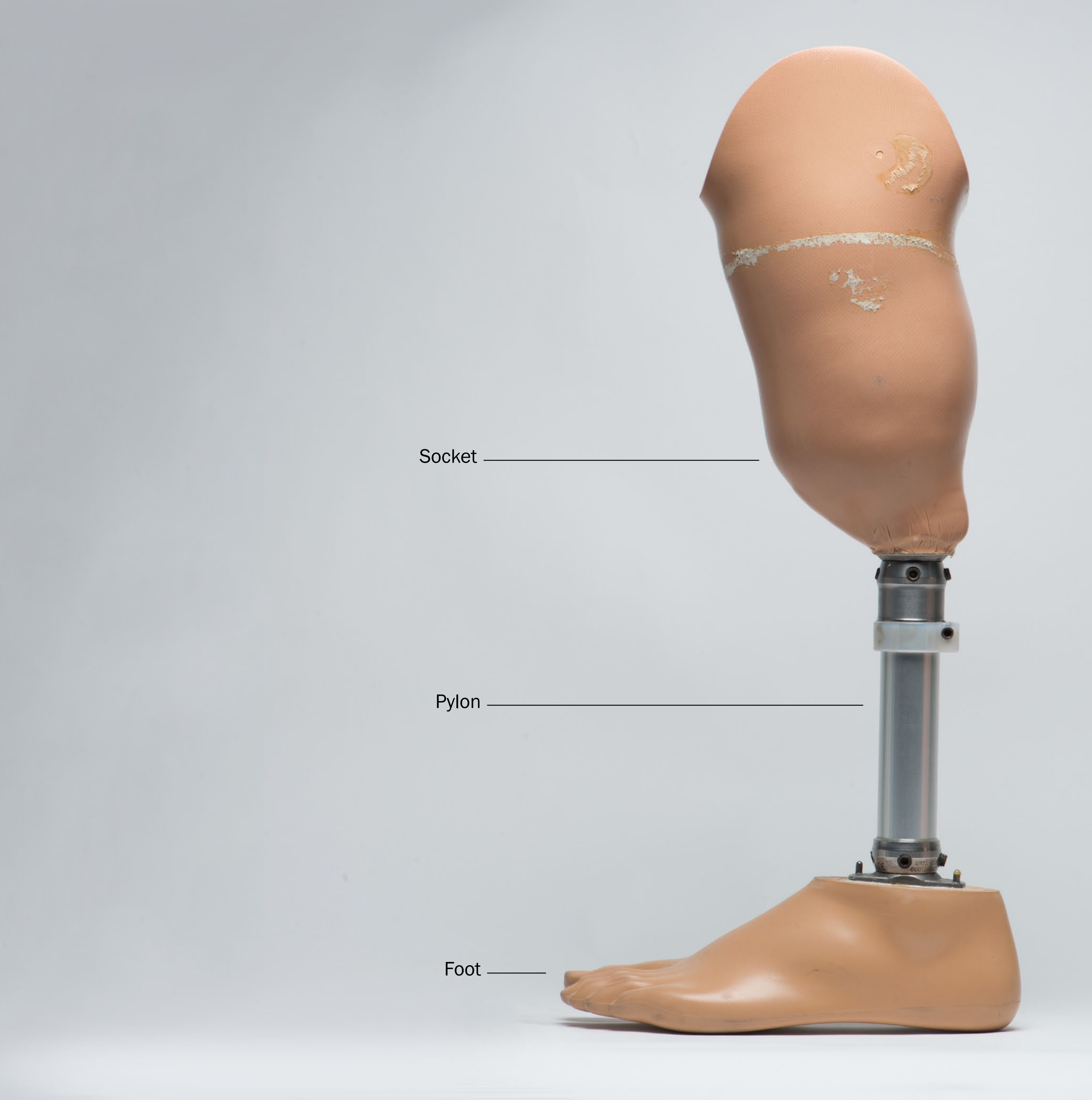

Figure 1.01

A traditionally fabricated fibreglass socket with its three main components labelled.

“

“The value of artificial limbs for recreation is well acknowledged by amputees and therapists alike … not everybody finds swimming with a single leg an enjoyable task due to the difficulties in getting to the water and the slight imbalance in the water.”

(Saadah, 1992, p. 140)

Contents

Abstract

A brief overview of this research

Figure 1.02

A workbench at the Wellington Branch of the NZALS.

Abstract

The practice of fitting and making prosthetic limbs using current techniques leaves little room for innovative research and design. Though market leaders are consistently producing more advanced components, prosthetic technicians are using traditional techniques to fabricate prosthetic limbs. New material and design technologies could enable progressive solutions to historic barriers such as fabrication time and cost. Increasing the amputee's accessibility to, and enjoyment of exercise may help to advocate and improve their physical and mental health.

Design research was used to develop a functional 3D printed swimming prosthesis for lower limb amputees with the use of 3D scanning, parametric software and Fused Deposition Modelling. Using digital technologies has the potential to provide a platform for cost effective specialty prosthetic limbs, enabling and enriching recreational sport for amputees.

Prototypes were developed with a unilateral trans-tibial amputee using an iterative process involving material testing and user testing. These prototypes allowed him to walk independently to the pool and produced positive effects on his swimming, including a recreated anthropometric symmetry. As advances in data collection and additive manufacturing continue to be made we will be able to more closely cater to the individual's needs whilst challenging the status quo in prosthesis craft.

Introduction

The context of this research

Introduction

The New Zealand Artificial Limb Service (NZALS), a professional entity and stakeholder in New Zealand prosthetics, has identified the need for a prosthesis for swimming that allows for a rectified swimming motion for lower limb amputees. This research questions how we can design a parametrically customisable swimming prosthesis for lower limb amputees. It will explore the benefits and limitations of 3D scanning, parametric design and FDM 3D printing when used to design and fabricate a prosthesis. Using these methods it will aim to assist in amputee fitness and rehabilitation by designing a feasible and desirable accessory limb.

Prosthetic fabrication still relies on many traditional techniques. Plaster casting, rasp filing and vacuum forming are all part of the standard procedure to construct a lower limb prosthesis. Fabrication by skilled technicians is a slow and expensive process, with high resource wastage due to the subtractive nature of traditional fabrication. Despite the cost and time involved, with years of experience many prosthetists have a rich intimacy with tools and materials. Such an in depth understanding of the body that has not yet be replicated by the digital process.

Due to the high cost and time involved in fabricating a prosthetic limb, amputees are often limited to one limb that must function in all physical and social conditions. Digital technologies could allow for multiple limbs to function in multiple scenarios.

In the past, industrial design has lent its knowledge to medical development through its understanding of ergonomics, fabrication and mass production. The results of these interdisciplinary works have offered beauty, empathy and other qualities that are often lost within the realms of engineering. A strong understanding of material, form and its relationship with the human is evident in designed examples of medical equipment. The Eames' have provided a reputable precedent for the designer-developed medical device that imbues the aforementioned qualities. The splint designed by Charles and Ray Eames in 1942 to aid medical staff on navy vessels has been regarded as a tool that married technological innovations with organic and functionalist design (Weems, 2012). With "anthropomorphized contours" the splints expressed an understanding that "the etiology [perception] of broken bodies ... was as much cultural and psychological as it was physical" (Weems, 2012, p. 47). If we understand what makes designs like this so human, we must now investigate how the digital form can imbue the qualities of empathetic design and the meticulous craft of artisan trades.

Digital data collection, such as 3D scanning provides a high accuracy for documenting the form of an amputee's limbs while fabrication methods like 3D printing dramatically increase the topographical accuracy of products whilst decreasing the man hours required to fabricate them. As 3D printing reduces the ability to edit a prosthesis after its fabrication the intimacy of digital craft lies not in physical output but the understanding of 3D scanning and how to manipulate 3D geometries to form an ergonomic socket.

The research was undertaken with the advice of clinicians from the NZALS and a research participant that is a trans-tibial amputee who lost a lower section of his left leg, from the middle of the tibia bone. The participant's amputation is both the most common type of amputation (trans-tibial) with the most common reason for amputation (physical trauma) in New Zealand. In 2014 below knee, or trans-tibial amputees, accounted for 53% of the 4311 amputee patients under the care of the NZALS. Above knee amputations accounted for a large minority of the remaining amputee patients and a final 25% of patients were a mixture of upper extremity amputees, symes amputees and more uncommon cases (NZALS, 2014). Every patient has a different backstory to their amputation, though reasons for amputation often stem from two prior problems: physical trauma, or vascular disease and diabetes. Though physical trauma was the cause of the participant's amputation, without preceding health issues he still continues to keep physically active, understanding exercise to be a recognised and important part of physical and psychological wellbeing (Deans, McFadyen & Rowe, 2008).

With a recent amputation the participant's attitude toward changes in lifestyle is positive. He is not complacent nor is his life routine. His consultation during this research has been invaluable with his engineering background helping him provide constructive, critical and concise feedback during prototype testing. As this research was limited in methods for measuring the fit of prototype due to resource constraints his understanding of his physiology and its relationship with the prototypes tested were paramount to receiving constructive feedback.

The written documentation of this research reads semi-chronologically, with contextual research including literature and precedent reviews, followed by written and visual documentation of the design and prototyping process of a swimming prosthesis.

Participant Relationship and Consent

One participant partook in this research. Contact between participant and researcher was established by the NZALS. This research received ethical approval from the Victoria University Human Ethics Committee. The participant's name has been removed for his privacy though images of him, including images of his face have been used in this document to communicate how important the person is in a human centred design process. The participant has consented to the use of all images in this document.

All interviews were carried out in an informal, face-to-face basis. Any correspondence and verbal information gathered from the participant has been in an open discussion format. This informality allowed for unadjusted qualitative feedback in a more comfortable environment (Martin & Hanington, 2012). It is also helpful to build a relationship with participants that are involved in the research over a long period of time. (Cohen & Crabtree, 2006)

Figure 1.03

The participant wearing his prosthetic leg.

Precedent Review

Other previous concepts and products

Precedent Review

Different approaches have been taken to the design and production of water oriented limbs. Two common though contrasting approaches are highly specified design concepts or solitary compositions of prosthetist sockets and retail swimming fins. Neither of these approaches offer an accessible solution. One is too technology oriented and production is restricted by cost or engineering feasibility, while the other is not designed to be reproduced.

The Elle prosthesis by Della Tosin (2013) is a highly praised concept, winning both IDEA and James Dyson Awards. This is a concept that has not been produced as a working prototype. It claims accessibility through low production costs (James Dyson Foundation, 2013) though this could be disputed with the several different manufacturing methods and complex materials required.

It approaches equality in sport by proposing that with this prosthesis amputees could compete alongside able bodied swimmers. This raises many questions regarding fair competition, and if we place the equality of the amputee before the equal competition of the able bodied swimmer. This concept sits outside of both the International Olympic Committee and the International Paralympic Committee regulations. As these regulations are strict and unlikely to change, stating “no swimmer shall be permitted to use a prosthesis, except ocular, or orthoses during the race” (International Paralympic Committee, 2014, p, 32) our research will not focus on competitive swimming but rather how swimming can be used as such a powerful rehabilitation tool both physically and emotionally (Deans et al. 2008).

Similar in approach to the Elle, the Neptune concept by Richard Stark is another moulded polypropylene concept. It focuses on adjustability rather than innate customisability. The intent of the “flower shaped cup” is to accommodate the end of the users stump with its flexibility. Attachment is created by the tension of an elasticated ribbon running under the patella (Fast Company, 2010). This concept would be cheaper to produce than the Elle though as a non-customisable design it skips any input from a prosthetist and makes the assumption that a swimmer’s stump, which vary dramatically, would fit the design. Stark has developed a slim and resolved design though the concept uses a rigid bar through the centre of the fin for walking poolside. This is not considered safe by the standard of NZALS prosthetists (NZALS Clinical Prosthetist, personal communication, March 11, 2016). Stark has produced a small amount of ‘proof of concept’ through video, though the Neptune prosthesis itself is never shown worn and there is limited detail available as to how effective the fit, adherence and propulsion of the concept prototype are.

Figure 1.04

Elle Prosthesis (Tosin, 2013)

Figure 1.05

Neptune Prosthesis (Stark 2010)

Figure 1.06

Murr-Ma (Essl, Johnson, Rocca, & Machida, 2013).

Figure 1.07

Water Leg (Standard Cyborg, 2015).

A third concept, the Murr-Ma by a group including Julia Johnson, Thomas Essl, Yuki Machida & Damien Rocca is specialised for beach use. Their presentation material lacks proof of concept, with no device being explained for adherence to the swimmer. (Yuki Machida, 2015)

There are a limited number of water based products that have been developed beyond their concept. Standard Cyborg's Water Leg (Standard Cyborg, n.d.) is one of these. It has been approached with simplicity to achieve low cost and accessibility. This simplicity and economy can be seen through the visual language of the prosthesis with minimal detailing in the form. Though this product uses 3D solutions to fabricate a contemporary waterproof walking prosthesis, this prosthesis is only structurally sound with the addition of a carbon fibre sleeve covering the whole exterior of the prosthesis.

Common practice for amputees requiring a prosthesis for wearing in water is the prescription of a Water Activity Limb or WAL. These limbs resemble a traditional pylon based prosthesis (figure 1.01, p. vi) but with the use of hydrolysis resistant materials and a rotating angle allowing for the foot to be positioned for swimming. They allow for mobility in water but are not designed for efficient swimming, still comprising of large amounts of steel and a heavy foot.

Literature Review

Previously Published Research

Literature Review

Overview

The following text reviews literature about water oriented prosthetic limbs as well as areas that could yield transferable ideas and technologies. This review contains a range of academic fields including health sciences, biology, prosthetics and industrial design. Together they were be considered from an industrial designer's perspective.

It also investigated studies of commercial swimming fins and animal morphology, analyse previous studies of swimming prostheses as well as traditional and contemporary prosthetic production for extractable technologies and ideas.

This review is intended to define direction for some aspects of this research. Appropriate resources were limited with many papers from the prosthetics discipline containing little or no transferable information. Understanding the scope and limitations of previous research has been important to assist in planning steps taken during this research's methodology.

Literature Review

Psychology of Amputation and Exercise

This section outlines the importance of exercise for physical health, emotional health and rehabilitation. Ruben and Fleiss have previously linked exercise and health stating; “sports participation contributes not only to physical but also to psychological well-being” (1983, p. 37) this notion is restated by Deans et al. (2008) with the further addition that “…amputation can often be associated with anxiety, isolation and depression, which may change social and free-time activities for the person with a lower-limb amputation.” (p. 186) This quote supports the notion that with the loss of a limb, amputees are liable to express interest in forms of training that will help maintain fitness, muscle tissue and support rehabilitation.

When surveyed by Hanspal and Nieveen (2002), 120 people consisting evenly of doctors, prosthetists and therapists showed that “competitive swimming and weekly leisure [swimming] ranked highly as an indication to prescribe a WAL [Water Activity Limb].” (p. 220) with the addition that “many respondents highlighted the frequency of any water activity as an influencing factor.” (p. 221) Though this survey only represents the Water Activity Limb as a waterproof walking prosthesis, it is an indication of the value placed on mobility in water by professionals working with amputees.

Swimming has been established as an effective manner to promote healthy lifestyles as “swimming is a low impact training activity [that can be used] to build endurance without traumatising the residual limb soft tissue” (Gailey & Harsch, 2009, p. 252). This is important because the amputee demographic have a high rate of cardiovascular disease. Research exists with “some 82% of those with lower-limb amputation in Scotland have lost a limb due to peripheral vascular disease, with 38.6% of this group having undergone amputation due to diabetes” (Deans et al. 2008, p. 187)

It is suggested that “the physiotherapy component of the immediate postoperative phase of rehabilitation should encompass design and implementation of an individualised exercise programme … an improvement in perception of body image, self-esteem, sense of control, competency, and success is likely to result.” (Deans et al. 2008, p. 192) *“swimming is a low impact training activity to build endurance without traumatising the residual limb soft tissue”*

(Gailey & Harsch, 2009, p. 252).

Literature Review

Fin Morphology and Hydrodynamics

This section was written to help define elements that could be considered or incorporated to design an effective and efficient swimming fin. Efficiency in water naturally lends itself to morphological studies and biomimicry. Liu and Bose completed studies that suggest “a lunate flapping-foil [a computational fin] is much more effective than a rectangular flapping-foil” (as cited by Zhang, Su, & Wang, 2011, p. 325) (figure 1.08). Xi et al. draw comparisons between a lunate flapping-foil and the tail of the tuna fish stating “a large aspect ratio, spanwise tapering tip and moderate sweepback angle enjoys the best efficiency” (2011, p. 325). Though the tuna fin is not restricted to width as a prosthesis is when a unilateral amputee retains one full length limb. Despite this, this understanding of fin efficiency will be incorporated into design and prototypes of this research to generate an efficient form within the physical parameters of the amputee’s body.

Multiple studies have also been performed on the flexibility of caudal (tail) fins. Fins “should be made of elastic materials with a variable thickness … in this type of caudal fin the stiffness decreases simultaneously from the fixed end to the free end and from the [left and right] edges to the middle” (Apalkov, Fernandez, Fontaine, Akinfiev, & Armada, 2012, p. 173). Bergmann, Iollo & Mittal state that their models are most efficient at an “intermediate flexibility” as too rigid caudal fins “lead to excessive lateral forces that increase power consumption without generating thrust” and “highly flexible caudal fins produce negative thrust during significant portions of the stroke”. (2014, p. 16)

Studies have also resulted in similar conclusions when market swimming fins were tested. “…a fin that is too flexible or too rigid [does] not perform as well as a fin that was intermediate in rigidity” (Pendergast, Mollendorf, Logue, & Samimy, 2003, p. 69). Acknowledging that “fins are meant to improve the fraction of force (thrust) that is useful to propel the body forwards” (Zamparo et al., 2002, p. 2665). These papers highlight that many details often used in the design of swimming fins are superfluous to the efficiency and propulsion of the fin. It is suggested that venturis and vents do not improve the economy of fins and “channelling of water down the fin by troughs or rubber channels does not appear to improve their economy” this also stands for vents, forward or back facing in the fin (Pendergast et al., 2003, p. 68).

In conclusion these papers suggest that the design of the swimming prosthesis fin retain a simple crescent form with just two channelling ridges along each edge to increase propulsion by directing force. The fin will also have dual variability in its rigidity though overall will be a moderately flexible fin.

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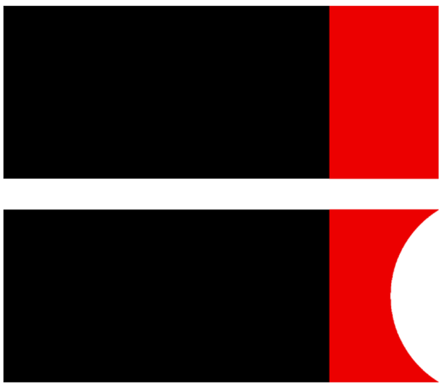


Figure 1.08

The forms of a rectangular flapping foil (top) and a lunate flapping foil (bottom).

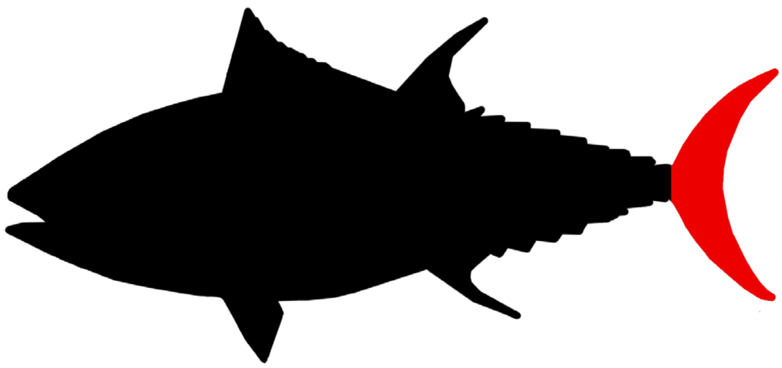


Figure 1.09

The caudal fin of the tuna, highlighted in red.

Literature Review

Lower Limb Prosthetics and 3D Printing

Traditionally "all major lower-limb prostheses are constructed with 3 major parts: the socket, the leg section [pylon], and the foot." (Herbert, Simpson, Spence, & Ion, 2005, p. 141) though a swimming prosthesis may not require a large "leg section" - possibly a smaller joint or transition between the socket and the fin.

The abilities of 3D scanning and FDM printing may provide the capability to re-iterate sockets more quickly to retain optimum comfort for any amputee experiencing muscle waste or growth. This is an area worth exploring as "prosthetic comfort, which is related to prosthetic fit, is one of the most important aspects of prosthetic acceptance and function" (Tsur, Loberant, Volpin, 2004, p. 713).

The construction of the swimming prosthesis will explore digital design and manufacture using 3D printing. Research in this area has begun with some tested sockets showing "functional characteristics similar to that of a traditional socket." (Ng, Lee, Goh, 2002, p. 53) Ng et al. have also explored the use of a wider road width (the thickness of the extruded material) in FDM printing with a Rapid Manufacture Machine, or RMM. Using a 3mm nozzle that extrudes a 4mm road, the RMM showed that the increased diameter offers an increased printing speed as each layer could be completed with a single sweep. Larger nozzle diameters also have other benefits such as an increased ability to build slanted surfaces without support material. Though this printer appears to have had limited testing and little information is available (2002).

Though companies are exploring the possibilities of 3D printed prosthetics, this commercial research has so far produced limited publication of knowledge with this research largely resulting in promotional material.

Design Methodology

Detailing methods used and their outcomes

Methods and Process Overview

This chapter outlines the methods used within this research process as well as their results. The research as a whole involved traditional contextual research through reputable sources as well as specific and specialty advice from clinical prosthetists and an amputee participant. These sources were utilised concurrently with exploration of materials and computer modelling through iterative testing processes.

Categories in this segment include participant observation, material exploration and fused deposition modelling, 3D printing experiments, 3D scanning, morphology and fitting the participant.

Participant Observation

Detailing the participant's swimming routine

Prior to swimming the participant's prosthesis was discussed. He wears a Patella Tendon Bearing (PTB) socket, meaning his weight is mainly held by a ridge in the socket, under the knee-cap. The prosthesis holds to the limb by suction, using a silicone liner with rubber rings that create a vacuum once the limb is pushed into the socket. Though other methods exist, NZALS clinicians advised that PTB suction sockets are the most common form of socket for trans-tibial amputees.

Time at the aquatic centre with the participant revealed some of the intricacies of living with an amputation and how complex this can make not only mobility but also the logistics of carrying out simple tasks and the large amount of reliance on pool staff.

The participant sees swimming as an effective form of exercise and does not let any difficulties the amputation causes stop him from getting into the pool. He has an exercise plan from his physiotherapist which includes a mixture of freestyle and backstroke swimming, and aqua jogging. He has to logistically plan his routine to meet his needs during his time at the pool with consideration as to when he has his walking leg on and off.

After entering the aquatic centre walking to the changing rooms provides no difficulty for him. Observation paused as he changed into swimming shorts though he describes a process that involves sitting, removing his walking prosthesis, changing his clothing then donning the prosthesis again. Once out of the changing room observation continued. After leaving his bag on a set of benches he walks to a water fountain at the farther end of the pool, fills his water bottle and returns to the bench area. After collecting a flotation belt he takes a seat on the bench and clips the belt around himself. At this point the prosthesis needs to be removed for a second time and his prosthesis liner is peeled off and placed on a plastic bag to keep the sticky interior from collecting any dust or dirt.

He communicates with a lifeguard who collects a large plastic wheelchair. The participant is helped into the seat and wheeled to the edge of the pool. He uses the handrail of the ladder to lift and support himself, standing for a moment before diving in hands first. From the edge of the pool he paddles over a lane rope before starting his first length.

Figure 2.01

The participant's limb after removing his prosthesis

Participant Observation

Detailing the participant's swimming routine

As he commences swimming the most noticeable effect his amputation has on his swimming style is an asymmetry in his arm stroke. His first length is a face down front crawl (or "freestyle") stroke. His arm stroke consists of a typical forward motion with his left arm followed by a larger outward stroke by his right arm. This is his body compensating for the lack of propulsion from his left stump. After his front crawl length the participant returned swimming backstroke. Similarly when swimming backstroke his right arm sweeps out to correct his path by pulling him back toward the centre. During both of these swimming styles his legs stayed consistent with even timing between strokes. It did not appear that the stump's stroke was any slower or faster than the leg's stroke. He continues on in a routine of five lengths of swimming followed by five lengths of aqua jogging, repeated these sets five times.

In later sessions to explore the asymmetry in his stroke he swam face down, with his hands by his side, kicking with just his feet. This resulted in a left turning path, with him rotating so much that he had moved from the centre of the lane to bumping the lane ropes within 4 metres. To cross reference this it was tested with the participant repeating the same premise but on his back, this time he also rotated toward his left, the observer's right. This confirmed that the left stump has a lower output of force than the right leg, causing a rotational path.

To get out of the pool he pulls himself onto the edge, kneels and then pulls himself up using the steel ladder before requesting the wheel chair again. He mentions that days occur when he is too sore to achieve this and the pool staff assemble a hoist that he can sit in to be lifted out.

Observation was undertaken to understand how amputation has affected the participant's swimming. According to Gunn and Logstrup participant observation is effective in highlighting not only the practical events of a scenario but also the social events, hierarchies and dynamics (2014). Physically several changes have occurred to his swimming style in the form of both conscious decisions and physiological effects. To reach the pool alone is an arduous task and once he reaches the water it's obvious how the lack of symmetry in his physiology has an impact on his movement.

Figure 2.02

The participant using the pool ladder to steady himself before jumping into the pool.

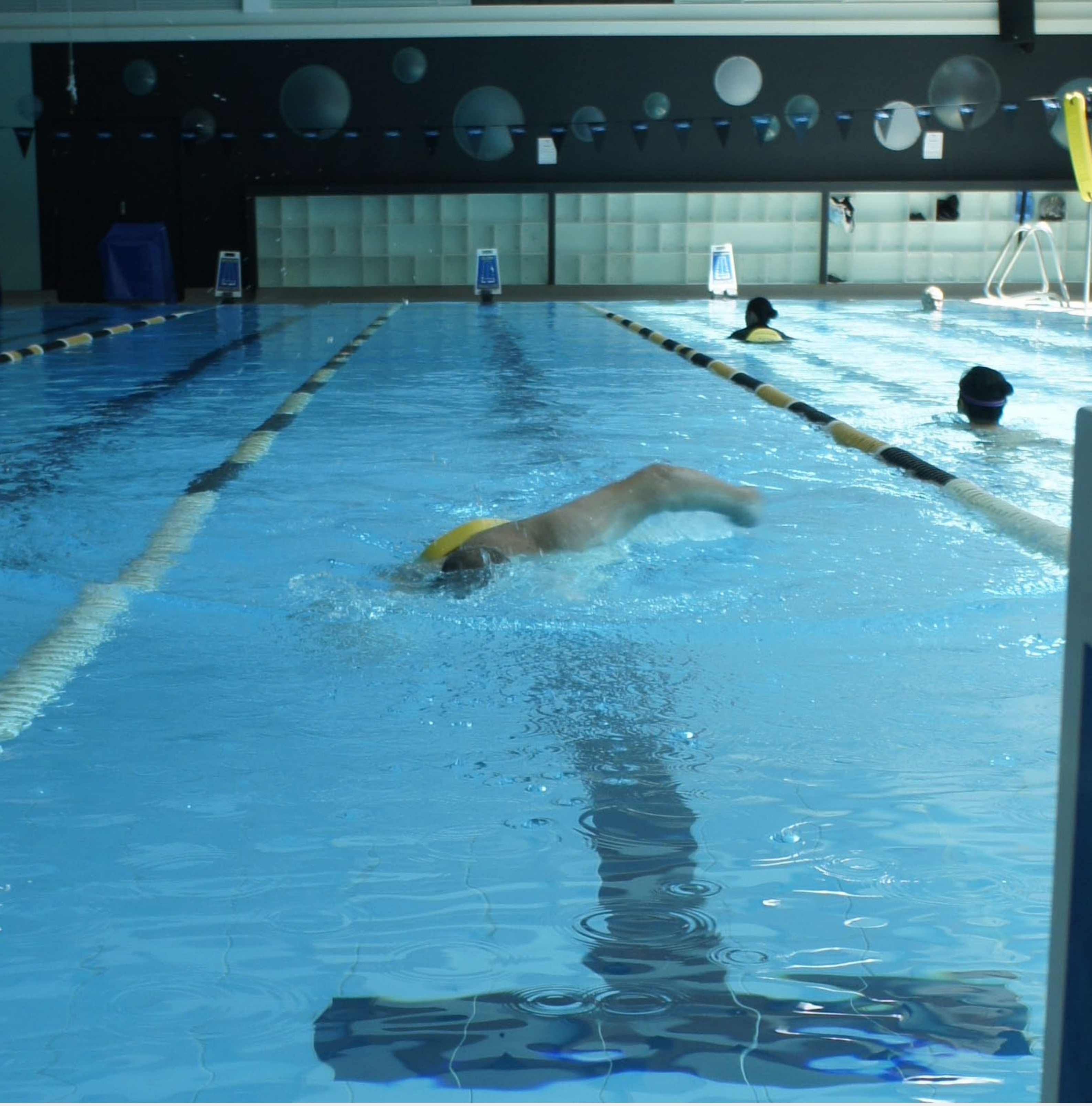


Figure 2.03

The right arm stroke of the participant, moving toward the camera.

Figure 2.04

The right arm stroke of the participant, moving away from the camera.

Research Through Design

Underlying methodology

This project has utilised both research through design and research for design. Research for design, using research material to develop an artefact (Martin et al., 2012, 146), was used to inform the design in areas where comprehensive and cohesive research has previously been performed. This involved a literature review, precedent review, and participant observation were performed to garner an understanding of the current context of prosthetic limbs, morphology and swimming. These methods helped build a basis where research through design could then be used to answer questions that arose from gaps in the knowledge available.

Research through design methods can be essential to reducing assumptions and uncovering unforeseen problems through in-context testing. The often interdisciplinary nature of design research (Milton & Rodgers, 2013) requires contextual placement. But when industrial design seeks not only to collate and draw conclusions but pragmatically design and build solutions, research through design can be incorporated to help understand materials, fabrication, to prototype and to test concepts.

There were many areas where material testing, CAD modelling, physical prototyping and other practical exploratory methods were incorporated within the design process of this prosthesis. These helped to understand specific material strengths and weaknesses, difficulties in fabrication, dimension and aesthetic refinement as well as aiding in communication during the heavily iterative design process.

The research through design process is extensive and has been heavily documented in this thesis using sketching, photography, rendering and screenshot. These are accompanied by notation.

Flexible Materials

3D printing of alternative materials

Before a material was physically tested there were several factors that needed to be considered. The material had to be compatible with the FDM 3D printers available to the researcher. After performing a literature search into the requirements of flexibility in a traditional swimming fin, which recommended a medium rigidity (around Shore 60A) the materials that were available for FDM printing were narrowed down dramatically. The main two types of materials that were available as appropriate filament around this flexibility were Thermoplastic Elastomers (TPE) and Thermoplastic Polyurethanes (TPU).

These materials have many almost identical physical properties. Their rigidity, melting temperatures were, for all intents and purposes, the same. Where they differ is in their chemical properties. To ensure a reasonable lifespan as a product the material also had to meet environmental requirements such as a level of water resistance and resistance to pool chemicals, particularly chlorine. TPE suffers from hydrolysis and is liable to absorb water which is not suitable for a pool environment. TPU on the other hand, according to Huntsman International LLC. is appropriate for use in water intensive environments (n.d.). TPU's can be divided into three main chemical classes. These are polyester, polyether and polycaprolactone. All of these categories would be sufficient for use in a pool environment but for longevity the first material that this research began using to test was a polyether TPU due to their excellent hydrolysis resistance, scratch and tear durability and resistance to microbial attack (Huntsman, n.d.). As a preliminary test this material was also exposed to chlorinated water for an extended period of time, with no noticeable physical changes occurring.

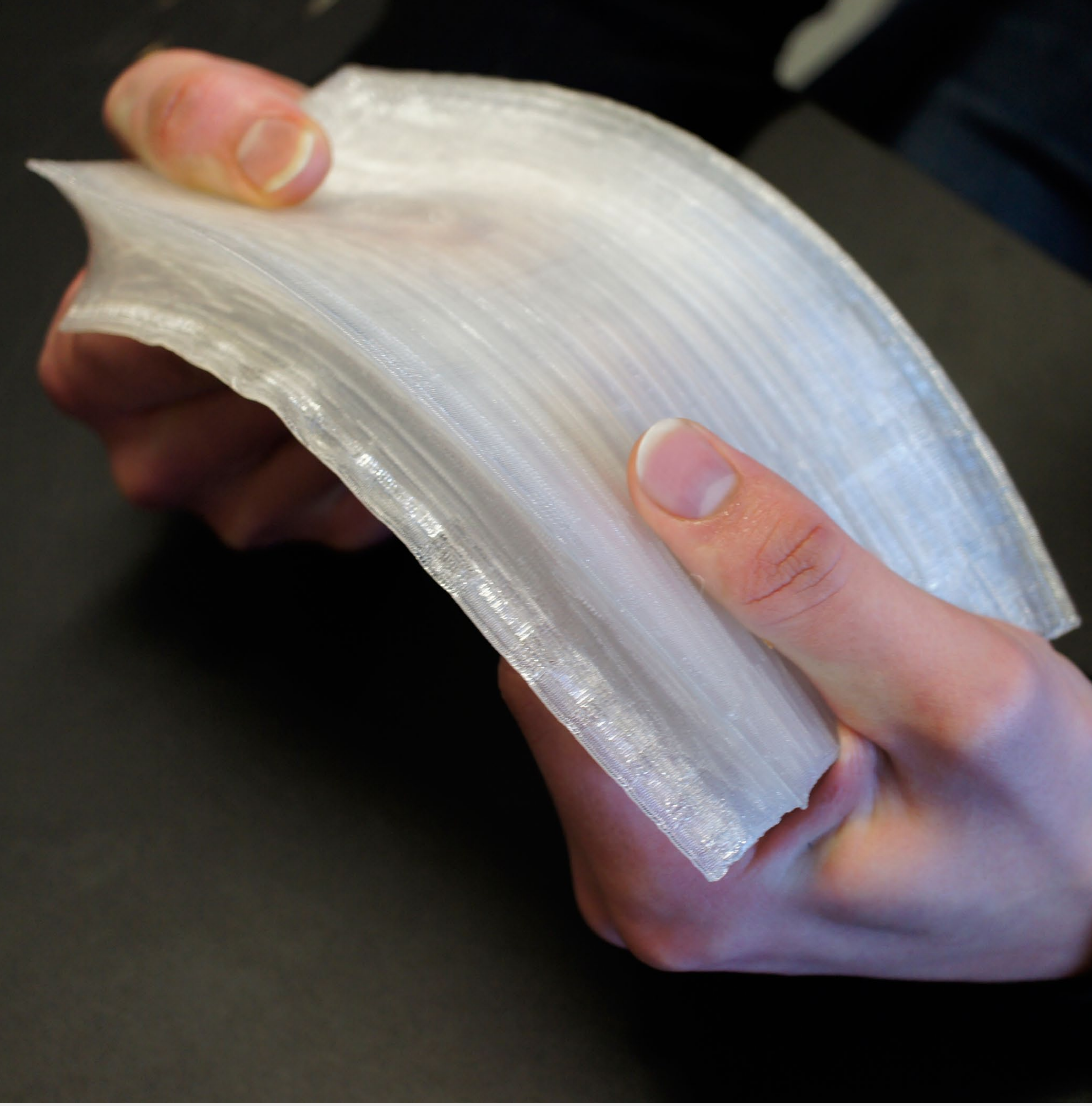


Figure 2.05

A TPU print being flexed. This material showed great flexibility and strength.

3D Printing

Fused Deposition Modelling

Fused Deposition Modelling, or FDM is a form of 3D printing that builds objects through the vertical layering of material in pre-determined profiles on a horizontal bed.

FDM 3D Printing was used as the predominant method of prototype fabrication throughout this research. FDM is one of the simplest and cheapest forms of 3D printing though this method offers many advantages over other methods of 3D printing. The Up Boxes (3dprintingsystems.com) used are both low cost machines that use relatively low cost materials. These were available to provide in house prints, reducing the time between feedback and iteration of physical prototypes.

Minimal examples of flexible material being printed through FDM machines exist, though with in-depth experimentation this research has succeeded in producing functional flexible TPU prints through an FDM process. To get to a successful TPU printing process the filament was tested thoroughly with changes in temperature, nozzle diameter, spacing from the nozzle head to the printing bed and the height of each layer. Attention was also paid to the wall thickness of models, and the degree of unsupported walls from the bed.

To gain maximum variability in temperature for testing the first printer used was an Up Mini with a temperature controller that allowed for selection of temperatures between 160 degrees Celsius and 300 degrees Celsius, in 10 degree increments. Tests of a 40mm high cone with a 1mm wall were repeated at various temperatures with a log kept of the exact settings and images documenting their quality. Though the manufacturer recommends a 200-210 degree window for the TPU to be printed in tests provided better results at temperatures closer to 230 degrees.

Final prototypes of the swimming fin used a custom drilled 1mm nozzle diameter. Nozzle diameters were tested between 0.4mm and 1mm. The 1mm nozzle diameter was the largest diameter that was effective in an Up Box printer before the speed of the machine's stepper motor, in combination with filament of 1.75mm diameter would lack enough pressure to extrude consistently. The benefit of using a larger diameter when printing flexible filament reduces the likely risk of burning filament and blocking the nozzle. It also produces a smoother surface with less tags and webbing as it moves from one surface to another.

Using a 1mm nozzle diameter required the extruder to move in larger increments up the Z axis than it would with a smaller nozzle. This is due to the larger road width. Using the expected Z axis setting of 0.20mm with this size nozzle resulted in blockages as the filament road would extrude around and above the nozzle tip. After testing, it was found that a Z axis of 0.35-0.40mm was sufficient to stop and nozzle blockages and let the filament flow freely. For the same reason the initial nozzle height of the extruder head had to be raised by 0.5mm (comparatively to ABS filament), creating this extra space between the print bed and the nozzle tip allowed for the raft to print without the nozzle dragging through previously placed filament.

Once these values were established, particularly the extruder temperature, the research was able to be continued on an UP Box. The major benefit of the UP Box, besides mechanical reliability, was a far larger print bed of 255 X 205 X 205mm (W X D X H).

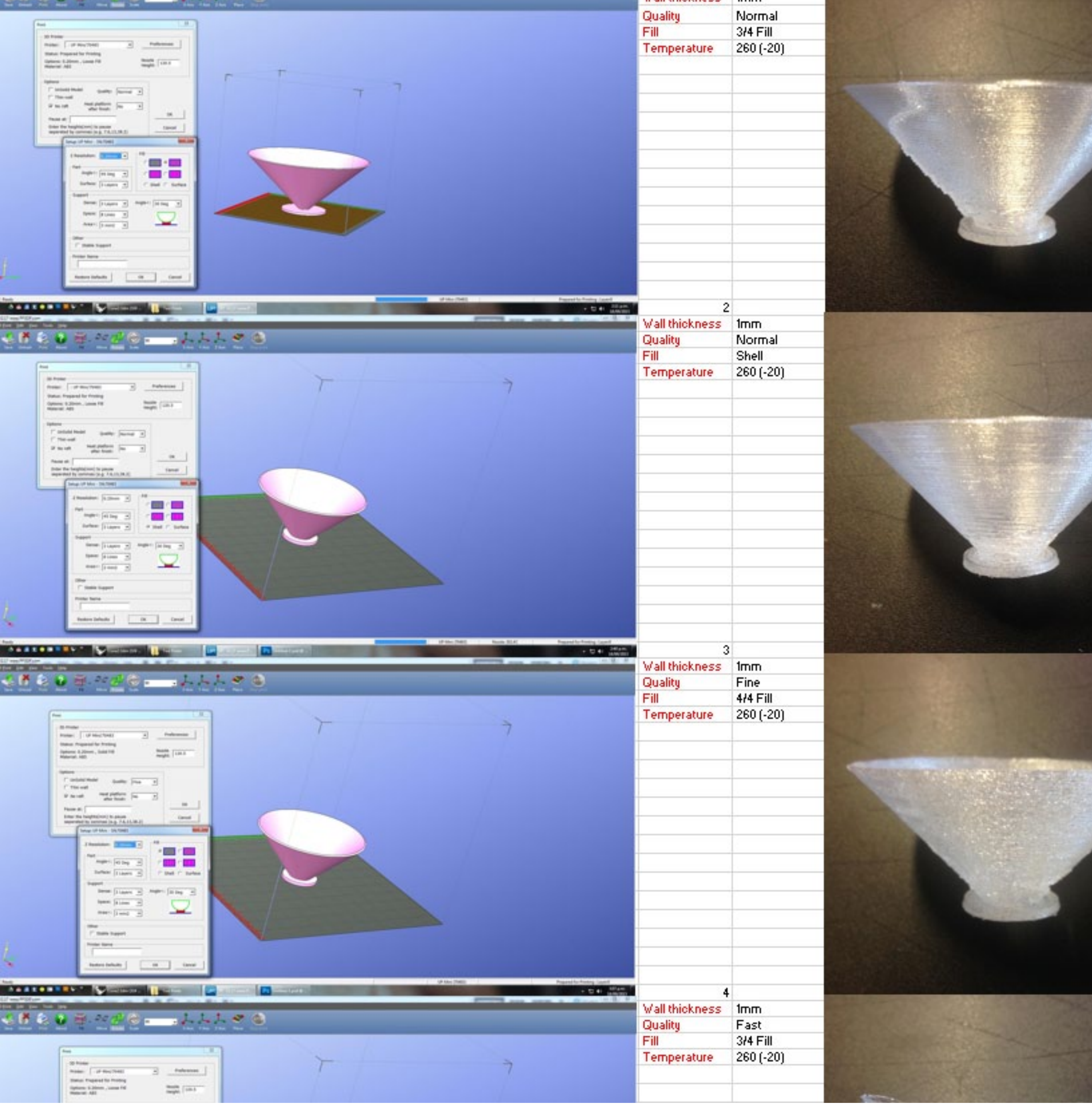


Figure 2.06

A screenshot of the log of TPU experiments that was kept. Thorough recording of results was essential to understanding the effects of settings and configurations.

Experiments and Developments

FDM printing of flexible materials

This chapter presents a workflow of printing experiments made in this research. Photography in this section was used to express the details, flaws and anomalies in the FDM process. These images are in chronological order with notation of findings as they occurred. Most prints in this process were TPU experiments, unless captioned otherwise.

An iterative process lends itself to thoroughly testing just one, or a few aspects at a time, especially with this prosthesis being made up of several components with differing functions. This allows for very accurate deduction of benefits, problems and their causes.

Figure 2.07

Initial TPU test prints were completed on an UP Box at 300 degrees Celsius. These served as a reference point for future tests. It was established that the ‘glue gun’ effect was due to a high temperature. These were using the stock 0.4mm nozzle and typical rigid material print settings.

Figure 2.08

Figure 2.09

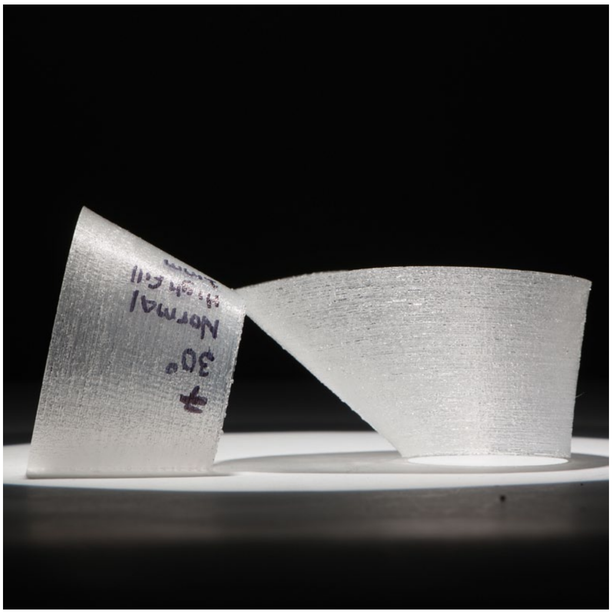


Figure 2.10

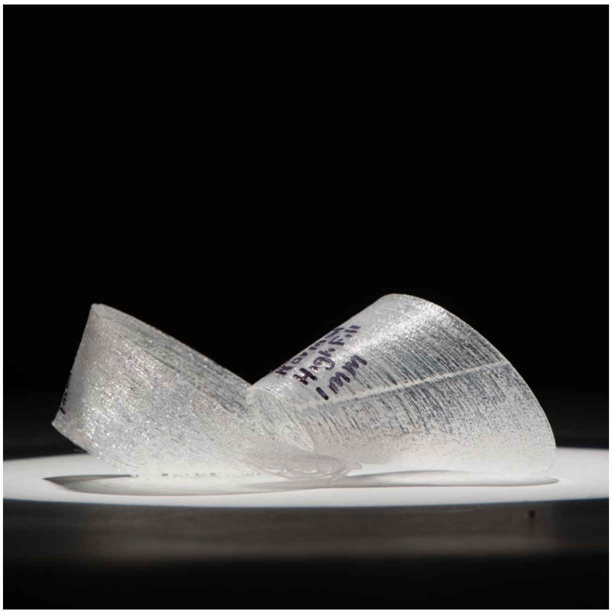


Figure 2.11

Figures 2.08-2.15: Prints were tested from 160 degrees Celsius to 300 degrees. A conical form was used as it has a simple build path and allows for the measurement of the angle of failure, where the wall starts to collapse.

Figure 2.11: A ‘gluey’ effect was a common issue with early prints.

Figure 2.12

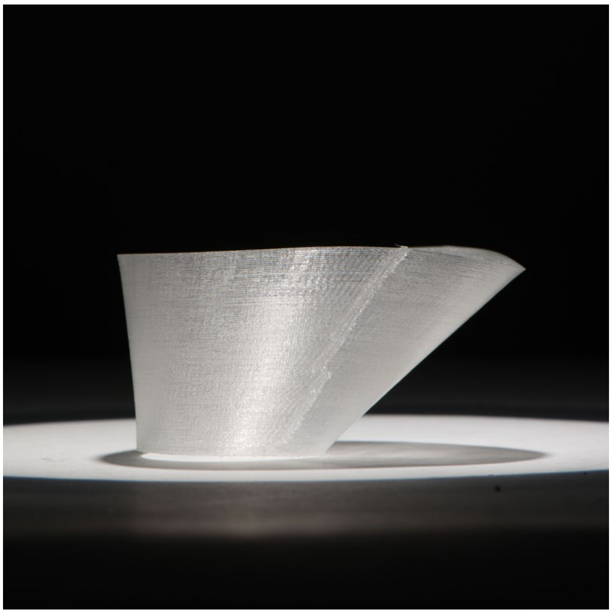


Figure 2.13

Figure 2.14

Figure 2.15

Figure 2.12: The failure angle, where filament droops from the wall, can be seen here at 45 degrees from vertical.

Figure 2.14: The webbing seen on the right model was a frequent issues due to the nozzle of the printer blocking.

Figure 2.15: The first completed, high quality prints were at 230 degrees Celsius.

Figure 2.16

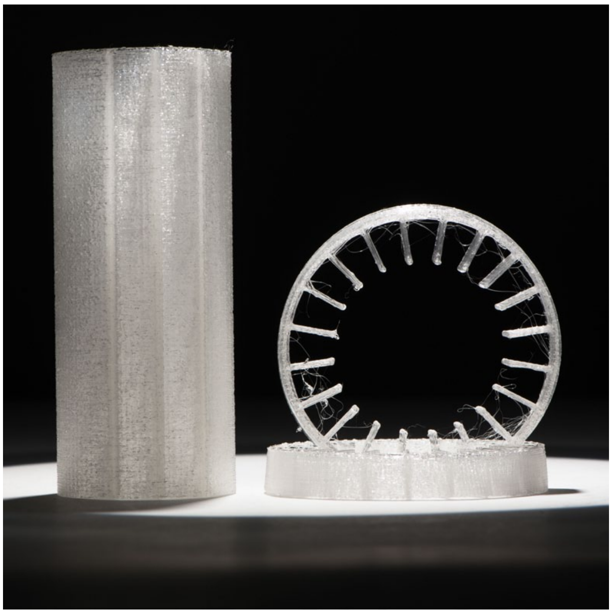


Figure 2.17

Figure 2.18

Figure 2.19

Figures 2.16 & 2.17: Other forms were tested with the purpose of exploring structures that could be used to replace prosthetic pylons.

Figure 2.18: The first TPU fin printed. Burning can be seen on the top right, this is from the nozzle sticking to previously laid filament

Figure 2.20

Figure 2.21

Figure 2.22

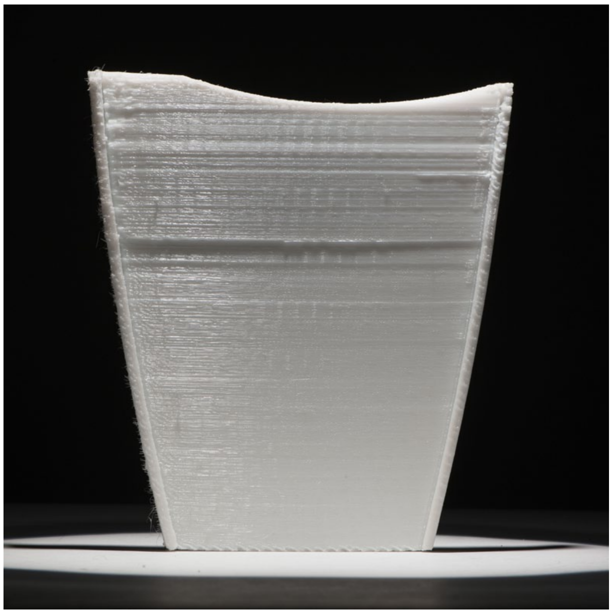


Figure 2.23

Figure 2.20: A test of a Fin/Pylon hybrid.

Figure 2.21: ABS maquette models were printed to test proportions.

Figure 2.23: The first test with a custom drilled 1mm nozzle. This provided far smoother results.

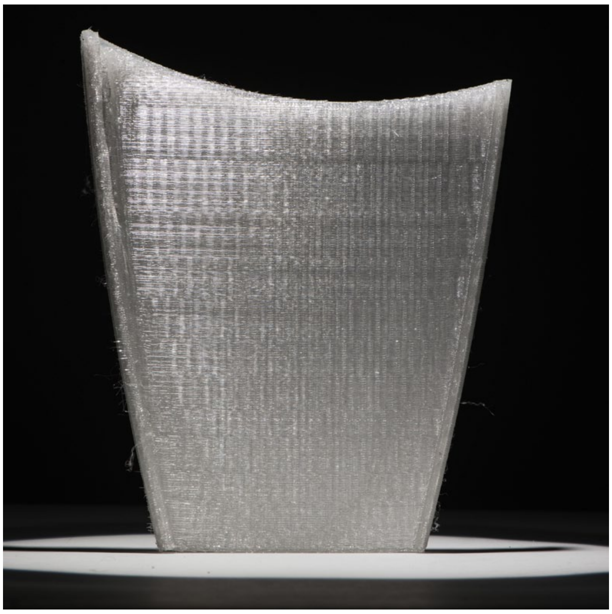


Figure 2.24

Figure 2.25

Figure 2.26

Figure 2.27

Figure 2.24: A cleaner TPU fin with less layer vibration than in figure 2.23

Figure 2.25: The lower end of a socket form printed to test a larger capacity.

Figure 2.26: The first parametric socket to be printed. Made with an anonymous limb scan, this had too much support as TPU cannot be sanded and must be cut out.

Figure 2.27: A second print showing the interior.


Figure 2.28


Figure 2.29


Figure 2.30


Figure 2.31

Figure 2.28: The interior of the first print of a full parametric model using an anonymous limb scan.

Figure 2.29: The first socket test in TPU using the participant's scan. The circles indicate areas where the wall was too thin and visible holes were appearing.

Figure 2.30: The whole socket was too large for a single print. Two pieces were attempted to be joined using heated plates at TPU is heavily resistant to solvents.

Figure 2.31: A cleaner join was achieved using a heat gun.

Figure 2.32

The first “1:1” prototype. During the first participant test this was found to be significantly too small to test (figure 4.11, p. 147). Understanding the craft in digital fitting became a significant area of this research.

This model has a rigid ABS housing with a female thread that allowed the reuse of expulsion valves during testing. These are stock products made by prosthetic producers for suction valves. Expulsion valves are one way valves that allow for air to escape as the amputee pushes their limb into a suction socket. Once the limb is in the socket the silicone rings of a suction liner (figure 2.43) create a vacuum, holding the prosthesis on until the expulsion valve is released allow air back into the socket.

Computer Modelling

CAD and Parametrics

To interface between the input of 3D scanning and output of 3D printing, Computer Assisted Design, or CAD was required. This research has an emphasis on parametric modelling where models are built using variable coordinates, relationships and algorithms rather than fixed numbers for greater control and customisability.

Several digital prototyping methods have been used during the design phase of this research. Initially the program Solidworks was used for quick visual representation of ideas and iterations. The benefit of the Solidworks (solidworks.com) modelling system is that it is quick and accurate though once a model is constructed it is difficult to manipulate. For increased control forms were resolved and constructed in Rhinoceros (rhino3d.com) using the parametric plug-in Grasshopper. This allows for the structure of the prosthesis, including socket shape, thickness, fin shape and size to all be adjusted to fit the amputee.

Parameters refer to the numerical or boolean controls that can be constructed to customise a CAD file. During initial modelling a large amount of parameters were constructed to offer maximum control, though these were continuously refined to remove any unnecessary, conflicting or overlapping parameters.

The first parametric models consisted of form without detailing allowing for form experiments. Details were later added to the exported models using Meshmixer (meshmixer.com) until it was confirmed these details were functional and they were added to the parametric Grasshopper definition. Meshmixer which offers unparalleled versatility when 3D sculpting mesh files. Equipped with brush tools it is very useful for making quick geometric changes.

The final CAD models were constructed using Rhinoceros and Grasshopper as they offer the strongest parametric control of the software available to the researcher. Grasshopper provides powerful compatibility and workability of .STL meshes, the high density, coordinate based output of most 3D scanners. With customisability for the amputee swimmer being paramount Grasshopper was also favoured for the manner in which it builds 3D objects; using relationships between coordinates and interchangeable nodes that deliver instructions.

Rather than fixed geometry these relationships allow for changes in coordinates and boolean inputs without disruption or breakages in the model. Ultimately offering a platform to build a 'definition' (adjustable model) where fin and socket are customisable by the number of parameters the developer chooses. The amputee swimmer's scanned limb file is subtracted from the socket by simply referencing it to a subtraction boolean in the definition. This simplicity provides the potential for any prosthetist to use this software without the requirement of mastering it.

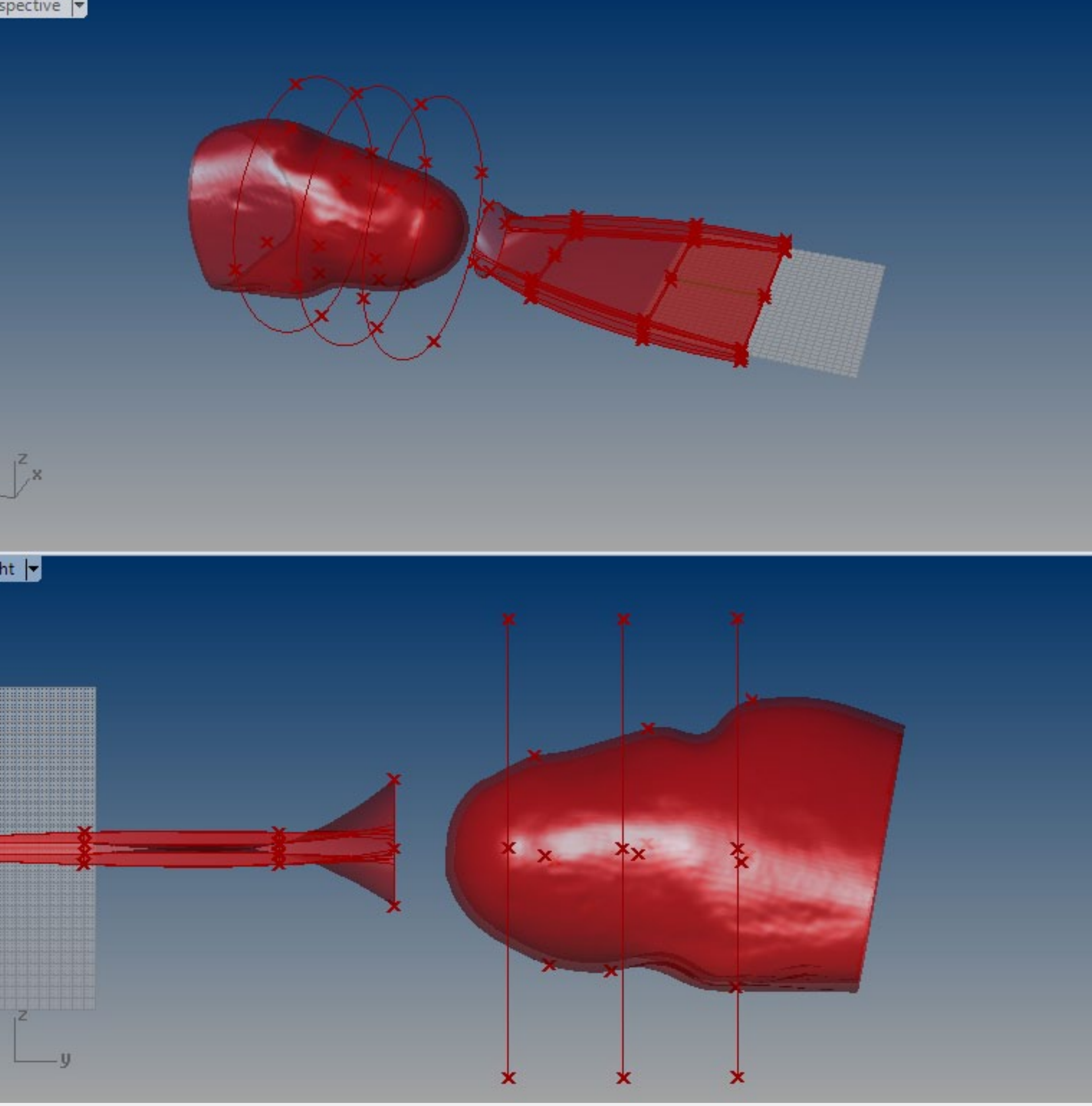


Figure 2.33

A screenshot of the display in Rhinoceros 5 using Grasshopper to model around an anonymous limb scan.

Computer Modelling

CAD and Parametrics

The cloud nature of the mesh generated by 3D scans does not lend itself to the Boundary Representation or "Brep" based geometries used in Rhinoceros or Solidworks. When a mesh is comprised of a set of floating points without relationships, computer modelling software often cannot render specific points for use. Grasshopper offers a very rare tool that overcomes this issue, isolating points in a mesh by deriving the closest point in the mesh from a set geometry. Repeating this tool around the exterior of the scan, on a set XY plane allowed for the construction of a profile curve that closely mimics the exterior of the scan at any given Z value (figure 2.34). Splines were repeated at several different Z values to allow for a loft to be constructed into the fin that retained the natural curve of the 3D scan. This piece of definition was an essential development to ensure that any scan imported could be offset and a 3D model built from.

To reduce mass and create a more honest aesthetic for the socket the Weaverbird plug-in was an essential tool used to build an adjustable offset of the 3D scan of the participant's limb, this offset directly replicated the interior of the socket giving a uniform wall thickness and visual cues as to how the socket offers support.

Development and self reflection of specific CAD models are available in the appendix.

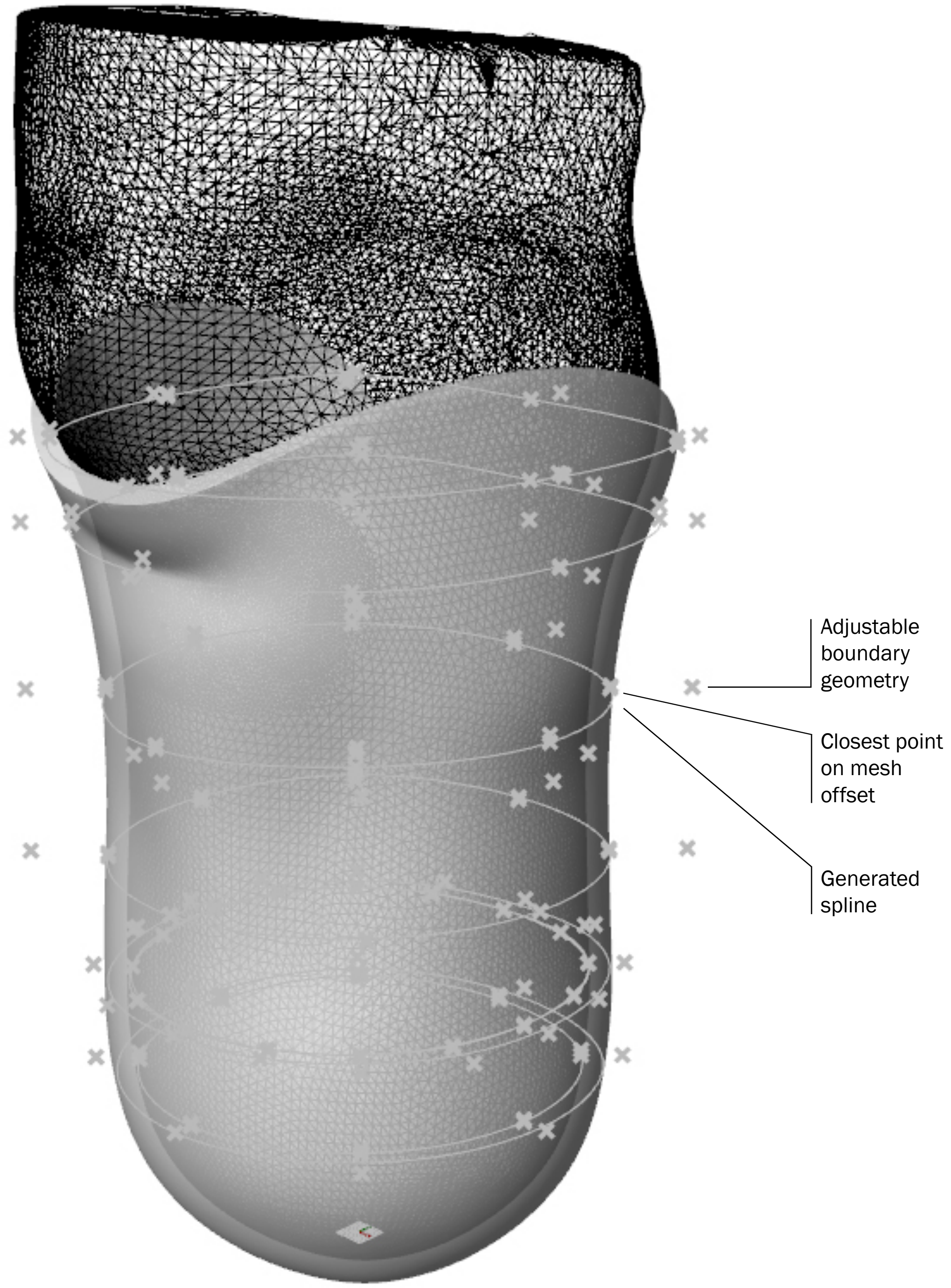


Figure 2.34

Showing the black mesh of the participant's 3D scan, the socket offset and the points and splines that are isolated the mesh. There are required for the prosthesis to be built from as the geometry of the mesh is not directly selectable.

Figure 2.34

Parametric software was used heavily to iterate the forms of fins, sockets, and the prosthesis as a whole throughout this project. These maquette prints are the output of a simple parametric model with adjusted parameters.

Figure 2.35

Figure 2.36

Figure 2.37

Figure 2.38

Figure 2.35: An early parametric model of a walking structure.

Figure 2.36: An iterated walking structure.

Figure 2.37: Scale fin and sleeve models for testing how models could slot inside each other.

Figure 2.38: A later scale iteration of fin and sleeve.

Fin Design

Hydrodynamics and Parametrics

A fin requires several factors to be taken into account to generate efficient forward propulsion. An analysis of previous studies was used to determine what these factors were. These studies included qualitative analysis of manufactured fins and studies of marine animal morphology.

The purpose of a fin is to extend the wearer's leverage whilst using kinetic and elastic energy to generate thrust in a specific direction. A medium-short length was chosen as this prosthesis is intended for pool use. Whilst longer diving fins with an oscillating motion provide greater thrust, shorter flippers which do not oscillate offer greater acceleration (Pendergast et al., 2003) and can match the length of the user's other foot, making them far less cumbersome and more appropriate in the pool.

The first detail required for an efficient fin, once a blade form is established, is a mechanism to channel water through the front of the fin, creating directional force. Pendergast et. al. highlight that a beam at each lateral edge of the fin offers sufficient channelling. Initial test models of fins used an I beam along each edge until this became a more incorporated feature in the final fin design. (2003)

The final fin has a lunate cutaway at the tip (figure 2.42, p. 57). The decision to include this has come from previous research completed by Liu and Bose that suggested a crescent offered greater efficiency, comparing the whale's truncated fin, the dolphin and the tuna (Zhang et al., 2012). Though it slightly decreases the total force output of the fin, efficiency is of great importance regarding prosthetics for amputees due to the lack of muscle mass from amputation and atrophy.

Another major factor to account for in efficiency are the points of flexibility and rigidity in the fin itself. Whilst overall Pendergast et al. recommend a fin of medium rigidity ultimately the thicknesses and stiffness of the ideal fin is more complex than this (2003). To truly catch the water it passes through and then thrust this forward, studies by Apalkov et al. (2012) suggest that the most efficient fins from a morphological perspective are those where rigidity "decreases simultaneously from the fixed end to the free end and from the edges to the middle" (p. 173). To achieve this each parametric model differentiated the exterior and interior of the fin creating a varied thickness, hydrodynamically smooth but offering different levels of rigidity with the centre tip flexing inward, catching water in a scooping motion with each kick.

As it developed in form the construction of the fin was refined into a smoother cross section, creating a more aesthetically resolved, singular form that retained the parametric control of previous versions. An advantage of this form is that it is cleaner to print in TPU as it removes interior right angles, areas where the nozzle was liable to catch on previously laid print wall.

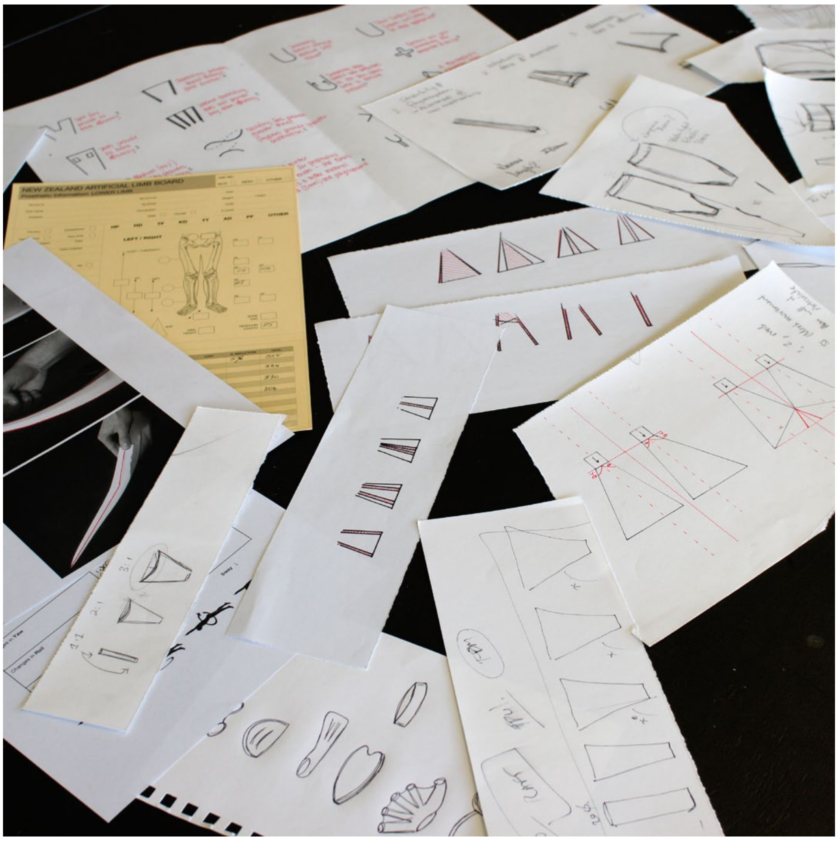


Figure 2.39

Sketches exploring fin shape, width and rigidity.

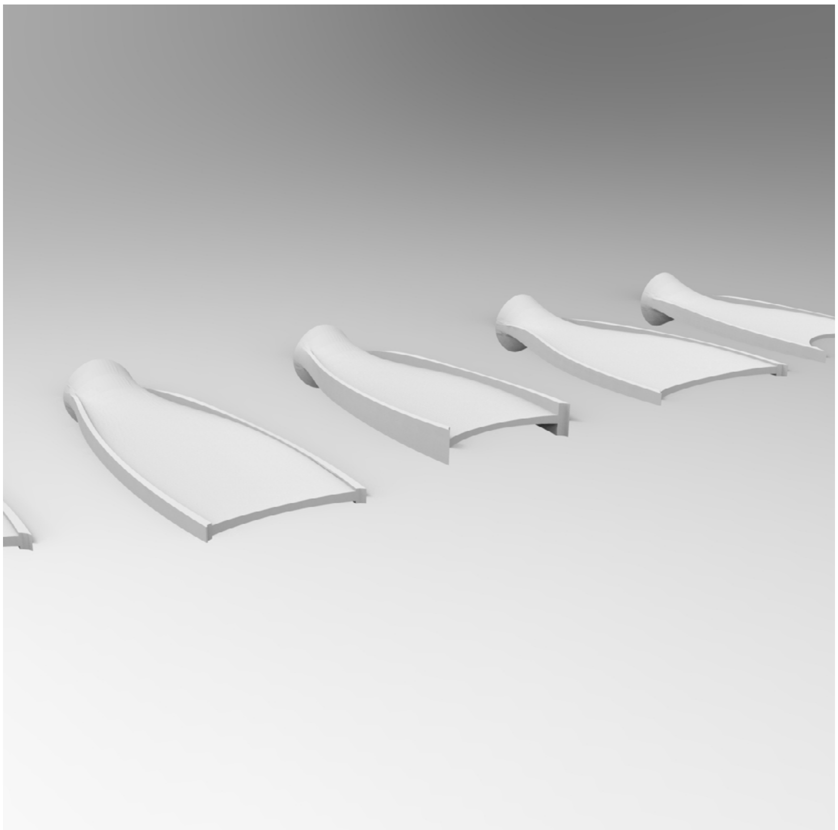


Figure 2.40

Early iterations of fin forms made with a parametric model. These explored thicknesses, widths and ridges.

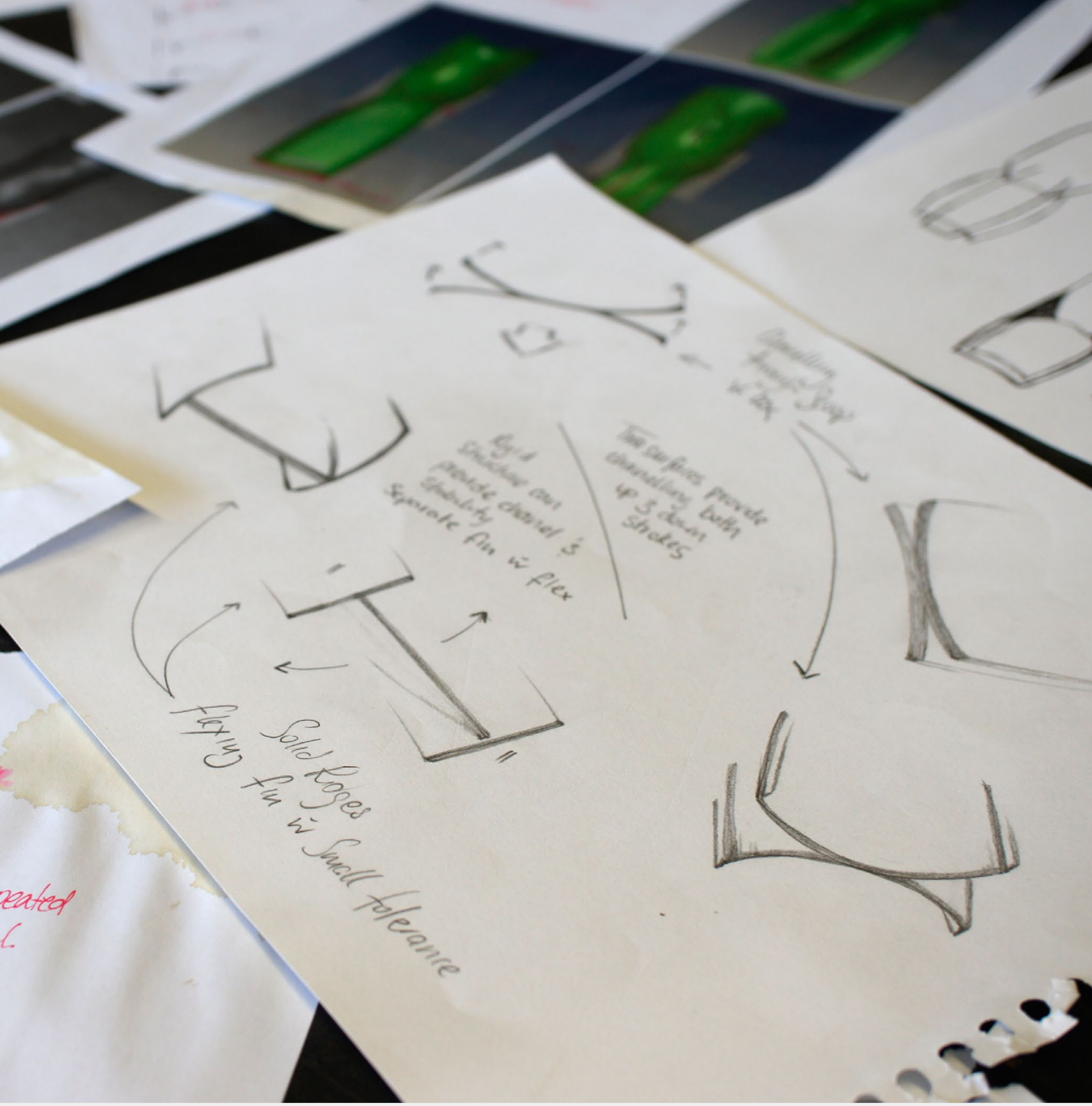


Figure 2.41

Sketches of contemporary fins.

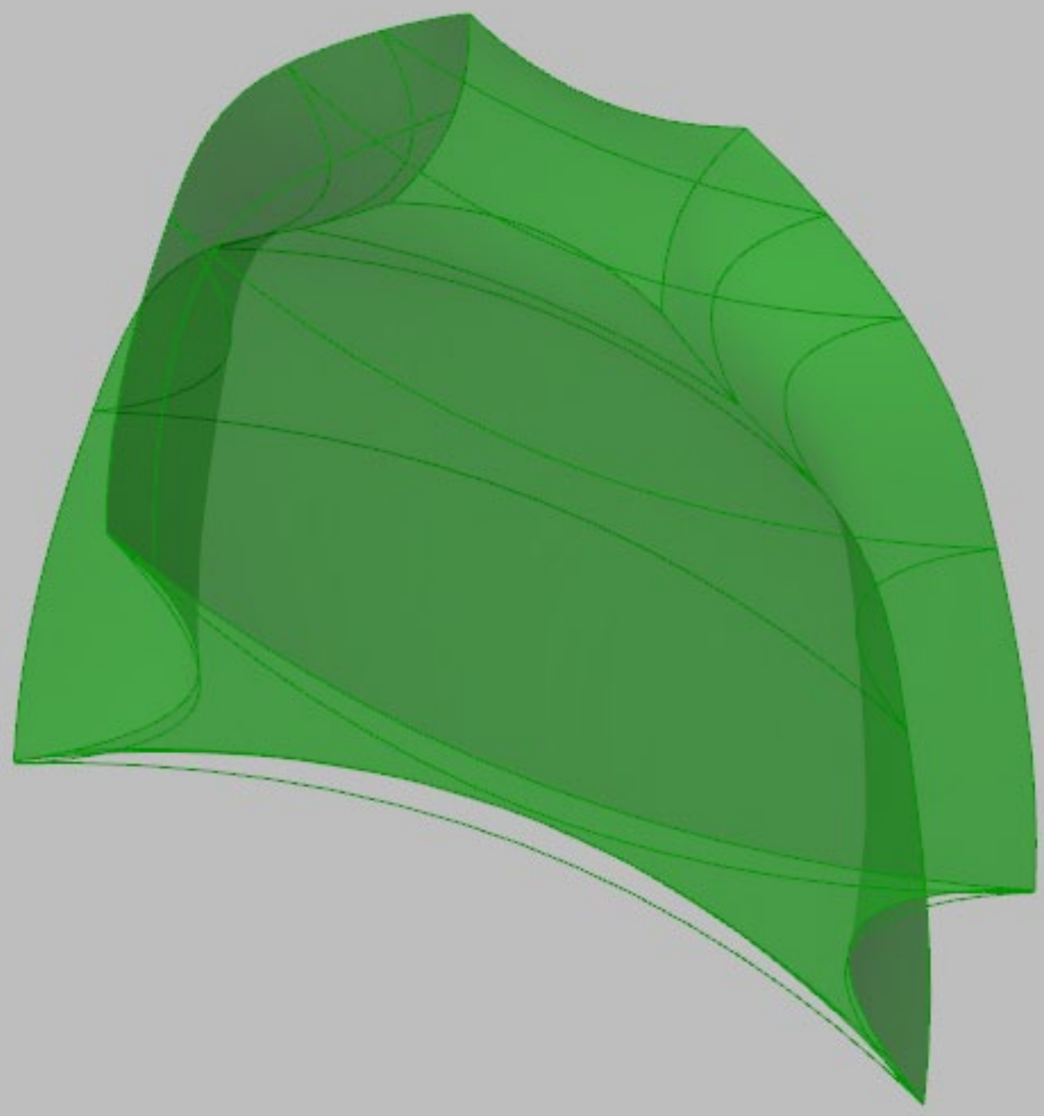


Figure 2.42

The final fin forms uses profiles similar to that of an X that allowed for a smoother printing process with the removal of right angles, yet still offered differences in rigidity and heightened edges for channelling water like ridges.

3D Scanning

Digital Measurement

Two sessions of 3D scanning were undertaken on the participant's limb. One was also attempted on the interior of his walking prosthesis socket and of an alginate cast of the socket interior. These scanning sessions were used to collect 3D data to construct prototypes and to compare the accuracy of the two systems used by Victoria University and the NZALS.

The first scanning session constituted of a clinical prosthetist, the participant and the researcher. The NZALS use a Willow Wood (willowwoodco.com) scanning system consisting of both the software and a handheld 3D scanner. This system is specially developed for the prosthetics sector, offering streamlined and controlled scanning and manipulation for prosthetists to quickly prototype limb forms. It is a very refined, even down to the semiotics and audible user feedback. The process undertaken to generate the 3D scan involves the amputee wearing their liner (suction or otherwise) and the prosthetist plastic wrapping the exterior to create a smooth surface for the scan. This is done to account for any space that the liner will take up in the prosthetic socket. Following this two black points are stuck to the limb, under the patella and at the end of the tibia. There are reference points for the scanner's software to automatically align the scanned images.

The scanning process took approximately ten minutes. After scanning the prosthetist began to manipulate the digital model, creating the traditional form of a suction prosthesis. This involves actions such as removing material under the patella to create the prostheses patella bar before building a cut line and exporting the file.

Figure 2.43

A prosthetist wraps the limb of the participant in a clear film to help with scanning. During scanning the amputee wears their liner to account for the extra space it takes between the limb and socket.

Figure 2.44

The prosthetist then uses specialised software and a brush stroke based tool set to digitally manipulate the scan.

When attempting to recreate this at the university, whilst the partial scans themselves were accurate, the Artec Studio 10 software was unable to automatically align such smooth geography. Due to the curvaceous nature of the limb the researchers could not manually align the separate scans either.

The main difference between these systems is the specialisation of the Willow Wood products used by the NZALS offering superior simplicity in capturing the simple geometries of the stump, and simplicity again in editing the 3D model to create the appropriate prosthesis interior. When replicating the technique used by the NZALS, the Artec Eva (artec3d.com) 3D scanner owned by Victoria University, though far higher in precision, was less effective due to the complex nature of its aim to function universally (Artec 3D, 2016).

After scanning the limb itself we attempted to scan the interior of the participant's favourite prosthetic socket to use this negative to understand the differences we were experiencing in the fit. Though we had previously completed this type of scan on a similar socket, the 3D scanner was struggling to image the bottom of the socket and lost reference due to the reflective and slightly transparent socket.

Alginate casting provided a non-intrusive manner of making a positive of the participant's socket (figure 2.45, p. 62). Using a plastic bag as a handle to remove the cast, the socket was filled with approximately 2 litres of casting mixture and let set. Due to rapid dehydration and deformation of alginate casts a 3D scan was taken within hours of it setting (figure 2.46, p. 63). This scan was a simple task using the Artec Spider Scanner. This scanner is incredibly precise and succeeded due to the ability to reference the dimpling in the alginate cast from air trapped during the casting process. This dimpling was then removed using a smoothing tool in the program Meshmixer.

Figure 2.45

Setting the alginate cast.

Figure 2.46

The alginate cast prior to scanning.

3D Scanning

Digital Measurement

This scan was then oriented and overlaid with the 3D model crafted by the NZALS (figure 2.47). It was clear that, although similar at the end of the tibia, the material removed everywhere above the immediate distal region of the stump was far higher than the participant's previous hand fabricated socket. This scan now offered a comparative insight into the shortcomings of digital manipulation as opposed to the intimate handcraft of traditional fabrication. Whilst these new technologies themselves are innately accurate, without the years of experience that a prosthetist has in traditional fabrication, it may take time before freehand digital manipulation is reliable.

This scan was developed for a Patella Tendon Bearing, or PTB socket. The decision to use a PTB socket with suction suspension came from conversation with clinical prosthetist who has highlighted his preference for this manner of adherence due to it's reliability and comfort. The physical form of a suction socket was also taken into account, being appropriate for FDM printing as a solid shell with little detailing. With accessibility in mind this type of socket can be recreated for New Zealand amputees as, according to NZALS clinicians, it is the predominant form of socket.

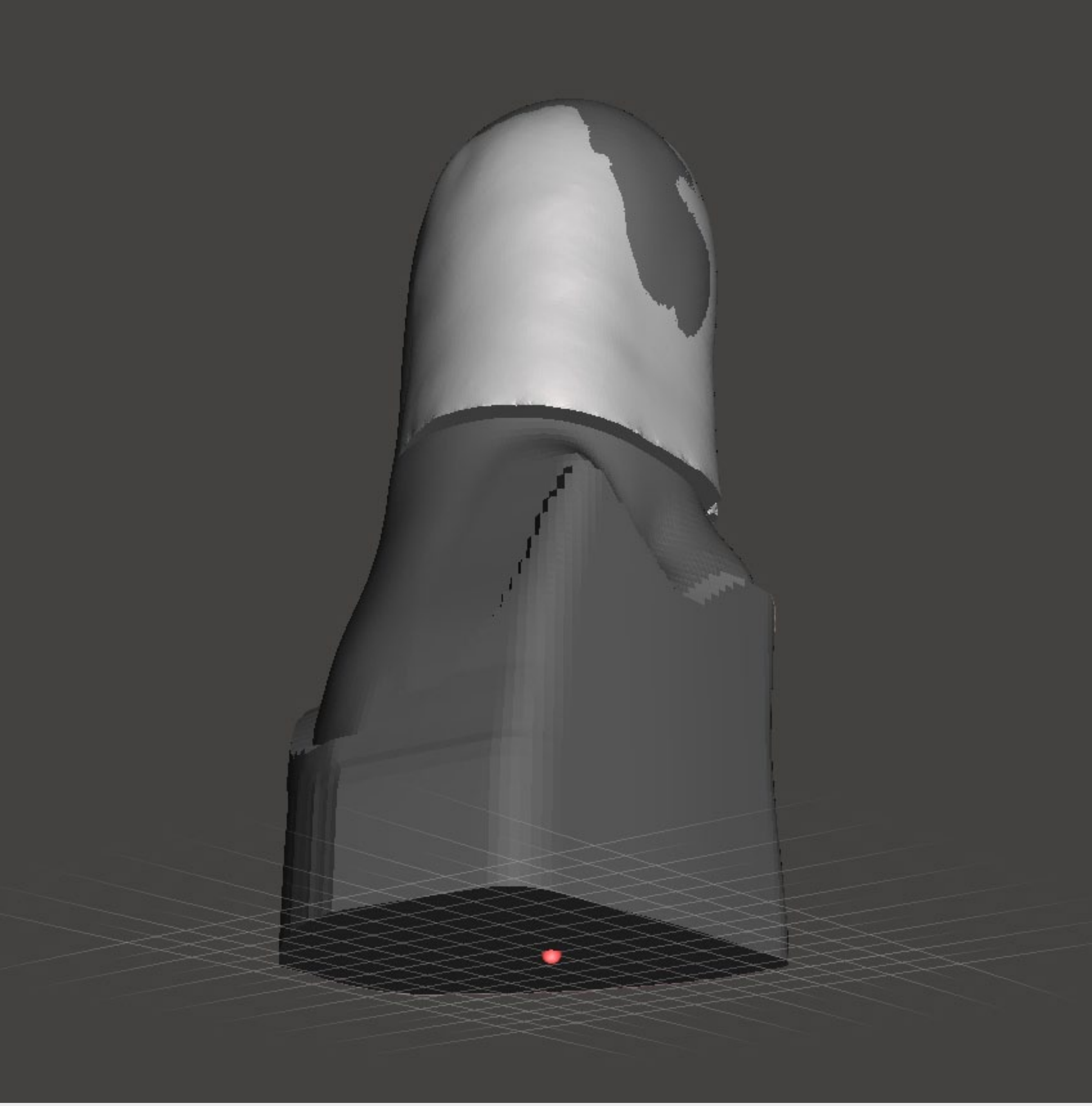


Figure 2.47

An overlay of the prosthetist's scan (dark grey) and the alginate cast scan (light grey) shows a clear difference in circumference around the middle of the limb but less of a difference at the end of the limb.

Fitting

Once a scan of the participant's limb was completed it could be imported into the parametric Grasshopper file to replace the placeholder limb. Prototype prints and testing were completed in frequent cycles to quickly acquire participant feedback and in turn integrate this feedback into the next iteration. User feedback is paramount as comfort can only be assessed by the user.

Flexible TPU was initially used in 3D printed test sockets (figure 2.48) as it was intended that the prosthesis could be fabricated from one single material; socket and fin. Limitations arose in testing, revealing that flexible materials alone are not suitable for prosthetics sockets - load bearing or otherwise.

One of the final ABS sockets (figure 2.54, p. 71) test became an unplanned exercise in participatory design. With the participant bringing a rasp file he was able to adjust the cut line at the back of the socket to account for some rubbing against his leg tendons, called the gastrocnemius. This muscle has been a repeated issue during fittings as these two tendons move a large amount with each flex of the leg, changing form and rigidity.

Figure 2.48

The researcher taking notes on a test socket as the participant advises where the socket may need adjusting.

Sockets in figures 2.48-2.52 were constructed with the second parametric model, figure 4.02 (p. 139). This model used an adjustable loft with the scan subtracted to create the interior.

Figure 2.49

An early test socket in TPU with adjustments noted during test fitting. This needed the back raised and the patella bar increased.

Figure 2.50

This socket was an 8% size increase, it also has an interior coating of polyurethane to fill any small holes in the wall to increase suction.

Figure 2.51

A socket that had been iterated with the knowledge gained from sockets in figures 2.49 & 2.50. Epoxy can be seen here which was added to fill small holes in a seam left by the FDM process.

Figure 2.52

A TPU socket that was tested to check if a clamping mechanism could provide sufficient adherence to the limb, much like Stark's Neptune Prosthesis. This did not hold with even the smallest amount of torque applied.

Figure 2.53

The first ABS socket was a direct offset of the scan with a 5mm wall. When tested this socket revealed that the scan was too long. This was noticed when fit requirements changed as the rigidity of the socket changed. It is thought that the hard socket gave the participant more tactile feedback. It was clearly too long and the patella bar was too high.

Sockets in figures 2.53-2.56 were constructed with the third parametric model, figure 4.03 (p. 141) using a direct offset of the participant's scan to create the socket wall.

Figure 2.54

The participant sculpting the cut line at the back of the second ABS socket iteration.

Figure 2.55

With an edited top profile the second ABS socket fitted the participant well.

Figure 2.56

The socket in figure 2.55 was replicated in TPU to confirm the differences between a rigid and flexible socket. This could not hold suction due to the thin, flexible wall warping and pushing away from the suction liner. It confirmed that and ABS socket was more appropriate, even when the prosthesis is no load bearing.

Swimming Pool Tests

User testing of concept prototypes

The socket in figure 2.51 (p. 69) was the first to fit and hold suction when tested out of water. It was then tested by the participant in the pool to see if the introduction of water or lateral kicking changed the quality of suction. This socket was built from the second parametric definition in a high density TPU with a wall thickness of 10mm. This was coated in a polyurethane spray over all interior surfaces to help fill any holes that may have been left in the FDM process. The first socket tested in water was very successful with the participant diving from the side of the pool and coming up from beneath the water with the socket remaining attached. He then proceeded to swim his usual routine, in the 25 metre lane pool, doing five lengths swimming and 5 lengths water jogging. The socket held throughout these sets with some minor loss of suction.

The first full prosthesis (figures 2.57-2.60) was the final output of the second parametric model (figure 4.02, p.139). When tested it presented some difficulties retaining suction. Complexities arose with the large amount of force required for the participant to push his limb into the suction socket. This force, specific to the participant, measured at 80 kilograms of mass to expel all of the air through the expulsion valve. The TPU fin intended for the end of this prosthesis was not going to be able to hold any weight as the participant put it on. Because of this it was decided to build the model in separate pieces offering a flat stable surface for the participant to safely push his limb into the socket and the three separate fins that could then be attached by screw (figure 2.57). Different sizes of fin were compared to estimate the amount of output required to match the participant's whole leg and recreate anthropometric symmetry.

Figure 2.57

Attaching the fin to the first prototype prosthesis.

Figure 2.58

The participant about to dive into the pool after being wheeled to the edge.

Figure 2.59

The participant diving into the pool from the edge wearing the first full prototype.

Figure 2.60

After swimming, sitting on the edge of the pool.

When swimming with the prototype prosthesis he noticed a dramatic increase in performance, reducing the time it takes for him to complete 5 lengths of freestyle from approximately 5 minutes to 3 minutes and 30 seconds. After testing his swimming speed he repeated the test that identified his asymmetry during the initial observation. With the prosthesis on he managed to double the distance he could swim with his eyes closed and hands by his side before breaching the side of the lane both with his body facing upward, and downward. Of the fins tested the participant preferred the larger of them, acknowledging that this was partially due to a thirst for speed rather than the intended symmetrical swimming stroke. The increase in propulsion from his left leg allowed him to swim more freely with less torsion in his body and less compensation by his right arm.

As testing continued and a functional swimming prosthesis was developed it was decided to investigate the issue of getting to and from the pool. Though the primary aim was to research the opportunity of developing a 3D printed swimming prosthesis it was observed that there was considerable difficulty, inconvenience and lack of independence when using a wheel chair to get to and from the pool.

The second full prototype tested (figures 2.61-2.64) was an amalgamation of the swimming fin and a prosthesis that had the convenience of walking, it was the third major development in the parametric model (figure 4.03, p. 141). The walking structure also allowed for him to don the limb as easily as his current walking prosthesis. It used an ABS socket with a TPU fin inserted. For load bearing structure there were two ABS and fibreglass blades running down the exterior of the fin with a stirrup for easy removal. The limb held his weight for testing purposes but it was clear, with visual buckling, that it would not have enough strength for extended use. As the participant walked to the pool he gave positive feedback on the walking experience. We learnt that the base of the limb needed to have the exterior, his left, increased by 4mm in length due to the angle that the leg makes contact with the ground.

Once in the water the socket held very well, with minimal water intrusion. A benefit of the singular piece being load bearing was that it allowed him to walk whilst in the pool, but this came at a dramatic cost as once he started swimming. We quickly learnt that the blades, intended to face forward and produce minimal drag, were channelling water too powerfully for him to control and drawing the prosthetic limb directly under his body with each stroke, making it uncomfortable and difficult to swim.

After testing and discussion it was decided that a structural sleeve, removable at the pool side or once in the water, would be a better option to allow the amputee to walk to the pool but also retain maximum comfort and efficiency in the water.

Figure 2.61

The participant donning the second full prototype.

Figure 2.62

The participant about to dive into the pool after walking from the changing room.

Figure 2.63

Downward strokes while swimming with this prototype were causing the limb to sweep under the participant's body uncontrollably.

Figure 2.64

Using the stirrup at the end of the prosthesis whilst activating the expulsion valve to remove the limb from the prosthesis.

Final Concept

A culmination of research, design and testing

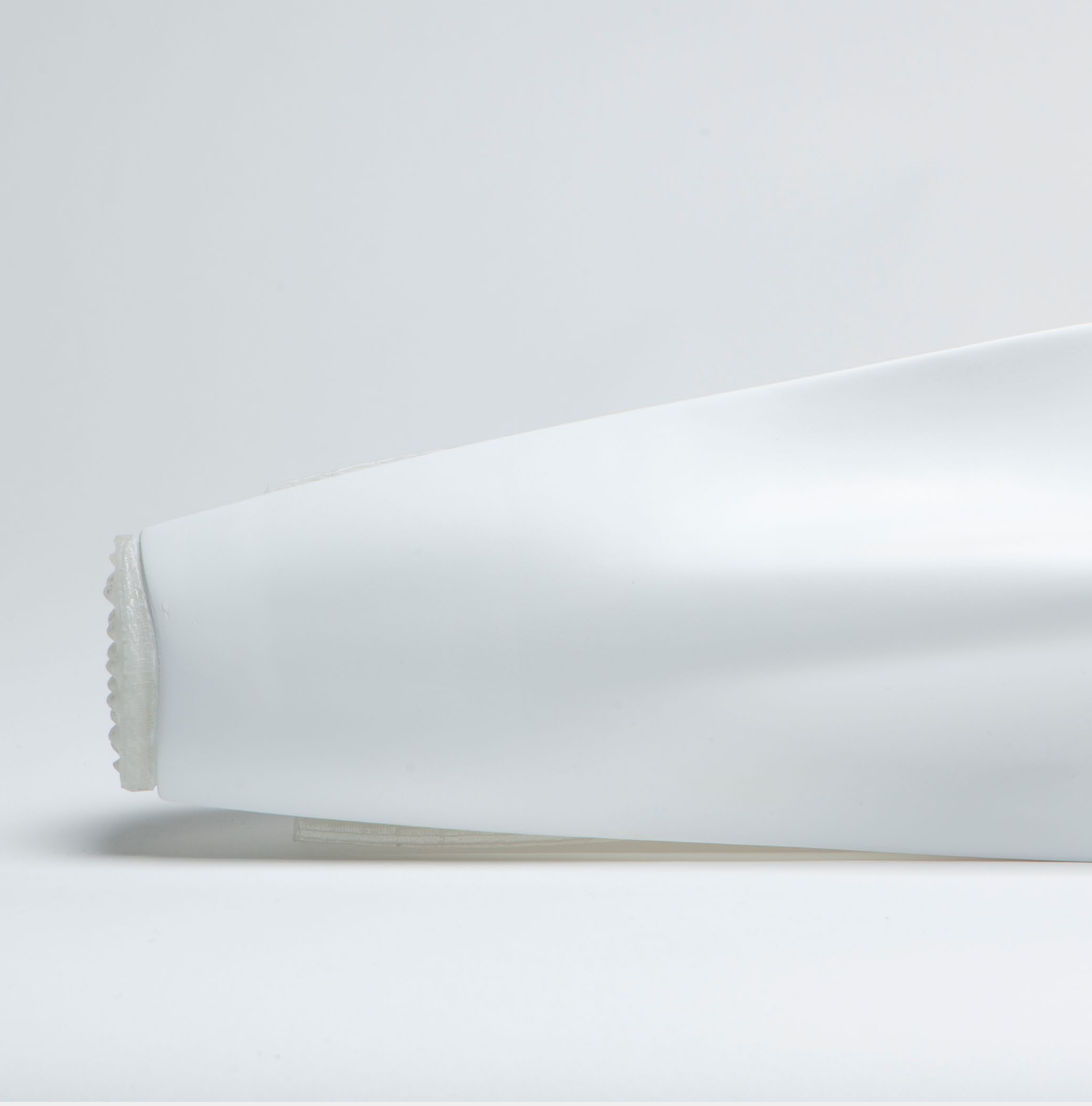


Figure 3.01

The front view of the final 1:1 prototype.

Figure 3.02

The right or exterior view of the final prototype showing the tibia and calf inspired forms as well as the expulsion valve.

Final Concept

Three full models of this concept were constructed, an initial test model, a hollow form test and a final prototype. Though the aesthetic changed dramatically from the second prototype these were still built off the same Grasshopper definition.

The final fin form (figure 3.04, p. 94) influenced the form of the swimming prosthesis as a whole. This was designed as one hydrodynamic flowing loft. It is physically very light with a 5mm thick socket, offset directly from the 3D scan, a moderately sized fin, and a lofting section joining these two components. The expulsion valve is nestled within the curves of this loft to avoid being knocked. The exterior sleeve (figure 3.03, p. 92) also takes visual cues from the fin. It mimics the tibia by holding weight directly under the patella, visually and physically similar to the leg's shin. It attaches when the interior prosthesis is inserted through a low tolerance between the two pieces and the flex of the fin.

For prototyping, the sleeve and interior prosthesis were both printed in 3 pieces due to the maximum build height of the printers used. In order to ensure no delamination of the print joins two fibreglass protrusions were inserted through the front and back extrusions of the sleeve, it became a very stable prototype with the 3D print offering a strong XY platform and the protrusions giving strength to the Z axis height of the print, the weakest element in the FDM process. Though printed TPU has been essential for the required flex of a swimming fin, the final prosthesis used TPU in just two prints, the fin segment itself and a grip that covers the foot of the prosthesis for non-slip contact with the ground. The body of the socket and the sleeve were constructed in ABS for structural security and its air-tight build.

The interior prosthesis is designed to flow almost seamlessly off the amputee's limb using a thin offset as an extension of their body. It uses a contemporary fin form that creates a more organic and curvaceous flow from the socket than a traditional I beam fin could.

The sleeve form was explored through the dissection of the previous concept with several iterative maquette models (figures 2.37 & 2.38, p. 53) though it was realised that the walking structure from the previous prototype was merely a legacy feature. The anatomy of the leg was explored until an abstraction of the calf muscle and tibia were formed around the interior prosthesis. These anatomical features were highlighted to give visual narrative to the sleeve and help anyone viewing the prosthesis to understand where the load was weighted (figure 3.03, p.92).

Final Concept

The result of the model's anatomical inspiration is a prosthesis that integrates with the body, regardless of gender. It communicates its function through a flowing, forward facing form and tells a visual narrative expressing the relationship between the interior swimming fin and protective, exoskeletal walking sleeve.

When the participant first saw the final model he expressed satisfaction with how it looked, indicating he would be proud to wear this, perceiving it as "futuristic". He donned the whole prosthesis without any issues. The fit was similar to his walking prosthesis. Though the swimming fin is very light, with the fin and sleeve together this limb weighed a very similar amount to his walking limb. He was able to stand up and walk easily to the changing room. The grip held to the wet floor of the changing room without any fault. Once changed and ready the participant walked to the edge of the pool. Researchers decided it was appropriate to let him decide how he wanted to enter the pool, with the options of a ladder, sitting on the side or diving. He dived in. Once resurfaced and standing he was able to slide off the sleeve with ease and placed this on the side of the pool.

Once swimming, the prosthesis increased his speed and reduced his rotational path and in turn reducing the amount his body compensated. He reported exhaustion after completing 5 lengths of the pool using the prosthesis. It was concluded between participant and researcher that this was related to the change in force that his amputated leg was exerting. During swimming this model presented superior suction to previous prototypes with a strong hold but after swimming was easily removed with the use of the prostheses' expulsion valve, much like a prosthetist crafted socket.

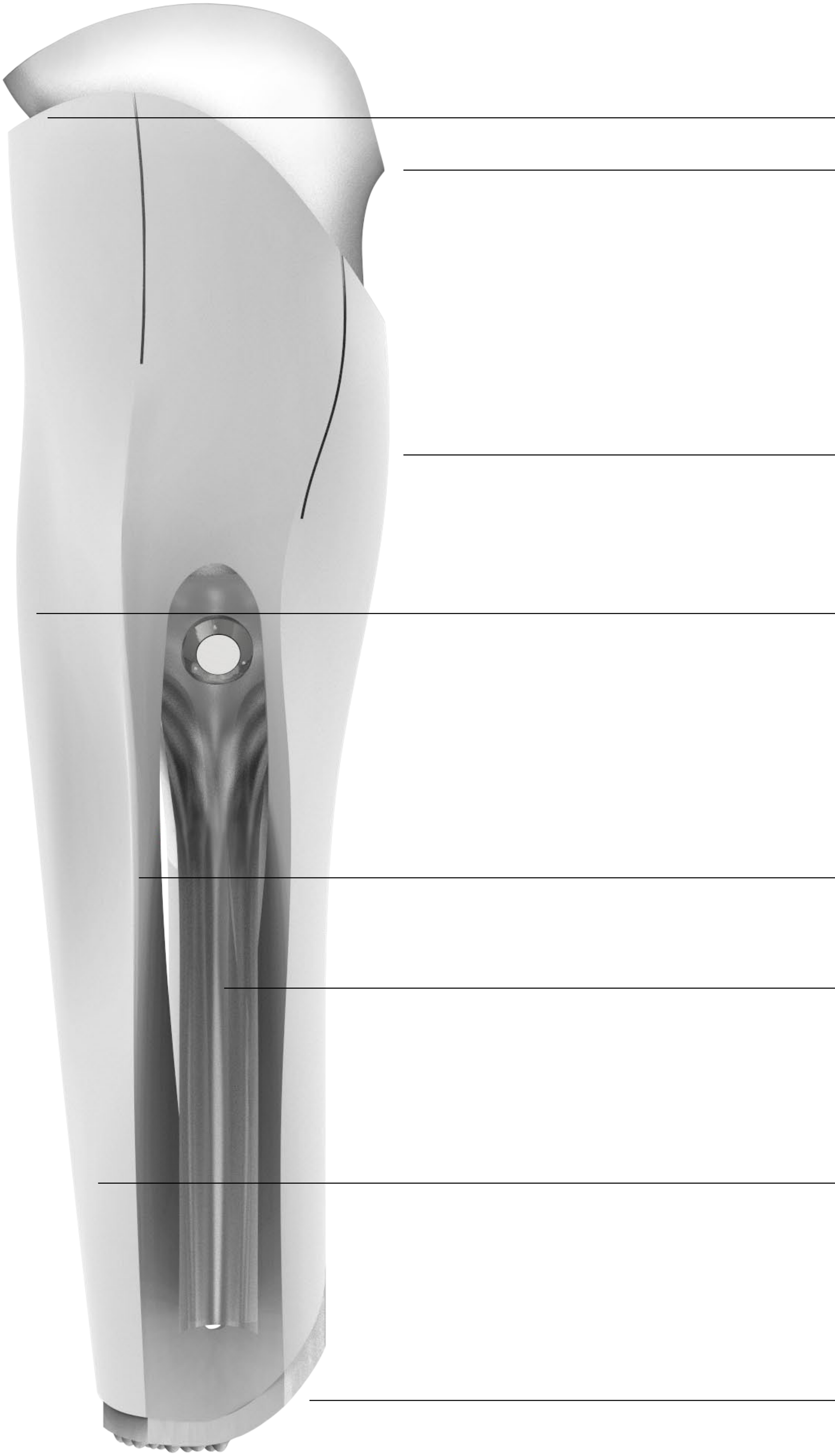


Figure 3.03

Patella Joint
visual connection and load/weight
Tendon Muscle

Calf Muscle

'Shin' Bone
visual forward direction

Exoskeletal Ridges
visual protection

Interior Fin
visual payload

Tibia
visual load/weight

Heel Bone
visual forward direction

Figure 3.04

A render of the interior fin, used for swimming once the sleeve is removed.

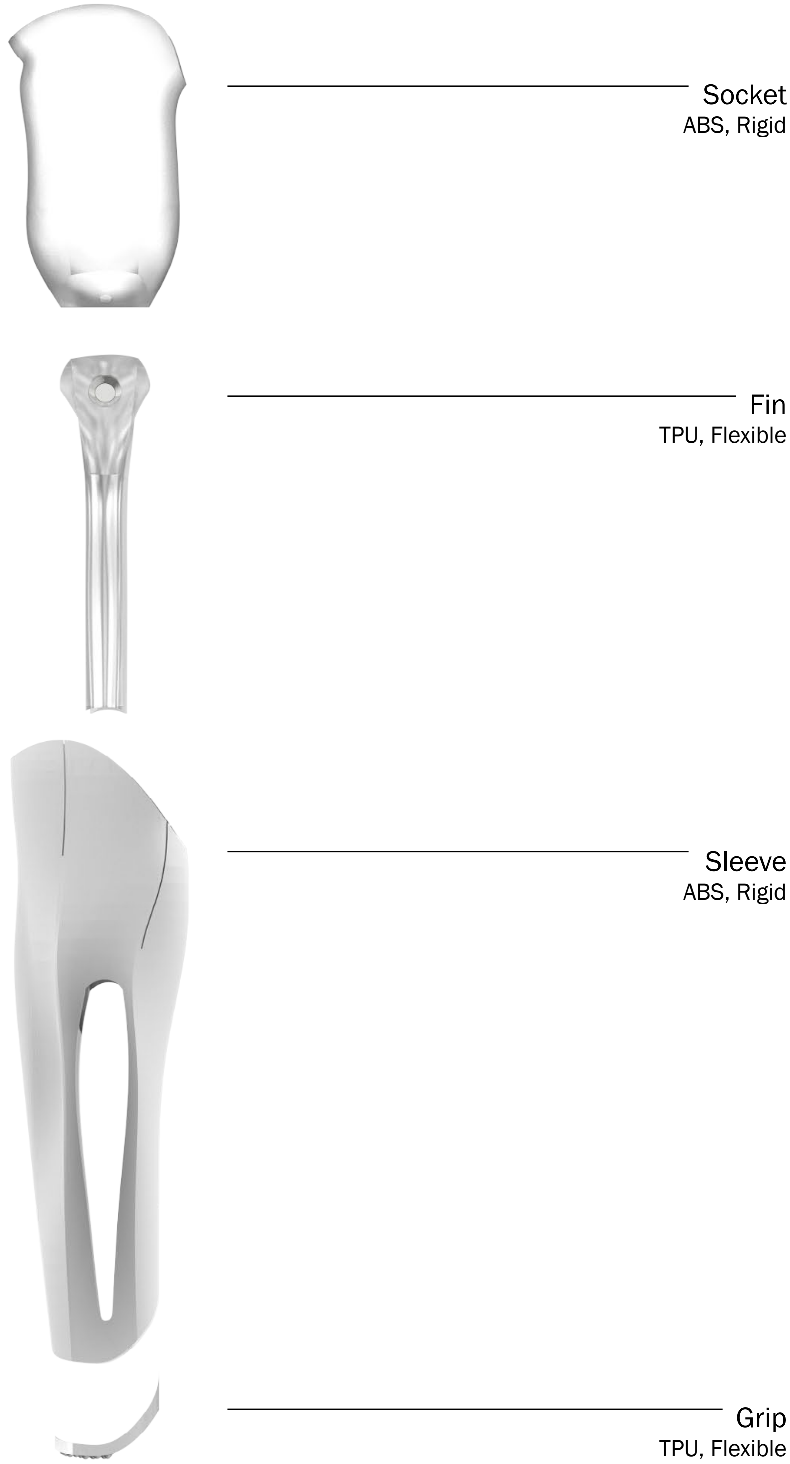


Figure 3.05

An exploded render of the four printed elements of the final design.

Figure 3.06

An image of the final prototype showing the anatomical referencing in the form and the relationship between the strong exoskeleton and ergonomic interior.

Figure 3.07

An image of the final interior fin prototype showing the changes in fill density used to achieve adequate weights, strengths and flexibility.

Figure 3.08

The participant standing at the edge of the pool after walking from the changing rooms wearing the final prototype.

Figure 3.09

The participant diving into the pool wearing the full final prototype.

Figure 3.10

The participant swimming with the interior fin after sliding off the structural sleeve.

Figure 3.11

The participant sitting at the edge of the pool after swimming, wearing the interior fin.

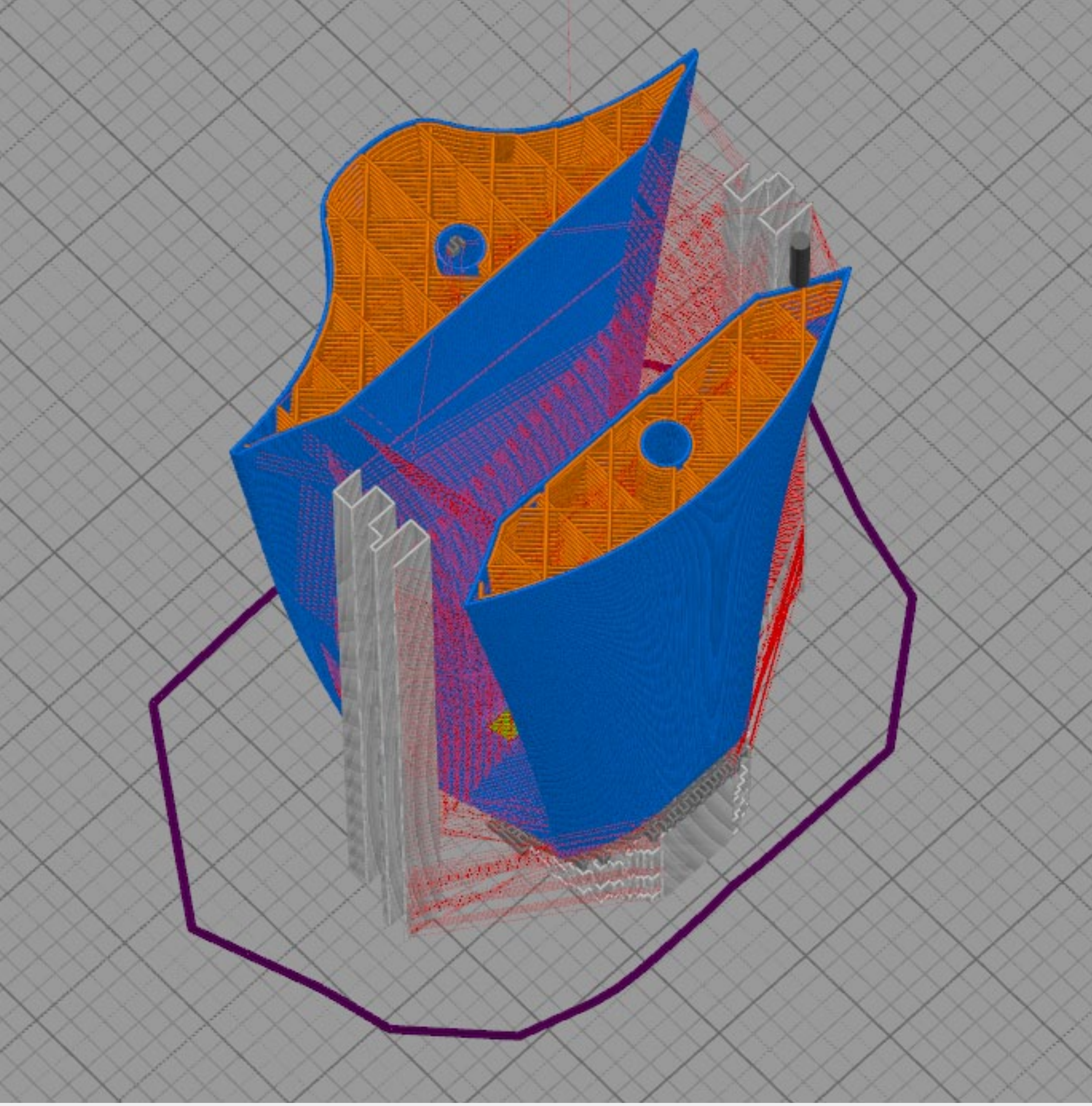


Figure 3.12

Software showing a customised fill pattern using angles at -45, 45 and 90 degrees from the X axis to provide support for lateral forces.

Large Format Tests

Toward the end of this research tests were completed using a large scale FDM printer, the BigRep One (bigrep.com). This printer has a build volume large enough to print the prosthesis concept as a single print ($1m^{3}$) and dual extruder heads two allow for both rigid and flexible materials to be printed together. This printer was used to construct a light weight shell of the final prototype sleeve. Reducing any post-fabrication and increasing the build strength. The model was built from bottom to top without the need for large amount of support material and though a low resolution it was successful in quality and consistency of build.

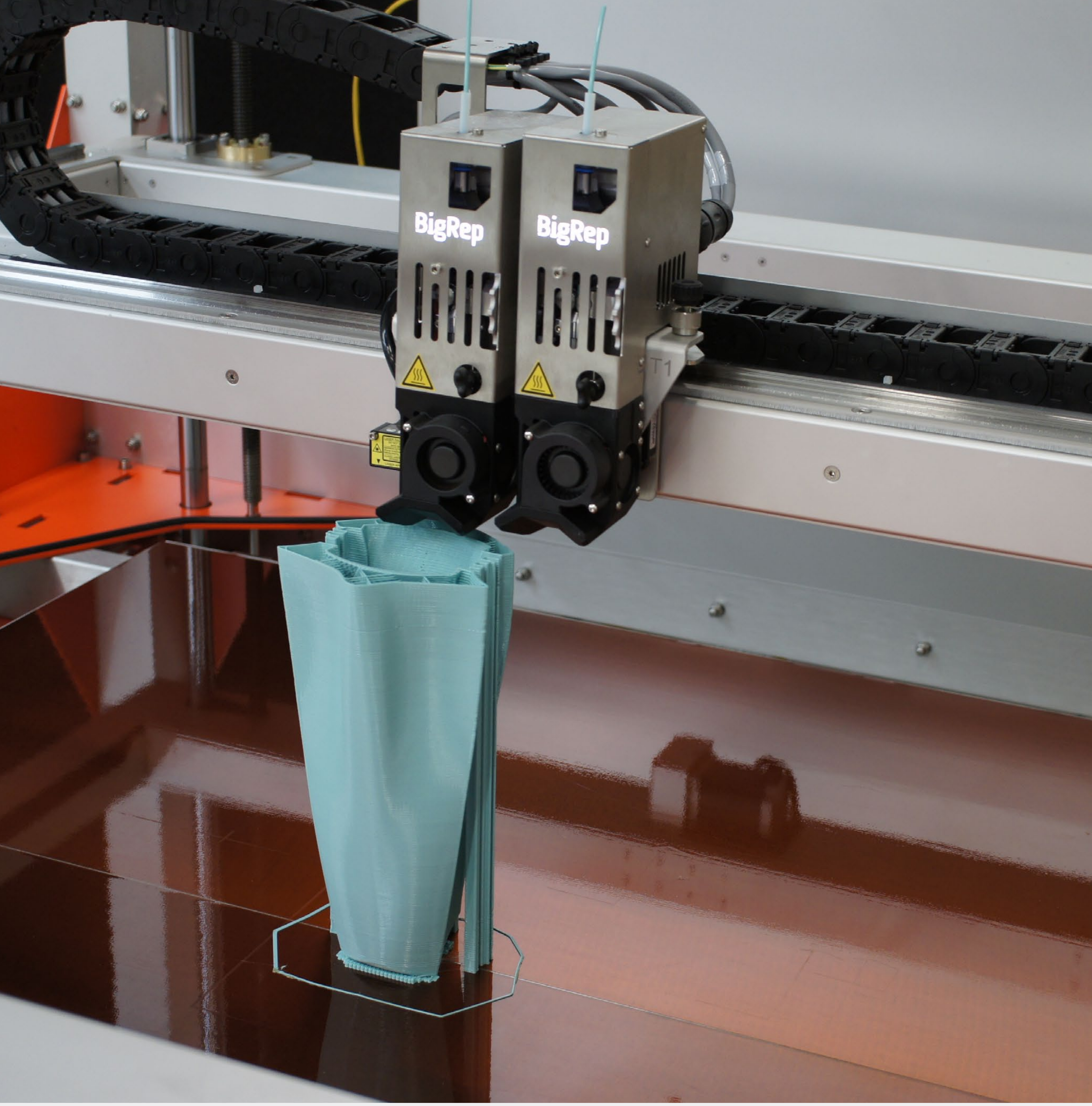


Figure 3.13

The BigRep One, a large format FDM 3D printer printing a shell of the sleeve in PLA.

Figure 3.14

A PLA shell of the sleeve printed in full scale, as one print.

Figure 3.15

With TPU and ABS materials available in a wide range of colours, customisation could be easily available for not just form, but colour too.

The participant was asked which colours he would ideally like each piece of the prosthesis to be, as the materials used are available in many colours. He chose a yellow sleeve and black fin to represent his favourite sports team.

Figure 3.16

A render of the participant, or wearer's view from above.

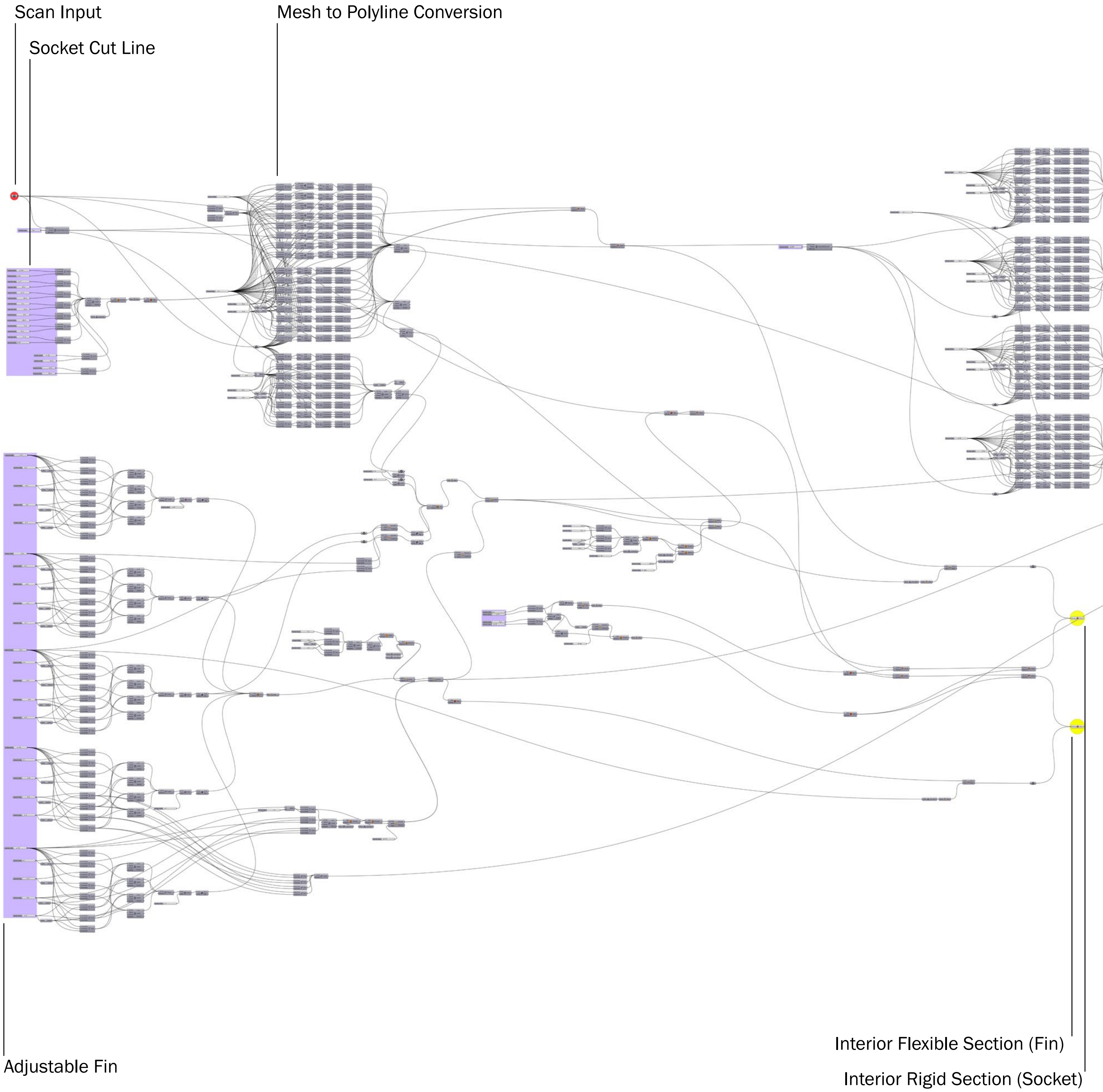
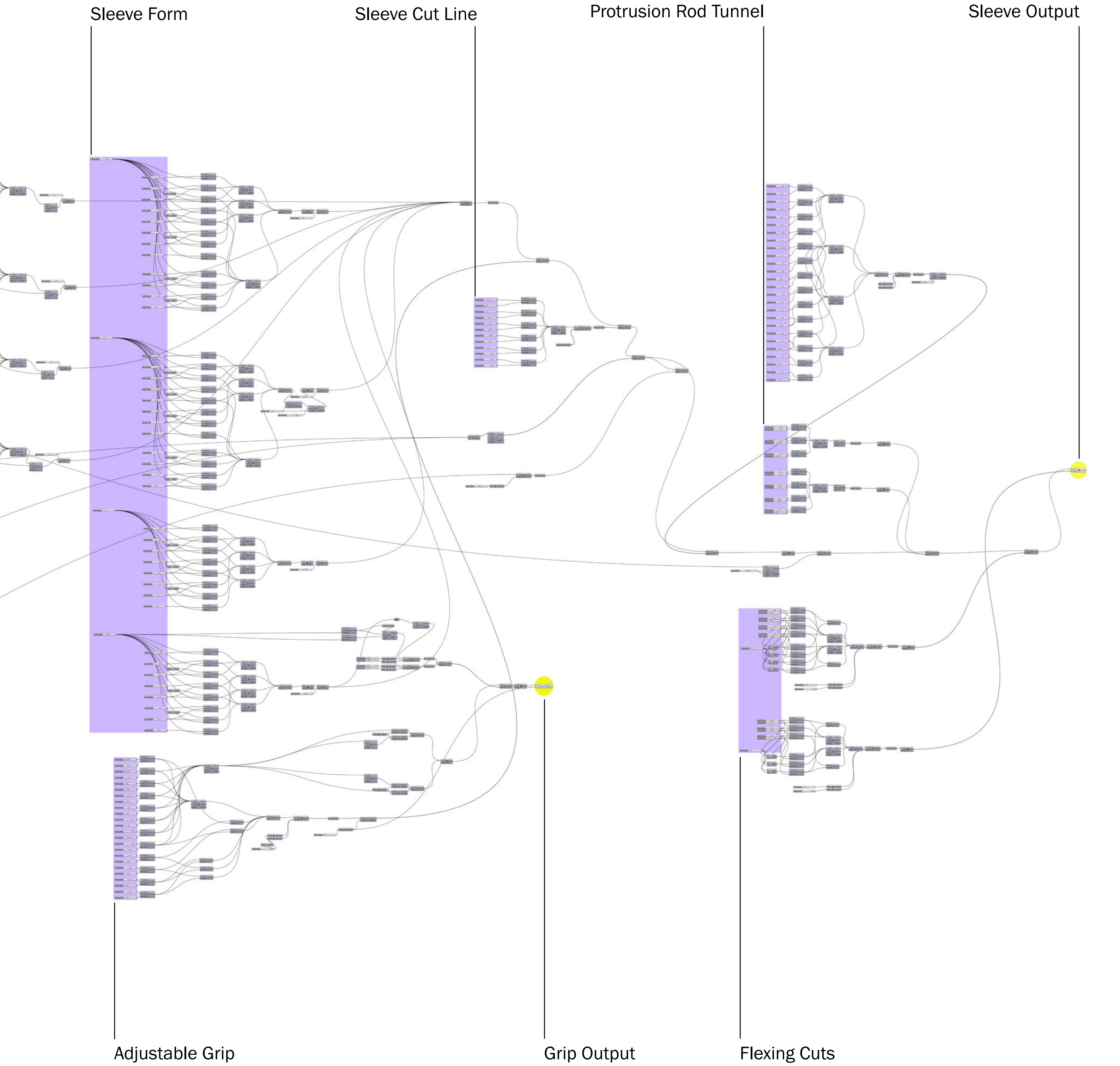


Figure 3.17

The final parametric definition as displayed by Grasshopper.


Sleeve Form
Sleeve Cut Line
Protrusion Rod Tunnel
Sleeve Output
Adjustable Grip
Grip Output
Flexing Cuts

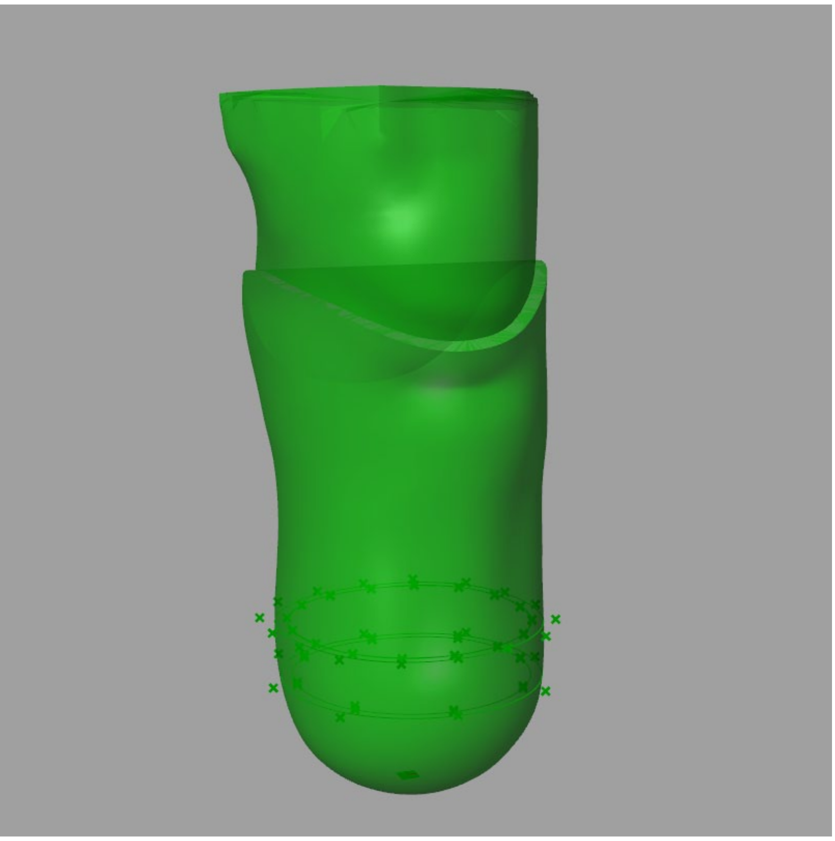


Figure 3.18

To create the basic socket form a scan of a limb needs to be imported. This is then directly offset by 5mm to create the exterior wall of the socket then subtracted to create the interior. A ‘difference’ along it’s side profile creates the top cut line. The thickness of the socket wall and the shape of the cut line are both adjustable.

Toward the end of the stump, as meshes have no selectable geometries, a definition was created to allow for a the location of several exterior points of the scan along a Z axis plane. These points are necessary for building off the direct stump offset and can be repeated at any point on the Z axis.

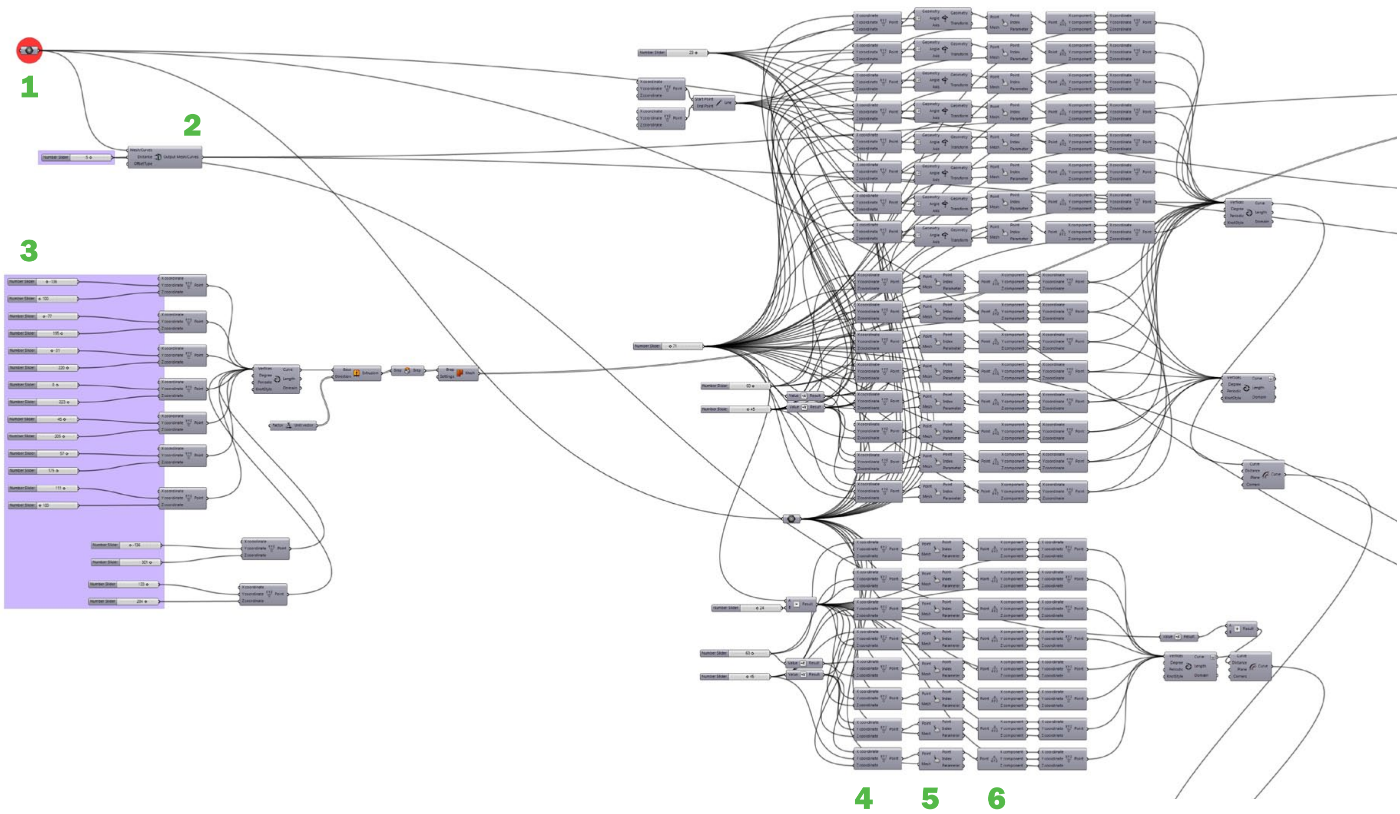


Figure 3.19

1: 3D scan is input. 2: Scan is offset to create socket thickness. 3: Adjustable top profile is cut. 4: Guide splines are created. 5: Closest points to the splines are located on the scan mesh. 6: Spline mimicking the limb profile is rebuilt.

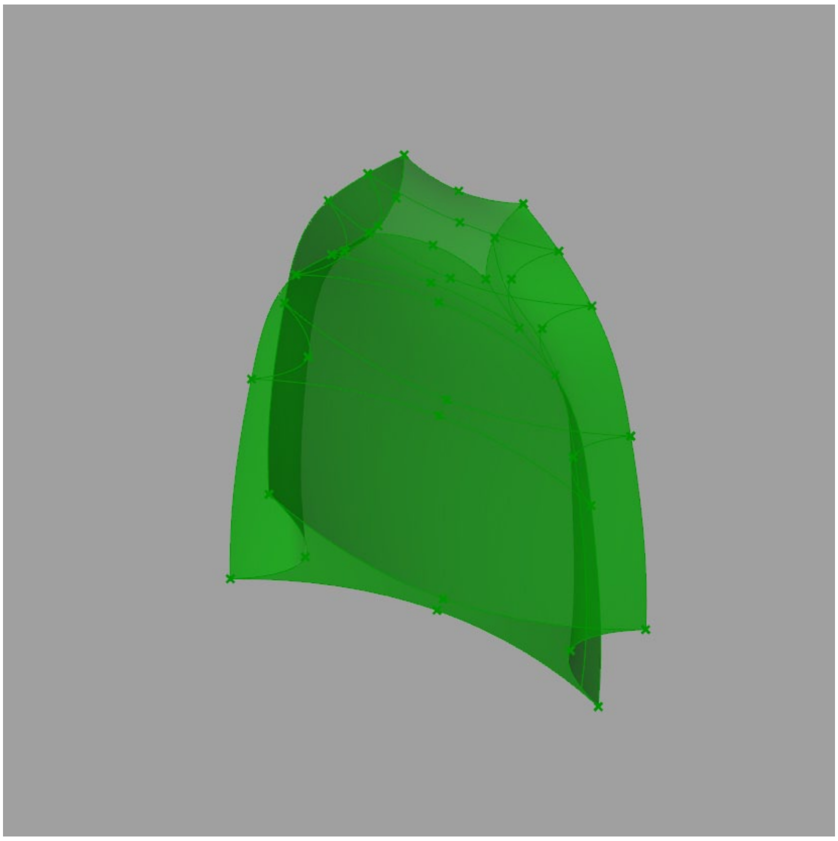


Figure 3.20

The fin was then constructed by lofting a series of profiles. Each of these profiles can be moved along the Z axis to extend the fin. They are also adjustable by number sliders through the width and thickness of both the centre and ridges. The crescent can also be cut from the tip, increased, decreased or made asymmetrical.

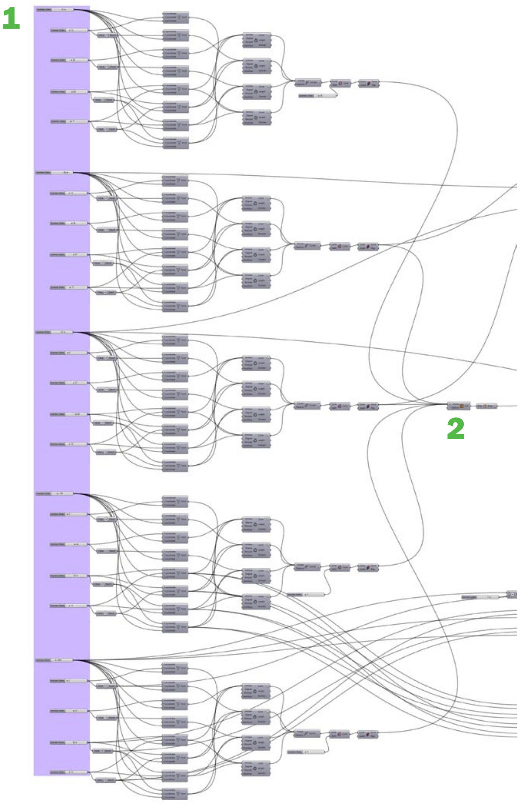


Figure 3.21

1: The adjustable measurements for the fin profiles. 2: The loft that builds the fin between these profiles.

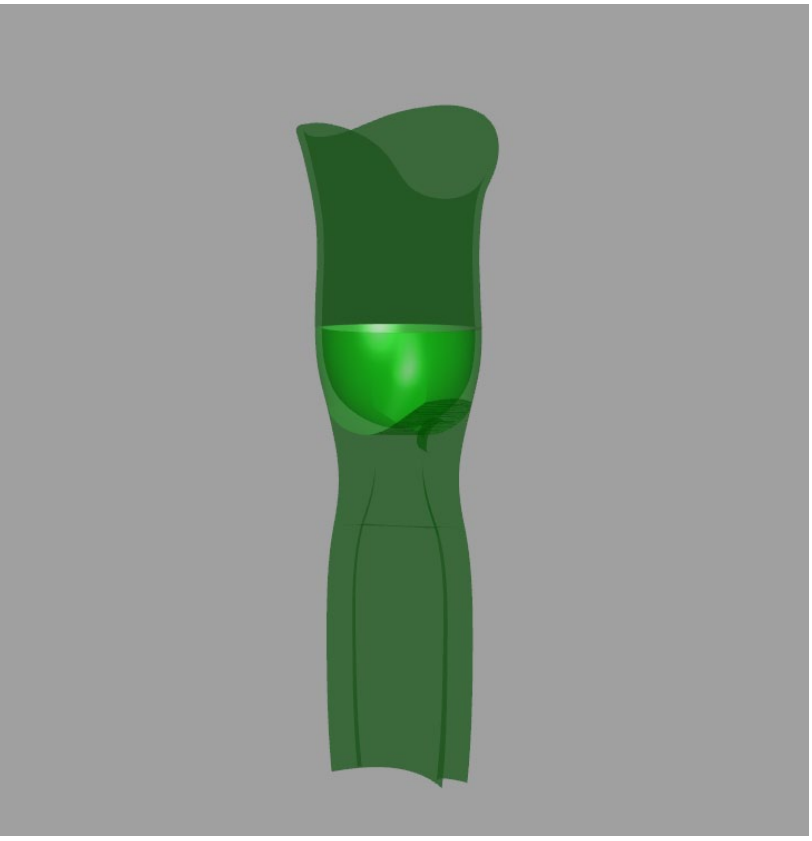


Figure 3.22

To connect the socket and fin a loft is created between the two pieces using geometry from the fin and the points defined on the stump scan. This creates a seamless integration between the two pieces. Into this loft the detail of the housing for the expulsion valve is then added in between the ridges on the exterior of the leg. This can easily be rotated from the left to right. Finally, to allow for joining, the fin and loft are converted to meshes, joined in combination with the socket and cut to separate the TPU fin segment and the ABS socket segment.

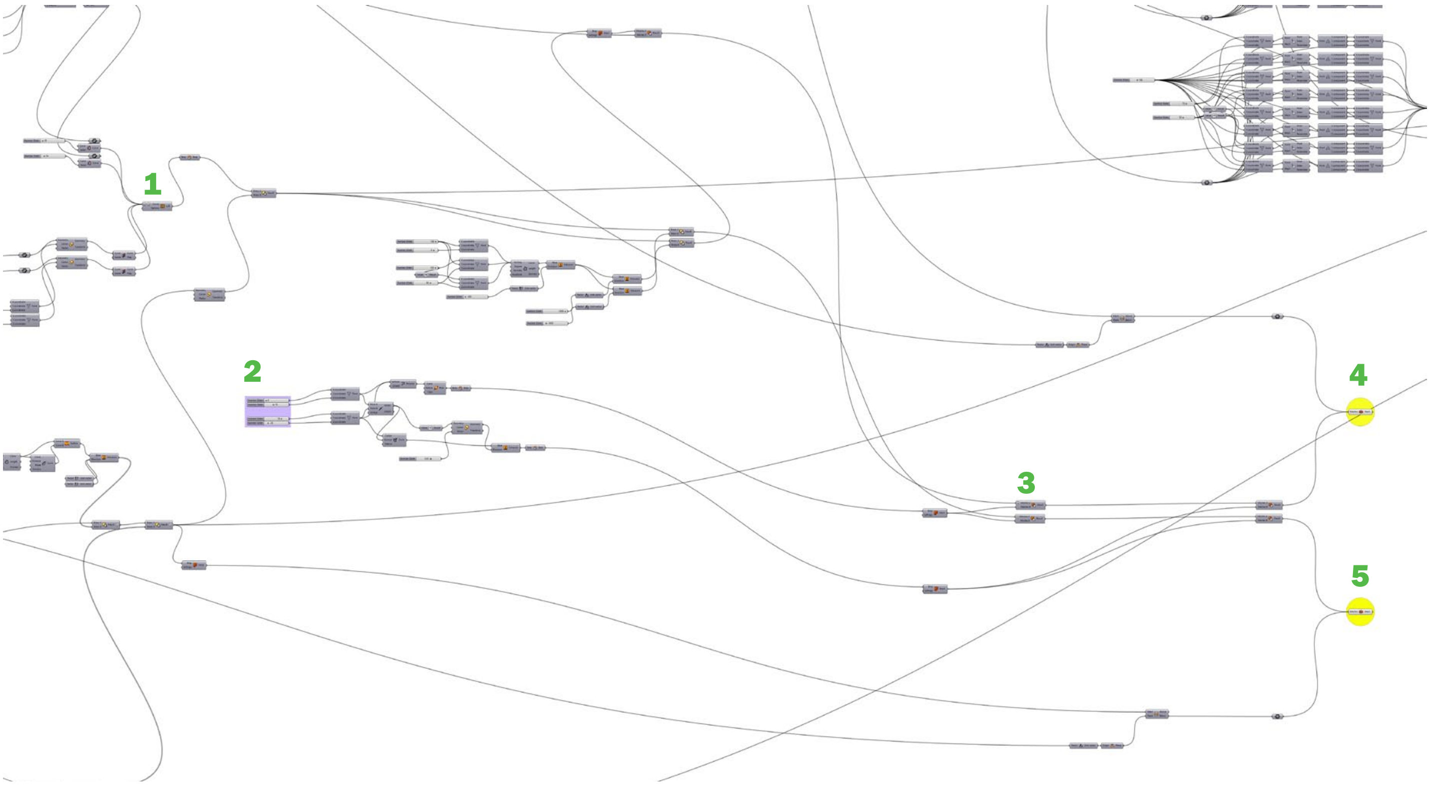


Figure 3.23

1: A loft joining the socket and fin. 2: Cylinders that subtract space for the expulsion valve. 3: Cutting the prosthesis into two segments for the flexible and rigid prints. 4: The rigid socket file. 5: The flexible fin file.

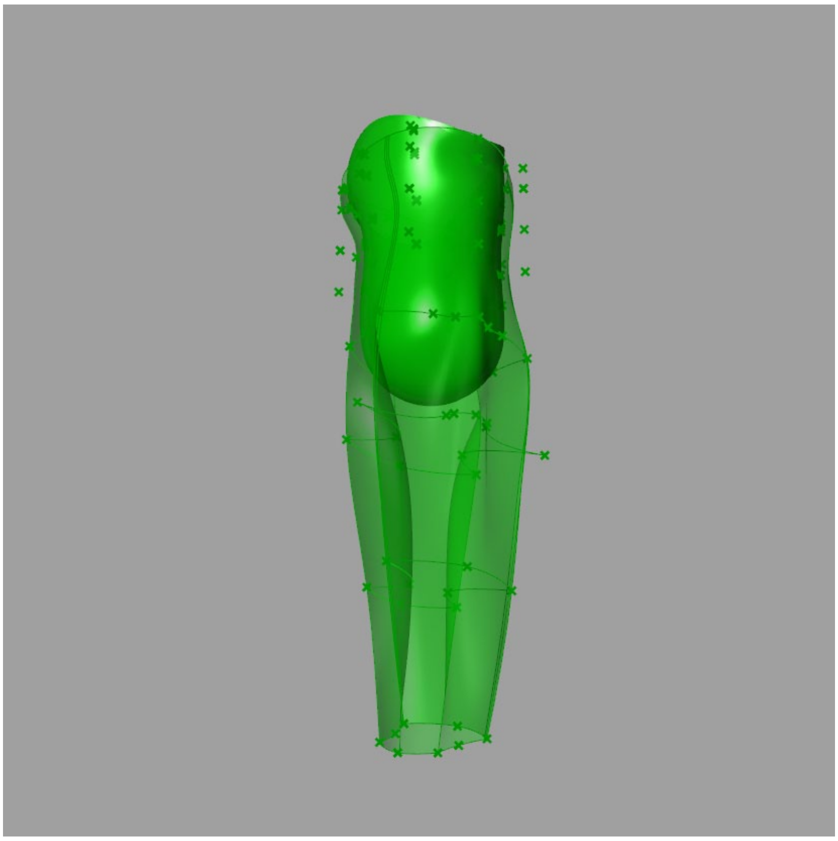


Figure 3.24

To create the sleeve the same process was used as in the interior prosthesis. Starting from a higher Z value, usable points are extracted from the stump scan as 4 splines and offset 5mm to create the interior wall. These spline lines are then offset by an adjustable 7mm for the wall thickness. These exterior lines are then lofted down the stump, joining with profiles that were abstracted from the fin form itself, for visual continuity.

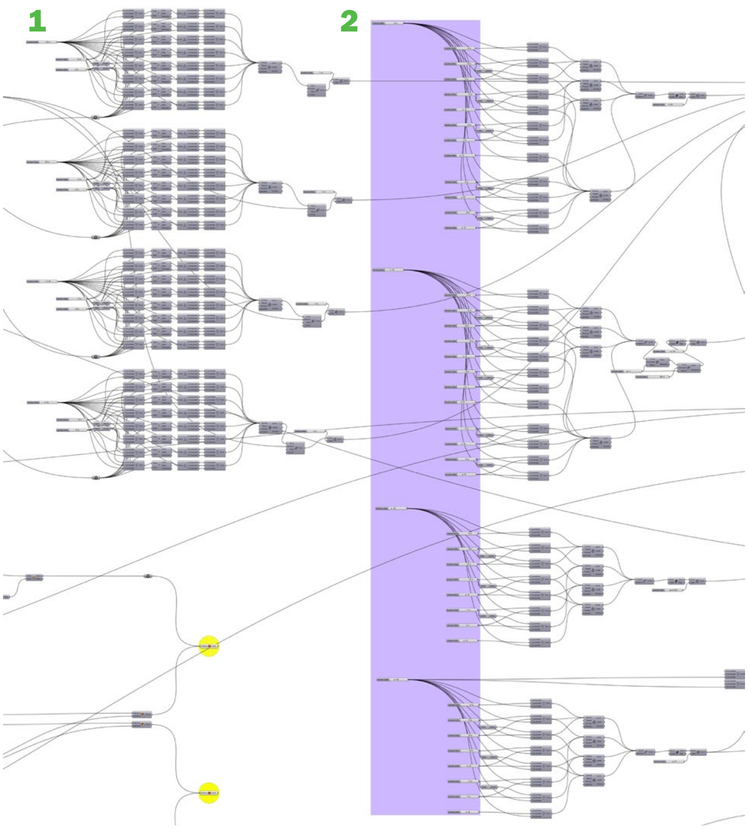


Figure 3.25

1: A secondary offset of the scan to build the top of the sleeve. 2: The designed profiles that generate the lower part of the sleeve.

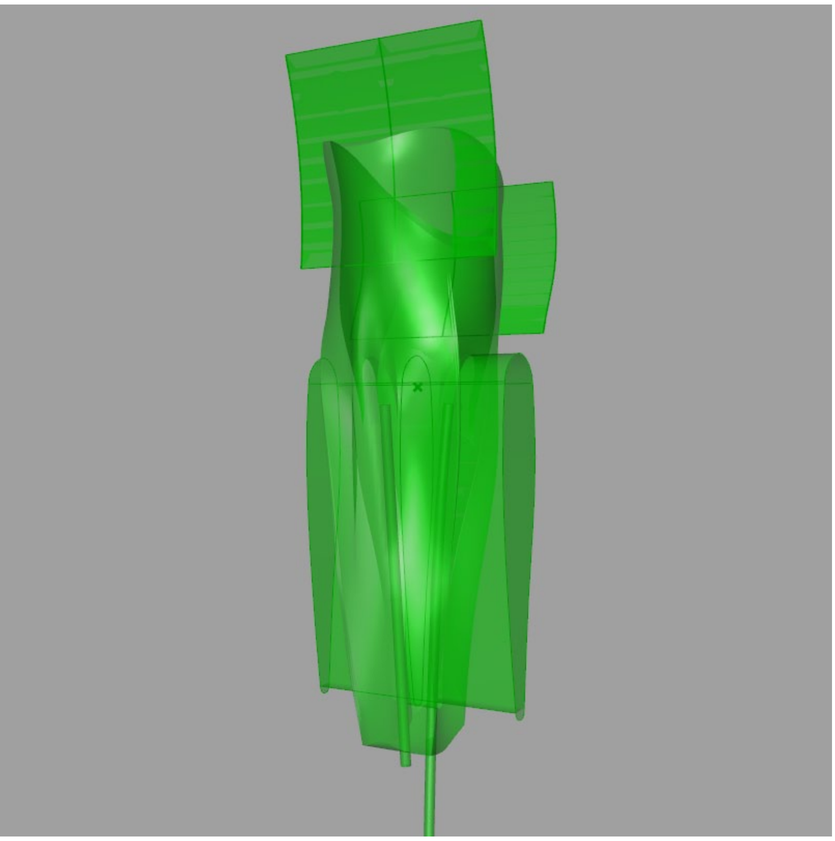


Figure 3.26

Once this loft is capped, the interior prosthesis is subtracted from the interior of the sleeve form. To finalise this form details are subtracted including space for fibreglass protrusions and cuts to allow the shell to expand, letting the prosthesis clip in.

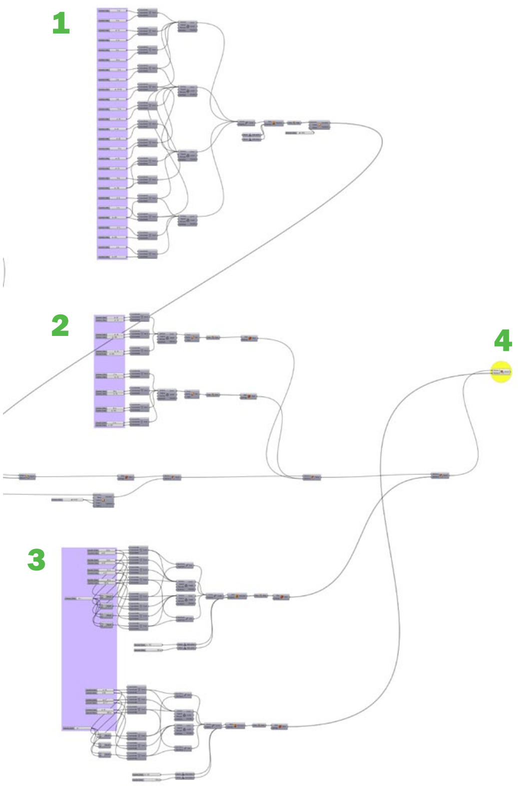


Figure 3.27

1: A cut producing space for the fin as it enters the sleeve. 2: Slit cuts that allow for appropriate tolerance as the socket enters the sleeve. 3: Cylinders that make space for fibreglass protrusions. 4: The sleeve output.

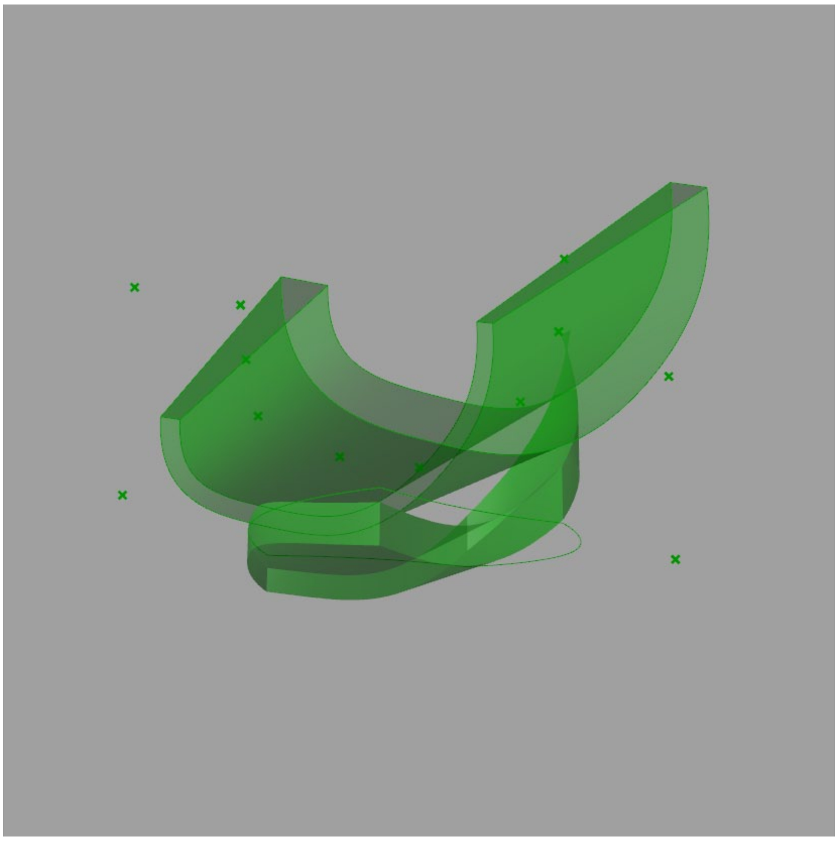


Figure 3.28

To create a safe walking platform and to also account for some asymmetry caused by the angle the prosthesis contacts the ground a TPU grip is created to attach to the bottom of the sleeve. This is formed by projecting the X axis of the bottom of the sleeve down a Z value of 5mm on the anatomical interior and 8mm on the exterior of the prosthesis. It can be then imported to Meshmixer as an STL file to create small extrusions as a gripping surface.

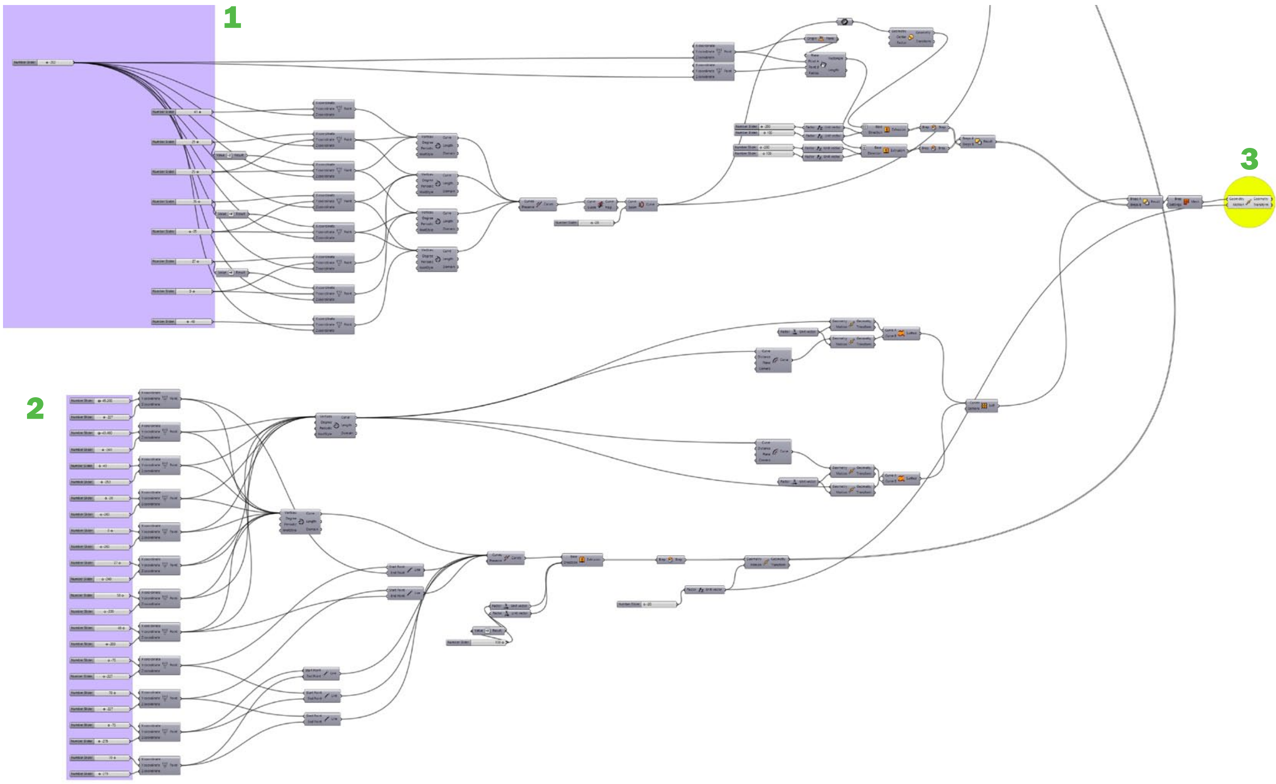
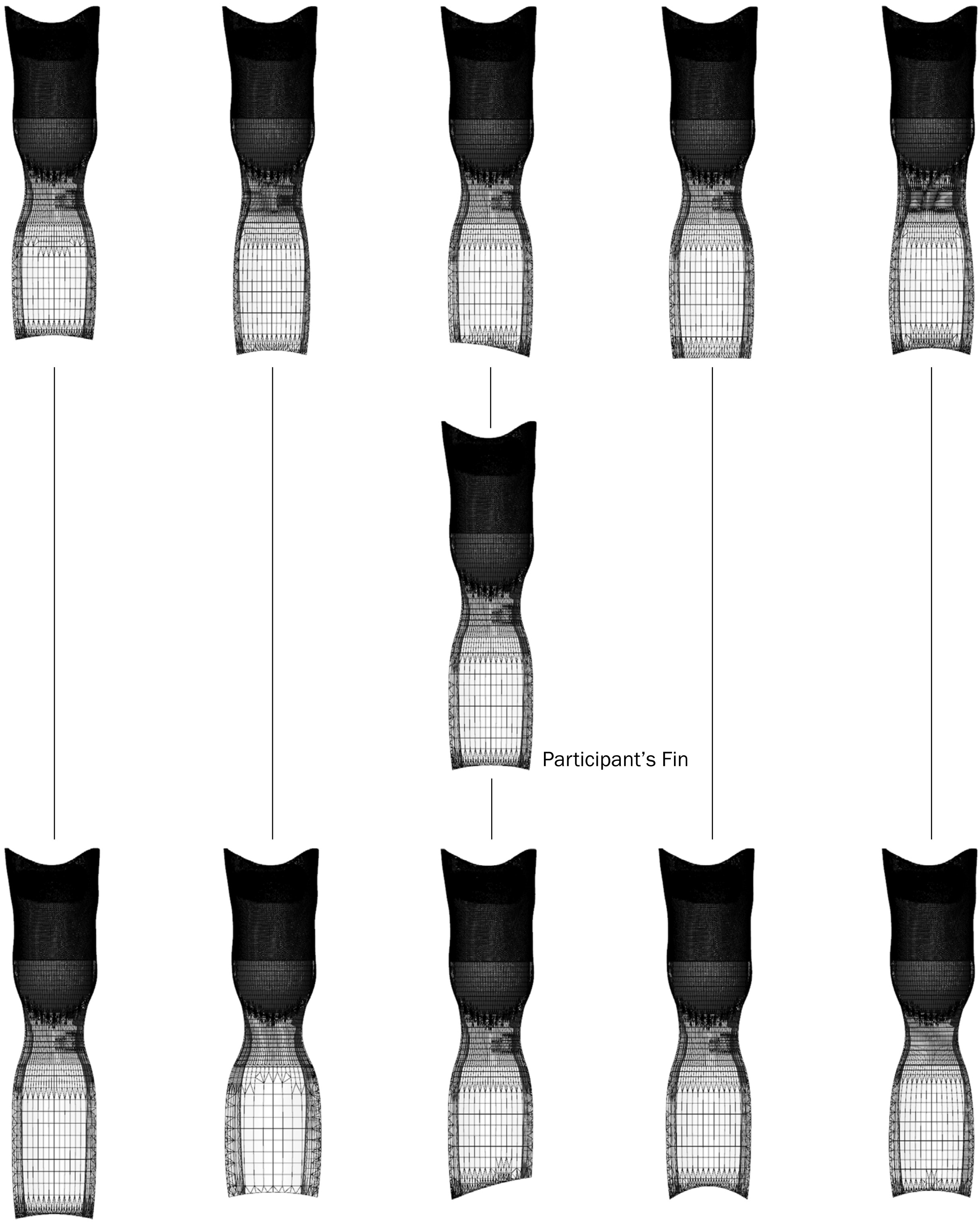


Figure 3.29

1: Definition that creates the Z heights of the asymmetrical grip. 2: Cuts out the profile of the grip. 3: The grip output.



Fin length

A longer fin can increase force output and vice versa.

Fin Width

A wider fin can increase force output and vice versa.

Fin Asymmetry

Asymmetry left or right could aid swimmer's direction.

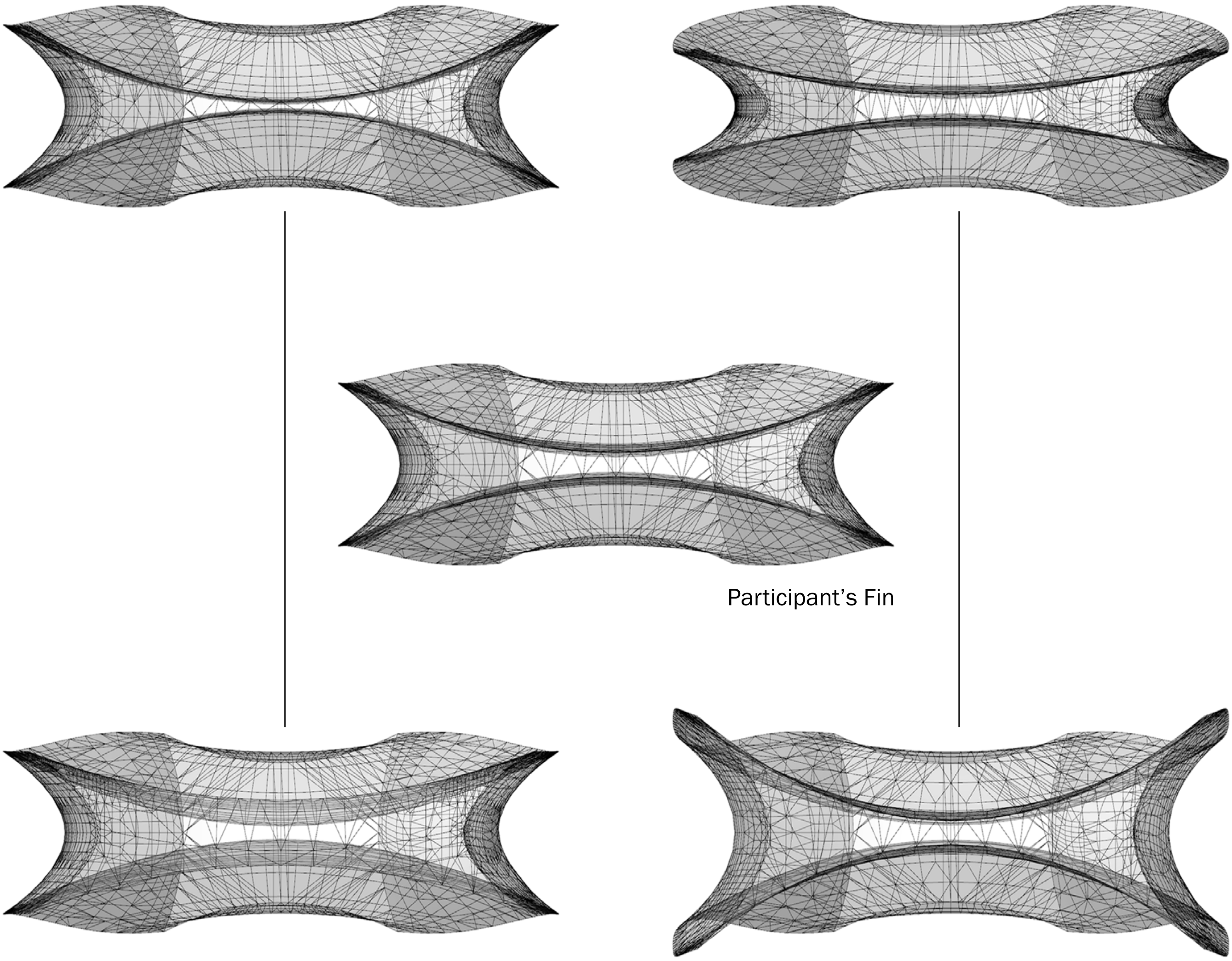
Fin Crescent

A larger crescent can increase efficiency but decrease force output.

Transition

A wider transition between fin and socket could increase resistance without increasing force for training.

Figure 3.30
The front view of the interior prosthesis showing different qualities that can be changed with the parametric definition.



Centre Thickness

A thicker centre will increase rigidity. 'Moderate' rigidity will produce the highest efficiency.

Ridge Thickness

Thicker ridges help to thrust water forward and increase propulsion. It hasn't been measured as to when the effect is saturated.

Figure 3.31
The bottom view of the prosthesis fin showing variations in thickness and ridge size that can be achieved in the parametric model.

Figure 3.32

The participant enjoying the hydroslide for the first time since losing his leg three years ago as he could now climb the access stairs and stand up to get out.

Findings

This research successfully achieved what it proposed by creating a prosthetic swimming limb, furthering this by also helping the amputee get to and from the pool, walk around the poolside and even use the hydroslide, an activity he had not been able to achieve since losing his leg. Not only increasing his independence, the participant indicated this prosthesis could also increase his confidence while wearing it.

With some limitations the participant's limb was successfully scanned and digitally manipulated into a prosthetic socket which was then printed using an FDM process. This print was accurate to the manipulated scan resulting in strong suction adherence and a structurally sound prosthetic socket. These prototypes confirm that 3D printed suctions sockets are a viable concept.

FDM printing of TPU was also achieved, with the fin form being printed at a high quality. The material used offered an appropriate flexibility and resistance to pool water. The fin itself was researched for appropriate size and hydrodynamic efficiency.

The combination of mesh and polysurface geometries were difficult to combine but this was eventually resolved with effective parametric modelling allowing for the limb's natural geometries to generate the prosthesis and influence it's form.

Both the interior prosthesis and exterior sleeve are very adjustable through parametric software. It offers the ability to input a scan and have the socket and prosthesis immediately build around this. After this the fin can be adjusted to meet the user's power output through it's length, width, asymmetry and various thicknesses. The exterior sleeve will automatically build around this interior and has adjustability to account for the user's height while the grip can account for small asymmetrical gaps between the bottom of the sleeve and ground.

The final concept helped the participant to swim efficiently and comfortably. He expressed this prosthesis was helpful for him to regain his independence and confidence in and around the pool.

Discussion & Conclusion

Discussion

The development of this swimming prosthesis should ideally generate a discourse around the design and production of recreational prosthetics. Though practically, this proof of concept suggests further development could produce a viable product. With fabrication by the NZALS in conjunction with an exercise plan this concept could benefit amputee fitness and increase exercise options.

Some limitations were encountered during this research process that altered the path of the concept's development. While limitations were found in materiality, fabrication processes and software control none have been insurmountable.

A larger than intended proportion of time during this research was spent on altering and fitting sockets to the participant's limb. Whilst the manipulation software used by the NZALS is simple to use it requires mouse controlled brush strokes. These are inaccurate and this software offers no restrictions or indication as to when the scan is being manipulated adequately. This was overcome with an iterative testing process that allowed the researcher to understand prosthetic fit in detail. It demonstrates an opportunity for companies such as Ohio Willow Wood to refine the control of their products.

The 3D printers predominantly used in this research restricted the size of each print. A print height of 210mm meant that the interior prosthesis and supporting sleeve prototypes both required 3 separate prints and were reinforced with fibreglass protrusions. This joining could possibly reduce the strength of the prototype though would be overcome on a large format printer.

Whilst the researcher is now able to complete very clean and accurate TPU prints these prints are not airtight meaning any TPU in a socket wall can result in loss of suction. This was realised during participant testing and was overcome by ensuring the interior of the socket was only fabricated in ABS. The reason that the FDM process leaves gaps in the wall when printing TPU, but doesn't when printing ABS, is unknown and an area that could be explored in future.

Further research could benefit the development of this prosthesis concept or its implementation. A reasonable first step would have the concept test for structural integrity by clinical prosthetists. Testing could then continue with a larger participant group to verify that the parametric model suitably adaptable for other amputees. Research could also further an understanding of hydrodynamics and how the fin could more accurately recreate symmetry when swimming.

This research has excelled at helping to understand how to use digital technologies to create a prosthetic fit and the benefits of 3D printing prostheses for economy, accessibility and iterative abilities. The mastery that has been developed by the researcher is not in the tactile hand craft of traditional prosthetics but the craft of digitally collecting data, manipulating digital forms and connecting digital technologies to fit the needs of a user.

Conclusion

The trilogy of 3D scanning, parametric modelling and 3D printing offer a plethora of benefits in the development and production of prosthetics. Their use in this research has demonstrated that digital technologies are most efficient when working together and now offer the capability to produce customisable 3D printed prosthetics.

This project has expressed how these technologies can be used to quickly iterate customised products with incredibly accurate results - though it was learnt that despite the accuracy between machines, during the scanning process it was learnt that there is still refinement required in the communication between machine and technician/designer/human.

Effective research helped to design and build prototypes that were successful in allowing the participant to independently walk to the pool, to enter the pool as well as recreating an anthropometric swimming style for comfortable and efficient swimming.

The concept used anatomical referencing and cohesive design forms to visually integrate with the participant's body, creating an empathetic product that can imbue confidence and respects the wearers natural form through the direct offset of the limb.

Though to prosthetists and other experts the notion of 3D printed limbs may be seen as radical, this research concludes that further investment into rapid fabrication of recreational, and other prosthetics could offer a near future bloom of opportunities for amputees and prosthetists alike.

This appears to be the first working prototype that allows an amputee to walk to the pool with ease, to swim with a recreated symmetry and to exit the pool. With the ability to be recreated for other amputees it could be a significant step forward in returning accessibility and dignity to exercise for amputees.

Beginning this project swimming was perceived by the researcher as a manner for amputees to maintain fitness. Upon concluding this research it has been realised that the ability to partake in a recreational activity, such as swimming, can offer so much more than exercise - with the right means it is an outlet of independence.

Figure 3.33

The final designed prosthesis.

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Figure List

All images are author's own excluding those listed below.

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Appendix

The NZALS

The New Zealand Artificial Limb Service (NZALS) is a New Zealand Crown entity and a provider of prosthetic limbs and related services to amputees within New Zealand. They aim to create "independent and productive lives for amputees." (NZALS, 2016)

Currently using mainly analogue measurement and fabrication methods the NZALS have recently been pursuing the exploration of digitised solutions to amputee problems.

For scale, the NZALS cater to over 4000 amputees in New Zealand (NZALS, 2014), producing around 650 new limbs each year and completing over 8000 maintenance jobs. Their holistic approach to amputee care includes resources and contacts to help advise amputees on a full range of common issues including mental health, physical health (specifically weight gain and diabetes) and information on living day to day with an artificial limb.

Whilst the NZALS have a large amount of solutions to increase amputee mobility, a swimming limb is not amongst these and the prescription of a Water Activity Limb (a waterproof walking limb) is uncommon due to it rarely being a necessity.

WAL's provide the opportunity for the amputee to wear a prosthesis in water that is resistant to hydrolysis and corrosion which normal prosthetic limbs are susceptible to. The WAL completes the basic functions of allowing the wearer to perform upright water based activities such as showering and lateral activities such as swimming with the use of a rotating ankle. Weaknesses of the WAL are apparent in the approach to its design; it mimics traditional prosthesis construction with minor adjustments rather than addressing the function and opportunities of the product and the needs of the amputee.

Parametric Model Self Critique 1

07.02.15

Using an anonymous 3D scan of an amputee's residual limb the first fully functional CAD model has been completed from fin to socket input. It currently generates a model that has a very large amount of variable parameters. These give total control over the fin form, several thicknesses and it's ridges. Other parameters include control over the socket radius, length and curvature of the knee support around the top of the socket.

Each of these parameters uses a set of points and vectors or values to affect the model, though some have similar effects and other may not be necessary at all. There are currently 49 changeable values in total, 37 of these in the fin. The number of variables largely increases due to the decision to keep many options for asymmetry, such as the slant in the fin's tail or an uneven curve through the fin face. For parameters to be refined tests will be conducted, informed by the literature review, to establish which parameters need adjustability, can be set, or can be removed.

In the next iteration construction will be revised to create a more seamless object. Currently the model is constructed of 3 major sections with 4 ridges added. I hope to reconstruct this as one continuous loft with 2 ridges. A major issue with this is the transition of the rectangular section of the fin shape to the ovular section of the socket shape. This could possibly be overcome by construction each as a polygon with the same amount of points but setting the points of the fin in a straight line.

Certain aspects of the model also need to be made more adjustable. Currently the ovals that are making up the socket loft are controlled by a centre point and two radii. Ideally each of the 4 points that make up the oval would be controllable to account for asymmetries along the widths. The curvature of the support around the knee also needs to be more informed as to where support is placed and where it would restrict.

Though adjustable, experimentation needs to be done regarding the overall length of the limb. It is yet to be determined if the pylon should extend the limb to a walking length and if the limb should be weight bearing for movement to and from the pool, though with logistics and safety in mind a fin form would not grip to a wet floor, nor would it be any use when climbing an in-pool ladder.

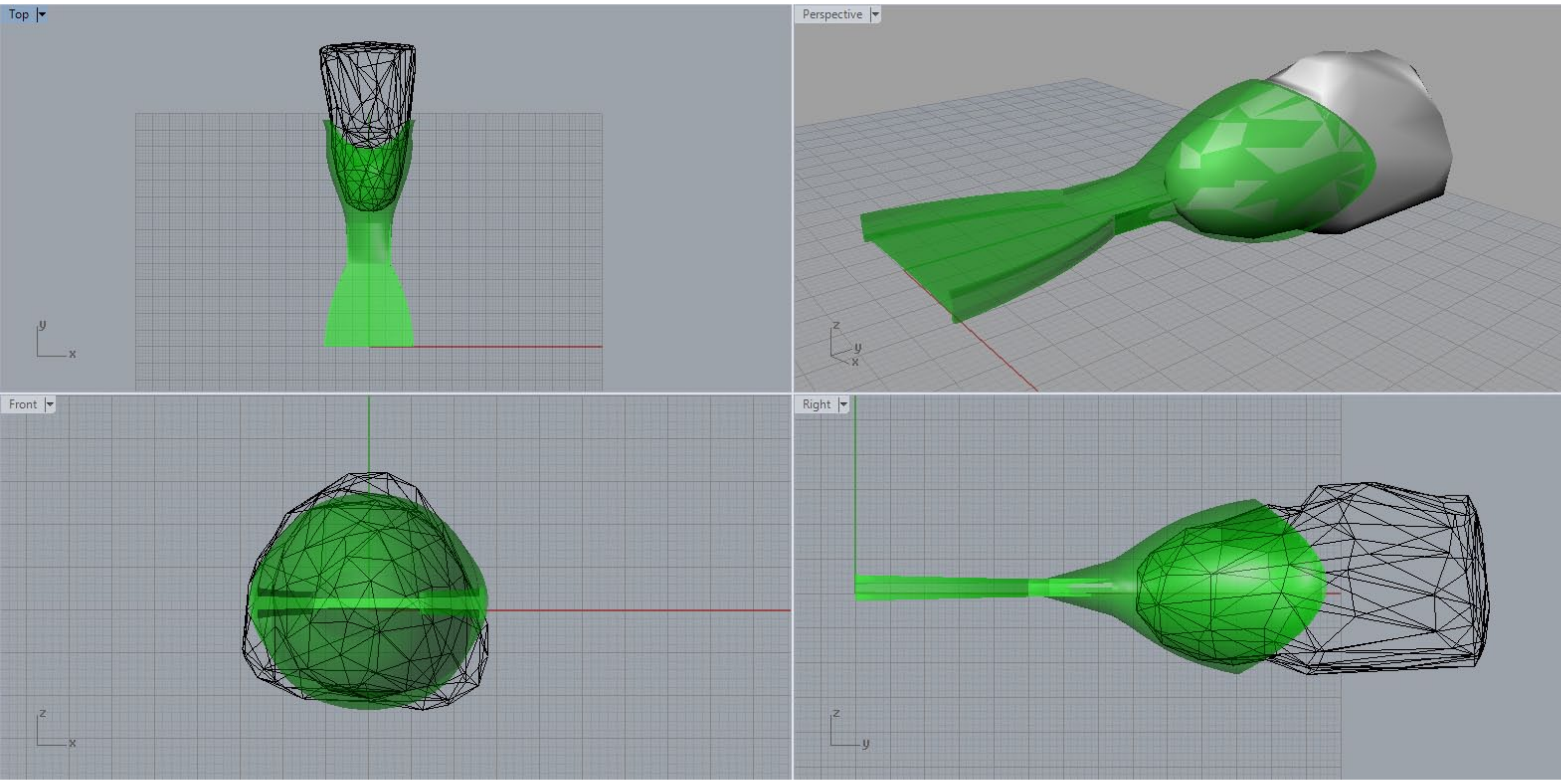

Figure 4.01

The first test using the parametric software Grasshopper to build a socket form and subtract the mesh limb from this. This was an anonymous scan provided by the NZALS prior to engagement with a participant.

Parametric Model Self Critique 2

13.01.16

The second model now integrates the participant's 3D scan that was completed by a prosthetist from the NZALS. It has both reduced and expanded variables, removing some of the fin parameters and increasing the control over the socket form. This model has improved stability as it is constructed of one continuous loft, rather than the previous which consisted of several parts. There are 7 profiles to the loft and 4 subtractions. The profiles comprise of 3 that make up the fin, 1 transitional and 3 that make up the socket. After the loft is constructed the crescent is removed to improve the efficiency of the fin, the stump is subtracted from the socket form and finally the opening of the socket is trimmed to reduce any excess material and form a soft radius.

This model includes a simple circular boss and channel that allows for a 3d printed ABS plug to be inserted, that houses the expulsion valve required to generate suction. During testing the boss is modelled outside of Rhinoceros and Grasshopper, using Solidworks and the STL's of the boss and the prosthesis are combined using Meshmixer. After this combination a solid variation of the ABS plug is subtracted from the model with the boss to produce the housing and air channel for the expulsion valve.

A challenge has been the seam rotation in some of the profiles of the loft, causing a lot of twisting in the model. The majority of this has been fixed, bar a small amount in the transition between the fin and the socket where the ridges can be seen spiralling around the socket. A possible fix will be testing fractional numbers as the rotation input as the whole number rotates the seam too far.

Asymmetries in the thickness and width of the fin are currently removed from the model, they could be added though this would almost double the amount of sliders required for each plane. Asymmetry in the crescent cut of the fin is also removed. These both require further investigation regarding the effects and validity of adding any asymmetries.

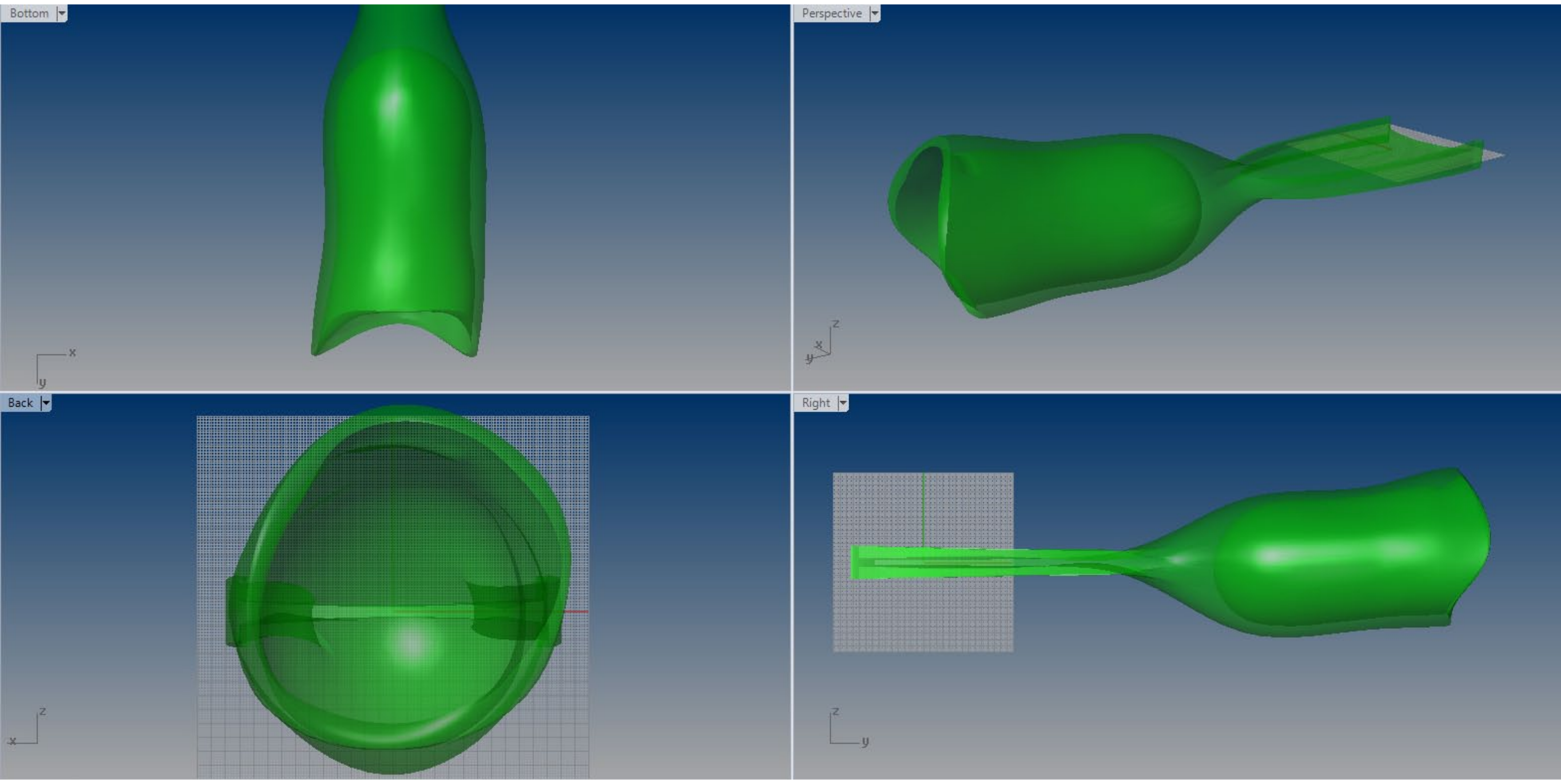

Figure 4.02

The second model, constructed using the skeleton of the first but with the scan of the participant. This model was used for the first prototype.

Parametric Model Self Critique 3

30.03.16

For a load bearing limb two options were explored through iterative sketching and modelling. Both of these identified the need to provide structure feeding from the socket to the ground but differed in their involvement with the swimming aspect of the prosthesis. The first idea proposed was that a rigid sleeve-like structure would provide support between the socket and the wearer while they walked to the pool but this sleeve could be unclipped once the wearer was in the water, revealing the TPU fin. This concept was the least cumbersome but more complicated for the wearer and did not allow for standing in the water. The second idea was to build a bladed structure from the socket to the ground that was rigid enough to allow the wearer to walk on but hydrodynamically efficient enough to stay on as the wearer swum. For the next prototype the latter was the concept that was pursued.

As these concepts could no longer be hypothesised as a single material with available technology due to load bearing requiring a more rigid material than just TPU therefore, as two materials, it was more logical to use ABS as the socket and structural components and TPU for the fin, being the only piece that requires flex.

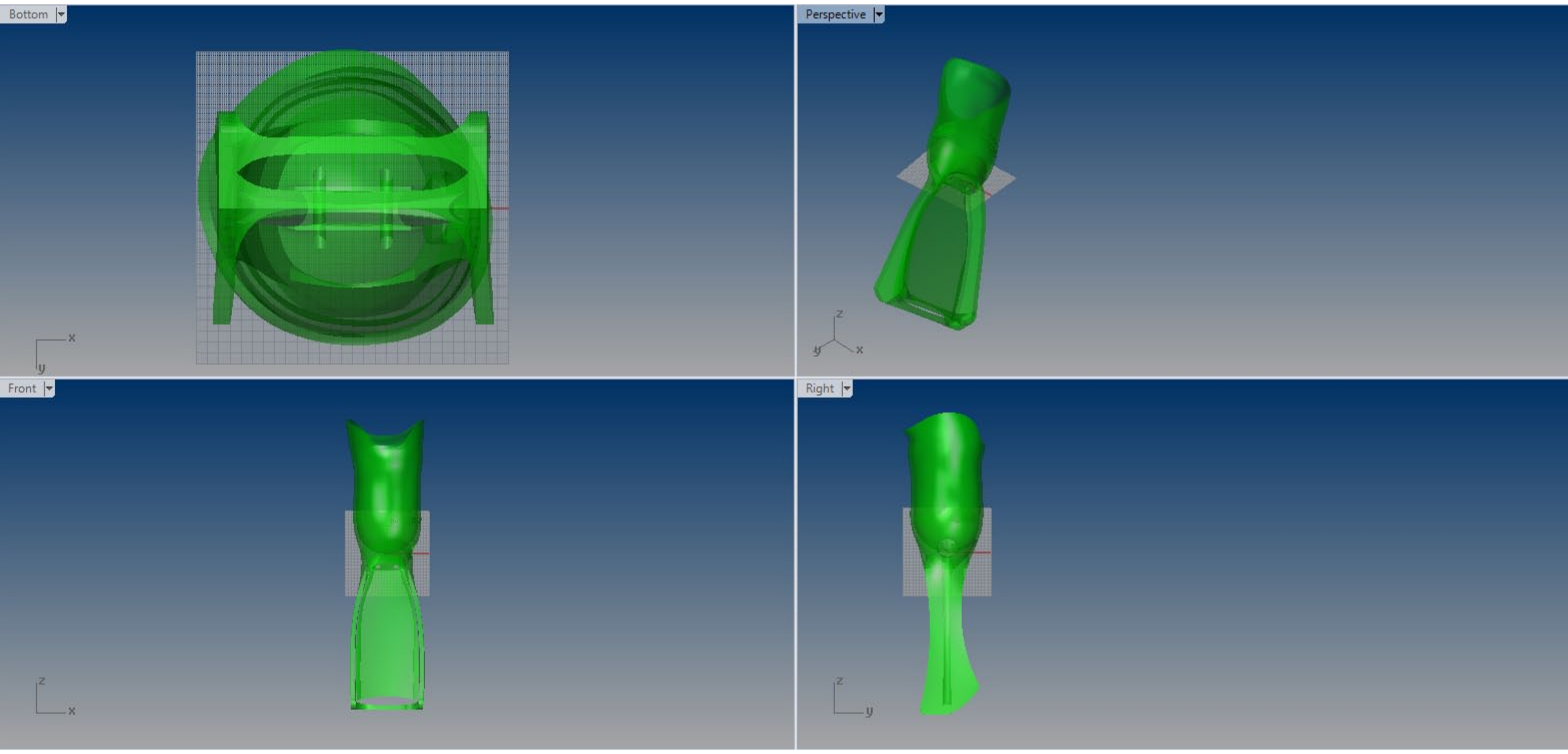

Figure 4.03

The third major iteration of the parametric model used a mesh controlling plug-in called Weaverbird to directly offset the socket from the participant's scan. It also used a custom built definition to create geometric points on the socket to construct the prosthesis from.

Parametric Model Self Critique 4

12.05.16

The final parametric model was developed using the skeleton of the third model, though this was stripped and the prosthesis was reformed into a resolved singular loft. For the walking sleeve interior the prosthesis socket was offset and lofted to a base using forms taken from the fin. To help with semiotic aesthetics and the communication of the form of the socket, fin and sleeve were envisioned as anatomical pieces with the sleeve providing bone like structure and the flexion of the fin generating elastic energy. To create the skeletal form the loft was manipulated to incorporate a “tibia” bone running through the centre. This sleeve effectively uses motifs from the prosthesis to retain visual cohesion. For strength along the Z axis the sleeve model has space for a fibreglass protrusion rod running down the centre front and back of the sleeve. The prosthesis itself has been cut three quarters down the socket where the build material changed from ABS to TPU. This is a subtle change visually making use of both materials where they are best suited - ABS’ rigidity holding suction and TPU’s flex to generate propulsion.

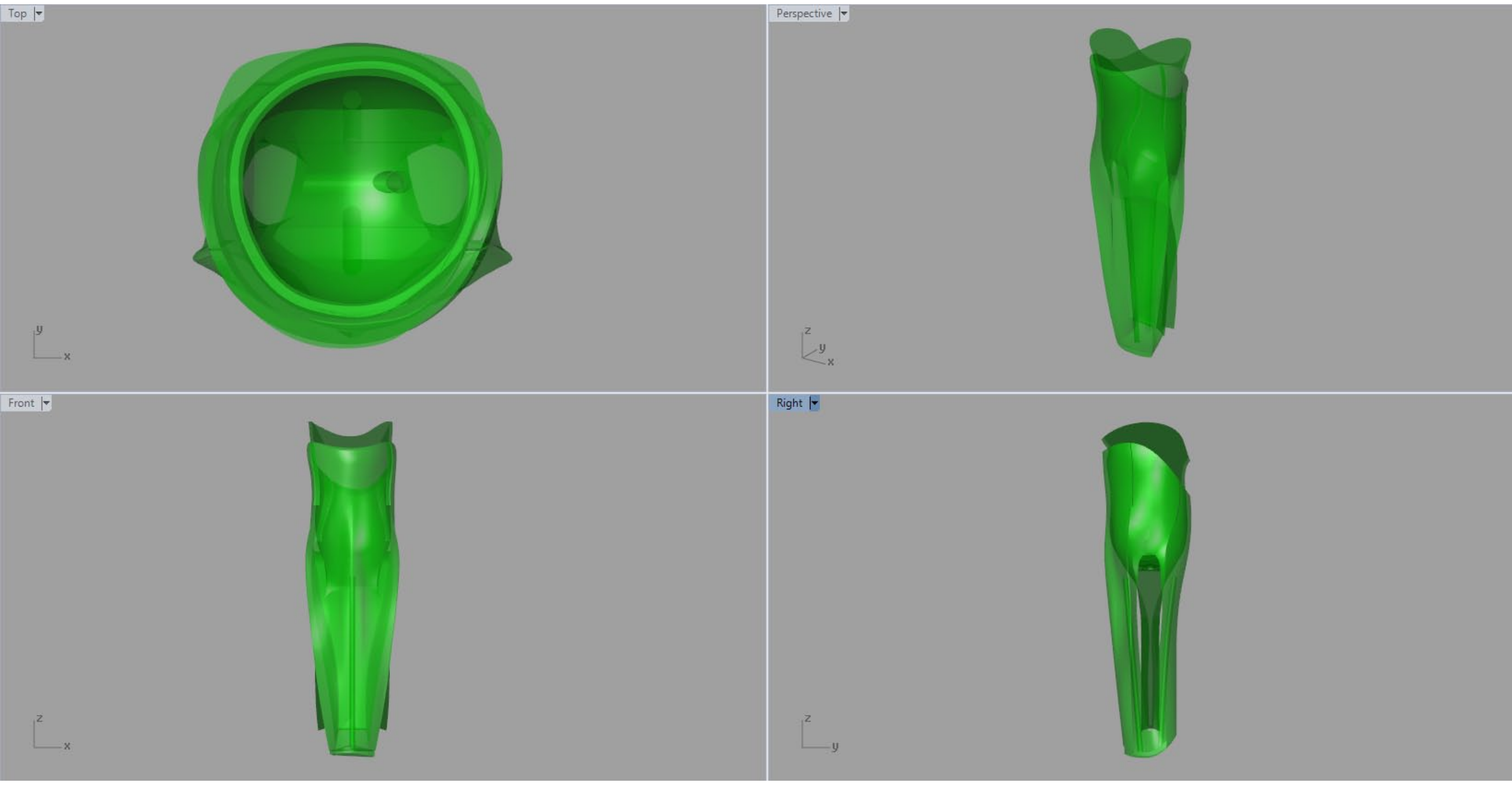

Figure 4.04

The final major iteration of the parametric model used a more harmonious loft to generate the prosthesis fin and a secondary offset of this loft to create a structural sleeve that could be walked on.

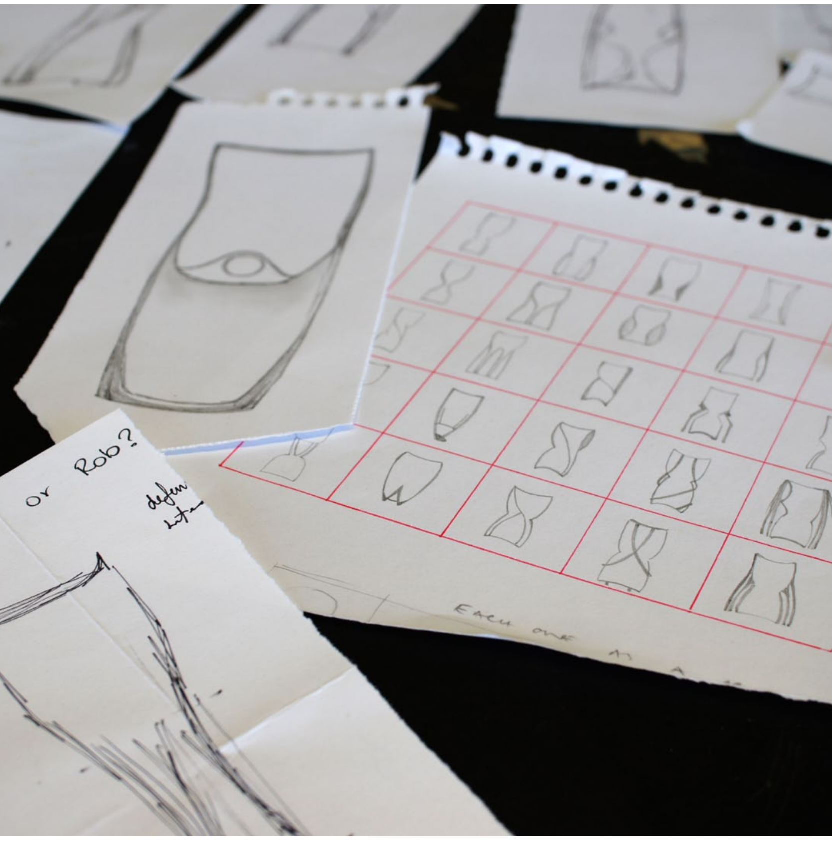

Figure 4.05

Early iterative form sketches.

Figure 4.06

A sketch of a structural concept for walking.

Figure 4.07

An early concept sketch.

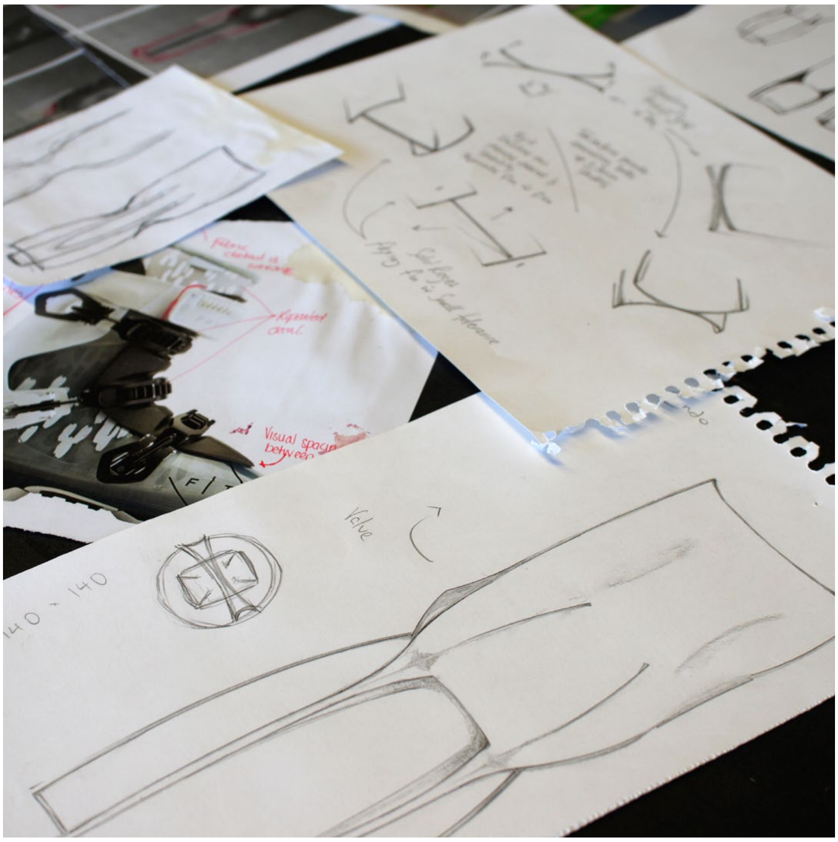

Figure 4.08

A late concept sketch exploring exoskeletal structure.

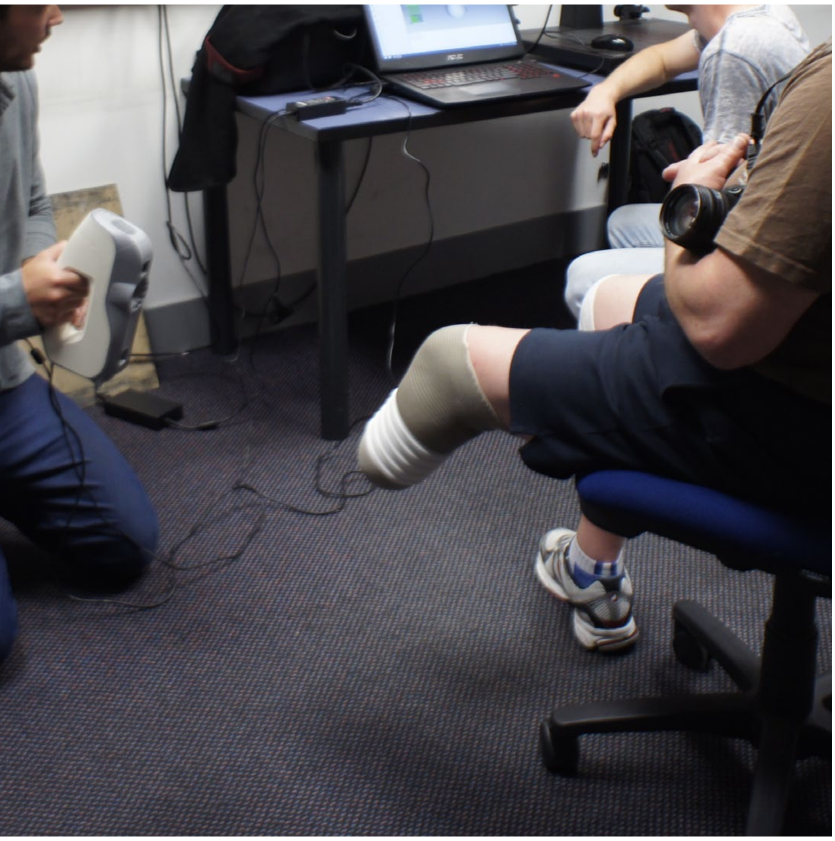

Figure 4.09

Scanning the participant at Victoria University.

Figure 4.10

Attempting to scan the participant’s socket

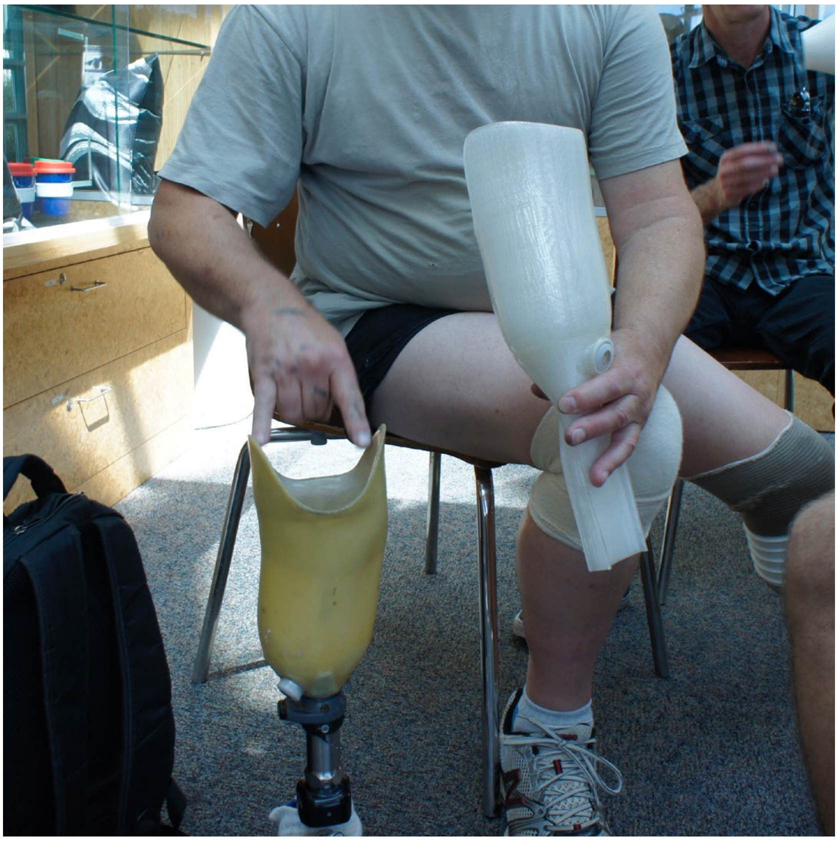

Figure 4.11

The participant expressing differences he noticed between a test socket and his walking limb.

Figure 4.12

The participant testing one of the first altered socket prototypes.

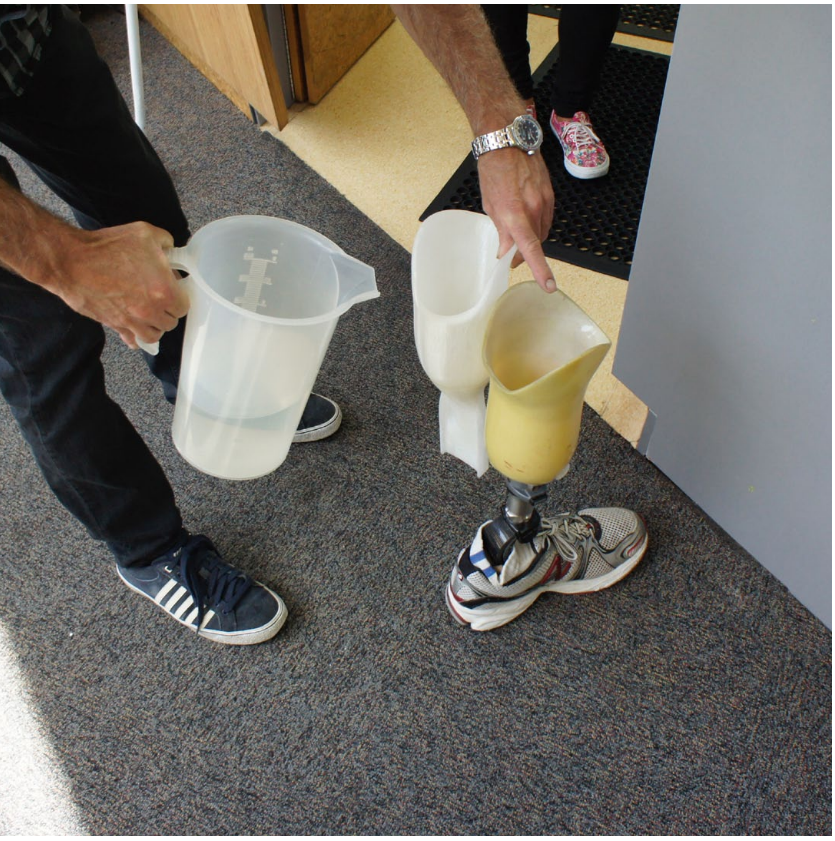

Figure 4.13

Using water to test the difference in volume between the participant's limb and a test socket.

Figure 4.14

Comparing a 3D print of the participant's scanned limb (NZALS version) to in walking prosthesis' socket.

Figure 4.15

Comparing tests with measurements.

Figure 4.16

One of the first fitting models. The space for the expulsion valve helped to identify where the bottom of the limb was when inside the socket.

Figure 4.17

The participant being wheeled to the edge of the pool to test the first prototype.

Figure 4.18

The first prototype during testing, for the participant's records.

Figure 4.19

Using clay modelling to further the form.

Figure 4.20

Sculpting onto the first model to help refine the form.

Figure 4.21

A crude walking test model that was never completed.

Figure 4.22

The participant testing the second prototype.

Figure 4.23

A comparitive image between an acrylic check socket (left) and a 3D printed socket (right).

Figure 2.24

Some of the tests completed in PETG on the BigRep One.

Figure 4.25

A studio image of the first prototype.

Figure 4.26

A studio image of the second prototype.

Figure 4.27

A studio image of the first of the final prototypes.

Figure 4.28

A studio image of the major prototypes from this project.

Ethics Information

VUW Ethics Approval Number: 22342
Printable Prosthetics
13.06.2015 - 12.06.2016