ADDITIVE ALTERNATIVES

a product system for recreational prosthetics

A 90-point thesis submitted to the Victoria University of Wellington in
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K E Y W O R D S

additive manufacturing (AM), design for additive manufacturing (DFAM), coastline, prosthetic, foot prosthetic, quick-release coupling, New Zealand Artificial Limb Service (NZALS), Nylon PA-12, Selective Laser Sintering (SLS),

A B S T R A C T

As an island nation, beach and coastline activities play a significant role in daily life in New Zealand. In promoting independent and productive lives for amputees, the New Zealand Artificial Limb Service (NZALS) encourages accessing these environments. However, carbon fibre foot prosthetics can be easily compromised by these conditions, as a result of abrasion and corrosion caused by sand and saltwater. To deliver on their mission statement 2017-2021 the NZALS seeks solutions to this issue (NZALS, 2016).

In response this research project explores the possibility of offering a range of customised lifestyle-specific prosthetics that can be interchanged easily with a carbon-fibre prosthetic, to accommodate different recreational activities and thereby offer greater choice and independence for their patients.

The project focuses on a case study for low-cost durable coastline prosthetic produced through Additive Manufacturing (AM) with Nylon PA-12 using design for additive manufacturing (DFAM) principles to facilitate a product that has a human form and dynamic three-dimensionality. This will be supported by the development of a quick-release coupling system allowing amputees to easily switch between prosthetic foot types for different uses. This incorporates height adjustment, ease of customising foot and fairing combinations and improved usability.

This project has been undertaken in collaboration with the NZALS and uses a two-part design research methodology. Research 'for' design has been conducted by summarising, collating, and/or synthesising existing research. This was done through literature reviews, product autopsies and context scenarios. This was followed by a research 'through' design approach. The methods used are body storming which enabled research on how the foot functions in the scenario, analogue and digital sketching, CAD modelling, and rapid prototyping through AM.

The project provides future reference points for the NZALS to improve and expand their product offerings and to facilitate their goal of remote service provision.

A C K N O W L E D G E M E N T S

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I N T R O D U C T I O N

A summer research scholarship provided the basis and background for this project with preliminary research that was conducted exploring AM foot shells for bespoke prosthetic feet. This progressed into exploring the dynamic quality of AM nylon recreational prosthetics. This was followed by a practicum (internship) through Callaghan Innovation's AddLab, where a project involving DFAM was explored. This project included heavy involvement in Nylon Selective Laser Sintering (SLS) printing, where experience and knowledge were gained, through hands-on involvement of modelling, printing, and running the machines. Metal Selective Laser Melting (SLM) printing was also introduced during this internship including a course on how best to design for this technology. All this experience informed a greater understanding of 3D printing technologies and practices as well as the potential for future applications in industrial design.

This led to a unique collaborative opportunity with the NZALS of exploring a product system proposal for lifestyle-specific AM foot prosthetics, to accommodate different recreational activities. A coastline foot shell was to be used as an activity-specific demonstrator for the larger system.

Through discussion with NZALS and identification within the broader context of recreational prosthetics, the New Zealand coastline was determined to be the project scenario. A contributing factor to this is New Zealand's extensive coastline. It also has a marine area 15-21 times larger than the land area (Ministry for the Environment & Statistics New Zealand et al., 2016). It is also due to clinical technicians finding that carbon-fibre prosthetics that are introduced to sand and salt erode prematurely and often the prosthetic needs to be replaced a couple of months after this interaction. Findings in the literature support this by stating that sand inside of a foot shell will act like sandpaper, rubbing holes through the spectra sock and allowing the carbon fibre to rub against the rubber foot shell (Victory Orthotics & Prosthetics, 2020).

As a way of substantiating the thesis, a three-way collaboration between the researcher, NZALS, and AddLab was formed. The resulting research project also offered an opportunity to build and explore the possibility of an ongoing relationship between these collaborators for future prosthetic development.

This design research project was conducted during the Covid-19 pandemic, with much of the Research through Design stage originally being allocated for the months that New Zealand was placed under lockdown. This led to limited access to software and supervision, as well as AddLab closing. While this did not halt research, it did disrupt and slow the process and development of this project.

Thesis Statement:

This thesis project proposes that additive manufacturing can facilitate the production of a coherent lower limb prosthetic product system, which demonstrates new visual and structural qualities, dynamic three-dimensionality, and improved usability for amputees. This system would include a recreational foot prosthetic, an intuitive coupling system between the foot and pylon, and additional components. Additionally, the study proposes that these products cannot be produced through traditional manufacturing methods, due to the complexity of the components.

A I M S & O B J E C T I V E S

Aims	Objectives
1. Contextualise the project.	<ul style="list-style-type: none"> a. A literature and design precedent review to establish current practices and products. b. Define scenarios for a recreational product system.
2. Build an informed technological basis for the project.	<ul style="list-style-type: none"> a. Seek advice from clinical experts at the NZALS. b. Seek experienced knowledge of additive manufacturing in New Zealand, through experts in the field, expanding on previous experience and knowledge base.
3. To produce a speculative product system for lifestyle-specific prosthetics.	<ul style="list-style-type: none"> a. Map out the different elements that constitute the product system.
4. Synthesise findings from <i>Aims 1, 2 & 3</i> in the form of design experiments.	<ul style="list-style-type: none"> a. Sketching through analogue and digital methods. b. Design experimental prototypes that test the abilities of state-of-the-art AM technology. c. Producing a range of design examples using findings from the design experiments. d. Assessing designs through iterative printing and product reflection.

M E T H O D O L O G I E S

D E S I G N & D E S I G N R E S E A R C H

Design research is an exploratory activity, which involves the synthesising and collation of trans-disciplinary knowledge to create new processes, products, and systems. "Unlike Scientific research, design research is not concerned with what exists but with what ought to be" (Milton & Rodgers, 2013).

"design is an activity for planning and implementing new products, which includes the byproducts of the processes involved such as drawings, models, plans, or manufactured objects." (Frankel & Racine, 2010)

The following section outlines a two-part design research methodology that has been used throughout this project.

R E S E A R C H ' F O R ' D E S I G N

Research for design, also known as "research to enable design", is a secondary research area, that provides the information, implications and data that designers can use to accomplish their design projects (Downton, 2003). Through this research, designers are involved in analysing, synthesising, organising, and evaluating knowledge in both specific and uniquely different clinical situations (Friedman, 2003). This is useful for contextualising and grounding a research topic within a field of interest. This often involves designers looking, learning and asking "in order to discover what people really need, want and do rather than just what they say they need, want and do" (Milton & Rodgers, 2013).

R E S E A R C H ' T H R O U G H ' D E S I G N

Research through design is practice-based research which involves taking 'something' from outside of design and translating it through the medium. Such work is often interdisciplinary and can range from an idea or concept to a new material or process. The designer is engaged in making work within a field of interest as well as reflecting and contextualising it (Milton & Rodgers, 2013). Through this methodology, an emphasis is placed on the designer creating new design knowledge, rather than a project solution. This is done through an action-reflection approach, where an explanation or theory within a broader context is sought by the designer (Frankel & Racine, 2010).

The Methods Included for Research 'For' Design,

as Described in "Research Methods for Product Design" (Milton & Rodgers, 2013):

Literature Review; Examines published articles, papers, books, and other relevant sources. To provide an informed description summarised by related design issues or area of exploration. Its purpose is to gain an overview of the significant literature that will allow the designer(s) to develop an informed opinion and perspective on a subject.

Product Autopsy; Gaining a better understanding of design decisions that have been made in existing products, such as materials used and manufacturing methods. Discerning why certain components have been used and aesthetic decisions have been made. It's also valuable for reviewing how a product has aged.

Context Scenarios; Representative profiles of settings and activities to provide reference points for customisation. It is useful for raising questions and issues, and to propose ideas and solutions for these points. Enabling designers to predict and interpret implications of user behaviour, informed by hard data and expert observation and allowing them to make informed decisions.

The Methods Included for Research 'Through' Design,
as Described in "Research Methods for Product Design" (Milton & Rodgers, 2013):

System Mapping; A form of concept mapping, a method of creating visual representations of words and ideas, to illustrate relationships between information. The method allows designers to present and evaluate key concepts and ideas while identifying knowledge gaps, intervention points and insights. This allows for the development of a cohesive interconnected series of products.

Body Storming; Idea generation and prototyping that involves physically experiencing a situation in order to drive new ideas i.e. going to the beach. While it was not possible to experience the use of a prosthetic during this project. Experiencing walking along a beach and around the coastline does provide examples of what a foot needs to accomplish in these scenarios.

Sketching; A key research and development tool that enables designers to evaluate their ideas.

Through:

- Analogue/paper
- Digital/CAD

Prototyping; The tangible creation of artefacts at various levels of resolution, for iterative development of ideas, testing, and reflection.

Through:

- Rapid prototyping
- 3D printing
- Sketch Modelling

Qualitative Reflection; A method of evaluating design research, which often involves the designer using their intuition to inform design decisions. This requires the designer to categorise and analyse important data, to create an understanding of the big picture, while highlighting important messages and findings to colleagues, clients and customers.

R E S E A R C H
F O R
D E S I G N

L I T E R A T U R E R E V I E W

A D D I T I V E M A N U F A C T U R I N G

Introduction:

Terminology is changing as rapidly as the industry itself. The term 3D printing is defined by the ISO/ASTM52900 as the fabrication of objects through the deposition of a material using a print head, nozzle or other printer technology (Wohlers, 2016), though this is a term that is often associated with low-end machines. Additive manufacturing (AM), previously known as Rapid Prototyping (RP) is defined by the American Society for Testing and Materials (ASTM)52900 as a process of joining materials to make objects from 3D model data, usually layer upon layer (Chua & Leong, 2014; Wohlers, 2016). In contrast, subtractive manufacturing starts with a block of material and removes any unwanted material, until one is left with the desired part (Diegel, 2019).

Capabilities:

3D printers use a 3D Computer-Aided Design (CAD) software that measures thousands of cross-sections of each product to determine how the layers are to be constructed (Berman, 2012). The original and still main use of additive manufacturing is in the making of prototypes (Sherman, 2009). Where designers produce a onetime model to grasp the three dimensionalities of a design. Additive manufacturing applications are becoming more prominent in small batch production of specialised products that serve small market segments. It is seeing especially large use in the medical, automotive and aerospace sectors (Berman, 2012). Recent advancements in additive manufacturing are allowing for the production of strong complex models that cannot be fabricated through traditional manufacturing (Stratasys, 2018).

AM is an expensive manufacturing method and due to it being a serial production method (production only according to order quantity) it is slower in comparison to some conventional mass manufacturing methods. Therefore, AM should only be considered when it is truly adding value to the design, such as through the creation of lightweight and complex geometries, which would be impossible with traditional manufacturing methods (Diegel, 2019).

These advancements lead to a market that is well suited for prosthesis production and allows us to re-think the way artificial limbs are made by targeting common pain points of customisation, weight, and cost. A company that has produced products that achieve many of these points is Bastion-Cycles an Australian company which produces custom high-end bicycles. These bikes are serially produced with each one custom-designed for the rider's body (Bastion Cycles, 2019). The lugs of the bikes are then 3D printed through RAM3D, an AM bureau in New Zealand specialising in metal printing. These parts are printed in Titanium 64, "which is a high-grade alloy, that boasts one of the highest strength to weight ratio of all engineering metals" (RAM3D, 2018). The parts have an internal lattice structure, resulting in reduced volume while still maintaining its strength with thin walls of 0.5mm, allowing Bastion to achieve their breakthrough of a lightweight bike that combines performance, comfort and price premium.

Design for Additive Manufacturing:

AM allows designers to be daring with their designs, producing almost any shape and create parts and products with complex features that could not be easily made through traditional manufacturing. This brings many advantages and challenges to designers and has initiated a change in the way we approach design. Process considerations are less prominent and very different when compared to conventional manufacturing, with limitations greatly reduced but not totally removed. This increase in freedom allows designers to concentrate more on the functionality and aesthetic quality of the part rather than manufacturing, increasing its overall value (Wohlers, 2016).

There is an increasing number of books available on the considerations and process of design for additive manufacturing, two that stand out are *Additive Manufacturing Technologies* (Gibson et al., 2010) and *A Practical Guide to Design for Additive Manufacturing* (Diegel, 2019). Both books relate mostly to the process of metal printing but many of the considerations they address translate to polymer printing as well. The first book (*Additive Manufacturing Technologies*) provides an extensive background into a range of different printing processes, it addresses build- related considerations from a design perspective, such as:

Part Orientation, which directly relates to the quality of the print. For example, if a cylinder was built on its end it will be made up of a series of circular layers, resulting in a well-defined cylinder. A cylinder built on its side will have a distinct layer pattern on the sides and will result in a less accurate print.

Removal of Supports; due to the correlation between part orientation and the need for supports, it is important to plan where and how supports are located during the printing process. Supports are needed to act as heat sinks, stress relievers and overall connecting the part to the print bed, this is only necessary for metal printing. Supports, however, leave small marks on the print and their removal increases post-processing time. This can also be addressed by creating permanent supports for parts.

Hollowing Out Parts; reducing the amount of material used in a print has the benefit of reducing machine time and overall cost. Many parts can have a honeycomb or lattice internal structure incorporated into the part, providing strength to the part, making the part lighter and reducing its cost.

Interlocking Features; AM machines have limited build volume and larger parts might not fit inside them. This can be solved by breaking the design into parts that can fit inside the printer. For reassembly, interlocking parts can be incorporated into the design, so that adhesives can be most effective. (Gibson et al., 2010)

Diegel's book takes these points further and starts discussing the added benefits of DFAM and how the process if used correctly, can add further value to designs. He does point out that not everything should be produced with AM, "if a part was designed to be machined on a 3-axis CNC machine, it will be cheaper and faster to CNC machine it than to 3D print it" (Diegel, 2019). He explains that it is more economical to manufacture geometrically simple parts with conventional methods. However, AM starts to shine when parts reach a high complexity level, at this point the designer should start analysing their product to see which value-adding strategies to adopt, for instance, improving the parts function, fit, form and process. It also does not cost any more to customise parts, this can include adding cosmetic details, branding, instructions, part numbers, etc. However, these strategies can be brought further by giving each product a unique aesthetic that can only be achieved through AM.

Processes and Materials:

AM includes many different processes and materials for manufacturing, with many AM system manufacturers naming their processes and material designations naming them uniquely to stand out from their competitors. This leads to confusion as many of the "different" processes and materials are the same. Fortunately, the industry has standardised a system for grouping processes into families as described in Wohlers Report (Wohlers, 2016) with further research provided for specialised processes. The main processes can be summarised as follows:

Material Extrusion; the process of selectively dispensing material through a nozzle. The most common version of this process is Fused Deposition Modelling (FDM), which is what most people refer to as, 3D printing with desktop printers being the most common machines. Materials that can be printed through this process are thermoplastics, but these plastics can have properties from other materials such as wood and metal for different applications and finishes. (Stratasys, 2019b)

Material Jetting; a process where droplets of UV-curable build material are selectively deposited. Known as Multi-Jet-Printing (MJP) (3D Systems, 2019c) and PolyJet (Stratasys, 2019d). It has applications in creating realistic multi-colour, multi-material parts, useful in the biomedical and film industries.

Binder Jetting; a process where a liquid bonding agent is selectively deposited to join powder materials. This has applications in binding metal, sands and plastics. Common versions are Colour Jet Printing (CJP) (3D Systems, 2019b) which is used for creating detailed colour prints out of powdered plastic and Multi Jet Fusion (MJF) (HP, 2019; Stratasys, 2019c) creating fast and accurate production models in Nylon PA12.

Sheet Lamination; a process where sheets of material are bonded to form a part. Because of the process of bonding sheets of material together, any material that can be rolled into a sheet can be used, such as metal and carbon fibre (Loughborough University, 2019b).

Vat Photo polymerisation; a process where liquid photopolymer in a vat is selectively cured by light-activated polymerisation. Known often as Stereolithography (SLA) the original 3D printing process is still used today for its speed and accuracy. (Stratasys, 2019e)

Powder Bed Fusion; a process where thermal energy selectively fuses regions of powder material. Selective Laser Sintering (SLS) the polymer version of powder bed fusion is capable of creating production-grade parts for many different applications and can print in many different materials, most common are Nylon powders in PA6, PA11 and PA12 (3D Systems, 2019d; Stratasys, 2019f). Direct Metal Printing (DMP) (3D Systems, 2019a), Direct Metal Laser Sintering (DMLS) (Stratasys, 2019a) also known as Selective Laser Melting (SLM) is capable of printing many metal alloys such as Titanium, Aluminium, Nickel, Cobalt Chrome and Stainless Steel. This has many applications from biomedical, dental, automotive, and aerospace.

Directed Energy Deposition; a process where focused thermal energy is used to fuse materials by melting them as they are deposited, commonly used to repair or add additional material to existing parts. This can only be used with metals such as Cobalt Chrome and Titanium. (Loughborough University, 2019a)

The AddLab:

Callaghan Innovation is a New Zealand Crown entity, responsible for accelerating the growth, scale, intensity, and success of innovation in New Zealand business through R&D and support export growth. It was established in February 2013 and takes its name from the late Sir Paul Callaghan (Ministry of Business, Innovation & Employment, 2019).

The AddLab is Callaghan Innovations 3D printing hub, it is there to enable New Zealand businesses to explore new R&D through additive manufacturing. "AddLab is designed to help you explore new business opportunities and find new solutions to your R&D problems through growing capability in new design, materials and manufacturing technologies" (Callaghan Innovation, 2017).

P R O S T H E T I C S

History:

Throughout history humankind has used science, innovation and creative spirit to defy extreme physical disability with the creation of artificial devices that could take the place of limbs lost to disease, injury and war. Gailey & Clemens describe the history of modern prosthetics, from the earliest mythological records telling of gods, goddesses, and mortals whose arms and legs of metal and ivory allowed them to carry on (2017). At the time of writing, they state that the oldest prosthetic discovered in a tomb in Capua was dated to 300 BC. However, the Cairo Toe said to be from 1000 BC has been found in a burial chamber in Egypt, showing a highly crafted prosthetic extension with an aesthetically natural look (Andrea Loprieno-Gnirs & Susanne Bickel, 2017). Gailey & Clemens went on to state that warfare was a contributing factor to prosthetic development, with many skilled craftsmen innovating on the previous designs (2017). There is a focus on developing lower-limb prosthetics, allowing amputated veterans to reintegrate within society. More recently Evans stated that diabetes, rather than warfare, is the most common cause of limb amputation, although veterans, particularly in the USA, have still helped drive development of new devices such as microprocessor knees and robot hands (2019).

NZALS:

The external partner of this project, the New Zealand Artificial Limb Service (NZALS), is reviewing its current practices and products in the lower-limb foot range. They have five centres around New Zealand providing prosthetic limbs and physiotherapy for amputees and are driving to provide equitable access to technology and services based on needs. In order to improve their service provision, they are focused on new technology and R&D, investing in research that will benefit their patients and has completed several research projects with Victoria University of Wellington (NZALS, 2016). This research allows the NZALS to begin digitisation of its practices, by transitioning from labour-intensive analogue production to digital production. Recent statistics show that NZALS service 4,290 amputees with 74% being male and 26% female (NZALS, 2018). Evans stated that this gender difference is attributed to riskier behaviour and jobs, as well as the fact that men with diabetes are more likely to be amputated (2019).

NZALS offer a range of nine different lower-limb prosthetic types with varying levels of weight, foot size, activity level and employment and recreational needs (NZALS, 2019). They are ordered from a handful of international companies, from a simple foam foot to ones with microprocessors. Some are designed for rough terrain, have shock absorbers, or adjustable heels for different shoes (Evans, 2019). These prosthetics are often made from layers of carbon fibre, which has been identified by clinical experts to be problematic with use at the beach as sand and salt get in-between the movable layers and corrode the prosthetic to a state where it needs to be replaced.

Specialised Prosthetics:

When it comes to a specialised prosthetic that embodies kiwi ingenuity, it would be prosthetic climbing legs designed for mountaineering in various conditions, known as dash foot by their creator. These prosthetics were created in collaboration between Wayne Alexander, who had an interest in designing high-performance prosthetics, and Mark Ingles a double amputee, who had a goal of returning to mountain climbing. The foot was made from steel and titanium for the working components with carbon fibre used for connecting the foot to the socket. This allowed for energy to be captured at heel strike and release as the front of the foot left the ground (Te Papa, 2019). An article in New Zealand Geographic describes the relationship and process between the two. With most amputees at the time relying on a solid ankle and cushioned heel (SACH) foot design, they proposed the opposite with a dexterous ankle and a solid heel allowing, for a flexible and elastic foot with springs acting as Achilles tendons (Frankham, 2014).

More important than how the foot functions were the emotional and freedom side of the prosthesis, with Ingles describing them as his Terminator's legs. He went onto the climb Mt Cook, the same mountain on which he had lost his legs to frostbite 20 years earlier. While these prosthetics would not appeal to everyone, they do demonstrate a triumph over adversity, allowing the ability to conquer mountains, with Ingles climbing the summit of Mt Everest in 2006. Many of these principles can be applied to the creation of a seashore/beach limb through DFAM, looking at a problem and possible solutions differently.

Figure 1. Alexander, W. (2002). *Prosthetic climbing legs* [Photograph]. Te Papa. <https://collections.tepapa.govt.nz/object/695863>

Human Foot:

This section will detail the foot in action, as described in *The Human Foot* (Klenerman & Wood, 2006). The book addresses how the foot has evolved over millions of years and the evolution of bipedalism within the Hominin Clade. With evidence suggesting that the chimp/human common ancestor was already adapted for plantigrade locomotion, this is the action of heel to toe walking. The book goes on to describe the function of the foot, as well as the development of gait.

Klenerman & Wood explain how the child grows and develops how to walk confidently upright over a three to four-year period (2006). During that time, they spend 60% of the gait cycle with both feet planted on the ground and 40% supported by one foot. This increases stability but reduces forward momentum. In comparison, the adult gait cycle spends 80% of the time supported by only one leg. When comparing this to an amputee's gait which is often asymmetric in step length, it shows a weaker propulsion-generating capacity on the prosthetic side. Evidence for this is shown by a shorter stance and longer swing phases for the prosthetic leg (Roerdink et al., 2012). This can be due to amputees feeling less secure and landing softer on their prosthetic.

Klenerman & Wood also describe some of the varieties of activity that push the function of the foot to the extreme and require maximal skill such as running, ballet, kicking, swimming, tightrope and fire-walking (2006). This section of the book is especially useful, as it helps define scenarios for very different prosthetic feet.

Running was shown to be much more efficient than expected, due to energy being converted to elastic strain energy. This mechanical conversion is like a bouncing ball which converts kinetic energy into elastic strain energy as it deforms and reverses the mechanical conversion as it leaves the ground. During running, tendons are where this elastic strain energy is stored, as tendons are a good elastic material with 93% of the energy used in stretching the tendons being returned in elastic recoil. However a tendon can only stretch by 8% of its length before breaking, so long tendons are needed to make effective springs (Klenerman & Wood, 2006).

The other prominent section that was addressed was that of swimming, with the propulsion of the kick requiring much more energy compared to the arms, stating that flexibility in the ankle joint and the ability to point one's toes like a ballet dancer is an advantage.

In conclusion, this literature suggests a range of flexibility and tension in design for prosthetics, providing direction for design with the specialised scenarios depicted. These scenarios help provide context for an NZ shoreline prosthetic, showing advanced movements that would be expected while at the beach.

Figure 2. Human *foot drawing*.

Culture:

In an age of consumer culture, body image is generally thought of like the mental image of one's body as it appears to others, where status and social acceptability is dependent on how a person looks, that a person's body is the reflection of themselves and that a person's inner personality will shine through the outer appearance (Featherstone, 2010). This statement of how consumer goods change how we perceive ourselves also leads into how amputees feel about their prosthetics. Generations also differ with how they wish to be perceived, where the older population tends to prefer a prosthesis to have a natural look that blends into the body without drawing attention. Whereas younger generations prefer to express themselves with artistic fairings (Ferrendelli, 2018). In another article, researchers go into how there is aesthetic anxiety to reactions of disability, where the persons with disability are devalued because they do not adhere to beauty standards and normality (Solvang, 2007). Recent designs and studies suggest that 3D printing begins to address these problems with the introduction of customisation and expression of one's self.

Hugh Herr, a biophysicist at MIT who lost both of his legs in a mountaineering accident due to frostbite, describes the aesthetic beauty of his artificial limbs. "We want the bionic limb to have a humanlike shape, but we don't want the bionic leg to look human. We want it to look like a beautiful machine, to express machine beauty as opposed to human beauty..." He explains that they want the wearer to be able to pull a black sock over the limb to blend in and appear biological and also be able to choose to expose the limb and their bionic body (NPR, 2011). This interview supports the fact that the visual expression of artificial limbs is becoming more prominent and design should reflect this.

Printed Prosthetics:

Many studies and examples of 3D-printed prostheses have been developed over the years. This section of the review will compare and contrast a range of printed prostheses from low-cost foot prosthesis to swimming prosthesis.

Currently, the typical low-cost prosthetic foot is a Solid Ankle Cushioned Heel model. While this foot is cheap, it does not allow for natural movement and can put a strain on the amputee's limb. A prosthetic foot that can be optimised according to the individuals' gait has been developed for around \$10 USD (Yap & Renda, 2015). While these prostheses do provide a cheap solution, they did need post-processing with a ¼ inch threaded rod embedded in a Fused Deposition Modelling PLA plastic print. Ideally, with the use of more advanced printing methods and materials, equally cost-effective but more reliable prostheses can be developed.

Another study investigated the topology optimisation of commercially available carbon fibre foot prosthesis (Fey et al., 2009). This research explored the use of selective laser sintering of Nylon-11 powder material to provide the same characteristics of a commercial carbon fibre prosthesis while reducing the material used in production. While the research did develop a prosthetic foot that is well suited for selective laser sintering on one plane, the three dimensionalities of the foot were not pursued. The design was also limited by the constraints of having to fit in a traditional prosthetic foot cover. Selective laser sintered nylon is very porous due to pores in the sintered material (Shaw & Dirven, 2016). However, with post-processing, this can allow for a robust, energy-returning foot that can withstand rough terrain. Initial exploration of sintered Nylon has been conducted in the form of a summer research scholarship that has shown promise to this claim.

Figure 3. Yap, J., & Renda, G. (2015). *CAD Concepts [Render]*. In *Low-cost 3D-printable Prosthetic Foot*.

Victoria University of Wellington

In a 2016 research thesis in association with NZALS and Victoria University of Wellington, an exploration into the design and development of a specialised additive manufactured swimming prosthesis was conducted (Baynes, 2016). This project showed a radical new approach to prosthetic design, showing that with additive manufacturing technology we can produce highly specialised one-off products that would never be made with traditional manufacturing due to the cost and time it would take to produce traditional tooling (Sherman, 2009). The design is a multi-material print which combined soft and fixable materials with hard fused deposition modelling techniques. This produced a two-part swimming prosthesis that used anatomical referencing and cohesive design forms to visually integrate with the participant's body. The two parts allowed the participant to walk from the changing room into the pool, where he then removed the outer shell to reveal a swimming flipper (Baynes, 2016). Due to several factors including print inaccuracies, friction, pressure and flexibilities, it was difficult for the participant to easily remove and put back on the outer shell while in the swimming pool. This led to him occasionally standing on the soft TPU fin. Another print issue like the \$10 USD foot prosthesis by Yap & Renda is that FDM printed plastic tends to snap under pressure and the swimming prosthesis required fibre-glass rods to be inserted in the outer shell before it was deemed safe to walk on (2015).

Figure 4. Baynes, S. (2016). *Swim Limb* [Render]. In *Printable Prosthetics: The design of a 3D printed swimming prosthesis*.

A second research thesis project was completed, in collaboration between NZALS and Victoria University of Wellington which lead to the creation of a performance art prosthetic (Richards, 2018). This was an exploration and development of artistic performance and prosthetic design, challenging the issue of social exclusion. The project aimed to promote diversity in different contexts and environments and to celebrate amputees by not blending in but standing out. This research brings up an interesting point of what is seen as the norm, with more diverse prosthetics being seen in different contexts and environments by the public, the more accepted and understood they will become.

Figure 5. Richards, F. (2018). *I Can Can: Prosthesis* [Image]. In *Celebrating the Spectacular: Discovering the New Enabled Through Performance Art*.

Customisation:

Traditionally all prosthetics are manufactured with identical components to reduce time and costs. Custom prostheses through additive manufacturing can allow for a sense of personalisation. For example in a project, the University of Nevada, Las Vegas and Stratasys created a series of low-cost 3D printed hands for a child born with Poland syndrome (Scott, 2017). These hands were printed with custom baseball details as the child enjoys watching baseball games. Low-cost custom printed prosthetics are perfect for children growing up as they usually have a new prosthesis fitted every year as they grow. But it also allows them to take back a part of their lives and be able to add a bit of individualism to what otherwise is another standard medical product. (Christie, 2018)

This product, designed by Glaze Prosthetics, a Polish start-up is offering customised 3D-printed lightweight prostheses. They aim to create a path of innovative design in the prosthetics industry by 3D printing a replaceable arm system that would “help amputees feel proud of their distinctiveness” (Haria, 2017). Custom designs are created through measurements of the amputee along with their input on the style, colour and modifications of the prosthetic. This along with an interchangeable system that allows for the prosthesis to be securely removed and replaced within three seconds, offers amputees a chance to express themselves through their prosthetic limb. This is a revolutionary system of design as it shows that prosthetics do not necessarily have to make an amputee look “normal”. A big factor in this design is the interchangeable system as it allows an even greater sense of freedom that is like putting on a different t-shirt or a pair of shoes. It is fascinating that one could have a prosthetic arm for around the house and another for a fancy-dress party.

Figure 6. Glaze Prosthetics. (2017). Four designs from the Glaze Prosthetics range [Photograph]. Retrieved from <https://3dprintingindustry.com/news/glaze-prosthetics-superhuman-3d-printed-prostheses-amputees-122974/>

This design by Aurelien Dantin is a prosthetic leg that gives sport-minded amputees the capability to play sports again and boost their confidence while doing so (Turner, 2013). The prosthesis consists of multiple 3D-printed sections that can be interchanged to the wearer's taste and style. This design combines functionality with aesthetics creating a form, that does not use the standard pylon found in lower-limb prostheses. However, this design is very conceptual with only renders being provided, it would be interesting to see if the prints could hold a person's weight. But with versatile plastic materials like Nylon-11 & 12, there is a possibility.

Figure 7. Dantin, A. (2015, March 12). *Adidas Impetus, Soccer Prosthetic* [Render]. Retrieved from <https://www.behance.net/gallery/11485739/ADIDAS-IMPETUS-Soccer-Prosthetic>

PRECEDENT REVIEW

LOWER-LIMB PROSTHETICS

Figure 8. Lower-limb prosthetic system.

Figure 9 (a). *Ottobock carbon fibre prosthetic.*

Figure 9 (b). *Silicone foot shell.*

Figure 9 (c). *Ottobock carbon fibre prosthetic & silicone foot shell.*

NZALS PRODUCT RANGE

The following section explores the current product range of the NZALS, identifying advantages and disadvantages of the product systems and how they relate to daily life.

Solid ankle cushion heel (SACH) foot - passive keel

The SACH foot with passive keel is the most basic type of foot....

Advantages

- SACH feet can be made lighter than almost any other foot of the same size.
- Reasonably waterproof.
- Quite durable.
- Inexpensive.
- Stable.
- Ideally suited to low activity and lighter weight users.

Disadvantages

- Rigid keel cannot bend.
- Heel height is fixed and cannot be readily customized.
- Minimal shock absorption.
- Almost no option to tune the foot to a user's requirements.
- Fixed with a single bolt which can fail without warning.
- Active users will quickly overpower a passive SACH foot.

Solid ankle cushion heel (SACH) foot - dynamic keel

Building on the basics of the SACH foot, a dynamic keel adds function....

Advantages

- SACH feet can be made lighter than almost any other foot of the same size.
- Quite waterproof.
- Quite durable.
- Inexpensive.
- Stable.
- Ideally suited to low activity and light to medium weight users.

Disadvantages

- Flexible keel cannot be customised.
- Heel height is fixed and cannot be readily changed.
- Improved shock absorption over passive SACH feet.
- Almost no option to tune the foot to a user's requirements.
- Fixed with a single bolt which has been known to fail without warning.

Single axis foot

Incorporates toe-up and toe-down movements at the ankle....

Advantages

- Heel height can be modified within limits.
- Increased stability and comfort on non-level surfaces.
- Quite waterproof.
- Reasonably durable.
- Improved function compared to passive SACH feet.
- Suited to low to medium activity levels.

Disadvantages

- An old design now largely surpassed by other types of feet (multiaxial and dynamic response).
- Quite heavy for the function they provide.
- Movement is restricted to one plane i.e. no inversion/eversion or rotation.
- Intolerant of wet conditions.
- Limited option to tune the foot to a user's requirements.
- Become looser as they wear, giving the user less control.

Figure 10 (a). NZALS product range.

SACH – passive:

- The simplest foot prosthetic often made of a wooden block.
- Inexpensive.
- Not much can be changed about the design.

SACH- dynamic:

- Uses layers of material creating a gradient of flexibility.
- Does require an outer shell to be fitted around it for the prosthetic to function.

Single Axis Foot:

- Beginning to see improved function.
- Made from moulded thermoplastic.
- Only good for low impact.
- Large toe lever.

Multiaxial foot

Multiple joints provide more natural function....

Advantages

- Heel height can usually be modified.
- Increased stability and comfort on non-level surfaces.
- Quite waterproof.
- More options to tune the foot to a particular user.
- Reasonably durable.
- Improved function compared to SACH / Single Axis feet.
- Suited to medium to high activity levels.

Disadvantages

- Heavier than SACH or Single Axis feet.
- More expensive to produce than SACH or Single Axis feet.
- Small bearing surfaces and bumpers can lead to wear and noise.
- Become looser as they wear, giving the user less control.
- Lacks significant shock absorption or energy return.

Dynamic response foot

Reduce energy requirements by returning energy at toe off....

Advantages

- Reduced energy expenditure.
- Significant shock absorption.
- Generally quite lightweight.
- Adapts to uneven terrain. A great offroad foot for trampers & runners.
- Suited to medium and higher levels of activity.
- Natural gait.
- About the same weight or lighter than multiaxial feet.
- Highly durable.
- Split toe options to enable inversion/eversion of the forefoot.
- Generally tolerant of wet conditions.

Disadvantages

- May become noisy when wet.
- Prone to failure if abused.
- Higher cost than multiaxial feet.
- Quite stiff at low activity levels.
- Not held in stock as each order is individualised. This may incur delays.

Variable heel height

These feet allow the heel height to be customized by the user....

Advantages

- Heel height can be easily modified.
- Reasonably durable.
- Improved function compared to SACH / Single Axis feet.
- Suited to medium activity levels.

Disadvantages

- Heavier than feet with otherwise similar function.
- Generally intolerant of immersion in water.
- Less energy return than dynamic response feet.
- May have an upper weight limit.
- Higher cost (especially computerised models).

Figure 10 (b). NZALS product range.

Multiaxial Foot:

- Looks the most promising for ideation with the multi axis movement.
- Moulded thermoplastic with aluminium pins
- Small bearing surfaces become a problem with sand and salt

Dynamic Response Foot:

- Most common foot for higher activity activity levels.
- Is expensive and has to be individualised.
- Has good shock and energy return, great for tramping and running.
- Designed to act like one big tendon/spring.

Variable Heel Height:

- Similar to the dynamic response foot in terms of design except the ankle is adjustable.
- Designed for people wearing heels and boots.

Vertical Shock Absorbers

Shock absorbers reduce forces transmitted to the socket....

Advantages:

- Reduces forces transmitted to the socket.
- Improves comfort and lowers skin abrasion.
- Simulates natural twisting of sound leg over the foot.

Disadvantages:

- Only one level of shock absorption can be set.
- Significantly heavier than feet with otherwise similar function.
- Generally intolerant of immersion in water.
- Lowers the energy return of dynamic response feet.
- May have an upper weight limit.
- Higher cost.

Special use (sports) Foot

Feet which have a special purpose, like sporting activities....

Advantages:

- Higher energy return than all other models of foot.
- Lower weight than conventional feet.

Disadvantages:

- Usually single-use design.
- May have an upper weight limit.
- Higher cost.

Computerised feet

Use a micro-processor to drive ankle function....

Advantages:

- Walking up and down slopes, stairs, and ramps is easier.
- Improved ground clearance during swing.
- Improved ground compliance.
- Enhances stability.
- Automatic adjustment of heel height.
- Adapts to walking speed of user.
- Improves symmetrical limb loading by mimicking normal ankle movement.

Disadvantages:

- Very complex.
- Heavier than other models of foot.
- Very high cost.
- Not intended for high levels of activity.
- Requires regular charging.
- Sensitive to environmental conditions (dust, vibration, salt or fresh water, chemicals, excess heat or cold, strong magnetic fields).

Figure 10 (c). NZALS product range.

Vertical Shock Absorbers:

- Reduces shock but has lower energy return.
- Better for day to day walking

Sports Foot:

- Very heavily specialised.
- Difficult to balance and walk on and only really good for sprinting.
- Acts as one giant tendon.

Computerised Feet:

- Very complex
- Basically takes the vertical shock absorbers and placed a computerised spring in the ankle.

From this review it was determined that multiaxial foot prosthetics would be the primary source for ideation as their purpose is to provide a stable platform on uneven surfaces. This led to their design having a larger platform and for lateral movement within the ankle. Further precedents within this area of foot prosthetics will be explored in the following section, along with 3D printed prosthetics and beach wear.

FOOT PRECEDENTS

Ottobock: 1M10

Blatchford: Multiflex

College Park: Truststep

Blatchford: Avalon

Figure 11 (a). Foot precedents, multi-axel prosthetics.

molded thermoplastic with
laminated carbon fibre and
aluminium fittings

designed for toe
off spring

Ottobock: Axion

has a split foot
design for multi-axle
support

long molded
sections to act as
springs for energy
return

Blatchford: Elite2

moving plates
that act as steps

unsure how this connects
to the socket

Blatchford: Elite Blade

this is to create a long continuous
"bendable" spring

Blatchford: Elite Blade VT

similar design to elite 2

has a long continuous
piece that leads to where a
standard aluminium pylon
should be

Figure 11 (b). Foot precedents, multi-axel prosthetics.

Figure 11 (c). Foot precedents, multi-axel prosthetics.

Figure 12. Foot precedents, 3D printed prosthetics & orthotics.

Figure 13. Foot precedents, beachwear.

Many of the multiaxial foot prosthetics have a similar design with laminated carbon fibre being combined with moulded thermoplastic to create bulk with strength and elastic properties. Many of them have opted for the split toe/foot design to provide multiaxial support. They also have implemented a large solid heel for added balance or have a tension designed part in place under the force point from the pylon. All the prosthetic designs apart from the Ottobock: 1M10 and Blatchford: Multiflex feet would have to be fitted into a silicon foot shell to give extra mass and a larger surface area under the foot for stability. This is also to provide a layer of protection to the expensive and delicate prosthetics. The Ottobock: 1M10 prosthetic has the option to function without a foot shell allowing for a lower cost compared to the other prosthetics, while still having a large enough form to fit inside a shoe. Whereas the Blatchford: multiflex has its own dedicated foot shell that conforms nicely to the thermoplastic design.

With AM foot prosthetics, only one stands out as a commercial product, the Mecuris: prosthetic foot, with its design form appearing to be influenced by multiaxial prosthetics, particularly the Blatchford: Avalon. This form would be able to function without the need for a foot shell, offering a stylised alternative to traditionally manufactured prosthetics. Further AM-designed products such as orthotics and explorative leg prosthetics showed a promising new style using thinner material while creating more complex 3D forms.

The last section of precedents showed footwear for use at the beach. There appears to be an expectation that these products will get wet, with all apart from the Reef Booties having opens areas for water to wash over the foot and be able to drain out. These products do require a foot form to fill the contours of the shoe and in the case of the jandal, a section between the big and second toe would have to be open for the jandal to slot in place.

COUPLING PRECEDENTS

At the start of the project, it was deemed relevant to create a system for amputees to simply and efficiently switch out their foot prosthetics, this was primarily to facilitate the idea of having multiple foot prosthetics for different recreational activities. To accommodate the spontaneous nature of these activities, this would be achieved through the development of a quick-release coupling system. The system would replace the standard OEM connector that is found between the prosthetic foot and the pylon.

The OEM connector provided by NZALS uses 4 grub screws to hold tension to the tapered pyramid connector on the foot, this was popularised by Ottobock. The four screws allow for technicians to pivot the connector along X, Y-axis depending on the angle of the knee. Technicians will then glue in the screws to prevent tampering and loosening due to wear. A technical drawing was produced to gain a better understanding of the geometry with measurements to make the process of CAD in SolidWorks simple.

The initial inspiration for a quick-release coupling mechanism came from the idea of using a coupling system such as standard hose connectors. Product autopsy was conducted by disassembling the coupling piece by piece and each stage documented. From these photos and measurements taken, a technical drawing was produced to create a better understanding of geometry and how parts will interlock. An open-source model of a coupling was also used as an example to gain a better understanding of geometry and tolerances.

Figure 14. Product autopsy of a hose connector.

outer shell has
keys cut out
so that it doesn't
rotate

main body where
plastic tension clips
are housed

mechanism without outer
shell shows a big
spring

The spring that keeps
the outer shell engaged
and the plastic inserts
under pressure

plastic clips
that are under
tension hold the
coupling together

Figure 15. Technical drawing of hose connector.

Figure 16. CAD drawing of a coupling connector.

Figure 17. CAD screenshot of coupling connector.

Figure 18. Product autopsy of OEM prosthetic connector between foot and pylon.

Figure 19. Technical drawing of OEM prosthetic connector between foot and pylon.

R E S E A R C H
T H R O U G H
D E S I G N

SYSTEM MAPPING

An overview of the proposed product system has been developed. This outlines the features and advantages of the system and indicates key elements for the research to focus on. This overview has been mapped out, to provide a coherent understanding of the system.

Remote Servicing;

- The amputee is able to remove their prosthetic foot in the case of failure and replace it themselves.
- Allows the NZALS to provide remote servicing, by allowing the amputee to interchange prosthetics

Life-style Specific Prosthetics;

- Allows amputees to have a range of recreational foot prosthetics, that are easily interchangeable without changing the entire leg.

Coastline Prosthetic;

- Provides a (salt)water-resistant prosthetic, which can be used in a coastline environment.
- The prosthetic can be disconnected from the leg for cleaning and maintenance.
- The system allows an amputee to travel to the beach in their everyday prosthetic and then switch to their coastline prosthetic.

Leg Fairing;

- The system facilitates the integration of a leg fairing.
- This leg fairing would be easily interchangeable, along with the rest of the system.

Getting Dressed;

- Allows amputees to disconnect their foot from the pylon, to facilitate putting on trousers.
- The system eliminates the need to thread pants over the foot prosthetic, due to amputees not being able to articulate the foot.

Specialised Prosthetics;

- The system opens avenues for future prosthetic design research.
- Specialised recreational prosthetics could include specialised sport situations (e.g. cycling foot) or specific cultural settings (e.g. marae foot).

Figure 20. System mapping of product system.

P R O J E C T O U T L I N E

Outline of Key Concepts/Factors/Defined contexts

Research through design has been split into three additional sections of development, the quick-release coupling system, foot prosthetic design, and supportive and contextual design product systems. These sections were designed in parallel with development stages overlapping each other. As a result, a lot of ideas and factors influenced design decisions in a nonlinear fashion unlike the linear presentation of this research portfolio.

BODY STORMING

ACTIVITIES & TERRAIN

- Walking on sand
- Running on sand
- Wading through water
- Exploring rock pools
- Launching a boat
- Fishing
- Laying on the beach
- Jumping off wharf
- Swimming
- Surfing
- Walking along rocks
- Beach sports

Figure 21. Collage of beach photos.

New Zealand's coastline is very varied with areas of New Zealand having rough stony shorelines that are hard to traverse and then in other areas a beach can be completely flat and smooth. A lot of beaches have sea debris, from shells to logs.

Through body storming, a set of criteria were produced for the design of a coastline prosthetic product system proposal. This research method was explored through spending time at the beach, to understand how these different surfaces and terrains change how we walk. These explorations showed that walking on sand requires significantly more effort, due to the sand giving under the pressure of the foot. The sand is also constantly uneven, requiring the foot to pivot slightly to accommodate the terrain. The criteria are as follows, in no particular order;

- To still maintain a human foot and leg form
- To fit in with a coastline context (form and style)
- Be able to spread and flex in soft sand and bend around rocks
- Be hardy enough that rough terrain will not break it
- Be able to grip both sand and slippery rocks
- Be easily cleanable
- To allow optimal movement in the water
- Have good energy return – allow for a more natural gait
- Be able to easily attach to a pylon
- Have a design that an amputee will trust standing on
- Be able to pivot on uneven terrain
- Be compatible with beachwear and footwear

C O U P L I N G D E S I G N

I N T R O D U C T I O N

The first phase was to design and rapid prototype a quick-release coupling system. This would use the findings developed throughout the Research 'Through' Design phase, particularly through the product autopsy of the hose coupling and standard connector utilised by the NZALS. It would also consider the developments and findings expressed in the opportunities and applications diagrams for the coupling system. Using the technical drawings of the connector between the pylon and foot, producing models inside of SolidWorks would be a simple task and iterating from that stage would allow for a base model to restore to between concepts.

The main considerations at this stage of development were to produce interlocking parts that would have enough clearance tolerance while maintaining a smooth fit. A tolerance of 0.2mm was decided for this section as through experience this has been the most successful tolerance with 3D-printed parts.

The next consideration was having live cam mechanism hinges that will be printed freely by offsetting the pin-hole and producing an assembly in SolidWorks to allow them to be orientated in a way that they will print without multi-bodies fusing together.

The last major consideration was the coupling mechanism and how multiple parts would mesh. This was particularly important between the interaction of the male connector and the mechanism levers, with the concave and convex curve ratios having to allow the parts to lock together but be able to rotate and pivot out of the way when disengaging.

ANALOGUE & DIGITAL SKETCHES

Two further digital technical sketches were created for the modified coupling parts. These parts included creating extra walls along the outside of the female component for the levers to lock into and provide a layer of protection. A key was also developed between the female and male components, this was mainly incorporated to prevent the parts from twisting during use. On the OEM part, twisting was prevented by the four grub screws holding the parts in place.

When developing the cam mechanism to mesh the couplings together, an assembly of all the parts was created in SolidWorks to check tolerances and to make sure that parts wouldn't interfere with each other. The concave curve on the male component was created at a radius of 7.14mm, this was because a 5mm radius curve removed too much material from the part and created a sharp angle that made it hard for the mechanism to operate. It was also shown in the two precedents that a much shallower curve was used, though this meant that the centre of the radius had to be offset for the curve to intersect the corner of the part.

A height-to-radius ratio of 1.4 was developed from these digital sketches. Further development of the coupling led to a ratio of 1.66 between the convex radius of the mechanism and the male component. $7.14/1.66 = 4.3\text{mm}$ mechanism radius.

Figure 22. Technical drawing coupling system.

Figure 23. CAD screenshot of coupling system.

Figure 24. CAD drawings of coupling system.

C O N C E P T O N E

Concept one is using the same body design as an OEM coupling between the pylon and the foot, with alterations. The inner body is designed to fit a custom male component designed after a hose coupling. It uses two levers to hold the two parts together.

Figure 25. Renders of coupling design, concept one.

Figure 26. *Images of coupling design, concept one.*

C O N C E P T T W O

Concept two, like concept one, is designed after an OEM coupling between the pylon and foot. The inner body is designed to fit a standard pyramid connector that is commonly used on foot prosthetics. It also uses two levers to hold the parts together.

Figure 28. Renders of coupling design, concept two.

Figure 29. Orthographic diagram of coupling design, concept two.

Q U A L I T A T I V E R E F L E C T I O N

- The overall shape and size of the couplings is satisfactory
- Moving parts were not orientated correctly so they fused with the main body
- The inner diameter for the pylon to slot into was too large at 30.5mm and has been reduced to 30mm
- It was determined the separate interlocking parts fit snugly at 0.2mm clearance
- For the printed live interlocking parts clearance was increased to 0.5mm, to allow for tolerances and minor deformation in printing.
- The top of the hinge needed to be redesigned to make it easier to interact with. The slotting mechanism had to be completely redesigned. (having a 1mm wall thickness around a hollow body with holes would ideally make the part flexible enough to bend into place, but it was too rigid
- The font size has been increased

Reprints

- Make sure that the cam mechanism is orientated so that they do not fuse with the main body
- Model and print a threaded coupling as well as a threaded pylon
- Redesign the top section of the hinge to make it easier for people to grab on to and move the part
- The male parts will not need to be reprinted
- Make sure that the pin for the hinge is printed this time

The reprints were successful with the tolerances and cam mechanism work exactly as intended. The two bodies intersect nicely and couple correctly with the inserted key.

NZALS Discussion

Presenting the designs to the NZALS, they seemed very open to the idea. However, they raised concerns about angle adjustments that would need to be tailored for individual cases depending on the patient. This adjustment is usually done through the same grub screws that connect the female component to the male component of the foot.

Possible solutions were to move the coupling higher, closer to the socket. While this does allow for the amputee to switch out the pylon and foot and have all of the height adjustments already tailored for them without need for adjustment, it still produces a problem for accessibility especially when it comes to switching components when wearing trousers. Another solution was to use two grub screws in the coupling system along with the levers, but this could be problematic with tolerances dependent on if the screws were set up tighter or looser. Lastly, as the system would be 3D printed, the suggestion was to incorporate any angle adjustments into the print.

After reflecting on these possible solutions and deciding that there was a slight flaw with all of them, we discussed alternative solutions with the NZALS. One promising alternative was to leave the grub screw system as it is and move the coupling system higher up so that it is the pylon that is removed. Developing on these ideas, three models were designed, they had a focus on creating a sleeker body to allow for a leg fairing to be incorporated into the system and would mean that it could slide over the coupling system.

DEVELOPMENT ONE

Development one utilises the body design of the OEM coupling using grub screws to connect to the foot prosthetics to the pylon while making it taller. This is to facilitate the coupling mechanism that connects to the pylon by a custom-printed male connector. The reasoning for the male connector to extend past the point of coupling is because of the horizontal forces from the person walking acting on the outer shell around it. It was deemed necessary due to concerns of the male part snapping under load. This part would connect to the pylon by overlapping the outer and inner walls and be held together through a tight tension fit and adhesion.

Figure 30. Renders of coupling design, development one.

Figure 31. *Images of coupling design, development one.*

SECTION A-A

SECTION B-B

Figure 32. Orthographic diagram of coupling design, development one.

DEVELOPMENT TWO

Development two moves where the connection is located, by having a part that uses the standard grub screw connector for the foot with the coupling between the foot and pylon placed just above. This allows for angle adjustment while having a small male part always connected to the foot. This part can be elongated to allow for height adjustment for different foot prosthetics. It has a larger wall thickness that creates an envelope for the levers to sit in but has an indented pattern to reduce material use and print time. The pylon would connect in a similar manner to the OEM. .

Figure 33. Rendert of coupling design, development two.

Figure 34. *Images of coupling design, development two.*

SECTION A-A

SECTION B-B

Figure 35. Orthographic diagram of coupling design, development two.

DEVELOPMENT THREE

Development three moves the focus away from the connection to the foot leaving a standard OEM connector in its place. The couplings connect to two separate pylons, one to the OEM foot and the other to the socket, with this concept being situated in the middle of the pylon. It uses the same indent pattern from concept two to reduce material use and print time.

Figure 36. Renders of coupling design, development three.

Figure 37. *Images of coupling design, development three.*

SECTION A-A

SECTION B-B

Figure 38. Orthographic diagram of coupling design, development three.

Q U A L I T A T I V E R E F L E C T I O N

Reflection of Nylon Prints:

- Having further developed the cam mechanism tolerances, meshing between the mechanism and male component is much smoother and produces a tighter fit between all components.
- By making the bodies smoother, the ergonomics of the lever was improved.
- Further development would require making the lever more ergonomic for amputees reaching down to their ankle to engage & disengage the mechanism, including creating a larger surface area to interact with the cam levers.
- The pattern ident on Development Two & Three was efficient at removing material while maintaining a larger envelope but left the part with a very industrial look.

These developments were a step in the right direction, although further emphasis on the ergonomics of the system was needed. The focus up until this point was on how the parts interact with each other rather than how a person interacts with them. It was deemed that Development One had the most promising user interaction, as pulling the levers up felt more natural for disengaging the mechanism and would allow people to kick them back down to engage. Its curved form also made it easier to fit a finger under the lever to pull it up. Developing the lever would mean creating a larger area to grab on and interact with, designing the end to be more spoon-shaped. Also protruding the end of the mechanism further out from the female component would give more room for people to place their fingers or toes under.

Developments Two & Three, while being promising, did have the issue of having a body that is wider than the pylon. This would make it difficult for a leg fairing to slide over and then conform to the pylon. The male component of Development One also has this issue, this can be solved by redesigning and inserting the part inside of the pylon.

F I N A L I T E R A T I O N S

The levers were iterated to have a larger surface area and be more ergonomic to ease the process of engaging and disengaging the coupling. Bike release mechanisms and brake levers were used as precedents during this process, because of their ergonomic form which has been developed for over 100 years (Duck, 1897). The spoon-shaped design has been incorporated at the end of the lever as previously discussed.

The male component was redesigned to be inserted inside and flush with the pylon. This was to create a uniform diameter that would allow a leg fairing to slide over it. At this stage, the component would be held inside of the pylon through friction and adhesion.

During assembly, it was discovered that the positioning of the lever pin was not ideal and was causing slight interferences with the mechanism. Iterating this required editing the sketch on the female component and moving the pinpoint until it showed in the assembly that the parts would not interfere with each other.

Figure 39. *Iterative process of lever design.*

FINAL PRINTED DESIGN

The final design is an advancement of Development One, with many details being implemented from the previous discussion. The body of the female component was altered by lengthening the indented area to incorporate more of the model and to allow more room for someone to reach under the levers. Otherwise, the design has not been altered.

Figure 40. Renders of coupling design, final printed design.

Figure 41. *Images of coupling design, final printed design.*

Figure 42. Orthographic diagram of coupling design, final printed design.

FOOT - PROSTHETIC DESIGN

INTRODUCTION

Many of the foot concepts have been designed with reference to traditional multi-axel foot prosthetics, using information researched from the NZALS line of prosthetics. The reason for this being that they offer the most stability and comfort on uneven surfaces and work for medium to high activity levels. Unlike multi-axel prosthetics, the foot will be printed as one part, removing bumpers and pins that lead to wear on the foot. This form will also lead to the foot being lower in ankle height allowing for it to accommodate a larger percentage of people dependent on where their amputation is.

Analogue sketching involved creating a grid template for sizing of the foot. Measurements were taken from a SACH prosthetic foot which included a foot shell, a grid of 230mm – 90mm was created. This grid was split into sections including how far the toes curve upwards, which sections are devoted towards the heel, actuation in the mid-foot, and where the foot will interact with the pylon/coupling. These measurements and sections were further explored through ideation of a drawing of the inner works of the foot(Fig. 2).

At this point in the research, two-dimensional drawings were sufficient to create reference points in CAD. These concept drawings were based on ideations developed during the precedent research stage.

Figure 43. Sketches of foot-prosthetic design, concepts.

C O M P U T E R A I D E D D E S I G N

CAD work in SolidWorks involved taking the two-dimensional sketches and scaling them to 1:1. From there, alterations were made in three-dimensions to give further form and to develop the functionality of the foot prosthetic. 3D-sketching and surface modelling in SolidWorks was explored to produce more complex forms that couldn't be created through solid modelling.

Based on previous experience and expert opinion at the AddLab, the minimum thickness that nylon SLS can be comfortably be printed at is 0.7mm. Based on these recommendations, the thinnest that parts will be modelled at is 0.8mm to allow for deformation and shrinkage during printing

C O N C E P T O N E

Concept one explores the use of minimal nylon straps that mimic the structures of tendons in the foot. This was done to explore a minimal prosthetic that is capable of mimicking gait movement. The overall structure gives the impression of a sandal design and has a small profile.

Figure 44. Orthographic diagram of foot-prosthetic design, concept one.

Figure 45. Images & renders of foot-prosthetic design, concept one.

C O N C E P T T W O

Concept two is designed after more traditional multi-axel foot prosthetics but begins to explore the material properties of nylon along with a structure that can only be made through AM. This is the bellows structure that is located below the pylon, which allows for compression and shock absorption during gait movement.

Figure 46. Orthographic diagram of foot-prosthetic design, concept two.

Figure 47. Images & renders of foot-prosthetic design, concept two.

CONCEPT THREE

Concept three is a much blockier prosthetic. Designed after Mark Ingles climbing prosthesis, which was created for uneven terrain found while hiking and was an ideal place to trial how AM could mimic traditional material designs; using multiple struts to create tension between parts and allow for energy transfer from heel-strike to toe-off.

Figure 48. Orthographic diagram of foot-prosthetic design, concept three.

Figure 49. Images & renders of foot-prosthetic design, concept three.

C O N C E P T F O U R

Concept four uses the same bellows design from concept two while filling out the shape of the foot with a larger profile. The design also allows for greater energy return with a continuous profile travelling the foot.

Figure 50. Orthographic diagram of foot-prosthetic design, concept four.

Figure 51. Images & renders of foot-prosthetic design, concept four.

C O N C E P T F I V E

Concept five has a novel design, with a similar shape to a traditional jandal, allowing for a flexible and springy toe. It has a large solid ankle/heel to allow for stability and balance when walking/standing.

Figure 52. Orthographic diagram of foot-prosthetic design, concept five.

Figure 53. Images & renders of foot-prosthetic design, concept five.

Q U A L I T A T I V E R E F L E C T I O N

- Concept One, the wall thickness was too small or print orientation was not ideal as the print ripped itself apart during the printing process. This is displayed by the gaps in the material.
- Concept One has a much smaller envelope than expected and what was displayed when designing, especially in the width of the foot. This can be increased to fill more of the foot form.
- The bellows design from Concepts Two and Four was highly successful with the parts able to compress and spring back to their original position.
- The rest of Concept Two's form was too stiff to allow for flexibility during gait movement.
- This lack of flexibility stems from the brittleness of Nylon Pa12 and design changes had to be incorporated for the material to be viable.
- Concept Three had too many constraints on the individual struts and parts, which led to the print breaking before it arrived due to being dropped. The fact that it did break so easily does show that this is not an avenue to further explore.
- Concept Four had the successful bellows design, but it also had more constraints on its ankle movement. This has led to a more successful print as it limits the compression around the ankle and transfers elastic strain energy to the mid-foot.
- Concept Five printed successfully with an elastic toe providing sufficient propulsion. The heel was printed with a light tread that was meant to flex with uneven terrain. Unfortunately, the thickness/form of the material left this rather inflexible.

Through discussion, the bellows design was deemed intriguing considering how well the system flexed as a 3D print. It was discussed, however, that the overall form of these prints didn't fill out the shape of the foot enough, particularly around the heel and ankle, which would be needed for fitting into shoes and other forms of footwear and that further development was needed. Concept three was a complete failure as the high amount of restraints on the parts meant that parts could not flex and make the most out of the material, but this did point the project in the right direction by focusing more on longer, flatter sections of material; leading on to further interest in developing Concept One's idea of using an outer shell as a dynamic foot.

The SLS printer can print a minimum thickness of 0.7mm. The minimum thickness that was used during these prints was 0.8mm to allow for material inconsistencies and to achieve a higher degree of flexibility out of the designs. This thickness was acceptable in most of the prints, particularly the bellows spring design which had a thickness of 0.8mm. However, in Concept One, the sections that were destroyed during printing were also 0.8mm, although the section under the ankle printed fine at this thickness.

D E V E L O P M E N T S

A further set of development explorations were designed, iterating on the bellows design from Concepts Two and Four.

These experiments provided valuable insights into print performance and dynamic properties, however, they did not meet the visual expectations of a foot.

However, further, development involved looking back at how the foot compresses and flexes during the gait cycle and annotating important areas and areas where material could be removed. It also involved creating small foot shells that could be drawn on and have material cut out to explore the dynamics without having to CAD and print different designs.

Figure 54. *Sketches of foot-prosthetic design, developments.*

DEVELOPMENT ONE

Figure 55. Orthographic diagram of foot-prosthetic design, development one.

Figure 56. Renders of foot-prosthetic design, development one.

DEVELOPMENT TWO

Figure 57. Orthographic diagram of foot-prosthetic design, development two.

Figure 58. Renders of foot-prosthetic design, development two.

F O O T - S H E L L D E S I G N

E X P E R I M E N T S

Sketch prototyping of Foot shells was modelled in SolidWorks from a recreated loft of an open-source foot scan, as a quick and dirty method of testing ideas. This was done by creating slices and lofting between the sketch planes. The reason for this was to improve workflow and to allow for greater control during modelling. The recreated model was simplified to be more shoe shaped to reduce complexities and time spent modelling. The foot shells were scaled down by 50% with a 1mm wall thickness and sent away to the AddLab to be printed in SLS Nylon.

Figure 59. Screenshots of human foot model.

Figure 60. Images of little foot sls print.

Based on these annotations developed through footage of a human gait cycle, an informed decision was made where to place cuts in the material to create flexible sections. With the use of a rotary tool and a bullnose cutter, these sections were successfully cut out and showed promising designs that could be developed from these findings.

Figure 61. Annotated diagrams of human foot gait.

Figure 62. *Experimental process of creating a dynamic foot shell.*

P R O S T H E T I C E X P E R I M E N T S

Using the same open-source 3D foot scan, new slices were made to be more accurate than the previous version. This included keeping the details from the toes, however, due to the new complexity of the model 3D spline sketches were needed to act as guide curves for the loft to be successful. The goal with the following modelling was to use the previous experiments as a reference to produce a foot shell that, with the use of corrugations in place of the cut sections, would be able to flex.

It was determined at the start of CAD modelling that the best way to design the foot shell prosthetic was to use surface modelling. This, in combination with 3D-sketching, would allow for greater control of which sections of the foot could be trimmed and which would have different thicknesses. From the surface model, the main body of the foot was thickened to 2mm, with the corrugations being sketched and modelled off the edges of this body and then thickened to 1mm, to allow for greater flexion in these areas.

Figure 63 (a). Screenshots of foot shell design, prosthetic experiments.

In one of the models, inner components from previous experiments were incorporated to explore how additional dynamic elements could be combined with a shell configuration. This included placing a similar plane as a carbon fibre foot from the toes to the ankle to provide extra tension. Under the ankle are two offset bellow springs, these are intended to provide extra support with the corrugations in these areas and to hold the spring plane from the toes.

This entire process was filled with errors and backtracking to get models to work. This was mostly due to difficulties in SolidWorks with thickening complex surfaces, mainly in the areas with toes. There were also interesting results from cutting solid bodies producing new sharp protruding faces. The main issues were with joining the corrugation bodies to the main foot body. These sections were produced by surface lofting converted 3D-sketches of the foot edges with guide curves to produce the curved shape. They were not 100% accurate and led to joining issues. To mitigate this, the edges were further offset in order to intersect the two bodies, so that they would be able to merge. This still had hidden issues, with a cross-section showing that these bodies were not fully connected.

Figure 63 (b). Screenshots of foot shell design, prosthetic experiments.

C O R R U G A T I O N

D E S I G N

F D M T E S T S

Before sending the models to be SLS printed, it was decided to test simplified corrugation models printed through FDM that would show whether these designs would compress as expected. These would be significantly cheaper than a full SLS print and could be printed internally at the School of Design. At this point, the hidden issues of bodies not being fully combined were discovered, further emphasising the need for testing. It also allowed time to test different modelling methods inside of SolidWorks. It was found that using solid modelling had much more favourable results due to the ability to use sweep-cuts to create corrugations and then shell the model to the desired thickness. Originally, this wasn't considered the best way of modelling the foot shell as it seemed better to have the main body thickness of at least 2mm with the areas of flexion 0.80-1mm and it didn't appear possible to have multiple thicknesses through shelling. This, was not the case, however, as the areas of the face that had no material removed can be offset and thickened, resulting in a part with multiple thicknesses.

Figure 64. Screenshots of corrugation design, *fdm test prints*.

Qualitative Reflection

Although common issues occurred, through FDM printing such as splitting along layer-lines and removal of support material, the experiments showed that there was still promise in the geometry, though it appears that it was not the curve itself that is compressing but the flat sections that connect to the wall. The curve mostly just helped relieve stress from the material flexing. This was further confirmed by examining stage one concept two's bellow design, where the curved sections remain rigid and the transition sections between them allow for flex.

Figure 65. Images of corrugation design, *fdm* test experiments.

S L S T E S T S

Two more models were developed to test the corrugations. These would be printed in SLS Nylon PA-12, hopefully avoiding the same issues found with the FDM prints of layer-lines splitting. The purpose of these models was to test finer details of the foot design where the corrugations end midfoot rather than underneath the sole. These details include having the ends taper out into the foot, having a sharp end that is closed off, and having the same sharp end but the section is open. They would be printed with a 1mm wall thickness.

A two-week turn around was required for these prints, during this time focus was on designing the foot prosthetics. Two different versions of these prosthetics would be created, one with the sharp ends, and one with the tapered ends, implementing the desired details when the results of the SLS test came back.

Figure 66. Screenshots & renders of corrugation design, sls test prints.

Qualitative Reflection

Upon testing the 3D prints the corrugations were stiff under hand pressure and required considerable force to compress them. Standing on the parts they were able to support an adult males' weight, with the corrugations compressing as intended. The only area of concern was towards the end of the corrugation with the material appearing to be buckling slightly. This could be due to the flat wall placing too many restraints on the model and could be mitigated on the foot design where there are fewer restraints. Further development included implementing the tapered design into the foot prosthetics, as from a style and design perspective these were the preferred details. The tapered design gave a sense of dynamics and momentum to the otherwise rigid shell.

Figure 67. Images of corrugation design, sls test experiments.

F I N A L F O O T D E S I G N

The final foot system focus was split into two different foot shell models, each with an iteration that includes inner components and one that is only the hollow foot shell. This was to explore the dynamic differences that could occur between the two options. It was not clear whether these internal components would place too many restraints on the model and cause it to break or if they would support the dynamic performance of the shell.

For the new foot designs, the base loft was refined to create a more accurate model and to remove errors that had occurred in previous iterations. The new foot would be created as a solid model that can be edited through cut operations and later shelled to create a hollow body. These cuts would use the same profiles as developed during the foot shell experiments as reference points (Fig. 61).

Due to these prostheses being used in coastline environments, a method for water to drain from the foot shell was needed. With the corrugated foot design, this was already solved with a section of the sole being cut to allow for the corrugation to flex properly. The slot foot design needed a small drainage detail added to the inside of the foot.

C O R R U G A T E D F O O T - P R O S T H E S I S

Modelling the corrugated foot prosthesis required creating 3D-sketched splines that were given a surface relation to the foot model to accurately conform to. These would then act as guide curves for a sweep cut operation. The sweep cut has the same profile as the bellow spring design but has offset the curve further into the model to accommodate a wall thickness of 1mm when the model is shelled. Through this method of modelling, the form of the prosthetic could be easily manipulated by editing and dragging the 3D-sketch spline until the preferred sweep was produced. The tapered detail on the foot was created simply by dragging the ends of the spline away from the foot.

Figure 68. Orthographic diagram of final foot design, corrugated foot-prosthetic.

Figure 69. Images of final foot design, corrugated foot-prosthesis.

S L O T F O O T - P R O S T H E S I S

The slot foot prosthesis uses the same cut profiles as the corrugated foot prosthesis, although it changes out the corrugations for a series of slots. These slots would allow for the prosthesis to compress and be dynamic while maintaining its three-dimensionality. For this, design a wall thickness of 2mm was decided upon, to mitigate material failure or not providing enough support to the amputee.

Figure 70. Orthographic diagram of final foot design, slot foot-prosthetic.

Figure 71. Images of final foot design, slot foot-prosthetic.

INNER COMPONENTS

The inner components included in the alternative designs for the corrugated and slot foot prostheses have a similar design as the ones developed during the first foot shell prosthesis. These components include a sheet of 2mm nylon that acts the same as a carbon fibre prosthetic design, through the use of a curved profile acting as a spring, as well as the use of a bellow spring design to provide extra support and stability.

Figure 72. Orthographic diagram of inner components, corrugated foot-prosthesis.

Figure 73. Orthographic diagram of inner components, slot foot-prosthetic.

A D D I T I O N A L P R O D U C T S & C O M P O N E N T S

During the development of this research project, some additional resources were produced as a way of assembling a coherent product system proposal. These resources include the designs for a TPU sole that can be further developed to be integrated into the foot design and a leg fairing that allows for access and interchangeability with the coupling system.

LEG FAIRING

The leg fairing uses the same 3D scan data as the foot design. It has a cut profile that is offset from the foot by 10mm, this was due to potential problems with tolerances and meshing of the fairing and foot, especially with the shrinkage that can occur during printing. The cut has a similar profile as what is used in the heel of the foot to give some unity to the two parts. A section has also been cut out to allow for access to the coupling mechanism.

Figure 74. Orthographic diagram of leg fairing.

Figure 75. Images of leg fairing.

S O F T S O L E

A soft sole that can grip onto rocks and other surfaces was deemed necessary for a cohesive product system, especially one that would be used in a coastline environment. Four different design solutions were explored, these are shown as follows;

- A series of custom TPU-printed inserts that would fit into the recess of the sole. These have a tread pattern reminiscent of those found on football cleats.
- By using ready-made rubber stoppers, a tread can be inserted into the sole, similar to the custom TPU inserts.
- A full TPU-printed sole that can be attached to the bottom of the foot. This sole would have a tread pattern that is reminiscent of how an FDM printer lays down material in a circular pattern.
- A silicone dip cast, where the sole of the prosthesis would be submerged to create a robust layer of protection to the foot design.

Figure 76. Renders of tpu-printed inserts.

Figure 77. Render of rubber stopper.

Figure 78. Render of tpu-printed sole.

PROPOSED PRODUCT SYSTEM

QUALITATIVE REFLECTION

All prints for this research portfolio were done via the AddLab, in SLS Nylon PA-12. This ensured a consistent material and print quality throughout the project, including some of the stiffness and snapping issues that had occurred. All the prints were successful, with no deformations, or otherwise notable problems. The AddLab team did note that there was some difficulty removing excess powder from inside the prints, particularly in the sections with bellows.

Figure 79. Orthographic diagram of proposed product system.

Figure 80. *Render of proposed product system, slot foot-prosthetic.*

Figure 81. *Render of proposed product system, corrugated foot-prosthetic.*

S L O T D E S I G N

The slot cut designs had an interesting dynamic quality to them, with the cut sections closing when the foot is engaged through the pressure of someone standing on it and opening back up as pressure is relieved and propelling the foot. This is particularly interesting with the foot design that includes internal components, as it shows an interesting dynamic of these components in action. The slats themselves required further development because they are rather flimsy and could be prone to breaking. This same sentiment was noted by the NZALS, with them noting that it has an interesting visual expression of the dynamic quality and being able to see inside of the foot is fascinating, but the slats would require more development.

Figure 82 (a). *Images of dynamics of slot foot-prosthetic.*

Figure 82 (b). *Images of dynamics of slot foot-prosthetic.*

C O R R U G A T I O N D E S I G N

Likewise, the corrugation designs had an interesting visual expression of flexion, however, the front of the foot with the double corrugation was too stiff/ the geometry was not ideal, as with one of the prints it exploded under tension. This could also be due to excess powder, that was found around the corrugations, stopping the print from flexing as intended. The other two corrugated cuts do work as intended, with them being able to compress and spring back. This is particularly apparent around the heel, with the two edges able to compress and touch. There are, however, some issues with the material buckling under tension, and this could cause issues with more wear.

Further development would require adjusting the geometry in the front of the foot, through editing the corrugation and opening the cut under the sole, to allow the edges of the corrugation to flex more inwards. Transitioning from PA-12 to PA-11 could potentially solve the fears and issues around the prints buckling and snapping under tension. It is said that PA-11 has more elastic properties in comparison to PA-12 and is more sensible for prosthetic development (Sculpteo, 2019).

"People often say that, for entrepreneurship and innovation, it is important to fail fast and fail often. With additive manufacturing, we now have the ability to fail extra fast and extra often. And that's a good thing!"
- (Diegel, 2019)

Figure 83. *Images of exploded corrugated foot-prosthetic.*

C O U P L I N G S Y S T E M

The coupling system printed flawlessly, with a good set of tolerances, allowing each component to integrate with the other. The male component was inserted into the pylon and sits with a friction fit. For connecting the female component to the pyramid foot component, the bottom four series of holes were tapped to fit an M8 grub screw. This is the same standard of screws that were found on the OEM coupling. Female and male components sit together, with the mechanisms meshing the components. There is little to no movement between the components when the mechanism is engaged and is sitting with ideal tolerances. Increasing the surface area at the end of the mechanism lever was a nice detail, as it makes the act of using the lever much easier.

LEG FAIRING

The leg fairing printed with no issues. An EVA foam insert was required to hold the fairing in place with the pylon, this was supplied by the NZALS and cut to fit. Due to the soft fit around where the user reaches into the fairing to engage and disengage the lever mechanism, little issues occurred. This, however, does require further development, as the few issues that did occur were concerning the fairing twisting and sliding down the pylon.

Figure 84. Images of developing eva foam insert for leg fairing.

STUDIO PHOTOGRAPHY

Figure 85. Image of product system proposal, studio image, slot foot-prosthetic.

Figure 86. Image of product system proposal, studio image, corrugated foot-prosthetic.

Figure 87. Image of product system proposal, studio image, leg fairing.

Figure 88. Image of product system proposal, studio image.

CONTEXT PHOTOGRAPHY

Figure 89. Image of product system proposal, context image.

Figure 90. Images of product system proposal, context image, dynamics of slot foot-prosthetic.

Figure 91. Images of product system proposal, context image, wearing slides.

Figure 92 (a). Images of product system proposal, context image, corrugated foot-prosthetic.

Figure 92 (b). Images of product system proposal, context image, corrugated foot-prosthetic.

Figure 93 (a). *Images of product system proposal, context image, slot foot-prosthetic.*

Figure 93 (b). Images of product system proposal, context image, slot foot-prosthetic.

D I S C U S S I O N
&
C O N C L U S I O N

D I S C U S S I O N

This section aims to explain and evaluate, how the design process and outputs address and relate to the original research statement. This evaluation helps to contextualise the research in the broader design discipline, through correlating and contrasting the literature and precedent review with the knowledge gained in the research through design phase. This section also discusses the limitations and opportunities of the research.

S U M M A R Y O F K E Y F I N D I N G S

This research project presents a design proposal for the NZALS, to allow them to consider the future development of 3D-printed prosthetics and to facilitate their goal of remote service provision. This project was conducted through a two-part design research methodology, research 'for' design and research 'through' design, with many different methods used under these methodologies (Milton & Rodgers, 2013). These methodologies address the main purpose of the research project, to produce new design knowledge.

The study shows that additive manufacturing can open a broad range of design possibilities that traditional manufacturing cannot compete with. However, as stated by Diegel, not everything should be produced through AM, and that only when the process adds value to a design should it be considered (2019). The prosthetic designs and systems shown throughout this research project demonstrate this added production value, by producing forms that cannot be made through traditional methods. Furthermore, AM allows each of these forms to be individually tailored to the amputee's biomorphic data and dynamic requirements. Due to fewer manufacturing limitations through AM, a focus was able to be placed on the aesthetic and dynamic function of the designs. This is supported by a Wohlers report, which indicates that this increased freedom increases the value of the parts (2016).

Research through design was split into three sections of development, the quick-release coupling system, foot-prosthetic design, and products to complete the product system, with DFAM being the driving criteria throughout the design process.

I N T E R P R E T A T I O N S

Rapid Prototyping

Throughout this design research project, AM has been utilised for its advantages in rapid prototyping, which used to be the main application of AM (Sherman, 2009). These advantages became very apparent during the research through design phase, as it allowed for the quick production of parts and components. This is especially evident during the *foot shell* and *corrugation* experimentations because it allowed a range of design experiments to be printed, analysed for ideal performance and form, and iterated as a series of experiments.

Rapid prototyping also shows its advantages when looking at more advanced printing methods such as SLS. Through SLS, components could be printed by the AddLab in a timespan one to two weeks. These prints, although being produced slower than on an FDM printer, showed a higher level of complexity. The reasoning behind the slower print times was the administration of the print files, rather than the print time itself. Print times for the AddLabs Pro-X 500 SLS printer are around 30hrs for a full bed print. While this does appear to take a fair amount of time, in the grand scheme of manufacturing, this is a very quick turn-around.

“With Additive Manufacturing, we now have the ability to fail extra fast and extra often, and that’s a good thing!” (Diegel, 2019). This quote in itself proves the advantages of experimental rapid prototyping through AM. This was, however, further demonstrated through the SLS design concepts and developments produced during research through design. During this phase, it was unsure whether the designs would work as intended, in a few cases they did not. These failures were able to be quickly analysed and modified as required.

Design for Additive Manufacturing

Design for Additive Manufacturing was the driving criteria for this design research project. Design knowledge around this area is limited due to AM being a relatively new process, with most of the research coming from Gibson and Diegel (2010; 2019). This knowledge was mostly focused on metal printing and is very engineering-focused, rather than design-focused.

DFAM, in the context of this research, was exploring the new possibilities that this design process can achieve, due to a decrease in limitations compared to traditional manufacturing (Wohlers, 2016). The study demonstrates highly complex models that have been designed through this process. This is shown through the development of the *quick-release coupling system* and the *foot-prosthetic designs*.

The coupling system used metal DFAM principles to produce a multi-component system that allows for the interaction between itself, the pylon, and the foot. Live parts were incorporated into the design of the female component, to be used as a lever mechanism. With a tolerance of 0.2mm, a fusion between these parts and the pins that they rotate around was avoided. The designs show an emphasis on how a part can be developed to use minimal material, while still producing a strong functional print.

DFAM takes a different approach through the development of the prosthetic foot designs. In this section of research through design, a focus was placed on creating dynamic forms out of a rigid material. It was shown that through smart designs and thicknesses, this could be achieved. This is especially seen with the bellows design, which demonstrates the unique dynamic quality of being able to compress and spring. This idea of using compression was iterated into the foot form by creating corrugated cuts. These cuts were ideally there to allow the foot to flex and spring in the same manner as the bellows. This, however, was not fully realised, as found through the mid-section of the *corrugated foot design*, which quickly exploded when a large force was applied. The idea still shows promise, as demonstrated around the heel and ankle of the foot, which does exhibit compression and articulation.

As shown through the *slot foot design*, DFAM again proves its use in creating complex dynamic forms. These designs not only allow for dynamic articulation but also exhibit a dynamic design aesthetic. This is shown through the tapering cuts, moving towards a point, through a sweeping motion. Further dynamics are demonstrated by the internal components that are visible through the slats. Here is where DFAM truly shines, as, through a manufacturing point, these internal structures would be impossible to be produced any other way. But, also from a design point, this shows the unique characteristics that this manufacturing method can achieve.

AM Prosthetic Production

The study shows that additive manufacturing's batch production is a perfect medium for prosthetic production. This is due to the prosthetics needing to be highly customised to the amputee, with each print having different forms and properties. Current methods of prosthetic production involve a labour heavy process of moulding the amputees' residual stump and casting a socket, usually out of fibreglass. From this point, different pre-made foot and pylon components are tried by the prosthetist and amputee, to achieve a natural gait.

This research demonstrates that sections of this process can be digitised. This is shown through the modelling of the leg fairing and foot designs. The process of developing these designs involved taking an opensource 3D-scan of a leg and foot, and recreating and manipulating the forms in CAD. This process could be further developed to involve creating 3D-scans of the amputees' leg prior or after amputation, and then be recreated for production through AM.

In addition to the discussion in the preceding DFAM section, AM for prosthetic production opens new dynamic possibilities, through the creation of complex models. Such models could exhibit more of a human form, in comparison to the thermoplastic-carbon-fibre prosthetics, while still demonstrating reliable articulation. The study also addresses claims in the literature, where the population prefers the choice of how their limbs look. This can range from subtle human-like forms to custom artistic prosthetics (Ferrendelli, 2018). This opens a wide range of possible design directions for fairing/foot combinations, which this research has only begun to touch on.

As a result of using AM for design and manufacturing of all components, the overall product system can exhibit a cohesive design language. By comparison, the NZALS currently use a wide range of different components, made by different manufacturers, which leaves the overall prosthetic feeling disjointed. The research project begins to establish the NZALS' goal of remote service provision, with AM prosthetic production being the driving force behind this development. Through traditional products and methods of production, this idea would not be possible. This is due to technicians not allowing the current connectors between parts, to be adjusted by the amputee. The product system proposed uses AM to provide a solution to this. This system, using the AM coupling connector allows technicians to set adjustments according to the amputee, from here the amputee is free to uncouple the components and switch out different foot prosthetics, for different situations. This also provides a safety point, where if a prosthetic were to break, the amputee would be able to change to another prosthetic, while they wait for a replacement from the NZALS.

I M P L I C A T I O N S

Most of the research and precedents found during the research for design stage were focused on either highly conceptual specific prosthetics or low-cost FDM printed prosthetics. Only one foot-prosthetic, produced through SLS is currently certified and available for purchase, this being the Next-Step foot (Mecuris, 2020). While this foot prosthetic does address many of the same objectives as found in this research, such as its ability to be used in water its form suggests a utility approach to design.

This research builds on these existing designs, to present a new product system proposal. Compared to the previous research this project aims to demonstrate a coherent design system, that is produced through AM and exhibits a unique design language, while still referencing a human form and suggests a human need for greater choice.

FUTURE RESEARCH

Further research is needed to establish a fully functional foot prosthetic. This requires further development of the foot forms, especially around the corrugation designs, as they show promise of having a dynamic foot prosthetic. Another option for creating a dynamic foot would be through the use of surface latticing, in place of the cut profiles. Surface latticing would allow for the material to deform and flex without breakage. This latticing could still have a corrugated shape while demonstrating the same dynamics as the slot design. Furthermore, research is needed to establish a certified product system that has undergone clinical and engineering testing and has explored a range of different materials and printing processes in greater depth.

Material Exploration

Due to the prosthetic research being printed through the AddLab, materials and processes were limited to what they had to offer. Originally this project was going to explore both nylon PA-11 & PA-12 materials, as they have different material properties and PA-11 is said to be better for prosthetic production (Sculpteo, 2019). The NZALS also tend to prefer the use of multi-jet-fusion, for their prosthetic production, as they believe that it produces more robust prosthetics. Further research is needed to identify the optimal printing process and material selection for the dynamic foot-prosthetic.

For the coupling system, an exploration into metal printing with materials such as titanium is needed, as well as a design exploration into internal latticing for the components. This latticing would allow the components to be produced much lighter, and at a lower-cost, while still maintaining a strong structure.

Further research is also needed, for the implementation of a soft sole. This sole would have to be able to integrate with the foot prosthetic, but also be easily replaceable. SLS TPU would be a good avenue to explore for this application.

Clinical Testing & Engineering

In the scope of this research project, clinical and engineering testing were not considered. This research project, in essence, is the foundation for further research and development, including clinical testing and engineering.

Clinical Testing;

- Gait-analysis is needed on a case by case bases to identify individual gait cycles of amputees. This data could feed into customisation of the foot-prosthetic, with components slightly altered to fit individual needs.
- User testing of the overall product system is needed to identify and improve usability for both the amputee and technicians.
- Expert advice from technicians at the NZALS would identify areas that the research may not have considered.

Engineering;

- Finite Element Analysis (FEA) is needed to identify stress points and deformations on the models and can be achieved through computer simulations. This would allow for the development of a certified product system.
- Latticing explorations done through complex computer generation, this would involve experimenting with different node types and cell sizes for development of an optimal part.

C O N C L U S I O N

This research aimed to produce an explorative project into the production of additive manufactured prosthetics. Through the development of this project, a focus was placed on producing a coherent lower-limb prosthetic system proposal, that demonstrates new visual and structural qualities, dynamic three-dimensionality, and improved usability for amputees. Additionally, the research claimed that these qualities could not be produced through traditional manufacturing. The research was conducted in collaboration with the NZALS, in an aim to address the need for a dynamic prosthetic system that could be used in a coastline environment and would not lead to abrasion, as found in carbon-fibre prosthetics. This is supported in the NZALS mission statements of 2017-2021. Based on qualitative analysis, a demonstrative product system proposal has been produced. More importantly, the design knowledge of how this system was developed, has been produced.

The study used a two-part design research methodology. Research 'for' design has been conducted by summarising, collating, and/or synthesising existing research. This was followed by a research 'through' design approach, where new design knowledge has been produced, with sketches, models and manufactured goods being the by-products of this process. These methodologies facilitated the development of a product system proposal, which demonstrates the unique characteristics that can be produced through AM.

This research project addresses the need for AM produced prosthetics, as well as the continued development in this field. It demonstrates a case study that has produced a range of different products, which together produce a coherent product system proposal. This system exhibits many different unique characteristics and qualities that are unique to the AM process. The research identified a current gap in the design sphere surrounding recreational AM prosthetics systems.

Further research into this field of AM prosthetics would build upon the knowledge produced during this study. This would include additional development of the coastline foot prosthetic system, through the exploration of different materials and forms, to produce a reliable product. Furthermore, the implementation of clinical technicians and engineers would allow for certification of this prosthetic.

Lastly, the project aimed to provide future reference points for the NZALS to improve and expand their product offerings and to facilitate their goal of remote service provision. Based on the knowledge that has been developed during this research project, NZALS would be able to identify key areas for further prosthetic development, through qualitative assessment.

FIGURE LIST

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A P P E N D I X

S U M M E R R E S E A R C H

This section shows a poster developed from a summer research scholarship through Victoria University of Wellington, into the development of 3D printed foot prosthetics.

ADDITIVE MANUFACTURING + Prosthetics

The development of affordable and customisable Additive Manufactured nylon foot prosthesis.

Vincent McQueen Bernard Guy, Simon Fraser, Emily Allison, Sean Grey, Aaron Johnston, Camille Hay

Customisation has become a staple of modern style and expression. A lifestyle of expression that amputees deserve. Creating a level of freedom similar to buying a pair of shoes, made possible with rising technology and versatile plastics.

Original observations were made to create a research project on shells for foot prosthesis. Focus was moved onto creating stylised prosthetics due to the advent of versatile nylon plastics. These versatile prosthetics wouldn't need the same level protection from erosion that their carbon fibre brethren require.

Rising technology in additive manufacturing through SLS (Selective Laser Sintering) and FDM (Fused Deposition Modelling) are allowing for new versatile (nylon) plastics to be printed. Through material experimentation and design, forms were created around the human foot with stylised trends of modern shoes. Nylon is a very versatile plastic as depending on structure and thickness it can provide incredible strength and rigidity or unbreakable flex.

Two branches of prosthetics were created to meet needs and desires. One is a highly stylised SLS printed prosthetic, which utilises the possibility of lattice structures in the design to create structural and tactile segments with minimal material. This stylised lifestyle prosthetic is customisable through parametric structures and colours, allowing for a unique look and feel.

The other is a low cost FDM printed prosthetic that can withstand the New Zealand environment. Made from versatile plastic the prosthetic allows the traversal of rough terrain.

Fig 1. render of SLS print showing colour

Fig 2-7. development of FDM and SLS prints

Fig 8. Render of FDM print

Fig 9. FDM print

Fig 10. SLS print

D F A M A I R N Z R E P O R T

This section shows sigments from a design report for a AM business class monitor arm. This was developed during a practicum study as part of the Masters of Design Innovation course requirements. This practicum was completed under supervision of Callaghan Innovations; AddLab and was a project for Air New Zealand.

To use a display purpose monitor as reference to produce two ranges of new demonstration models that utilise Additive Manufacturing. These models would be able to withstand a force of 754N applied downwards. The equivalent of a passenger lifting themselves out of their seat.

One model that preserves the OEM aesthetic but removes all of the excess weight. Surfaces should appear the same from the front, top, and back. The only element of the underside to be preserved is the cable channel, otherwise it is open to change.

The second demonstrators is to exhibit the design possibilities achieved through AM. The only aspect that needs to be preserved is the basic envelope of the arm – so that it stills fits into the seat recess, otherwise all surfaces can be modified.

TOPOLOGY OPTIMISATION

Finite Element Analysis was conducted on the recreated OEM model in SolidWorks. In the simulation fixtures were applied to the pivot of the arm and 754N of static force was applied downwards on the edge where the monitor contacts the arm. This showed a maximum displacement of 3.54mm, with most of the stress around the first bend near the pivot of the arm.

A topology study was also conducted in order to see how much material was necessary. The simulation used the same inputs as the static displacement, with critical parts being preserved. It showed that up to 42% of the model had unnecessary material. The diagrams that were produced were good reference and helped inform my design decisions going through the project.

L A T T I C I N G

Lattices are simplified versions of topology optimisation, which involves transforming a section of a solid body often the infill into a truss structure. They offer a major advantage in reducing part weight without reducing part strength.

Based on a suggestion by Olaf Diegel the main lattice structure used through out the project was a dodecahedron cell type with a sphere node type. This was due to the self-supporting nature of the structure.

The Lattice used in this design is a dodecahedron cell type with a sphere node type. It has a cell size of 5mm x 5mm x 5mm, with a node diameter of 1.2mm and connector diameter of 1mm. This lead to an infill 31.2% with the outer walls being 3mm.

D f A M C O U R S E

The process of additive manufacturing, adding material layer by layer means that almost any shape can be produced. It allows use to be more innovative and daring with our designs and no longer being limited to tool paths allows for a great deal of complexity in these designs.

Not everything should be made using AM, if it is a simple part that can be easily tooled then that is the best way to make it. However, AM also allows for design to be more heavily incorporated into what was once more engineering focused. It doesn't cost any more to add design details, logos, etc.

Hole Sizes

To avoid internal supports and/or post machining, holes 45 degrees from horizontal shouldn't be larger than 10mm in diameter. A teardrop is a useful trick for creating a hole without support as the top of the diamond has an angle greater than 45 degrees.

Filletlet Everything

Sharp corners cause stress concentrations, which increases the need for support.

Avoid Larger Areas of Material

Build Considerations

Orientating and placement on the build plate are just as important as the design it's self as the quality, strength, surface quality and amount of support are all related to print orientation.

Support structures have both their advantages and disadvantages when it comes to the final build. They want to be avoided as it increases both the build time and post processing time. This can be avoided by having build angles 45 degrees and steeper. However, support structures have several key functions. They conduct excess heat away reducing stress, strengthen and fix the part to the build platform, prevent warping and are often part of critical surface finish areas that need to be post-processed anyway.

Usually parts are orientated on a scale of 1 to 8 (h), leading to many prints being orientated on a slight angle. This is often to reduce the area that is melted at once, reducing stress and warpage. Most of these prints however were printed completely vertical and came out perfectly straight. This is due to the angled OEM walls present and the latticing providing reinforcement to the walls.